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Study of Vertical Dense Jet Dilution in a Marine Environment

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A thesis submitted in partial fulfillment of the requirements for the degree in Doctor of Philosophy

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STUDY OF VERTICAL DENSE JET DILUTION IN A MARINE ENVIRONMENT
(Thesis format: Integrated Article)

by

Nadeem Ahmad

Graduate Program in Civil Engineering
Department of Civil and Environmental Engineering

Submitted in partial fulfillment
of the requirements for the degree of
Doctor of philosophy

The School of Graduate and Postdoctoral Studies
The University of Western Ontario
London, Ontario, Canada

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ABSTRACT

Brine is a byproduct of many industrial and mining processes, including desalination. Brine is commonly conveyed in long pipe lines and disposed in the bottom of the sea through multiport diffusers, forming dense jets, also known as fountains. An acceptable level of brine concentration is required to be achieved at the boundary of a regulatory mixing zone surrounding a point of discharge. Such mixing zones are allocated with the objective of limiting environmental deterioration within their boundaries. Mixing zones are, nevertheless, not allowed when discharging brine in sensitive areas and when brine is toxic.

The main contribution of this study is the introduction of the concept of minimum return point dilution, to regulate brine at the point of discharge, as an alternative to the mixing zone approach, which has well recognized limitations.

This study examined experimentally the dilution and development of turbulent negatively-buoyant upward and downward fountains. The study included low and high densimetric Froude number investigations of fountains in stagnant surroundings, and for linear water equation of state conditions. The dilution and spread of fountains were measured with fast responding thermocouples. Downward thermal fountains were found dynamically similar to upward dense fountains. The mean and maximum vertical jet penetrations obtained using temperature data were consistent with previous studies based on visual data. The minimum return point dilution of vertical fountains was found by analyzing the temperature data to be always located just outside the edge of the nozzle. The proposed minimum return dilution equations are providing simple modeling tools to design vertical fountains to comply with any required regulatory dilution at the source. This study also recognized the advantage of using vertical fountains, as opposed to inclined fountains. This is to take advantage of variable sea currents occurring in any direction. Furthermore, the study revealed that relative density difference, on a broader range applicable to the desalination industry, reduces noticeably dilution and height of fountains. Finally, a theoretical two-coefficient entrainment model of fountains was formulated based on mass, momentum, and buoyancy conservation principles, and the
sensitivity of model predictions to the calibrated values of entrainment coefficients are discussed.

**Keywords:** Fountains, negatively buoyant jets, dense vertical jets, mixing zones regulations, dilution of fountains, multiport diffusers.
CO-AUTHORSHIP

This thesis has been prepared in accordance with the specification of integrated article format stipulated by the Faculty of Graduate Studies at the University of Western Ontario. All the experimental work was conducted the Hydraulic Laboratory at University of Western Ontario by the author under the supervision of Professor Raouf E. Baddour. Major portion of the work outlined in this thesis has been published or are under review (see list below) for possible publication in peer reviewed technical journals. The co-authorship from Chapter 2 to Chapter 6 is as follows:

Chapter 2: A Review of Sources, Effects, Disposal Methods, and Regulations of Brine into Marine Environment

Nadeem Ahmad and R. E. Baddour

Submitted in Journal of Ocean and Coastal Management with manuscript number OCMA-D-13-00196.

Contributions
Nadeem Ahmad reviewed studies, extract required information, and conclude.

R. E. Baddour initiated the study and assisted in reviewing.

Chapter 3: Dilution and Penetration of Vertical Negatively Buoyant Thermal Jets

Nadeem Ahmad and R. E. Baddour


Contributions
Nadeem Ahmad set the experimental apparatus, designed experimental program, conducted experiments, analyzed data, interpreted results, and wrote the draft of the paper.

R. E. Baddour initiated the study and assisted the interpretation of test results and writing of the paper.
Chapter 4: Minimum Return Dilution Method to Regulate the Discharge of Brine from Desalination Plants

Nadeem Ahmad and R. E. Baddour


Contributions
Nadeem Ahmad designed experimental program, conducted experiments, analyze data, interpreted results, and wrote the draft of the paper.

R. E. Baddour assisted the interpretation of test results and writing of the paper.

Chapter 5: Density Effect on Minimum Return Point Dilution and Height of Fountains

Nadeem Ahmad and R. E. Baddour

A version of this paper will be submitted in Journal of Hydraulic Engineering, ASCE.

Contributions
Nadeem Ahmad sets experimental apparatus, designed experimental program, conducted experiments, analyze data, interpreted results, and wrote the draft of the paper.

R. E. Baddour assisted the interpretation of test results and writing of the paper.

Chapter 6: A Two-Coefficient Entrainment model of a Vertical Turbulent Fountain

Nadeem Ahmad and R. E. Baddour

A version of this paper will be submitted in Journal of Hydraulic Engineering, ASCE.

Contributions
Nadeem Ahmad developed theoretical model, wrote program code, analyzed data, interpreted results, and wrote the draft of the paper.

R. E. Baddour assisted in developing model, interpretation of model results, and writing of the paper.
To my parents, sons, and wife
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<th>Symbol</th>
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<tbody>
<tr>
<td>$B_j$</td>
<td>Buoyancy at any point in the inner jet of the fountain</td>
</tr>
<tr>
<td>$B_0$</td>
<td>Initial buoyancy</td>
</tr>
<tr>
<td>$B_p$</td>
<td>Buoyancy at any point in the outer plume of the fountain</td>
</tr>
<tr>
<td>$Fr$</td>
<td>Densimetric Froude number at the discharge point</td>
</tr>
<tr>
<td>$g$</td>
<td>Acceleration due to gravity</td>
</tr>
<tr>
<td>$g'$</td>
<td>Buoyancy acceleration at any point in the fountain</td>
</tr>
<tr>
<td>$g'_1$</td>
<td>Buoyancy acceleration at the point of minimum return point dilution</td>
</tr>
<tr>
<td>$g'_j$</td>
<td>Buoyancy acceleration at any point in the inner jet of the fountain</td>
</tr>
<tr>
<td>$g'_{j\text{\text{r}op}}$</td>
<td>Buoyancy acceleration of the inner jet entering the top part</td>
</tr>
<tr>
<td>$g'_0$</td>
<td>Discharge buoyancy acceleration</td>
</tr>
<tr>
<td>$g'_p$</td>
<td>Buoyancy acceleration at any point in the outer plume of the fountain</td>
</tr>
<tr>
<td>$g'_{p\text{\text{r}op}}$</td>
<td>Buoyancy acceleration of the outer plume leaving the top part</td>
</tr>
<tr>
<td>$g'_s$</td>
<td>Gravity scale</td>
</tr>
<tr>
<td>$l$</td>
<td>Intermittency</td>
</tr>
<tr>
<td>$L_s$</td>
<td>Length scale</td>
</tr>
<tr>
<td>$M_j$</td>
<td>Momentum at any point in the inner jet of the fountain</td>
</tr>
<tr>
<td>$M_0$</td>
<td>Initial momentum at discharge point</td>
</tr>
<tr>
<td>$M_p$</td>
<td>Momentum at any point in the outer plume of the fountain</td>
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<td>$Q_0$</td>
<td>Initial discharge of the nozzle</td>
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<tr>
<td>$Q_j$</td>
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</tr>
<tr>
<td>$Q_{j\text{\text{r}op}}$</td>
<td>Discharge of the inner jet entering the top part</td>
</tr>
<tr>
<td>$Q_p$</td>
<td>Discharge at any point in the outer plume of the fountain</td>
</tr>
<tr>
<td>$Q_{p\text{\text{r}op}}$</td>
<td>Discharge of the outer plume leaving the top part</td>
</tr>
</tbody>
</table>
\( r \) Radius of the fountain at any point from the centre of the nozzle

\( r_j \) Radius at any point in the inner jet part of the fountain

\( r_{j\text{\text{top}}} \) Radius of the inner jet at the top part

\( r_0 \) Radius of discharge the nozzle

\( r_p \) Radius at any point in the outer plume part of the fountain

\( r_{p\text{\text{top}}} \) Radius of the outer plume at the top part

\( S \) Salinity at any point in the fountain

\( S_1 \) Salinity just at the outer edge of the nozzle

\( S_a \) Ambient salinity

\( S_0 \) Discharge salinity

\( T \) Temperature at any point in the fountain

\( T_1 \) Temperature just at the outer edge of the nozzle

\( T_a \) Ambient temperature

\( T_0 \) Initial discharge temperature

\( T_s \) Temperature scale

\( U_j \) Velocity at any point in the inner jet of the fountain

\( U_{j(\text{ent})} \) Entrainment velocity of the inner jet

\( U_{j\text{\text{top}}} \) Velocity of the inner jet entering the top part

\( U_0 \) Initial discharge velocity

\( U_p \) Velocity at any point in the outer plume part of the fountain

\( U_{p(\text{ent})} \) Entrainment velocity of the outer plume

\( U_{p\text{\text{top}}} \) Velocity of the outer plume leaving the top part

\( z \) Height above the nozzle level

\( z^* \) Height below lower edge of the top part of the fountain
$z_m$ Average of consecutive frontal peak heights

$Z_{mean}$ Arithmetic average of all the penetrations

$\frac{z_m}{r_0Fr}$ Normalized maximum height

$\frac{z_{mean}}{r_0Fr}$ Normalized mean height

$z_p$ The peak height attained by the jet

$\delta$ Characteristic radial dimension

$\delta_m$ Maximum radial dimension

$\theta$ The angle in the degrees of the discharge nozzle with the horizontal

$\sigma_T$ Standard deviation of the temperature fluctuating signals

$\alpha_j$ Entrainment coefficient of fluid entering into the inner jet from the outer plume

$\alpha_p$ Entrainment coefficient of fluid entering into the outer plume from ambient

$\alpha_i$ Entrainment coefficient of fluid transferred from the inner jet into the outer plume

$\rho_0$ Initial discharge density

$\rho_a$ Ambient water density

$\frac{\Delta \rho}{\rho_a}$ Relative density difference

$\mu$ Dilution at any point in the fountain

$\mu_{min}$ Minimum return point dilution which occurs just outer edge of the nozzle

$\mu_s$ Dilution scale

$\mu_{average}$ Average dilution

$\frac{\mu_{min}}{Fr}$ Normalized minimum dilution

$\Delta S$ Excess salinity at any point in the fountain
\( \Delta S_0 \)  Excess salinity at discharge point in the fountain

\( \Delta T \)  Excess temperature at any point in the fountain

\( \Delta T_0 \)  Excess temperature at discharge point in the fountain

\( \Delta T_1 = \Delta T_{max} \)  Excess temperature just outer edge of the nozzle

\( \Delta S_1 = \Delta S_{max} \)  Excess salinity just outer edge of the nozzle
Chapter 1
INTRODUCTION

1.1 Introduction

Brine is a dense hot liquid produced as a by-product during various industrial and mining processes. During the last few decades brine production has increased exponentially due to rapid rise of various industrial and mining processes such as desalination, solution mining of salt domes, and potash and oil mining. Brine is usually disposed into the sea where high salinity and temperature of discharged brine have negative impacts on marine life (Jirka 2008). There are well known recent biological studies (NOAA 1978; Mabrook 1994; Pillard et al. 1999; Talavera and Ruiz 2001; Gacia et al. 2007; Matsumoto and Martin 2008) which have indicated that elevated salinity and temperature levels above the normal sea levels are harmful for the marine ecosystem. Even a slight increase of salinity above ambient is harmful for embryo, eggs, and larval of fish (Matsumoto and Martin 2008). In addition to high salinity and temperature, brine may contain harmful metals such as copper zinc, cadmium, manganese, and naphthalene which are harmful for marine life (Hutchesen 1983; Andreasen 1983).

Managing the disposal of brine into the sea is more challenging than urban effluents because brine is dense and sinks and spreads on the bottom of the sea, where it can disrupt the marine ecosystem. Moreover, brine is not allowed to discharge into freshwater resources. Traditionally, near-shore surface discharge of brine is still practiced in many parts of the world resulting in high concentrated saline water accumulation on the shores (Einav 2003). On the other hand, new environmental regulations of brine in various parts of the world are emerging in response to increased societies awareness of environmental issues. In the last decade, selection of a suitable brine disposal method to satisfy existing environmental regulations was an important issue in the feasibility of desalination plants in various parts of the world (Didier 2003; Safrai and Zask 2004; GCD 2005; Zander
Moreover, accommodation to future environmental regulations is also an important issue in the planning of a brine producing industry.

Now-a-days preferred methods for brine disposal involve the use of submerged multiport diffusers deep into the sea (Jirka 2008). Multiport diffusers discharge brine at the bottom of the sea forming dense jets (also called negatively buoyant jets or fountains) and acceptable levels of concentration of salt and temperature are achieved at some distance away from the discharge point. Figure 1.1 illustrates a vertical fountain of brine emanating from a vertical port of a diffuser. The region surrounding a fountain where concentration of brine is above the acceptable level is known as the impact zone or mixing zone (EPA 1994). Mixing Zone concept is widely used in the world to regulate brine to protect marine life (IMDs 2007). The allocation of a mixing zone around a discharge point is an economical strategy at the cost of environmental deterioration inside the limited area of the mixing zone. Allocation of mixing zones may have limitations in case of environmentally sensitive areas such as areas close to the drinking water intakes, fish habitat, recreation, and sensitive biota (EPA 1994; Rutherford et al. 1994; IMDs 2007; CCME 2008).

Figure 1.1: A Vertical Dense Jet (or fountain) and the Mixing Zone to Regulate the Brine Discharge.
There is a need to find an alternative to mixing zones by controlling brine at the source point so that harmful effects on marine life could be minimized. In this regard, detailed studies on dilution properties of fountains could be useful to design optimal diffuser systems and avoid limitations associated with mixing zones. Unfortunately, previous studies have not provided the required information on dilution of vertical fountains. The main focus of previous studies was to analyze vertical fountain penetration (Turner 1966; Abraham 1967; McDougall 1981; James et al. 1983; McLellan and Randall 1986; Baines et al. 1990; Zhang and Baddour 1998; Kaye and Hunt 2006; Baddour and Zhang 2009). Also recent studies (Nemlioglu and Roberts 2006; Kikkert et al. 2007; Gungor and Roberts 2009; Shao and Law 2010; Marti et al. 2011; Papakonstantis et al. 2011) are focusing on the dilution behavior of inclined dense jets with the objective of maximizing dilution of brine. However, inclined jet design strategy increases the size of mixing zones and also can reduce dilution when sea currents are in a direction opposite to the inclined jets (Robert and Tom 1987).

Experimental studies on the dilution of fountains were considered the best approach to address in the thesis the stated limitations of mixing zones. Extensive dilution data in laboratory fountains were obtained with fast responding thermocouples to draw dilution contours and dilution horizontal profiles at various distances above the source of vertical fountains. Dilution contours and horizontal profiles revealed that a fountain completes most of its dilution when it returns back to the level of the source. More importantly, dilution at the source level was found to have a minimum value just outside the edge of the nozzle. Figure 1.1 is showing the point of minimum return dilution just outside the edge of the port when the dense jet returns back to the level of the source. So, minimum return dilution achieved just outside the edge of the port is proposed in this thesis as a possible criterion to design vertical diffusers.

There are also other research topics of interest to this thesis in the field of fountains. Among them are (i) the effect of density difference on fountain height and dilution and (ii) prediction of entrainment characteristics of fountains. The first topic is important since brine produced from industries has variable densities ranging from very low relative density difference \( \frac{\Delta \rho}{\rho_a} = 0.001 \) of Multi-Stage Flash in desalination to very high \( \frac{\Delta \rho}{\rho_a} = \)
0.2 of oil and potash mining, and solution mining of salt domes (Tong and Stolzenbach 1979; Lattemann and Hopner 2008). It is important, therefore, to investigate the relationship between dilution and $\frac{\Delta \rho}{\rho_a}$ of fountains. Understanding the entrainment characteristics of fountains is also important as dilution of fountains depends on entrainment of surrounding fluid. Entrainment studies are also important in other fields such as volcanology where entrainment of external air into volcanic fountains affects volcanic eruption behavior (Carazzo et al. 2008). There is a need to develop a theoretical model of fountains so that entrainment behavior could be investigated.

To investigate the effect of density difference on minimum return point dilution, a series of experiments were performed and it was found that the parameter $\frac{\Delta \rho}{\rho_a}$ has noticeable effect on both dilution and height of fountains. To study the effect of entrainment on minimum return point dilution, a fountain model with two entrainment coefficients was developed based on conservation of mass, momentum, and buoyancy. The model predictions were used to examine the effect of the entrainment coefficients on minimum return point dilution.

### 1.2 Research Objectives

The main goal of this study is to find an alternative method to the mixing zone approach to regulate vertical fountains of brine. This goal was addressed by investigating the dilution of turbulent fountains over a wide range of Froude numbers. A physical model of a vertical fountain was developed to study the dilution of turbulent fountains in the Environmental Hydraulics Laboratory at Western University, London, Ontario. Both thermal downward fountains and thermal-saline upward fountains were investigated. Dilution was measured with fine wire thermocouples located at strategic locations throughout the tank. Experiments were conducted under stagnant water conditions as a worst case scenario of a turbulent fountain dilution. Only turbulent fountains (Reynold number >2000) were considered as discharge of multiport diffusers is normally turbulent in practice. The wall effect during experimentation was minimized by locating the discharge nozzle 15 cm above an elevated base plate of the experimental tank (or 15 cm below the free surface in the case of thermal downward fountains). To ensure that
fountain behavior was unaffected by wall effects, a long term test was performed to select a steady state window of time for the experiments.

The specific objectives of the thesis are to:

1. Review environmental regulations of brine around the world, as information of sizes of mixing zones and regulatory allowable limits are important to decide the experimental scheme in the laboratory.

2. Study the dilution and spread of turbulent fountains under stagnant and linear water equation of state conditions for high and low Froude numbers.

3. Compare downward thermal fountains with upward dense fountains within the same range of densimetric Froude numbers.

4. Determine the best discharge nozzle orientation by reviewing and comparing results of previous studies.

5. Determine the effect of relative density difference on dilution and heights of fountains.

6. Develop a theoretical model of vertical fountains and analyze their entrainment behavior.

1.3 Methodology

Figure 1.2 is a definition sketch of a vertical upward thermal-saline fountain. Immediately after the discharge the flow moves as a conical jet in the upward direction. The momentum of the starting jet is, however, gradually suppressed by the negative buoyancy of the flow. At some point above the source the momentum of the jet ceases, and the fluid returns back down as an annular heavy plume surrounding the upward conical jet.
During the upward and downward movements of the fountain, ambient water is entrained and mixed with the discharge. Dilution at any point in the fountain dilution ($\mu$) was determined by analyzing the temperature data and is defined as:

\[
\mu = \frac{\Delta T_0}{\Delta T} = \frac{T_0 - T_a}{T - T_a}
\]  

(1.1)

Where, $\Delta T_0$ and $\Delta T$ are excess temperature of the discharge and the fountain above the ambient temperature. $T_0 =$ temperature of the discharge, $T_a =$ temperature of the ambient water and $T =$ temperature at any point in the fountain.

In the case of dense thermal-saline fountains the definition of dilution applies to both temperature and salinity due to conservation of heat and salt. In this case, the dilution can also be defined as:

Figure 1.2: Definition Sketch of an Upward Fountain Generated by a Thermal-Saline Dense Jet
\[ \mu = \frac{\Delta T_0}{\Delta T} = \frac{\Delta S_0}{\Delta S} \]  \hspace{1cm} (1.2)

Where, \( \Delta S_0 \) and \( \Delta S \) are excess salinity of the discharge and the fountain above the ambient salinity.

In the case of linear water equation of state the buoyancy at any point in the fountain \((g')\), which is proportional to both temperature and salinity can also be used to define dilution. This is practically the case when experiments are conducted using water at temperatures above 15°C (Baddour 1994). In this case the dilution can further be defined as

\[ \mu = \frac{g'_0}{g'_1} = \frac{\Delta T_0}{\Delta T_1} = \frac{\Delta S_0}{\Delta S_1} \]  \hspace{1cm} (1.3)

Minimum return point dilution \((\mu_{min})\) is defined in this thesis as the dilution just outside the edge of the nozzle where the fountain returns back to the level of the source, as shown in Figure 1.2. The minimum return point dilution was determined experimentally by averaging the data of four thermocouples placed around the outer edge of the nozzle

\[ \mu_{min} = \frac{g'_0}{g'_1} = \frac{\Delta T_0}{\Delta T_1} = \frac{\tau_0 - \tau_a}{\tau_1 - \tau_a} \]  \hspace{1cm} (1.4)

Where, \( g'_0 \) = the discharge buoyancy; \( g'_1 \) = buoyancy just outside the edge of the nozzle. \( T_1 \) = mean temperature measured just outside the edge of nozzle at \( z=0 \),

Dilution of a fountain is directly related to its height. The maximum height of a fountain \((z_m)\) is generally known to be given by

\[ z_m = f(Q_0, M_0, B_0) \]  \hspace{1cm} (1.5)

Where, \( Q_0 (= \pi r_0^2 U_0) \) represents mass flux, \( M_0 (= \pi r_0^2 U_0^2) \) represents momentum flux, and \( B_0 (= \pi r_0^2 U_0 g'_0) \) represents buoyancy flux at the source; \( r_0 \) = radius of the source; \( U_0 \) = mean exit velocity. For turbulent high Froude number, and low relative density difference \((\frac{\Delta \rho}{\rho_a})\) fountains, dimensional analysis yields the following relationship (Zhang and Baddour 1997):
Eq. 1.6 shows that properties of high Froude number turbulent fountains depend mainly on the densimetric Froude number, which is defined as:

\[ Fr = \frac{U_0}{\sqrt{g_0 r_0}} \]  

(1.7)

Where \( U_0 = \frac{Q_0}{\pi r_0^2} \) = mean exit discharge velocity; \( g_0' = g \frac{\rho_a - \rho_0}{\rho_a} \) = discharge buoyancy (or effective gravity), \( \rho_0 \) = discharge density and \( \rho_a \) = ambient water density. The absolute value of the density difference is adopted in the definition of \( g_0' \) to accommodate both upward and downward flow configurations.

The \( r_0 Fr \) term in equation Eq. 1.6 is a relevant length scale for the analysis of turbulent fountains, assuming the water equation of state is linear. This length scale is defined as:

\[ L_s = r_0 Fr \]  

(1.8)

The corresponding dilution scale \( \mu_s \) can be defined as:

\[ \mu_s = \frac{g_0'}{g_0} = \frac{\Delta T_0}{T_s} \]  

(1.9)

Buoyancy scale \( (g_0') \) governing high \( Fr \) is \( \sim \frac{B_0^{3/2}}{M_0^{5/4}} \). Substituting for initial momentum \( (M_0) \) and initial buoyancy \( (B_0) \) and reorganizing gives:

\[ g_0' = \frac{\rho_0'}{Fr} \]  

(1.10)

For a linear equation of state, Temperature scale \( (T_s) \) and Buoyancy scale are proportional to each other, and

\[ \frac{T_s}{g_0'} = \frac{\Delta T_0}{g_0} \]  

(1.11)

Substituting \( g_0' \) from Eq. 1.10 into Eq. 1.11, and reorganizing for \( T_s \)
Substituting $T_s$ from Eq. 1.12 into Eq. 1.9 gives the following non-dimensional dilution scale that is applicable to both thermal and dense jets

$$\mu_s = Fr$$  \hfill (1.13)

The data acquired in this study were normalized using the length and dilution scales defined above.

Effect of density difference on dilution and height is investigated in Chapter 5. Maximum height of dense fountains is (Baddour and Zhang 2009):

$$z_m = f \left( Fr, \frac{\Delta \rho}{\rho_a} \right)$$  \hfill (1.14)

And a dimensional analysis yields the following relationship (Baddour and Zhang 2009):

$$\frac{z_m}{r_o Fr} = f \left( \frac{\Delta \rho}{\rho_a} \right)$$  \hfill (1.15)

In the same way, the effect of $\frac{\Delta \rho}{\rho_a}$ on minimum return point dilution at the edge of the nozzle can be studied as

$$\frac{\mu_{min}}{\mu_s} = f \left( \frac{\Delta \rho}{\rho_a} \right)$$  \hfill (1.16)

A theoretical model of fountain with two entrainment coefficients is developed in chapter 6 based on conservation of mass, momentum, and buoyancy. The entrainment coefficient, which represents fluid flow transferred from the inner jet to the outer plume, was argued to be negligible and ignored. Three governing equations were developed for each of the inner jet and outer plume and a control volume used to model the upper part of the fountain.
1.4 Thesis Outline

This thesis is divided into seven chapters and is presented in an integrated-article format stipulated by the Faculty of Graduate Studies at The University of Western Ontario. Each chapter, except for the first and last chapters, is presented in a paper format without an abstract. Tables and figures for each chapter are embedded in the text. The nomenclature is consistent throughout the thesis. In Chapter 2 mixing zones limitations are recognized by reviewing scientific studies. In Chapter 3 and 4 dilution properties of fountains at large and small Froude numbers are analyzed and minimum return point dilution was proposed to find an alternative method to the mixing zone approach. In Chapter 5 and 6, the study was extended to examine the effect of density difference and entrainment on the minimum return point dilution. Detailed organization of the thesis is summarized as follows:

Chapter 1 is an introductory chapter of the thesis introducing mixing zones and describing their limitation in sensitive areas, reviewing previous studies to solve the problem, setting objective and methodology of the study, outlining thesis structure, and highlighting the original contribution of the thesis.

In Chapter 2, sources, effects, disposal methods, and regulations of brine into marine environment are critically reviewed. Various sources of brine around the world such as desalination, solution mining of salt domes, potash and oil mining are mentioned and described. Impacts of brine on marine environment are discussed in light of scientific studies. Various disposal methods to dispose of brine are briefly discussed along with their disadvantages. Salinity and environmental regulations around the world are reviewed with special reference to mixing zones. Layout of commonly used multiport diffusers is also presented.

In Chapter 3, dilution and penetration properties of vertical negatively buoyant jets are presented and compared with previous studies. Wall effect of a high densimetric Froude number over a long period of time was presented and discussed to select a suitable steady state window of time. Thermal contours, excess temperature, and dilution profiles for high Froude number at the level of the nozzle are presented and discussed to find the
point of minimum return point dilution, which occurs just outside the edge of the nozzle. A minimum return point dilution equation for high Froude number is derived to regulate discharge of brine in sensitive areas. Minimum return point dilution of vertical fountains was compared with previous inclined fountain dilution to select the best orientation for discharges.

Chapter 4 extends the study presented in Chapter 3 to small Froude number fountains. This chapter also presents new experimental data on intermittency and turbulent intensity.

In Chapter 5, the effect of relative density difference $\frac{\Delta \rho}{\rho_a}$ on normalized dilution $\frac{u_{min}}{Fr}$ and normalized height is presented, discussed, and compared with previous studies. An equation is proposed to calculate dilution at different density difference.

In Chapter 6, derivation of a theoretical model of a fountain based on conservation of mass, momentum and buoyancy is presented. Two entrainment coefficients are used to model the fountain entrainment behavior. Sensitivities of numerical results to the values of the entrainment coefficients are presented and discussed.

The general conclusions of the thesis are summarized in Chapter 7.

Three appendices A, B, and C are provided at the end of the last chapter. Photographs of the apparatus are presented in Appendix A. Transient development of a typical fountain and wall effect demonstration are presented in Appendix B. The experimental data related with Chapters 3-6 are provided in Appendix C. Figures and tables in Appendices are named according to their relevance with chapters. For example, Figure A(3-6).a means Figure a of appendix A related to Chapters 3 to 6.

The System International (SI) system of units is used throughout the thesis.

1.5 Original and Practical Contribution of the Thesis

This thesis provides new information on dilution and spread of vertical turbulent fountains under stagnant water conditions. The work is expected to help brine producing industries to design optimal disposal systems satisfying existing and future more stringent
environmental regulations. Environmental protection agencies could also apply the information in this thesis to develop new environmental policies and regulations pertaining to the disposal of brine.

The main contributions of the thesis can be summarized as follows:

1. Selection of point of minimum return point dilution just outside the edge of the nozzle by analyzing thermal contours and horizontal dilution profiles of fountains at the level of the source.

2. Development of modeling equations for the point of minimum return dilution to facilitate the design vertical fountains of brine to comply with any required regulatory dilution.

3. Recognition of the advantage of using a vertical fountain as opposed to an inclined fountain when discharging brine into the sea. It is particularly the case in the presence of tides and winds, which cause variable current magnitudes and directions.

4. Confirmation that the relative density difference $\frac{\Delta \rho}{\rho_a}$ (if looked over a broader range) has noticeable effect on height and dilution of fountains, and cannot generally be ignored. An equation describing the effect of relative density difference $\frac{\Delta \rho}{\rho_a}$ on dilution is provided.

5. Study of the performance of a two-coefficient entrainment model.

References


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Chapter 2

A REVIEW OF SOURCES, EFFECTS, DISPOSAL METHODS, AND REGULATIONS OF BRINE INTO MARINE ENVIRONMENTS

2.1 Introduction

Brine (hot salty water) is a main byproduct of many industrialized and mining processes. During the last few decades, production of brine in the world has increased exponentially due to rapid increase in various industrialized and mining processes. New environmental regulations related to brine have also emerged in various parts of the world due to increased environmental consciousness. Disposal of brine is different than urban effluents as brine is generally not allowed to be discharged into fresh water resources. Selection of a suitable brine disposal method, to satisfy existing environmental regulations, plays an important role in the feasibility of a brine producing industry. Moreover, accommodation to future environmental regulations is also an important issue in the planning of an industry. Review of brine environmental regulations is, therefore, helpful in providing general principles and pertinent information on both current and future regulations trends. Review of brine disposal methods is also helpful in choosing suitable disposal systems based on economy, environment, and technical feasibility at a specific location.

Brine is produced in various quantities by many industrial processes. Understanding the main sources of brine and their impact on the environment are important to develop and implement appropriate environmental policies by environmental protection agencies.

There is a need to clarify misconceptions about the detrimental effects of brine. In particular, the general public often believes that disposal of brine into the sea is not affecting marine life since the sea is already saline. Although brine does not appear harmful to marine life in the short term, the long term environmental effects on marine life are well recognized in the scientific community (Einav et al. 2002; NOAA 1978;

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1 Ahmad, N. and Baddour, R.E. (2013) paper has submitted in Journal of Ocean and Coastal Management
An effort is required to inform the general public on short and long term environmental impacts of brine when discharged into the sea. This effort would help raise public awareness on environmental issues related to brine disposal and drive the development of new environmental regulations in many countries where they are lacking.

Brine disposal into the sea is certainly the preferred method of managing waste brine when industry is close to the sea. Current brine disposal systems have various layouts and dimensions depending on different constraints, regulations, and design parameters. A review of typical existing marine disposal systems provides some guidelines to design new disposal systems.

The objectives of the present review on management of brine in coastal waters are: (i) raise public awareness about detrimental effects of brine on marine life (ii) improve design of diffusers (iii) develop a foundation for new environmental regulations based on minimum return dilution to protect more effectively the marine environment from brine discharges.

2.2 Sources of Brine

Brine is produced during various industrialized and mining processes. The main industrial processes that produce large quantities of brine are:

2.2.1 Desalination of Seawater

Desalination is a process that separates dissolved salt from seawater for the production of freshwater. According to Global Water Intelligence (2006) report’s projection, the world’s desalinated installed capacity in 2015 could reach 100 million cubic meters per day (i.e equivalent to 1157 m3/sec) which is more than half of the Niagara Fall discharge. The two major types of technologies, used around the world for desalination, are Multi Stage Flash (MSF) and Reverse Osmosis (RO). In Reverse Osmosis, brine concentration is 1.3-1.7 times that of the original seawater and in Multi Stage Flash (MSF) brine
concentration is 1.1-1.5 times that of the original seawater (Einav 2003). Desalination is popular in coastal areas and has especially increased in the last decade for three reasons: (i) traditional sources of fresh water such as rivers or artesian wells are becoming scarce in meeting the demands of fresh water; (ii) high population growth rate in coastal areas; (iii) new advancements in Reverse Osmosis have reduced the cost of treatment of desalination. According to the Population Reference Bureau approximately 3 billion people, about half of the world population, live within 200 kilometer of coastline areas (Creel Liz 2003).

2.2.2 Solution Mining of Salt Dome for Hydrocarbon Storage

Large quantities of highly concentrated brine (up to 250 parts per thousand (ppt) are produced during solution mining of salt domes (James et al. 1983). Solution mining of salt dome is a process in which a borehole is first drilled through a salt deposit. Water is then injected to dissolve salt, and the resulting highly concentrated brine solution is pumped to the surface. This process requires large quantity of water, equivalent to 8 to 9 barrels of fresh water for every barrel of space created (Bergman 1984). Salt domes are large subsurface geological structures that consist of vertical cylinders of salt up to 1 km in diameter and several km deep. If salt is removed from salt dome, the created space can be used for storage of hydrocarbons such as oil and natural gas. The walls of the dome are strong and impermeable to hold hydrocarbons (Evans Davis 2009).

Storage of oil is considered an important economic security for any country which relies heavily on imported oil. After the oil embargo 1973, the United States implemented the Strategic Petroleum Reserve (SPR) program to store one billion barrel oil in salt domes (Andrews and Pirog 2012). The large salt domes in Gulf of Mexico along the Gulf Coast were selected and the resulting brine from solution mining of salt domes was disposed off shore through a pipe line and diffuser system (James et al. 1983). Underground storage in salt domes is the most economical, safest, and environmentally friendly option when compared to surface steel tank storage. If good rock conditions are available, underground storage of oil is 50-70 % less costly than surface storage (Bergman1984).
2.2.3 Mining Processes – Oil and Potash Mining

Brine is also produced during many mining processes, including potash mining and oil mining. In mining processes, large quantity of freshwater is pumped into the ground to extract minerals. For example, in oil mining, according to the American Petroleum Institute estimate, nine barrel of water is recovered for each barrel of oil during a typical extraction process. Brine of mines contains high salt content and dangerous chemicals, which could be very dangerous for marine life (Roach et al.; Obire 2003; Andreasen et al. 1983; Ahmadun et al. 2009; Vonhof 1975). Disposing the mining producing brine is, therefore, one of the biggest environmental challenges of Canada since it is the largest potash producer of the world with 46 percent of the total world potash reserves (Natural Resource Canada news release 2012). Most potash production in Canada is from Saskatchewan and Nova Scotia provinces. In Saskatchewan deep-well injection and surface storage in ponds are used to dispose of excess brine, and is considered a major source of contamination of groundwater resources (Vonhof 1975; Water Working Group Report 2012). In New Brunswick potash mining, the brine produced is disposed into the sea and was shown to be harmful to marine organisms (Hutchesen 1983).

2.3 Environmental Impacts of Brine

Brine can be harmful to the environment due to its salinity and due to its temperature. Salinity (concentration of salts) and temperature of brine depend upon its production processes. Salinity of brine produced by desalination is around 60 parts per thousand (ppt), potash mining is 350 ppt, oilfield mining is 100 ppt, and solution mining of salt domes is 250 ppt (Tong and Stolzenbach 1979; Hutchesen 1983; James et al. 1983; Howe et al. 1982). Temperature of brine produced by evaporation technologies such as Multi Stage Flash (MSF) and Multi Effect Distillation (MED) is very high. In Saudi Arabian desalination plants, operational temperature during MSF process ranges between 90-115 °C (Al-Mutaz et al. 2002) and cooling water (usually from electric power generation plants) is mixed with the produced brine to reduce the temperature of the discharged brine to within 10-15 °C above ambient (Hoepner 1999). The brine produced by mining processes may also contain toxic substances. Metals commonly in mining brines are lead,
zinc, copper, arsenic, cadmium, manganese, and nickel (Tong and Stolzenbach 1979; Hutchesen 1983; Howe et al. 1982). Oilfield brine contains organic hydrocarbons such as naphthalene, which is extremely toxic to aquatic organisms even at low concentration (Armstrong 1979).

High salinity and temperature of desalination brine have negative impacts on marine life. Extensive body of environmental research (Einav et al. 2002; NOAA 1978; Garcia 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. The increase of salinity disturbs the osmotic balance of marine species with their environment. It results in dehydration of cells, decrease of the turgor pressure, and may lead to death of species (Einav 2002). High temperature of brine above ambient water has also many detrimental effects on marine life as toxicity of metals and chemicals increase with temperature (Hoepner 1999). In addition, the solubility of oxygen decreases with temperature resulting in lower levels of dissolved oxygen in the receiving body (Davies et al. 2008). Even a slight variation of temperature (such as 1°C) above ambient water over an extended period of time can change species composition in an area (Hiscock et al. 2004). Marine life can temporarily adapt to minor changes in temperature, but not permanently. Extended long-term temperature change can be fatal for marine life (Lattermann 2008). For this reason the highly thermal brine, derived from MSF technology, is generally blended with cooling water from a nearby power generation plant to reduce its temperature. Highly thermal brine may also become positively buoyant due to the effect of temperature and can in this case affect the surface water marine ecosystem (Lattermann 2008). Hoepner (1999) argued that thermal impact of desalination is more harmful than commonly assumed. In addition to high salinity and temperature, desalination brine may contain residues of pretreatment, cleaning chemicals, and heavy metals that are all dangerous for marine life (Lattermann 2008).
### 2.4 Disposal Methods of Brine

Various methods are currently used to dispose brine. These are summarized and briefly explained in the following table.

Table 2.1: Summary of Methods Used to Dispose of Brine.

<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>Brine disposal method</th>
<th>Principle and description</th>
<th>% of total capacity</th>
<th>Disadvantages or limitations</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Deep well injection</td>
<td>Brine is injected into porous subsurface rock formations</td>
<td>17</td>
<td>Contamination of ground water and triggering earthquakes</td>
</tr>
<tr>
<td>2</td>
<td>Land application</td>
<td>Brine is used for irrigation of salt-tolerant crops and grasses</td>
<td>2</td>
<td>Salinization of soil if the method is used on large scale production of crops</td>
</tr>
<tr>
<td>3</td>
<td>Evaporation ponds</td>
<td>Brine is allowed to evaporate in ponds while the remaining salts accumulate in the base of the pond</td>
<td>2</td>
<td>High capital costs due to high land acquisition costs. Bad impact on environment such as contamination of underlying aquifers due to leakage issues, and problematic for breeding and migrating birds</td>
</tr>
<tr>
<td>4</td>
<td>Zero liquid discharges</td>
<td>Brine concentrator can reduce brine to dry solid cakes which is easy to handle for disposal</td>
<td>0</td>
<td>High capital costs. Sometimes, the capital and operational costs of these can exceed the cost of the desalination facility</td>
</tr>
<tr>
<td>5</td>
<td>Sewer discharge</td>
<td>Discharge of brine into an existing sewage collection system. Low in cost and energy</td>
<td>31</td>
<td>Reduce biological treatment processes performance in case of large quantity of brine</td>
</tr>
<tr>
<td>6</td>
<td>Seawater discharge</td>
<td>Brine is discharged on the surface of sea water. The</td>
<td>41</td>
<td>Marine pollution due to improper dilution</td>
</tr>
</tbody>
</table>
most common method for all big desalination facilities worldwide

<table>
<thead>
<tr>
<th>Submerged discharge</th>
<th>Brine is discharged offshore through multiport diffusers installed on the bottom of the sea</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Practical due to high dilution capabilities. Proper design of diffusers required to achieve high dilution</td>
</tr>
</tbody>
</table>

Source: Based on brine disposal methods presented in Zander (2008).

When a desalination plant is situated close to sea, the brine is generally discharged into sea and inland disposal methods listed in Table 1 are not commonly used.

Surface discharge of brine into the sea had initially been practiced for many years before the implementation of various environmental regulations. Unfortunately, this practice still exists in some third world countries. In the surface discharge method, brine is discharged on the seawater surface very close to the shore resulting in high concentrated saline water accumulation on the shores. Surface discharge of brine is, therefore, causing significant marine pollution in the world due to improper dilution with seawater (Einav 2003). Submerged discharge methods are necessary for modern large capacity plant to ensure high dilution to minimize harmful impacts on marine life (Jirka 2008). Figure 2.1 is showing a disposal system where a long pipe line is constructed from a desalination plant to discharge brine deep into sea. A vertical riser (a single port is shown in this case) with a smaller diameter exit nozzle is connected at the end of the long pipe line. The nozzle is designed to increase the momentum (i.e Densimetric Froude number) of the discharge and achieve a desired dilution of brine with seawater. The brine rises first above the nozzle to some height due to its initial momentum and returns back down, similar to a fountain, due to its negative buoyancy. The brine finally spreads on the sea floor around the point of discharge. Figure 2.1 is showing a mixing zone around the source of brine where concentration of brine is exceeding an environmental water quality standard. Presently, the mixing zone approach is applied to control and limit brine pollution within a specified mixing zone around the point of discharge.
In practice, a number of ports with small diameter nozzles at the end of discharge pipe are also used to increase dilution with seawater. Important design parameters of diffusers include the length and diameter of the pipeline; orientation and rise of ports above the seabed; and diffuser layout. Design of diffusers may also vary with topography, economy, environmental priority, available head, and sea current direction and magnitude.

Figure 2.2 is showing some typical layout of marine outfalls provided with multi ports at the end of a long pipeline. The mixing zones are delineated around the multiport diffusers. Figure 2.2(a) is a V-shape diffuser system used in Barka II plant to dispose of brine (Purnama 2011). Figure 2.2(b) is a long pipe line of gradually decreasing diameter and diffuser system used at Boston Harbor (Sherman et al. 1994). Figure 2.2(c) is showing a very long pipe line almost 20km long with a straight diffuser extending over a distance of 936 m (McLellan and Randall 1986).
2.5 Environmental Regulation of Brine

Environmental regulations for brine disposal around the world vary significantly from region to region, possibly due to variations in general awareness of the detrimental environmental effects of brine. For example, there are relatively few environmental regulations in the Middle East, where about two third of desalination plants and oilfields of the world are located and adequate brine disposal systems are lacking (Einav 2002). On the other hand, in some other countries, many environmental regulations related to brine discharges into the sea exist. A summary of environmental regulations pertaining to brine discharges is presented here.

2.5.1 Salinity Regulations

In North America there are limited environmental regulations pertaining directly to the salinity of the discharge of brine into the sea. Salinity of brine is generally treated as any other toxic discharge. The concept of mixing zone is widely used in North America to regulate pollutant and toxic discharges (US EPA 1994; Rutherford et al. 1994; IMDs
Mixing zones are stipulated to protect human health, aquatic habitat, and the water body as a whole. The general principles are: (i) mixing zones should not impair the integrity of the water, (ii) there is no lethality to organisms passing through the mixing zones, and (iii) there should be no significant health risks for humans. US EPA allows the states to adopt their own mixing zone regulations as part of the water quality standard 40 CFR 131.13. The mixing zone regulations of various states are subject to review and approval by US EPA. Each state develops detailed administrative rules and requirements, which have to be fulfilled before getting any permit to discharge a pollutant into a natural water body. The administrative rules and requirements for mixing zones are based on engineering and ecological assessments, and economic feasibility (US EPA 1994). For example, the Oregon Administrative Rule (OAR) 340-041-0053(2)a(A) allows an acute mixing zone and a chronic mixing zone. Acute mixing zone is provided so that immediate dilution will reduce toxicity below lethal concentrations. The acute criteria must be met at the end of the pipe unless it can be demonstrated that immediate dilution of the effluent within the Regulatory Mixing Zone (RMZ) reduces toxicity below lethal concentrations and will not cause lethality to passing organisms (IMDs 2007).

In Australia, building a desalination plant near the coast requires approval from the Australian Environmental Protection Agency (EPA) for Environmental Related Activities ERAs 7, 16 and 19. An environmental impact assessment must be undertaken, showing no significant impacts on the surrounding environment. Any foreseen impacts must be minimized with the implementation of appropriate management measures. To construct the Gold Coast Desalination Plant, Gold Coast City Council proposed a mixing zone 120 m wide and 225 m long for safe disposal of brine from the desalination plant. The size of the mixing zone was the result of modeling of diffuser plumes from the desalination plant (GCD 2006). In the case of the Seawater Reverse Osmosis plant at Perth metropolitan, Australian EPA requires that salinity be within 1.2 ppt of ambient levels within 50 m of the discharge point and within 0.8 ppt of background levels within 1,000 m of the discharge point (WEC 2002).

In Oman, according to Article 5 of Omani Ministerial Decision No. 159/2005, no liquid waste shall be directly or indirectly discharged in the marine environment without
obtaining prior license. To obtain the license, a company has to fulfill pipe discharge limits on effluents and a mixing zone of 300 m in diameter around the outfall where salinity should not more than 2 ppt above the standard ambient water conditions (Sultanate of Oman 2005).

2.5.2 Temperature Regulations

Marine thermal environmental regulations are generally not directly aimed at regulating the discharge of brine. In North America there are general guidelines and regulations at federal, state, and provincial levels to protect the ecosystem from temperature variations due to disposal of any thermal effluent into water bodies. For example, US EPA limits the maximum acceptable increase in the weekly average temperature resulting from artificial sources to 1 °C during all seasons of the year (US EPA 1986). Canadian Water Quality Guidelines (CWQG) for protection of marine life limits maximum temperature variation to 1 % of ambient water temperature for any human activity (CCME 2008).

The World Bank, in its Environmental, Health, and Safety (EHS) Guidelines (2007), limits to 3 °C the rise in temperature above ambient water within a scientifically established mixing zone. The mixing zone is defined in The Pollution Prevention and Abatement Handbook, which specifies a mixing zone of 100 m from the point of discharge in non sensitive areas (World Bank Group 1998).

There are, however, a few examples of thermal environmental regulations directly aimed at regulating the discharge of brine. In the Omani regulations on the discharge of liquid waste into the marine environment, the temperature of brine at the discharge point should not exceed 10 °C over the temperature of the ambient water. Moreover, Omani regulations specify a mixing zone of 300 m around the discharge point with a limit of 1°C increase in temperature above ambient water (Sultanate of Oman 2005). Also in Australia, the Department of the Environment (DoE) requires the temperature of brine from desalination power plants in the Burrup Peninsula entering King Bay at the end of the outlet pipe to be less than 2°C above the ambient temperature. The increase of temperature at the edge of the mixing zone (area of 0.01 km²) is to be less than 0.1°C (Bath et al. 2004). Furthermore, in Israel, for the Ashkelon Seawater Desalination Plant,
the thermal brine regulations limit the temperature rise to 4 °C above ambient at the discharge point (Safrai and Zask 2004).

It can be concluded from this review that the salinity of brine discharges is presently regulated by allocating mixing zones, which vary in size from 0 m to 500 m from the discharge point. The size of the mixing zones depends upon toxicity of brine, sensitivity of area, and environmental awareness of the detrimental effects of brine on the marine ecosystem. On the other hand, the temperature of brine has been regulated by limiting the temperature at the source as well as the edge of a mixing zone.

2.6 New Approaches to Fulfill Environmental Regulations in Sensitive Areas

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. Regulations for toxic effluents state that acute criteria must be met at the end of the pipe. An important example of such type of regulation is Oregon Administrative Rule (OAR) 340-041-0053(2)(a)A, which states that acute criteria must be met at the end of the pipe unless it can be demonstrated that immediate dilution of the effluent within Regulatory Mixing Zone (RMZ) reduces toxicity below lethal concentrations and will not cause lethality to passing organisms (IMD 2007).

Ahmad and Baddour (2012) proposed a new concept of Minimum Return Point Dilution to regulate discharge of brine in sensitive areas. Minimum Return Point Dilution in the case of a vertical discharge of brine implies the dilution at the outer edge of the discharge nozzle, as shown in Figure 2.1. Minimum Return Point Dilution criterion could practically be used in sensitive areas, where large mixing zones are not applicable.
The selection of discharge orientation is also an important consideration when designing diffusers systems, as the Return Point Dilution may increase or decrease. Presently, vertical port diffusers exist in the world that are similar to the outfall layout sketched in Figure 2.1. However, in many cases, brine diffusers are designed with inclined orientations (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). Ahmad and Baddour (2012) investigated and compared the dilution of vertical and inclined fountains. They found that the inclined orientation of a diffuser is advantageous only in calm water and when ambient currents are weak and unidirectional. The data suggested that the vertical discharge is performing better in the cases of reversing currents and strong co-currents. Since ambient currents are seldom unidirectional they recommended the use of vertical discharges to take advantage of currents in all directions.

2.7 Conclusion

Desalination is the main source of brine in the world and causing marine pollution. Rapid increase of desalination is due to scarcity of traditional resources of water, high concentration of population in coastal areas, and advancement of Reverse Osmosis desalination technology. Other sources of brine are solution mining of salt domes for petroleum storage, and oil and potash mining. According to the American Petroleum Institute estimate, nine barrel of water is recovered for each barrel of oil during extraction process.

Salinity (concentration of salts) and temperature of brine depend upon its production processes. Salinity of brine produced by desalination is around 60 parts per thousand (ppt), potash mining is 350 ppt, oilfield mining is 100 ppt, and solution mining of salt domes is 250 ppt. Brine in addition to high salinity sometimes contains toxic substances such as lead, zinc, mercury, copper, and naphthalene.

High salinity and temperature for extended periods of time impact marine life badly. Extensive body of environmental research has shown that even a small increase of salinity may be harmful to marine life.
If desalination plant is located close to the sea, brine is commonly discharged into the sea and inland disposal methods are not used. Table 2.1 summarized various inland disposal methods, that include deep well injection, land application, evaporation, zero liquid discharge, and sewer discharge methods.

Submerged multiport diffuser methods are considered the best methods to protect the sea shores from environmental degradations of brine. Commonly used layouts of marine disposal systems were shown in Figure 2.2.

Environmental regulations for brine disposal around the world vary significantly from region to region, possibly due to variations in general awareness of the detrimental environmental effects of brine. In the Middle East, where more than two third of desalination plants are situated, brine regulations are lacking. In North America, brine is considered as any other toxic discharge and the concept of mixing zone is widely used to regulate pollutant and toxic discharges.

Mixing zones have limitations in regulating the discharge of brine, particularly in environmentally sensitive areas. A Minimum Return Point Dilution method was recently proposed to regulate the discharge of brine in sensitive areas where large mixing zones are not applicable.

References


Global Water Intelligence Report. 2006. 7(10), October.


Roach, R. Will., Carr, R. Scott., and Howard, Cynthia L. Howard. An assessment of produced water at two sites in the Galveston Bay system.


3.1 Introduction

Studies of dense jets (or fountains), have focused in recent years on the behavior of inclined jets with the objective of maximizing dilution of brine (hot dense salty water) from desalination plants. It has been established that in the absence of an ambient current the near field dilution is maximized when the angle of the discharge with the horizontal is about $\theta = 60^\circ$ (Zeitoun et al. 1972; Pincince and List 1973; Chu 1975; Tong and Stolzenbach 1979; Roberts and Tom 1987; Robert 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). It has also been established that in the presence of a unidirectional current it is advantageous to align the inclined jet in the direction of the current (Robert and Tom 1987). Discharging the inclined jet against the direction of the current may reduce the dilution below the level of dilution of a vertical jet (Robert and Tom 1987). In the presence of tides and variable along-shore currents, it is, therefore, advisable to discharge the brine vertically upwards in order to take full advantage of the currents in any direction. Understandably, however, the worst case dilution of the vertical dense jet would occur at times when the ambient current vanishes. It is important, therefore, to have a good understanding of this worst case dilution scenario when designing a vertical diffuser.

Previous studies of vertical dense jets have provided data mainly on vertical jet penetration (Turner 1966; Abraham 1967; Baines et al. 1990; McDougall 1981; James et al. 1983; McLellan and Randall 1986; Zhang and Baddour 1998; Bloomfield and Kerr 2000, Kaye and Hunt 2006 and Baddour and Zhang 2009). On the other hand, specific information on dilution of vertical dense jets is scant. In particular, there is need to determine the minimum dilution of a vertical dense jet at the level of the source ($z=0$) as

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depicted in Figure 3.1. This minimum dilution represents a worst case scenario, which could be used to regulate vertical dense discharges, such as brine from desalination plants.

Figure 3.1: Definition Sketch of an Upward Fountain Generated by a Dense Jet

3.2 Methodology

We adopted in this study the downward thermal fountain, shown in Figure 3.2, to simulate in the laboratory the behavior of an upward vertical dense jet (or fountain) of a miscible fluid, such as brine. The thermal flow experiment was easier to perform and provided accurate temperature data. The dynamic similarity of thermal and dense flows was achieved by matching the discharge Densimetric Froude number, which is defined here as:

$$Fr = \frac{u_0}{\sqrt{g_0 r_0}}$$  (3.1)
Where \( U_0 = \frac{Q_0}{\pi r_0^2} \) = discharge velocity, \( Q_0 = \) discharge flow rate, \( r_0 = \) radius of discharge nozzle, \( g' = g \frac{\rho_0 - \rho_a}{\rho_a} \) = discharge buoyancy (or effective gravity), \( \rho_0 = \) discharge density and \( \rho_a = \) ambient water density. The absolute value of the density difference is adopted in the definition of \( g' \) to accommodate both upward and downward flow configurations.

![Figure 3.2: Definition Sketch of a Downward Fountain Generated by a Thermal Jet](image)

The similarity of dense and thermal flows is expected to hold when the water equation of state is linear. It is practically the case when experiments are conducted using water at temperatures above 15°C (Baddour 1994).

This study is concerned, as explained in the introduction, with the worst jet dilution scenario, which occurs when the ambient water is stagnant. Zhang (1996) carried out a detailed experimental study of the effect of Reynolds number on the height of vertical fountains. He found that when the Reynolds number \( Re > 2000 \) the height of the
fountains were practically unaffected by the Reynolds numbers. In the present study the Reynolds number was always above 2000 and the properties of the fountains are on dimensional grounds assumed in Eq. 3.1 depend only on the Froude number.

Detailed investigations of the temperature field obtained with thermocouples have determined in this study the vertical and horizontal penetrations of the jet as well as its dilution. Particular attention was given to the minimum dilution achieved at the level of the source (z=0). As will be shown, this minimum dilution occurred just outside the edge of the nozzle and is defined as

\[ \mu_{\text{min}} = \frac{g_0}{g_1} = \frac{\Delta T_0}{\Delta T_1} = \frac{T_0 - T_a}{T_1 - T_a} \] (3.2)

Note that buoyancy or temperature differences can be used in Eq. 3.2 since they are linearly proportional to one another. Also, \( T_0 \) = temperature of discharge, \( T_a \) = temperature of ambient water and \( T_1 \) = mean temperature measured just outside the edge of nozzle at z=0.

### 3.2.1 Scaling and Normalization

At large discharge Froude numbers the properties of turbulent dense jets are well understood to be mainly governed by their initial momentum (\( M_0 = Q_0 U_0 \)) and buoyancy (\( B_0 = Q_0 g_0 \)) fluxes (Turner 1966 and others). The relevant length scale derived from these fluxes is, therefore, \( \sim \frac{M_0^{3/4}}{B_0^{1/2}} \), and substituting for \( M_0 \) and \( B_0 \) it can be shown that the following length scale is suitable to normalize all vertical and horizontal jet penetration data of large Froude number jets.

\[ L_s = r_0 Fr \] (3.3)

Based on visual data on vertical jet penetrations, Zhang and Baddour (1998) found that this large Froude number approximation is applicable when \( Fr > 7 \).

Using a similar approach, the buoyancy scale governing high Froude number jets is \( \sim \frac{r_0^{3/2}}{M_0^{1/4}} \). Substituting for \( M_0 \) and \( B_0 \) and recognizing again that buoyancy and excess
temperature are proportional to one another, the appropriate scales to normalize jet buoyancy and excess temperature are, respectively,

\[ g_s' = g_0' / Fr \quad \text{and} \quad T_S = \Delta T_0 / Fr \] (3.4)

Furthermore, using Eq. (3.2) the dilution scale for dense and thermal jets can be expressed as

\[ \mu_S = \frac{g_0'}{g_s'} = \frac{\Delta T_0}{T_S} \] (3.5)

And substituting from Eq. 3.4 into 3.5 gives the following non-dimensional dilution scale that is applicable to both thermal and dense jets

\[ \mu_s = Fr \] (3.6)

The data acquired in this study were normalized using the length and dilution scales defined above.

### 3.3 Experimental Arrangement and Procedure

The negatively buoyant thermal jet experiments were carried in the apparatus shown in Figure 3.3. Fresh hot water was discharged vertically downward through a nozzle, of radius \( r_0 = 8.75 \text{ mm} \), into a transparent tank filled with cold water. The tank made of acrylic was 1 m deep and 1m x 1m in cross section. The double walled construction of the tank minimized the loss of heat and maintained constant ambient water temperature for long periods of time. The tank prior to all tests was filled with cold water to a level 200 mm above the exit of the nozzle. This precaution allowed during the experiment the warm buoyant layer from the jet to accumulate on the surface of the water without affecting the jet behavior below the source (\( z=0 \)). It was determined (see Figure 3.5) that the window of time available in this study to capture a steady state behavior free of any temperature build up from the accumulation of the surface warm layer was between 200 and 400 s. In addition, the cold water in the tank was allowed to settle for about 20 min prior to each test to create a stagnant ambient water condition. Two pipes supplying hot and cold water to the laboratory were connected to a mixing valve that produced the
warm jet discharge at a desired temperature for each test. A temperature dial readout helped adjust the required blending of cold and hot water for each test. A flow meter and a discharge valve located downstream of the mixing valve controlled and maintained a constant discharge of water through the nozzle.

The penetration and dilution properties of the thermal jets were examined in this study with fine wire thermocouples, which measured the water temperature. The thermocouples were arranged as vertical and horizontal profilers depending upon the scope of the experiment. A few individual thermocouples were also deployed during the experiments inside the nozzle and outside of the jet to continuously monitor the temperature of the
discharge and ambient water. The thermocouples used in this study were of Type T. They were 0.254 mm in diameter and 1830 mm in length and provided a temperature measurement accuracy of $\pm 0.1^\circ C$.

Thermocouples operate on the principle that the junction of two dissimilar metals generates a voltage signal that varies with temperature. A data acquisition module was connected to the thermocouples to simultaneously scan and convert their analog voltage signals into digital voltage signals. A computer then converted the digital voltages into temperature data using standard thermocouple calibration curves. The temperature signals from the thermocouples were generally scanned in this study at 0.1 s intervals to capture the temperature fluctuations within the boundary of the jet and stored in the computer for further analyses.

Five series of experiments, summarized in Table 3.1, were conducted in this study to achieve a set of specific objectives. As seen in Table 3.1, turbulent flow conditions were maintained with discharge Reynolds numbers $Re$ ranging from 3,699 to 12,000. The smallest Froude number $Fr$ was 4.7 and the largest was 24. The five series of experiments are described in the following and the locations of thermocouples associated with them are illustrated in Figure 3.4.

<table>
<thead>
<tr>
<th>Experiment Series</th>
<th>Objective</th>
<th>No. of Measuring Points</th>
<th>Number of Tests</th>
<th>Densimetric Froude No. $Fr$</th>
<th>Reynolds No. $Re$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Long term temperature signals</td>
<td>1</td>
<td>1</td>
<td>24</td>
<td>12,000</td>
</tr>
<tr>
<td>B</td>
<td>Vertical profile</td>
<td>9</td>
<td>4</td>
<td>6.21-8.7</td>
<td>3,699-4,969</td>
</tr>
<tr>
<td>C</td>
<td>Temperature contours</td>
<td>70</td>
<td>7</td>
<td>8.7</td>
<td>4,969</td>
</tr>
<tr>
<td>D</td>
<td>Horizontal temperature profile</td>
<td>24</td>
<td>4</td>
<td>9.77-19.1</td>
<td>5,521-1,1319</td>
</tr>
<tr>
<td>E</td>
<td>Minimum dilution</td>
<td>4</td>
<td>39</td>
<td>4.7-23</td>
<td>4,211-11,320</td>
</tr>
<tr>
<td>---</td>
<td>------------------</td>
<td>---</td>
<td>----</td>
<td>--------</td>
<td>-------------</td>
</tr>
</tbody>
</table>

\[ r_o = 8.75 \text{ mm}, \quad T > 15 \, ^\circ \text{C} \]

*Experiment Series A* was designed to test the limitations of the apparatus and experimental procedure and assess the capacity to model the steady state near field behavior of the jets. A long term test with the highest Froude number \((Fr = 24)\) was performed for this purpose over a period of six minutes. Thermocouples placed inside the nozzle and near the bottom monitored continuously the temperature of the discharge and ambient water, while a thermocouple located just outside the edge of the nozzle monitored the temperature of the returning fluid at the source height \((z=0)\).

*Experiment series B* was designed to obtained vertical excess temperature profiles on the centre line of the jets. Vertical jet penetration properties were examined with these profiles and compared with the vertical penetrations data obtained visually in previous studies. The vertical profiler was made of nine thermocouples and a total of four experiments with different Froude numbers were performed.

*Experiment series C* was designed to construct excess temperature contours and recognize the location where dilution is minimum. An experiment with a Froude number \(Fr = 8.7\) was repeated seven times in order to acquire the required set of temperature data for the contours. The vertical profiler was moved laterally to a new radial position, away from the centre of the jet, for each of the seven tests. Due to symmetry, the temperature data were gathered along a radius on one side of the jet.

*Experiment series D* was designed to gather detailed excess temperature profiles on the horizontal surface \(z=0\) and confirm the point of minimum dilution. The required temperature data for this series were captured with a horizontal profiler made of 24 vertical thermocouples with their tips opposing the return flow at \(z=0\). The horizontal thermocouple profiler was placed on one side of the edge of the nozzle, as shown in Figures 3.3 and 3.4. Four experiments with different Froude numbers ranging from 9.77-19.1 were performed.
Experiment series E 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 source (see Figure 3.4). In order to cover the widest possible range of experimental conditions within the limitations of the present apparatus, thirty nine (39) experiments with different $Fr$ ranging between 4.7 to 23 were performed.

3.4 Results and Discussion

Figure 3.5 shows temperature signals over a period of 600s obtained inside and outside of the jet during the Experiment Series A with $Fr = 24$. The sudden increase of temperature
that can be seen at $t = 125\,\text{s}$ is associated with the opening of the discharge valve, and the 1st peak is caused by the first (starting) front of the fountain. An apparent steady state period of turbulent fluctuations can be seen during the limited period $\,200\,\text{s} < t < 400\,\text{s}$. Beyond this limited window of time the mean temperature of the fountain is evidently ramping up due to the finite size of the tank and associated wall and/or surface effects. Based on this finding, the data in all the other series of experiments were analyzed only within this window of time (200s-400s). It was a conservative steady state window of time since it was established using data for the highest Froude number test. Jets with smaller Froude numbers are expected to exhibit longer steady state periods before interacting with the walls and/or surface of the tank.

Figure 3.5: Long Temperature Trace Analysis

Figure 3.6 shows five instantaneous vertical profiles of excess temperature obtained along the jet centre line during one of the tests of Experimental Series B. It can be seen that there is a sharp drop of temperature across the interface separating the warmer fluid inside the fountain and colder fluid outside. We have defined in this study the instantaneous height of the thermal fountain at the location of maximum temperature gradient. As in Baddour (1991) a polynomial was fitted to each instantaneous vertical
profile captured every 0.1 s. The coefficients of the polynomial were then used to
determine the instantaneous location of the maximum temperature gradient.

Figure 3.6: Sequence of Five Normalized Instantaneous Temperature Profiles

The instantaneous fountain heights $z_i$ obtained in this manner are plotted versus time in
Figure 3.7. This constructed trace of instantaneous height shows both the mean and
frontal structures of the fountain height. The height $z_{mean}$ is considered as the arithmetic
average of all the instantaneous penetrations, and, following Zhang and Baddour (1998),
the height $z_m$ is considered as the average value of consecutive frontal peak heights. The
data in Figure 3.7 give $z_{mean} = 2.71 r_0 Fr$ and $z_m = 3.21 r_0 Fr$.

The value of $z_m$ estimated from a single test above using four dominant frontal peaks in
Figure 3.7 is within 5% of $z_m = 3.06 r_0 Fr$ obtained from visual observations of large
number tests by Zhang and Baddour (1998).
An alternative method to determine \( z_{\text{mean}} \) is to locate the maximum temperature gradient directly from the vertical profile of mean temperature. The mean vertical profile of excess temperature of the four tests conducted in Experimental series B is given in Figure 3.8. The maximum temperature gradient \( \left. \frac{dT}{dz} \right|_{\text{max}} \) of the mean profile occurs in Figure 3.8 at \( 2.67 \frac{r_0}{Fr} \). This value is very consistent with the mean height determined in Figure 3.7 using the constructed time series of instantaneous heights.

A third height, \( z_p \), can also be defined as the peak height attained by the jet, which is the peak height attained by the first front (Kay and Hunt 2006). The measurement of \( z_p \) are, nevertheless, not reliable, since this height could depend on the time required to open the discharge valve and the length of pipe connecting the valve to the nozzle. No attempt was made in this study to determine \( z_p \).
Figure 3.8: Normalized Vertical Mean Temperature Profiles

Table 3.2: Summary of Vertical Jet Penetration Properties and Comparison with Previous Studies

<table>
<thead>
<tr>
<th>Reference</th>
<th>$\frac{Z_m}{r_0 Fr}$</th>
<th>$\frac{Z_{mean}}{r_0 Fr}$</th>
<th>$\frac{Z_p}{r_0 Fr}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turner (1966)</td>
<td>-</td>
<td>2.46</td>
<td>-</td>
</tr>
<tr>
<td>James et al. (1983)</td>
<td>-</td>
<td>2.21 &amp; 2.57</td>
<td>-</td>
</tr>
<tr>
<td>McLellan and Randall (1986)</td>
<td>3.11</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Baines et. al. (1990)</td>
<td>-</td>
<td>2.46</td>
<td>3.52</td>
</tr>
<tr>
<td>Zhang and Baddour (1998)</td>
<td>3.06</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Bloomfield and Kerr (2000)</td>
<td>-</td>
<td>2.26</td>
<td>3.08</td>
</tr>
<tr>
<td>Kay and Hunt (2006)</td>
<td>-</td>
<td>2.46</td>
<td>3.52</td>
</tr>
<tr>
<td><strong>Present study:</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Instantaneous vertical temperature profiles (Figure 3.7)</td>
<td>3.21</td>
<td>2.71</td>
<td>-</td>
</tr>
<tr>
<td><strong>Present study:</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean vertical temperature profiles (Figure 3.8)</td>
<td>-</td>
<td>2.67</td>
<td>-</td>
</tr>
</tbody>
</table>

A summary of jet penetration properties and comparison with previous studies are given in Table 3.2. Note, previous studies determined the jet penetration visually, and we have determined the jet penetration based on two different analyses of temperature data. Also, the values for high Froude numbers reported by Kay and Hunt (2006) are likely from
Baines et al (1990). Table 3.2 shows large variation in the peak height \( z_p \), which might not be easily reproducible, as explained above. On the other hand, \( z_{\text{mean}} \) and \( z_m \) appear both consistent within acceptable experimental errors.

The mean thermal structure of the jet is presented in Figure 3.9 using normalized contours of excess temperature \( \Delta T / \Delta T_0 \). The temperature data at 70 points were collected in Experiment Series C to determine these contours (see Figure 3.4). Since dilution as defined in Eq. 3.2 is inversely proportional to the excess temperature, it will have a minimum value at a location where the excess temperature is a maximum.

![Figure 3.9: Excess Temperature Contours](image)
Hence, it can be seen in Figure 3.9 that the jet achieves a minimum dilution as it returns to the level of the source (z=0) at a location immediately outside of the nozzle. We have adopted hereafter this location at z=0 immediately outside the nozzle as a reference point to characterize the jet dilution. The minimum dilution of the returning flow at the level of the source is relevant since it can potentially be used in practice to regulate the near field dilution of vertical dense discharges.

Further detailed investigations of temperature and dilution properties were pursued at the level of the source (z=0) using a horizontal profiler (Experiment Series D), and the results are presented in Figures 3.10 and 3.11. The horizontal excess temperature and dilution profiles exhibit a reasonable self-similar behavior in Figure 3.10 and 3.11. As expected the temperature profiles have a maximum value $\Delta T_1$ at $(r - r_0) = 0$ (i.e just outside the nozzle) where the dilution is minimum. In addition, a characteristic radial dimension $\delta$ of the returning flow at the level of the source was defined in Figures 3.10 and 3.11 at a radius where the excess temperature is half the maximum value (i.e $\Delta T = \Delta T_1/2$ or $\mu = 2\mu_{min}$).

Figure 3.10: Shape and Spread of Mean Horizontal Temperature Profile at the Level of the Source
Figure 3.11: Mean Horizontal Dilution Profile at the Level of the Source

The data in Figure 3.10 gives

\[ \delta = 0.31 \, r_0 \, Fr \]  \hspace{1cm} (3.7)

and the intersection of the mean profile with the horizontal axis suggest a maximum radial dimension of the return flow

\[ \delta_m = 1.4 \, r_0 \, Fr \]  \hspace{1cm} (3.8)

Normalized minimum dilution \( \mu_{min}/Fr \) obtained in Experiment series E are presented in Figure 3.12. The minimum dilution was calculated using the average temperature of four probes symmetrically located around and just outside the nozzle. The probes did not affect the fountain flow behavior, as the probes were placed at the outside edge of the nozzle where the fountain downward velocity was small. For completeness, the minimum dilution values extracted from the horizontal profiles of series D were also included and separately labeled in Figure 3.12. The best linear fit of all the data gathered in this study on minimum dilution is

\[ \frac{\mu_{min}}{Fr} = 0.581 \]  \hspace{1cm} (3.9)
Figure 3.12: Normalized Minimum Dilution $\frac{\mu_{\text{min}}}{Fr}$ Versus Froude number $Fr$

Figure 3.13: Normalized Minimum Dilution $\frac{\mu_{\text{min}}}{Fr}$ Versus Angle of Discharge $\theta$
The normalized minimum dilution given in Eq. 3.9 is compared in Figure 3.13 with the normalized minimum dilution of inclined dense jets in calm ambient water. The information was obtained from previous studies of inclined jets (Robert et al. 1997; Nemlioglu and Roberts 2006; Kikkert et al. 2007; Shao and Law 2010; Marti et al. 2011; Papakonstantis et al. 2011). The angle in Figure 3.13 is the angle in degrees of the discharge nozzle with the horizontal. A quadratic fit of the data is also presented. In calm water, the dilution of the vertical jet \( \theta = 90^\circ \) is about one half of the maximum dilution achieved around 60°.

### 3.5 Conclusions

This study has examined the penetration and dilution properties of vertical downward thermal jets, which are dynamically similar to vertical upward dense jets. The thermal experiment was simpler to conduct and provided accurate data. The main conclusions of this study are:

1. Temperature measurements were effective in examining both penetration and dilution properties of negatively buoyant jets.

2. Three heights characterizing the vertical penetration \( (z_{mean}, z_m, z_p) \) were defined and summarized in Table 3.2. The height of the initial front \( z_p \) is not considered a reproducible measure of vertical jet penetration. Only \( z_m \) and \( z_{mean} \) are likely reproducible.

3. The scales characterizing the horizontal jet penetration are given in Eqs. 3.7 and 3.8. The horizontal penetration of the return flow at the level of the source was \( \delta_m = 1.4 \ r_0 \ Fr \), which is about half the mean vertical penetration \( z_{mean} = 2.67 \ r_0 \ Fr \).

4. The critical location of minimum dilution of the returning flow at the source height \( (z=0) \) was just outside of the nozzle, and for high Froude numbers \( (Fr > 7) \) this minimum dilution can be calculated as \( \mu_{min} = 0.581 \ Fr \).
References


Chapter 4

MINIMUM RETURN DILUTION METHOD TO REGULATE DISCHARGE OF BRINE FROM DESALINATION PLANTS

4.1 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 4.1 shows historic and forecast data on world desalination capacity (Global Water Intelligence Report 2006). Worldwide desalination has increased exponentially in the last decades.

Figure 4.1: Global Desalination Capacity

Worldwide desalination capacity has reached 64 million m$^3$/d in 2010 and is projected to reach 98 million m$^3$/day 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

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3 Ahmad, N. and Baddour, R.E. (2013) paper has submitted in Canadian Journal of Civil Engineering.
research (Einav et al. 2002; NOAA 1978; Garcia 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 now-a-days considered the best practical solutions, as they have high diluting capabilities (Jirka 2008). Figure 4.2 shows a typical submerged brine diffuser system at the end of a long pipe line connected to a desalination plant.

![Diagram](image)

Figure 4.2: A Typical Submerged Brine Diffuser System Showing a Vertical Dense Fountain and Mixing Zones in Calm Water

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 source was about \(1.40 \, r_0 \, Fr\), where \(r_0\) 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.

### 4.1.1 Mixing Zones and Concept of Minimum Return Point Dilution

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 Figure 4.3, can replace the less defined mixing zone approach and could help address more stringent end of pipe criteria for toxic discharges. The brine in Figure 4.3 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.
Figure 4.3: Definition Sketch of a Vertical Dense Fountain Illustrating the Concept of Minimum Return Point Dilution at the Outer Edge of the Riser

4.2 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:

$$\text{Fr} = \frac{u_0}{\sqrt{\frac{g'_0 r_0}}}
$$

(4.1)

Where $U_0 = \text{discharge velocity}$, $r_0 = \text{radius of discharge nozzle}$, $g'_0 = g \frac{\rho_0 - \rho_a}{\rho_a} = \text{discharge buoyancy (or effective gravity)}$, $g = \text{gravity}$, $\rho_0 = \text{discharge density}$ and $\rho_a = \text{ambient water density}$.

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

\[
\mu = \frac{\Delta T_0}{\Delta T} = \frac{\Delta S_0}{\Delta S} \tag{4.2}
\]

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 \(S_a\). \(\Delta T_0\) and \(\Delta S_0\) are the initial excess temperature and excess salinity at the point of discharge. According to Eq. (4.2), the minimum dilution is associated with maximum temperature and salinity. And, as shown in Figure 4.3, the minimum dilution at the level of the source occurs at the outer edge of the riser (Chapter 3-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

\[
\frac{\mu_{\text{min}}}{Fr} = 0.581 \quad Fr > 7 \tag{4.3}
\]

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. (4.6) 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, \(\Delta S_{\text{max}}\), and maximum excess temperature, \(\Delta T_{\text{max}}\), 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):

\[
\Delta S_{\text{max}} = \frac{\Delta S_0}{\mu_{\text{min}}} 
\]

\[
\Delta T_{\text{max}} = \frac{\Delta T_0}{\mu_{\text{min}}}
\]

Where \( \Delta S_0 \) = the initial excess salinity and \( \Delta T_0 \) = initial excess temperature, both calculated at the point of discharge. Eliminating \( \mu_{\text{min}} \) using Eq. (4.3), 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

\[
\frac{\Delta S_{\text{max}}}{\Delta S_0} = \frac{\Delta T_{\text{max}}}{\Delta T_0} = \frac{1.72}{Fr} \quad Fr > 7
\]

4.3 Experiments

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). Some high Froude number experiments using higher spatial resolution probes were also performed to further analyze the properties of high Froude number fountains.

Three Series of experiments, summarized in Table 4.1, were conducted in this study to achieve a set of specific objectives. As seen in Table 4.1, turbulent flow conditions were maintained with discharge Reynolds numbers \( Re \) ranging from 2253-6232. The smallest Froude number \( Fr \) was 0.96 and the largest was 12.8. The Three series of experiments are described in the following, and the locations of thermocouples associated with each one of them are illustrated in Figure 4.4.

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 source (see Figure 4.4). To keep turbulent flow conditions at very low \( Fr \), a larger
diameter nozzle \((r_0=17.25\text{mm})\) was used. A total of 18 tests were performed in Experiment Series I with \(Fr\) ranging between 0.96 and 6.7.

Table 4.1 Summary of Experimental Conditions

<table>
<thead>
<tr>
<th>Experiment Series (1)</th>
<th>Objective (2)</th>
<th>Radius of nozzles (r_0) (mm) (3)</th>
<th>No. of Measuring Points (4)</th>
<th>Num. of Tests (5)</th>
<th>Densimetric Froude No. (Fr) (6)</th>
<th>Reynolds No. (Re) (7)</th>
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</thead>
<tbody>
<tr>
<td>I</td>
<td>Minimum dilution</td>
<td>17.25</td>
<td>4</td>
<td>18</td>
<td>0.96-6.7</td>
<td>2993-6232</td>
</tr>
<tr>
<td>II</td>
<td>Vertical profiles</td>
<td>8.75</td>
<td>23</td>
<td>3</td>
<td>10.2-12.8</td>
<td>3040-3734</td>
</tr>
<tr>
<td>III</td>
<td>Horizontal profiles</td>
<td>8.75</td>
<td>10</td>
<td>5</td>
<td>3.43-7.25</td>
<td>2253-4989</td>
</tr>
</tbody>
</table>

\(T > 15 \, ^{\circ}\text{C}\)

Figure 4.4: Definition Sketch Showing the Location of Thermocouples for Different Series of Experiments

Experiment Series II was designed to obtain vertical excess temperature profiles on the centre line of the jet \((r = 0)\). Vertical jet penetration, intermittency, and turbulence
properties were examined with these profiles. The vertical profiler was made of 23 thermocouples, and three tests were performed to assess repeatability within a narrow range of Froude numbers 10.2-12.8.

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 low Froude number point of minimum 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, as shown in Figure 4.4. Five experiments with different Froude number ranging from 3.43-7.25 were performed.

4.4 Results and Discussion

4.4.1 Vertical Profile Analysis and Vertical Height

In Figures 4.5, 4.6, and 4.7, the height of the fountain was analyzed by considering the vertical profiles of (i) mean temperature, (ii) intermittency, and (iii) turbulence intensity, measured along the jet centre line (\(r=0\)). In Figure 4.5, a mean height is determined by locating the maximum temperature gradient. Based on three tests conducted in Experimental Series II, the maximum temperature gradient \(\frac{dT}{dz}|_{max}\) of the mean profile occurs at 2.41 \(r_oFr\). This height is about 10% smaller than the height determined previously in Ahmad and Baddour (2012). A better accuracy of locating the maximum gradient was achieved in the present study by using more closely spaced thermocouples.

Figure 4.6 shows the vertical intermittency profiles obtained along the centre line of the fountain. The intermittency \(I\) is defined as the fraction of time a given probe is experiencing a temperature above ambient. A small threshold, above ambient temperature, was determined first from the noise of each thermocouple signal. This threshold was added to ambient temperature when calculating the intermittency. This noise-related threshold determined under still ambient water conditions for each thermocouple varied between 0.04 to 0.11°C. These thresholds are consistent with the accuracy of the thermocouples (0.1°C).
The intermittency profiles in Figure 4.6 show that the frontal height of the fountain fluctuated between a minimum and maximum height of about 2.25 and 3\( r_0 Fr \). The height
corresponding to an intermittency $I = 0.5 (50\% \text{ of the time within the fountain})$ occurred at $2.66 \, r_o Fr$. In Figure 4.7, the vertical turbulence intensity ($\frac{\sigma_T}{\Delta T_0}$) profiles were determined by calculating the standard deviation ($\sigma_T$) of the temperature fluctuating signals along the fountain centre line. Figure 4.7 clearly shows that the turbulent intensity is amplified in the region where the front of the fountain is fluctuating (i.e region $z = 2.25$ to $3 \, roFr$). The turbulent intensity can also be seen in Figure 4.7 to reach a peak value at $2.5 \, roFr$ and, as expected, vanished beyond $z = 3 \, roFr$.

![Figure 4.7: Vertical Turbulence Intensity Profiles along the Fountain Centre-Line ($r =0$)](image)

**4.4.2 Horizontal Profile Analysis and Minimum Dilution**

The horizontal profiles are analyzed in Figures 4.8, 4.9, 4.10, and 4.11. In Figure 4.8, mean horizontal excess temperature profiles of low Froude number fountains are compared with 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.
Figure 4.8: Horizontal Excess Temperature Profiles at the level of the Source ($z = 0$) for Small and Large Froude number Fountains

Figure 4.9: Horizontal Dilution Profiles at the Level of the Source ($z = 0$) for Small and Large Froude number Fountains
The data suggest a reduction of fountain radius at the level of the source from $r_0 = 1.4 \, roFr$ at high Froude number to $r_0 = 1.0 \, roFr$ at low Froude number. The radius $r_0$ can be used to define the impact zone of the fountain at the level of the source. Note, however, 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 ($\Delta T_{\text{max}}$, $\Delta S_{\text{max}}$) and the dilution is always minimum ($\mu_{\text{min}}$), as shown in the dilution profiles plotted in Figure 4.9.

The horizontal profiles of intermittency and turbulence intensity are presented in Figures 4.10 and 4.11. The intermittency profiles in Figure 4.10 indicate fluctuations of fountain radius between about 0.5 to 1.5 $roFr$. More importantly, in Figure 4.11 there is no peak in turbulent intensity as observed in the vertical profiles (see Figure 4.7). Visually, it was observed that the turbulent boundary of the fountain at the level of the source was generally more stable than the vertical front of the fountain. This observation would explain why the horizontal turbulent intensity profile in Figure 4.11 does not have a pronounced peak value near the edge of the fountain.

Figure 4.10: Horizontal Intermittency Profiles at the Level of the Source ($z = 0$) for Small Froude number Fountains
Figure 4.11: Horizontal Turbulence Intensity Profiles at the Level of the Source ($z = 0$) for Small Froude number Fountains

The results for the normalized minimum dilution $\frac{\mu_{\text{min}}}{F_r}$ plotted versus $F_r$ are presented in Figure 4.12. The low Froude number fountains have a significantly different behaviour than the high Froude number fountains. While for high Froude number fountains $\frac{\mu_{\text{min}}}{F_r}$ was constant, for low Froude number fountains $\frac{\mu_{\text{min}}}{F_r}$ clearly decreased with the Froude number. A best linear fit of the low Froude number data in Figure 4.12 is

$$\frac{\mu_{\text{min}}}{F_r} = 1.24 - 0.15 F_r \quad F_r < 5$$ (4.7)

Note, for all practical purposes the high Froude number behavior given in Eq. 4.3 may be used for $F_r > 5$. Also the minimum dilution in Figure 4.12 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).
Eqs. 4.3 and 4.7 provide a pair of modeling equations to design a vertical fountain of brine to comply with any required regulatory minimum return dilution.

Figure 4.12: Minimum Return Dilution for Small and Large Froude number Fountains

Figure 4.13: Maximum Excess Temperature (or Salinity) at the Level of the Source for Small and Large Froude number Fountains
Furthermore, the normalized maximum excess temperature data ($\frac{\Delta T_{\text{max}}}{\Delta T_0}$) for low and high Froude number fountains are plotted in Figure 4.13 versus the Froude number ($Fr$) using a logarithmic scale. There is a clear demarcation in Figure 4.13 between low and high Froude number behaviour. The power-law trend lines drawn in Figure 4.13, for the low and high Froude number regimes, are, respectively, $\frac{\Delta T_{\text{max}}}{\Delta T_0} = \frac{\Delta S_{\text{max}}}{\Delta S_0} = 0.84 Fr^{-0.56}$ and $\frac{\Delta T_{\text{max}}}{\Delta T_0} = \frac{\Delta S_{\text{max}}}{\Delta S_0} = 1.72 Fr^{-1}$. These power-law equations 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.

Figure 4.14: Definition Sketch of an Inclined Dense Fountain Showing the Minimum Return Dilution at some Distance away from the Source
4.5 Minimum Return Dilution for Inclined Dense Discharge

The basic properties of inclined dense discharges have been extensively studied (Zeitoun et al. 1970; Pincine 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 Figure 4.14). This \textit{minimum return dilution} is a function of the discharge Froude number \( Fr \) and the angle \( \theta \) of the discharge with the horizontal.

The normalized minimum return dilution (\( \mu_{\text{min}}/Fr \)) 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 Figure 4.15 versus the angle \( \theta \). For completeness, the present low Froude number data (Exp series I) and high Froude number data of Ahmad and Baddour (2012) for vertical fountains (\( \theta = 90^\circ \)) are also plotted in Figure 4.15.

![Figure 4.15: Effect of Discharge Orientation on Minimum Return Point Dilution of Dense Fountains in Calm Water](image)

Figure 4.15: Effect of Discharge Orientation on Minimum Return Point Dilution of Dense Fountains in Calm Water
Understandably, the present low Froude experiments at $\theta = 90^\circ$ are showing a large range in dilution due to effect of Froude number, as explained in Figure 4.12. Also all previous inclined jet data in Figure 4.15 correspond to high Froude number jets. The quadratic fit to high Froude number behavior shown in Figure 4.15 suggests a maximum value of $\mu_{\text{min}}/Fr$ when $\theta$ is about $60^\circ$. 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 the vertical fountain. As demonstrated below, smaller dilutions compared to vertical fountains may occur with strong co-currents and weak counter-currents.

![Figure 4.16: Effect of Discharge Orientation on Minimum Return Point Dilution of Dense Fountains with Varying Velocity Currents and Directions](image)

The data of Roberts and Toms (1987) are plotted in Figure 4.16 to demonstrate the effect of current strength and direction on the return dilution of vertical ($\theta = 90^\circ$) and inclined ($\theta = 60^\circ$) fountains. Figure 4.16 shows that dilution of the inclined fountain ($\theta = 60^\circ$) 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 Figure 4.16 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 in order to take full advantage of the currents in any direction.

4.6 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. Eqs. 4.3 and 4.7 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.
References


Global Water Intelligence Report. 2006. 7(10), October.


Chapter 5

DENSITY EFFECT ON MINIMUM RETURN POINT
DILUTION AND HEIGHT OF FOUNTAINS

5.1 Introduction

Figure 5.1 is showing a vertical dense jet (fountain or negatively buoyant jet) into a tank filled with freshwater. Dilution and height of fountains have been studied previously without considering the effect of relative density difference \( \frac{\Delta \rho}{\rho_a} \), where \( \Delta \rho = \rho_0 - \rho_a \), \( \rho_0 \) is density of fountain at a discharge point, and \( \rho_a \) is density of ambient water. The effect of relative density difference on the maximum height of a vertical fountain was reported by Baddour and Zhang (2009). It is important to investigate the density effects on brine discharges since \( \frac{\Delta \rho}{\rho_a} \) of brine discharges may vary significantly in practice. For example, brine discharge by Reverse Osmosis (RO) processes in desalination has typically a salinity of 70 parts per thousand (ppt) (Lattemann and Hopner 2008). So, brine discharge of RO into the sea with 70 ppt salinity results in a dense jet with about \( \frac{\Delta \rho}{\rho_a} = 0.01 \). Brine discharge by Multi-Stage Flash (MSF) desalination technique has a typical salinity of 50 ppt and temperature 100 °C (Lattemann and Hopner 2008). Cooling water from co-located power plant of lighter density is mixed to decrease the temperature of desalinated brine. So, the resulting \( \frac{\Delta \rho}{\rho_a} \) of dense jets from MSF brine is about 0.003 and could be positively buoyant in some extreme cases. The oil brine or potash brine ranging in salinity from 200-300 ppt result in dense jets with \( \frac{\Delta \rho}{\rho_a} = 0.12 \) to 0.2 (Tong and Stolzenbach 1979). There is, therefore, a need to study the effect of \( \frac{\Delta \rho}{\rho_a} \) on dilution of fountains.

Ahmad and Baddour (2012 & 2013) studied dilution of turbulent vertical dense jets. They studied dilution of fountains without considering the effect of relative density

\[^4\text{Ahmad, N. and Baddour, R.E. (2013) paper to be submitted to ASCE Journal of Hydraulic Engineering.}\]
difference $\left(\frac{\Delta \rho}{\rho_a}\right)$. During their studies, $\frac{\Delta \rho}{\rho_a}$ ranged between 0.002 and 0.006 where Boussinesq approximation is expected to be applicable due to small density difference.

Figure 5.1: Picture of a Vertical Dense Fountain Captured in the Hydraulics Laboratory at Western University – Horizontal Bar Refers to the Exact Level of the Source at the Exit of the Nozzle ($r_0 = 9.8 \text{ mm, } Fr = 3.1, Re = 3831, S_0 = 40, \text{ and } \frac{\Delta \rho}{\rho_a} = 0.03$)

Moreover, most previous studies (e.g. Turner 1966; Zeitoun et al. 1970; James et al. 1983; Baines et al. 1990; Zhang and Baddour (1998); Kay and Hunt 2006; Abou-Elhaggag et al. 2011; Ahmad and Baddour 2012; Ahmad and Baddour 2013) did not consider the effect of density difference on height of fountains. Baddour and Zhang (2009) performed experiments and showed that the maximum height $\left(\frac{z_m}{r_0Fr}\right)$ of fountains is a function of $\frac{\Delta \rho}{\rho_a}$.

In the present study, effect of $\frac{\Delta \rho}{\rho_a}$ is investigated on both dilution and height of fountains. The present work is the extension of previous work by Ahmad and Baddour (2012 & 2013) to include the effect of $\frac{\Delta \rho}{\rho_a}$ on dilution and height.
5.2 Methodology

Baddour and Zhang (2009) used the following equation to study the effect of \( \frac{\Delta \rho}{\rho_a} \) on \( \left( \frac{z_m}{r_0 Fr} \right) \) of turbulent fountains as

\[
\frac{z_m}{L_s} = f \left( \frac{\Delta \rho}{\rho_a} \right)
\]  

(5.1)

Where, \( L_s = r_0 Fr \) is a length scale used to normalize vertical heights; \( z_m \) is considered as the average value of the consecutive frontal peaks (Zhang and Baddour 1998); \( Fr \) is densimetric Froude number which is defined as

\[
Fr = \frac{U_0}{\sqrt{g_0 r_0}}
\]  

(5.2)

Where \( U_0 = \frac{Q_0}{\pi r_0^2} \) = discharge velocity, \( Q_0 = \) discharge flow rate, \( r_0 = \) radius of discharge nozzle, \( g' = g \frac{\rho_0 - \rho_a}{\rho_a} = \) discharge buoyancy (or effective gravity), \( \rho_0 = \) discharge density and \( \rho_a = \) ambient water density.

In the same way, the effect of \( \frac{\Delta \rho}{\rho_a} \) on minimum return point dilution \( (\mu_{min}) \) at the edge of the nozzle can be studied as

\[
\frac{\mu_{min}}{\mu_s} = f \left( \frac{\Delta \rho}{\rho_a} \right)
\]  

(5.3)

Where, \( \mu_s \) is dilution scale for temperature and salinity and \( \mu_s = Fr \) under linear conditions of water above 15°C (see Chapter 3 - Ahmad and Baddour 2012).

Minimum return point dilution in upward saline thermal fountains just at the edge of the nozzle as shown in Figure 5.2 could be determined by conserving heat and salt (see Chapter 4 Ahmad and Baddour 2013) as:

\[
\mu_{min} = \frac{\Delta T_0}{\Delta T_1} = \frac{\Delta S_0}{\Delta S_1}
\]  

(5.4)
Where $\Delta T_j = T_j - T_a$ and $\Delta S_j = S_j - S_a$ are, respectively, the excess temperature and excess salinity of the brine above the ambient values $T_a$ and $S_a$. $\Delta T_0$ and $\Delta S_0$ are the initial excess temperature and excess salinity at the point of discharge.

![Definition sketch of an upward fountain generated by a thermal dense jet](image)

**Figure 5.2**: Definition sketch of an upward fountain generated by a thermal dense jet

### 5.3 Experimental Arrangement and Procedure

Dense vertical upward thermal tests were performed in the apparatus shown in Figure 5.3. Dense water (hot or cold saline water and cold fresh water depending on experiment conditions) was discharged vertically upward through a nozzle into a transparent tank filled with freshwater. The tank made of acrylic was 1.15 m deep and 1.15m x 1.15m in cross section. A smaller circular elevated base plate was inserted 6 cm above the bottom of the tank to prevent the spreading dense layer from backing up rapidly and run steady state fountains for longer periods of time with minimal wall effects. A discharge nozzle was located in the center of the experimental tank 15 cm above the base plate. This
A saline solution was prepared in a mixing tank by mixing salt in freshwater. The salt solution was pumped from the mixing tank into an overhead tank. The salt solution was then discharged by gravity under a constant head from the overhead tank into the experiment tank. Discharge of saline water was controlled and maintained by three flow meters with various flow ranges. The vertical penetration and dilution properties of the generated fountains were examined in this study with fine wire thermocouples, which measured the water temperature with an accuracy of ± 0.1°C. A more complete
description of thermocouples and methodology can be found in Ahmad and Baddour (2012). The thermocouples were arranged horizontally on a vertical profiler to determine the height of fountains, and were arranged vertically around the nozzle to determine the minimum return point dilution of the fountains. During the experiment, a thermocouple was deployed inside the nozzle to continuously monitor the temperature of the discharge. Another thermocouple was also deployed, near the top of the tank, far away from the fountain, to measure the ambient water temperature.

Six series of experiments, summarized in Table 5.1, were conducted to achieve a set of specific objectives. As seen in Table 5.1, turbulent flow conditions were maintained with discharge Reynolds numbers $Re$ ranging from 2294.6 to 9578. The smallest Froude number $Fr$ was 2.13 and the largest was 15.7. The six series of experiments are described in the following and the locations of thermocouples associated with them are illustrated in Figure 5.4.

<table>
<thead>
<tr>
<th>Test series</th>
<th>Nozzle diameter (mm)</th>
<th>No. of tests</th>
<th>No. of measuring points</th>
<th>Density difference $\left(\frac{\Delta \rho}{\rho_a}\right)$</th>
<th>Froude number $(Fr)$</th>
<th>Reynold number $(R)$</th>
<th>Discharge salinity (ppt)</th>
</tr>
</thead>
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<tr>
<td>A</td>
<td>19.6</td>
<td>8</td>
<td>4</td>
<td>0.0014-0.01</td>
<td>7.95-9.52</td>
<td>2298.8-5447</td>
<td>0 (pure-thermal)</td>
</tr>
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<td>B</td>
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<td>4</td>
<td>0.0096-0.064</td>
<td>6.9-13.2</td>
<td>4966.6-9578</td>
<td>20-90</td>
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<td>C</td>
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<td>4</td>
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<td>2.83-6.9</td>
<td>3352-7662</td>
<td>20-40</td>
</tr>
<tr>
<td>D</td>
<td>19.6</td>
<td>15</td>
<td>20</td>
<td>0.0015-0.0057</td>
<td>7.461-9.52</td>
<td>2294.6-4693.4</td>
<td>0 (pure thermal)</td>
</tr>
<tr>
<td>E</td>
<td>19.6 &amp; 9.45</td>
<td>19</td>
<td>20</td>
<td>0.005-0.064</td>
<td>7.06-15.7</td>
<td>3575.9-7997.9</td>
<td>1.5-90</td>
</tr>
<tr>
<td>F</td>
<td>22.18 &amp; 19.6</td>
<td>14</td>
<td>20</td>
<td>0.015-0.027</td>
<td>2.13-7.06</td>
<td>2962.5-6465.4</td>
<td>30-40</td>
</tr>
</tbody>
</table>

Experiment series A, B, and C were designed to investigate the effect of $\frac{\Delta \rho}{\rho_a}$ on the minimum return point dilution. The accuracy of minimum return point dilution was improved by measuring dilution directly with four equally spaced thermocouples around the nozzle at the level of the source (see Figure 5.4).
In Experiment Series A eight pure dense thermal tests were performed by discharging fresh coldwater into a tank filled with warm freshwater, and $\Delta \rho / \rho_a$ ranging between 0.0014 to 0.01. Pure dense thermal tests were specially performed to compare with downward thermal tests of Ahmad and Baddour (2012). In Experiment Series B and C, saline thermal tests were performed by discharging hot and dense salt solution into the tank filled with coldwater. In Experiment Series B, ten tests were performed with $\Delta \rho / \rho_a$ and $Fr$ ranging between 0.0096-0.064 and 6.9-13.2 respectively. In Experiment series C, 21 low $Fr$ tests (ranging between 2.83 to 6.9) were performed to investigate the effect of $\frac{\Delta \rho}{\rho_a}$ ranging between 0.012 to 0.028.

*Experiment series D, E, and F* were designed to investigate the effect of $\frac{\Delta \rho}{\rho_a}$ on height of fountains. In Experiment series D, 20 freshwater thermal dense tests were performed by discharging cold freshwater into a tank filled with warm freshwater, and $\frac{\Delta \rho}{\rho_a}$ ranging
between 0.0015 to 0.0057. Pure upward thermal tests were specially performed to determine and compare heights with downward thermal tests of Ahmad and Baddour (2012). In Experiment series E and F, thermal saline water was discharged into the tank filled with coldwater. In Experiment series E, 20 tests were performed at high $Fr$ with $\frac{\Delta \rho}{\rho_a}$ ranging between 0.005-0.064. In Experiment series F, 20 low $Fr$ tests (ranging between 2.13 to 7.06) were performed to investigate the effect of $\frac{\Delta \rho}{\rho_a}$ ranging between 0.015 to 0.027.

### 5.4 Results and Discussions

Figure 5.5 and 5.6 are presented to show the effect of $\frac{\Delta \rho}{\rho_a}$ on dilution. Figure 5.5 is showing that normalized dilution $\frac{\mu_{\text{min}}}{Fr}$ is decreasing with increase of $\frac{\Delta \rho}{\rho_a}$. Ahmad and Baddour (2012) performed pure thermal downward experiments with $\frac{\Delta \rho}{\rho_a}$ ranging from 0.002-0.006 and found the normalized minimum return point dilution at the source as

$$\frac{\mu_{\text{min}}}{Fr} = 0.581 \quad Fr > 7$$  \hfill (5.5)

![Figure 5.5: Effect of $\Delta \rho/\rho_a$ on Minimum Return Point Dilution](image)
The minimum return point dilution of Ahmad and Baddour (2012) is shown by a straight dotted line in Figure 5.5. $\frac{\mu_{\text{min}}}{F_r}$ of pure thermal upward tests with $\frac{\Delta p}{\rho_a}$ ranging from 0.002 to 0.006 agrees with Ahmad and Baddour (2012) value of 0.581. It confirms that $\frac{\mu_{\text{min}}}{F_r}$ of a downward thermal fountain is dynamically equivalent to an upward fountain of comparable density difference.

The best power fit of data (Experiment Series A and B) is

$$\frac{\mu_{\text{min}}}{F_r} = 0.1726 \left( \frac{\Delta p}{\rho_a} \right)^{-0.205}$$

(5.6)

This equation shows a relationship between $\frac{\mu_{\text{min}}}{F_r}$ and $\frac{\Delta p}{\rho_a}$ and can be used to determine normalized return point dilution for a given value of $\frac{\Delta p}{\rho_a}$.
In Figure 5.6, $\frac{\mu_{\text{min}}}{Fr}$ versus $Fr$ is drawn of various series which have different $\frac{\Delta \rho}{\rho_a}$. Experiment series with higher $\frac{\Delta \rho}{\rho_a}$ is showing less dilution than experimental series with lower $\frac{\Delta \rho}{\rho_a}$. Dilution of pure thermal upward fountains is equal to pure thermal downward fountains. Experiment Series B is divided into low and high dense to further show the effect of $\frac{\Delta \rho}{\rho_a}$ on dilution. The part of Experiment Series B with lower $\frac{\Delta \rho}{\rho_a}$ is showing higher $\frac{\mu_{\text{min}}}{Fr}$ than other part of Experiment Series B with higher $\frac{\Delta \rho}{\rho_a}$. In Figure 5.6, low $Fr$ number data is also included. Low $Fr$ numbers data of Experiment Series C is showing less $\frac{\mu_{\text{min}}}{Fr}$ than higher $Fr$ numbers of pure thermal tests as Experiment Series C tests are comparatively very dense. However, the data of Experiment Series C is in continuation with less dense part of Experiment Series B (at $Fr$ number 7) as both have nearly the same $\frac{\Delta \rho}{\rho_a}$. The data of Experiment Series C (low $Fr$ number data) is showing less $\frac{\mu_{\text{min}}}{Fr}$ than Ahmad and Baddour (2012) as Experiment Series C tests are denser.

Figure 5.7 and 5.8 are drawn to show the effect of $\frac{\Delta \rho}{\rho_a}$ on normalized maximum height $\frac{z_m}{r_0 Fr}$. Figure 5.7 shows that height is decreasing by increasing $\frac{\Delta \rho}{\rho_a}$ in agreement with observations by Baddour and Zhang (2009). In Figure 5.7, previous studies data is also plotted to compare with present experiments data.

Ahmad and Baddour (2013) performed pure thermal downward experiments with $\frac{\Delta \rho}{\rho_a}$ ranging from 0.0023-0.004 and found the maximum normalized height

$$\frac{z_m}{r_0 Fr} = 3.0$$

(5.7)

$\frac{z_m}{r_0 Fr}$ of Ahmad and Baddour (2013) is drawn by a straight line in Figure 5.7. $\frac{z_m}{r_0 Fr}$ of pure thermal upward tests with $\frac{\Delta \rho}{\rho_a}$ ranging from 0.0023 to 0.004 agrees with Ahmad and Baddour (2013) value of the height 3.0. It confirms that $\frac{z_m}{r_0 Fr}$ of a downward thermal fountain is equal to an upward dense jet.
The best power fit of data (Exp. Series D and E) is

\[ \frac{z_m}{r_0 Fr} = 2.0961 \left( \frac{\Delta \rho}{\rho_a} \right)^{-0.056} \]  

(5.8)

This equation shows a relationship between \( \frac{z_m}{r_0 Fr} \) and \( \frac{\Delta \rho}{\rho_a} \) and can be used to determine the fountain height for a given value of \( \frac{\Delta \rho}{\rho_a} \).

In Figure 5.7, \( \frac{z_m}{r_0 Fr} \) versus \( Fr \) is drawn of various series which have different \( \frac{\Delta \rho}{\rho_a} \).

Experiment series with higher \( \frac{\Delta \rho}{\rho_a} \) are showing less height than lower experiment series with lower \( \frac{\Delta \rho}{\rho_a} \). Height of a pure thermal upward fountain is equal to a pure thermal downward fountain. Experiment Series D is divided into low and high dense to further show the effect of \( \frac{\Delta \rho}{\rho_a} \) on height. The part of Experiment Series D with lower \( \frac{\Delta \rho}{\rho_a} \) is showing higher \( \frac{z_m}{r_0 Fr} \) than other part of Experiment Series D with higher \( \frac{\Delta \rho}{\rho_a} \). In Figure 5.8, low \( Fr \) number data is also included. The data of Experiment Series F is in continuation.
with Experiment Series E (at Fr number 7) as both have nearly the same $\frac{\Delta \rho}{\rho_a}$. The data of Experiment Series F (low Fr number data) is showing less $\frac{z_m}{r_0 Fr}$ than Zhang and Baddour (1998) as Experiment Series F tests are denser.

![Figure 5.8: Effect of $\Delta \rho/\rho_a$ on Height at Various Froude numbers](image)

### 5.5 Conclusion

This study has examined the effect of relative density difference on height and dilution of vertical dense jets. The main findings of this study are:

1. $\frac{\Delta \rho}{\rho_a}$ has a noticeable effect on dilution and height of fountains that cannot be ignored. There is a sharp decrease in height and dilution for $\frac{\Delta \rho}{\rho_a}$ ranging 0.0014-0.01. A best power fit of the data is drawn in Figure 5.5 and 5.7, respectively, for dilution and height. The relationship describing the effect of relative density difference on minimum return point dilution and height are respectively given in Eq. 5.6 and 5.8.
2. Present data (Figures 5.5 to 5.8) are in good agreement with previous studies.

3. Pure thermal downward fountain was found dynamically equivalent to a pure thermal upward fountain.

4. Present study data (Experiment series F in Figure 5.8) for low Fr is showing less normalized height than Zhang and Baddour (1998) as the present study data is denser than the previous study data.

References


Chapter 6

A TWO-COEFFICIENT ENTRAINMENT MODEL OF A VERTICAL TURBULENT FOUNTAIN\(^5\)

6.1 Introduction

In practice, brine and other industrial dense effluents are commonly conveyed deep into the sea through long pipe lines and discharged by multiport diffusers above the sea bed forming vertical fountains (dense vertical jets). The design objective of these outfall diffusers is to dilute the discharge. The dilution within these fountains depends entirely on the capacity of the flow to entrain surrounding ambient water. It is, therefore, important to study the concept of entrainment as it applies to fountains. In other fields, such as physical volcanology, quantitative prediction of entrainment of external air into volcanic fountains is also important (Carazzo et al. 2008) since entrainment affects volcanic eruption behavior (such as rise, spread, and concentration of material inside volcanic fountains).

The entrainment behavior of pure jets and pure plumes is relatively simple and well understood (Morton et al. 1956; Morton 1962; List and Imberger 1972 and many others). The reported values of single entrainment coefficients of pure jets and pure plumes are 0.056 and 0.085, respectively (List and Imberger 1972). On the other hand, due to the complexity of the rising and falling flows (double-plume structure) multiple entrainment coefficients may be required to model the fountain behavior (McDougall 1981). In previous studies (Bloomfield and Kerr 1998; Baddour and Zhang 2005; Kaye and Hunt 2006; Papanicolaou and Kokkalis 2008), only the entrainment behavior of starting fountains (before the down flow) was discussed. Some researchers (McDougall 1981; and Bloomfield and Kerr 2000) developed more comprehensive entrainment models for vertical fountains; however, the lack of experimental dilution data seems to have prevented these studies of determining specific values of fountain entrainment coefficients.

In this paper, we first present the governing equations of a two-coefficient entrainment model for vertical fountains in homogeneous environments. An attempt is then made to determine values of the two entrainment coefficients associated with the vertical fountain. The entrainment coefficients were determined by calibrating the model predictions with the dilution data obtained experimentally by Ahmad and Baddour (2013). We finally discuss the sensitivity of the results to the values of the entrainment coefficients.

6.2 Methodology

6.2.1 Vertical Fountain Entrainment Properties

Figure 6.1 shows a schematic of a vertical dense jet. At steady state, the flow takes the form of a fountain, which can be divided into three parts; inner jet, outer plume, and top part. In general, three entrainment processes can be identified and they are parameterized by three entrainment coefficients $\alpha_j, \alpha_p, \alpha_t$.

\[ \alpha_j = \text{Entrainment coefficient of fluid entering into the inner jet from the outer plume,} \]

\[ \alpha_p = \text{Entrainment coefficient of fluid entering into the outer plume from ambient,} \]

\[ \alpha_t = \text{Entrainment coefficient of fluid transferred from the inner jet into the outer plume.} \]

The inner jet is an upwards moving conical jet. The outer plume is a downwards moving annular plume, surrounding the inner jet. Entrainment currents in the fountain occur across turbulent mixing layers, which develop (i) between the rising jet and falling plume, and (ii) between the falling plume and surrounding environment. The turbulent vorticity in the mixing layers produce net pressure reductions, which drive entrainment currents (i) from the outer plume into the inner jet and (ii) from the surrounding ambient into the outer plume. The two entrainment currents described above are represented by the coefficients $\alpha_j$ and $\alpha_p$, respectively. The third coefficient $\alpha_t$ which represents entrainment (or unidirectional mass transfer) from the inner jet to the outer plume appears physically less important and was ignored in the present model.
A turbulent dense jet experiment was performed to study the turbulence and entrainment characteristics of a vertical fountain. The radius of the nozzle was $r_o = 0.96$ cm, Froude number $Fr = 8.49$, and relative density difference $\frac{\Delta \rho}{\rho_a} = 0.017$. Profiles of standard deviations of temperature fluctuations were obtained at various heights above the source and on the one side of the nozzle. The apparatus, method, and procedure was explained in Chapter 5 (Ahmad and Baddour 2013). Figure 6.2 shows the horizontal profiles of normalized standard deviation of temperature fluctuations $\left( \frac{\sigma}{\Delta T_0} \right)$. Here, $\Delta T_0$ is the initial excess temperature of a fountain above ambient temperature. The profiles in Figure 6.2 are showing a rapid decrease in the intensity of temperature fluctuations in the turbulent mixing layer separating the inner jet and the outer plume. It can be inferred from these profiles that the entrainment current is mainly in the direction from the low turbulence
side (outer plume) towards the high turbulent intensity side (inner jet). It is the basis for the assumption of ignoring $\alpha_i$ in the present model.

![Horizontal Profiles of Normalized Standard Deviation of Temperature Fluctuations Measured at Various Heights from the Nozzle](image)

Figure 6.2: Horizontal Profiles of Normalized Standard Deviation of Temperature Fluctuations Measured at Various Heights from the Nozzle

McDougall (1981) and Bloomfield and Kerr (2000) included the third coefficient $\alpha_i$ in their models but did not discuss neither its relevance nor its magnitude.

6.2.2 Entrainment Assumption

The classical entrainment hypothesis of Morton, Taylor and Turner (1956) can be applied to the fountain. At a distance $z$ above the source, the inner jet is moving at a velocity $U_j$ against the falling plume, which has a downward velocity $U_p$. Recognizing the net shear velocity $(U_j + U_p)$ as the characteristic velocity of the mixing layer (Morton 1962,
Baddour et. al 2006), the entrainment current from the outer plume into the inner jet can be expressed as

\[ U_{j(\text{ent})} = \alpha_j(U_j + U_p) \]  

(6.1)

Where \( U_{j(\text{ent})} \) = jet entrainment velocity

Entrainment from the stagnant surrounding into the outer plume is based only on the downward plume velocity \( U_p \), and

\[ U_{p(\text{ent})} = \alpha_p U_p \]  

(6.2)

Where \( U_{p(\text{ent})} \) = plume entrainment velocity

### 6.2.3 The Entrainment Model

In the following governing equations it is assumed that the velocity, temperature and salinity profiles are all uniform (i.e top hat profiles) in the inner jet and outer plume. It is also assumed that the water equation of state is linear and hence the buoyancy is linearly proportional to the excess temperature and excess salinity.

As shown in Figure 6.1, The inner jet is characterized by a radius \( (r_j) \), fluid velocity \( (U_j) \) and buoyant acceleration \( (g'_j) \). The three equations governing the development of the inner jet are:

(i) **Mass conservation equation**

\[ \frac{d}{dz}(U_j \pi r_j^2) = \alpha_j 2\pi r_j(U_j + U_p) \]  

(6.3)

(ii) **Momentum equation**

\[ \frac{d}{dz}(U_j^2 \pi r_j^2) = -g'_j \pi r_j^2 - \alpha_j 2\pi r_j(U_j + U_p)U_p \]  

(6.4)

(iii) **Buoyancy equation**

\[ \frac{d}{dz}(U_j g'_j \pi r_j^2) = \alpha_j 2\pi r_j(U_j + U_p)g'_p \]  

(6.5)
Where, \( z \) is the height above the nozzle, \( U_p \) and \( g'_p \) are fluid velocity and buoyancy, respectively in outer plume part of the fountain.

Similarly, the three equations governing the development of the outer plume are:

(iv) \textit{Mass conservation equation}

\[
\frac{d}{dz^*}[U_p \pi (r_p^2 - r_j^2)] = \alpha_p 2\pi r_p U_p - \alpha_j 2\pi r_j (U_j + U_p) \tag{6.6}
\]

(v) \textit{Momentum equation}

\[
\frac{d}{dz^*}[U_p^2 \pi (r_p^2 - r_j^2)] = g'_p \pi (r_p^2 - r_j^2) - \alpha_j 2\pi r_j (U_j + U_p) U_p \tag{6.7}
\]

(vi) \textit{Buoyancy equation}

\[
\frac{d}{dz^*}[U_p g'_p \pi (r_p^2 - r_j^2)] = -\alpha_j 2\pi r_j (U_j + U_p) g'_p \tag{6.8}
\]

Where \( z^* \) is the height measured below the top of the fountain, and \( r_p \) is the radius of the outer plume.

6.2.4 Numerical Procedure and Solution

A computer program in Matlab was used to obtain a numerical solution of the six governing equations. Initial values at \( z = 0 \) for the inner jet were set from the discharge conditions at the exit of the nozzle, i.e

\[
U_j = U_0; \quad r_j = r_0; \quad \text{and} \quad g'_j = g'_0
\]

Given the above initial conditions, the three Eqs. 6.3, 6.4, and 6.5 were integrated numerically, along \( z \), using a single step method and a step size \( dz = 7.8125 \times 10^{-5} \). The upwards integration of the inner jet was stopped in a manner similar to MacDougall (1981) when the velocity \( U_j \) has fallen below \( \sqrt{2g'_j r_j} \). For the first integration of the inner jet we assumed \( U_p = 0, \quad \text{and} \quad g'_p = 0 \), which means we ignore the presence of the outer plume (i.e starting jet solution). Having reached the end of the inner jet integration, the
three equations of the outer plume were integrated along \( z^* \) down to the level of source (\( z=0 \)). During this downward integration the values used for \( r_j, U_j, \text{and} \ g'_j \) are those derived at each level by the previous integration of the jet part. These successive integrations (up the inner jet and down the outer plume) were performed many times (typically 10 times) until a steady state solution was achieved.

The small step size \( dz = 7.8125 \times 10^{-5} \) was selected based on observed convergence of the steady state solution (see Figure 6.3).

![Figure 6.3: Convergence of Steady State Solution at Small Integration Step Sizes](image)

6.2.5 Control Volume Analysis of the Top Part of the Fountain

The top part of a fountain is a transitional domain linking the upward jet with the downward plume. It is a complex region which cannot be modeled using the jet or plume equations given above. In the top part, fluid of the upward jet slows down, spreads laterally, and sinks down forming the annular plume around the jet. The top part of the
fountain is treated as a cylindrical control volume located above the inner jet and outer plume, with its lower boundary at a height where the jet velocity has fallen to \( \sqrt{2g_j r_j} \).

It is further assumed that in the top part of the fountain there is no appreciable mixing with the surroundings. At steady state the buoyancy acceleration and flow rates entering the top part (from jet) and leaving the top part (into plume) are, therefore, identical

\[ g'_{jTop} = g'_{pTop} \]  
\[ Q_{jTop} = Q_{pTop} \]  

Where, \( g'_{jTop} \) and \( Q_{jTop} \) are buoyancy acceleration and discharge entering the top part from the jet. \( g'_{pTop} \) and \( Q_{pTop} \) are buoyancy acceleration and discharge leaving the top part into the plume. The initial discharge of the plume is given by

\[ Q_{pTop} = \pi \left( r_{pTop}^2 - r_{jTop}^2 \right) U_{pTop} \]  

Where, \( r_{pTop} \) and \( r_{jTop} \) are radii of the outer plume and inner jet, respectively. \( U_{pTop} \) is the initial downward plume velocity.

Substituting \( Q_{pTop} \) value from Eq. 6.11 into Eq. 6.10 and solving for \( r_{pTop}^2 \), we have

\[ r_{pTop}^2 = \frac{Q_{jTop}}{\pi U_{pTop}} + r_{jTop}^2 \]  

Applying the momentum principle to the control volume gives

\[ g'_{jTop} \pi r_{pTop}^2 h = U_{jTop}^2 \pi r_{jTop}^2 + U_{pTop}^2 \pi \left( r_{pTop}^2 - r_{jTop}^2 \right) \]  

Where, \( U_{jTop} \) is the terminal velocity of the inner jet entering the top part.

Substituting the value of \( r_{pTop}^2 \) from Eq. 6.12 into Eq. 6.13, we obtain a quadratic equation, which gives the value of \( U_{pTop} \) as
\[ U_{\text{pTop}} = \frac{-(u_{\text{trTop}}^2 \pi r_{\text{trTop}}^2 - g'_{\text{trTop}} \pi r_{\text{trTop}}^2 h)^\frac{3}{2}}{2 g_{\text{trTop}}} + \frac{4 Q_{\text{trTop}} (g'_{\text{trTop}}) h}{2 Q_{\text{trTop}}} \] (6.14)

Where \( h = \frac{u_{\text{trTop}}^2}{2 g'_{\text{trTop}}} \)

The positive solution in Eq. 6.14 determined \( U_{\text{pTop}} \) and it was used to calculate the other initial conditions required to integrate the outer plume.

### 6.3 Results and Discussion

#### 6.3.1 Model Calibration

Since dilution is the most important design parameter of a fountain, we used an experimental dilution measurement to calibrate the model. A turbulent fountain experiment was performed with \( r_0 = 0.96 \text{ cm, } Fr = 8.49, \text{ and } \frac{\Delta \rho}{\rho_a} = 0.017 \). The normalized minimum return point dilution was \( \left( \frac{\mu_{\text{min}}}{Fr} = 0.39 \right) \). The apparatus, method, and procedure to get the minimum return point dilution were explained in Chapter 3 to 5.

For the condition of this experiment, the model gives an average normalized return dilution \( \left( \frac{\mu_{\text{average}}}{Fr} \right) \). Note, the top-hat profiles model predicts an average return dilution. To calibrate the model with the experiment result, we converted \( \frac{\mu_{\text{average}}}{Fr} \) of the model into \( \frac{\mu_{\text{min}}}{Fr} \) as

\[
\frac{\mu_{\text{min}}}{Fr} = \frac{\mu_{\text{average}}}{Fr} \times \frac{1}{2}
\]

\( \frac{\mu_{\text{average}}}{Fr} \) in the model average normalized dilution determined as

\[
\frac{\mu_{\text{average}}}{Fr} = \frac{g_0'}{g_p'} / Fr
\]

A good agreement of the experiment with the model was achieved with entrainment coefficients \( \alpha_f = 0.05, \text{ and } \alpha_p = 0.31 \).
The model predictions are compared in Fig. 6.4 with the minimum return dilution data of the dense jet experiment.

![Figure 6.4: Comparing Numerical Result with Experimental Results](image)

### 6.3.2 Sensitivities of Entrainment Coefficients

In Figure 6.5 and 6.6, sensitivity of the results to different values of entrainment coefficients was analyzed. In Figure 6.5, sensitivity to $\alpha_j$ is examined by keeping $\alpha_p$ constant at 0.31. Figure 6.5 shows that by increasing $\alpha_j$ the dilution of the fountain decreases. Entrainment of fluid from the outer plume into the inner jet affects dilution in two ways. First, increase of $\alpha_j$ increases jet discharge but at the same time decreases its momentum as shown in Eq. 6.4. The decrease in momentum of the inner jet is significant and it reduces the height and dilution of the fountain. Second, increase of $\alpha_j$ brings lighter fluid from the outer plume into the inner jet and, hence, decreases the negative buoyancy force, which tend to increase height and dilution. The second factor was found less significant than the first and the resultant dilution generally decreased with increasing $\alpha_j$. 
Figure 6.5: Showing Sensitivity of $\alpha_j$ Keeping $\alpha_p$ Constant at 0.31

Figure 6.6 examines the sensitivity of dilution to $\alpha_p$ by keeping $\alpha_j$ constant = 0.05. Figure 6.6 shows that dilution of the fountain increases with increasing $\alpha_p$. Entrainment of liquid into the outer plume also affects dilution in two ways. First, increase of $\alpha_p$ increases plume discharge but also decreases momentum, which result in a smaller plume velocity as shown in Eq. 6.7. The reduction of outer plume velocity increases the momentum and velocity in the inner jet as shown in Eq. 6.5. Second, addition of lighter liquid decreases the density of the outer plume, and when the inner jet entrains this less dense fluid, it becomes more diluted. Therefore, an increase of $\alpha_p$ always contributes to an increase in dilution of the inner jet.

In addition, Figures 6.5 and 6.6 indicate that dilution results are more sensitive to $\alpha_j$ than $\alpha_p$. It is due to the fact that $\alpha_j$ has a more significant presence in all the governing equations, while $\alpha_p$ is only present in Eq. 6.6. The effect of $\alpha_p$ can be observed over a wider range, as shown in Figure 6.7.
Figure 6.6: Sensitivity of $\alpha_p$ Keeping $\alpha_j$ Constant at 0.05

Figure 6.7: Sensitivity of $\alpha_p$ Keeping $\alpha_j$ Constant at 0.05 over a Wider Range
6.4 Conclusion

A two-coefficient entrainment model of a vertical dense jet was developed based on conservation equations of mass, momentum, and buoyancy. The sensitivity of the predicted dilution to the values of the entrainment coefficients were studied. The main conclusions of the study are:

1. A two-coefficient model was selected based on shear flow theory as explained in section 6.2.1.

2. Governing equations for the inner jet and outer plume were presented in Eqs. 6.3 to 6.8. And, the top part of the fountain linking the inner jet to the outer plume was analysed as a control volume. The complexity of the problem is explained in section 6.2.5.

3. The model was calibrated to an experimental dilution data and the values $\alpha_j = 0.05$ and $\alpha_p = 0.31$ provided a good agreement.

4. A two entrainment model is capable of simulating basic fountain behavior, such as dilution and height.

5. Sensitivity analyses presented in Figures 6.5-6.7 show that the entrainment coefficients affect the dilution of fountains. Increase in $\alpha_j$ decreases dilution of a fountain as more fluid is entrained from the outer plume into the inner jet, which reduces momentum resulting in shorter, less diluted fountain. On the other hand, increase in $\alpha_p$ increases dilution of a fountain as lighter fluid from surrounding ambient is entrained into the fountain reducing both density and velocity of outer plume. Moreover, reduction of velocity and density of the outer plume increase the momentum and decrease the density of the inner jet, which result in more dilution of the fountain.

6. It is observed that the model predictions are more sensitive to $\alpha_j$ than $\alpha_p$ within equal range of coefficient change. The reason behind this observation is that $\alpha_j$
has a more important contribution in all the governing equations while $\alpha_p$ is only contributing to Eq. 6.6.

References


Chapter 7
CONCLUSIONS AND RECOMMENDATIONS

7.1 Concluding remarks

The basic purpose of this project was to study the dilution properties of vertical fountains of brine in order to address well recognized limitations of mixing zones in environmentally sensitive areas. Vertical penetration of fountains was also studied to confirm the validity of capturing the fountain properties with thermocouples. The important findings of the study are summarized below.

A review of the literature showed that brine discharges are mainly regulated by allocating mixing zones, which vary in size from 0 m to 500 m around a discharge point. Nevertheless, several documents in North America (US EPA 1994; Rutherford et al. 1994; IMDs 2007; CCME 2008) have recognized limitations of the mixing zone approach. It is particularly the case in sensitive areas, such as areas close to drinking intakes, fish habitat, recreation, and sensitive biota.

The main contribution of the present study is in the development of an alternative minimum return point dilution approach to regulate dense brine discharges. For vertical discharges the minimum return point dilution in calm water (worst case scenario) occurs always just outside the edge of the nozzle. Excess temperature contours and dilution profiles at the level of the nozzle confirmed this critical location for all turbulent fountain regimes (i.e. small and large Froude numbers). The mean thermal structure of the fountain presented in Figure 3.9 shows that dilution within the body of the fountain is completed as the flow returned back to the level of the source (z=0). Further detailed investigations of temperature and dilution at the level of the source are presented in Figures 3.10 and 3.11 for large Froude numbers and Figures 4.8 and 4.9 for small Froude numbers.

The experimental investigation on the effects of density difference reported in Chapter 5 have indicated that fountain dilution and height decreased significantly as the relative
density difference increased. This behavior is shown in Figures 5.5-5.8. These Figures also showed that dilution and height of upward dense jets are comparable to downward thermal jets when their relative density differences are equal. A best power fit of the data is presented in Figures 5.5 and 5.7 for the fountain dilution and height behavior, respectively. The relationship between normalized minimum return point dilution, and height and relative density difference are given in Eqs. 5.6 and 5.8.

The width of fountains is important when designing the spacing between nozzles of multiport diffusers. Radius of fountains at the level of the source was analyzed in detail in Chapter 4 using excess temperature, intermittency, and turbulence intensity data.

Selection of discharge nozzle orientation is important for minimizing return point dilution. In the absence of ambient currents, dilution of inclined fountains can be almost double the dilution of a vertical fountain (see Figure 3.13). However, in actual sea current conditions, which vary in magnitude and direction, the dilution of inclined fountains could be less than the dilution of vertical fountains (see Figure 4.16). In these cases, therefore, it is recommended to adopt vertical fountains to take advantage of sea currents in any direction.

Selection of entrainment coefficients is important to properly model a fountain. A two-coefficient entrainment model was developed assuming the inner jet entrains fluid from the outer plume, and not vice versa, due to its higher turbulence and lower pressure. A two entrainment model is capable of simulating basic fountain behavior, such as dilution and height.

### 7.2 Suggestions for Future Research

In the present study, fountain behavior was studied under homogeneous ambient environment. However, sometimes, actual ambient environment may be density stratified due to thermal stratification. So, study of fountain behavior under density stratified environment is one of the future directions of the present work.

In the present study, fountain behavior was studied under deep water as deep water conditions are usually available and preferred for brine discharge. Sometimes, deep water
depth is unavailable near a shore and so long pipe line is required to reach into deep shore which increases total cost of desalination plants. So, study of fountain behavior under shallow depth is another topic for future research.

In the present study, the model equation of dilution is very conservative as it is based on minimum return point dilution which occurs just at the edge of the discharge nozzle. A more accurate total return point dilution equation could be derived based on average dilution by analyzing horizontal dilution profiles at the nozzle level (z=0).

In the present study, steady state condition of fountains and ambient are considered. In the future, fountains behavior in case of unsteady discharge or unsteady ambient currents could be studied.

References


Figures A(3-6).a-g present pictures of the apparatus used to perform the upward dense jet experiments. Figure A(3-6).a is the general view of all the various components of the apparatus. Figures A(3-6).b-g shows individual components in more detail.
Figure A(3-6).b: Overhead Tank

Figure A(3-6).c: Thermocouple Holder Arrangement
Figure A(3-6).d: Data Acquisition System

Figure A(3-6).e: Thermocouples Arranged Vertically in the Experimental Tank
Figure A(3-6).f: A Fountain Discharge in the Experimental Tank
Figure A(3-6).g: Shadowgraph View of a Fountain in the Experimental Tank
APPENDIX B

DEMONSTRATION OF A STARTING FOUNTAIN
TRANSIENT DEVELOPMENT AND INVESTIGATION OF
WALL EFFECTS DURING EXPERIMENTATION

Figure B(5).a-r shows the development of a vertical fountain at various time intervals. The dense jet initially rises up and after attaining a certain height above the nozzle it returns back down and spreads on the base plate. A dense layer of brine can be seen spreading on the base plate after 4.5 sec of the discharge.

Figure B(5).a: Fountain at 0 sec

Figure B(5).b: Fountain at 2.2 sec
Figure B(5).c: Fountain at 3.7 sec

Figure B(5).d: Fountain at 4.5 sec

Figure B(5).e: Fountain at 6.67 sec
Figure B(5).f: Fountain at 8.7 sec

Figure B(5).g: Fountain at 14.4 sec

Figure B(5).h: Fountain at 19.6 sec
Figure B(5).i: Fountain at 21.07 sec

Figure B(5).j: Fountain at 26.4 sec

Figure B(5).k: Fountain at 41.26 sec
Figure B(5).l: Fountain at 56.67 sec

Figure B(5).m: Fountain at 1 min, 6 sec

Figure B(5).n: Fountain at 1 min, 16 sec
Figure B(5).o: Fountain at 1 min, 27 sec

Figure B(5).p: Fountain at 2 min, 10 sec

Figure B(5).q: Fountain at 2 min, 43 sec
Figure B(5).r: Fountain at 5 minutes

Figure A(5).a-r: Demonstration of Starting Fountain Transient Development and Wall Effects at Various Times Intervals
APPENDIX C: EXPERIMENTAL DATA RELATED WITH CHAPTERS 3 TO 5

Table C(3).a: Densimetric Froude number Versus Normalized Minimum Return Dilution Data of Figure 3.12

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Table A(3).b: Densimetric Froude versus Normalized Minimum Return Dilution Data of Studies at Various $\theta$ of Figure 3.13.

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A(4).c: Data of Densimetric Froude number versus Normalized Minimum Return Dilution
Presented in Figure 4.12.

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Table A(5).d: Data of Dilution versus Relative Density Difference of Figures 5.5 and 5.6.

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<th>Froude number ((Fr))</th>
<th>Reynold number ((Re))</th>
<th>Discharge salinity ((So))</th>
<th>Minimum return dilution (\mu_{\text{min}})</th>
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<tr>
<td>July 15-1</td>
<td>19.6</td>
<td>0.025</td>
<td>6.9</td>
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<td>2.55</td>
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<td>Jan24-1</td>
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<td>90</td>
<td>3.2</td>
<td>0.31</td>
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| Exp. Series C | | | | | | | |
| July 13-5    | 19.6   | 0.013 | 4.22 | 3352 | 20  | 2.6  | 0.62 |
| July 12-2    | 19.6   | 0.013 | 4.78 | 3831 | 20  | 2.4  | 0.51 |
| July 13-3    | 19.6   | 0.015 | 5.66 | 4310 | 20  | 2.69 | 0.48 |
| July 13-4    | 19.6   | 0.012 | 6.2  | 4789 | 20  | 2.85 | 0.46 |
| July 14-1    | 19.6   | 0.024 | 4.4  | 4789 | 40  | 2.3  | 0.52 |
| July 14-4    | 19.6   | 0.027 | 2.94 | 3352 | 40  | 2.2  | 0.74 |
| July 14-3    | 19.6   | 0.026 | 3.4  | 3831 | 40  | 2.3  | 0.67 |
| July 14-2    | 19.6   | 0.025 | 3.7  | 4171 | 40  | 2.24 | 0.61 |
| July 14-6    | 19.6   | 0.028 | 4.11 | 4171 | 40  | 2.32 | 0.56 |
| July 14-7    | 19.6   | 0.028 | 4.5  | 5268 | 40  | 2.35 | 0.52 |
| July 14-5    | 19.6   | 0.027 | 4.96 | 4171 | 40  | 2.6  | 0.52 |
| July 15-1    | 19.6   | 0.025 | 6.9  | 7662 | 40  | 3.1  | 0.45 |
| July 15-2    | 19.6   | 0.025 | 5.996| 6704 | 40  | 2.65 | 0.44 |
| July 15-3    | 19.6   | 0.025 | 5.44 | 6225 | 40  | 2.47 | 0.45 |
| July 15-4    | 19.6   | 0.026 | 4.98 | 5747 | 40  | 2.41 | 0.48 |
| July 15-5    | 19.6   | 0.028 | 5.3  | 4171 | 40  | 2.31 | 0.44 |
| June 30-1    | 22.18  | 0.025 | 2.83 | 3808 | 40  | 2.28 | 0.8 |
| June 30-3    | 22.18  | 0.027 | 3.07 | 4232 | 40  | 2.23 | 0.73 |
| June 30-4    | 22.18  | 0.027 | 3.34 | 4655 | 40  | 2.34 | 0.69 |
| June 30-5    | 22.18  | 0.027 | 3.62 | 5078 | 40  | 2.43 | 0.67 |
| June 30-6    | 22.18  | 0.028 | 4.21 | 5924 | 40  | 2.55 | 0.61 |
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Post-secondary Education and Degrees

University of Engineering and Technology Taxila, Pakistan 1993-1998

The University of Waterloo Waterloo, Ontario, Canada 2004-2005 M.Sc

The University of Western Ontario London, Ontario, Canada 2007-2009 M.Eng

The University of Western Ontario London, Ontario, Canada 2010-2013 PhD

Honours and Awards:

Western Graduate Research Scholarship The University of Western Ontario London, Ontario, Canada 2010-2013

Ross and Jean Clark Scholarship The University of Western Ontario London, Ontario, Canada 2011

Queen Elizabeth II Graduate Scholarship in Science and Technology (QEIIGSST) Government of Ontario, Canada

Related work Experience

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2010-2013

Publications

Ahmad, Nadeem, and Baddour, R. E. (2012). Minimum source dilution as a method to regulate discharge of toxic brine from industries and mining processes, Proceedings of 2012 CSCE Annual Conference, Edmonton, AB.


