Mixing Behavior of Multiport Diffusers with Non-Uniform Port Orientation

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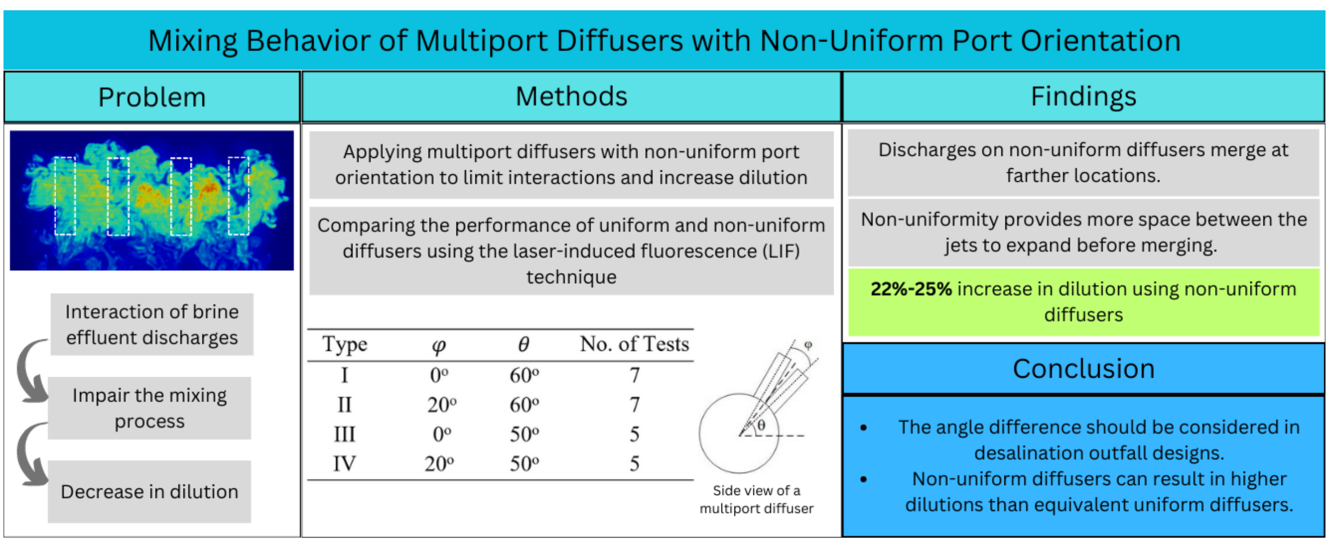
Highlights

- An experimental program was developed to study the mixing behavior of multiport diffusers with non-uniform port orientations.
- Experiments were conducted using the Laser Induced Fluorescence (LIF) method.
- A novel concept for modifying multiport desalination outfalls was proposed to enhance mixing of the brine.
- Non-uniform diffusers resulted in higher dilutions than equivalent uniform diffusers.
- The angle difference between adjacent jets on a multiport diffuser played a significant role in mixing.



Abstract

This study addresses disposal of hypersaline brines from desalination plants through multiport diffusers into seas and oceans. Experiments are reported on multiport diffusers with non-uniform port orientations to limit the negative effect of jet merging on the mixing process and therefore augment dilution. Laboratory experiments on uniform and non-uniform diffusers, with varying port angles in the range of highest reported dilution rates for dense discharges (40^{o}-70^{0}), are reported. Concentration fields were mapped using the laser-induced fluorescence (LIF) technique, and the major flow properties and merging processes were compared. The investigations revealed that the non-uniform diffusers had 22% to 25% higher dilution rates, attributed to different mixing behavior in the interaction zones resulting from different jet spacings. Non-uniform port orientation provided more space between the jets to expand before interacting with their neighbors, resulting in higher dilutions. This study questions the application of formulae obtained from experiments conducted with single discharges for multiport diffuser designs and proposes considering source characteristics specific to multiport diffusers, such as angle difference, for efficient design of desalination outfalls. The new data and analysis can benefit the design of desalination discharge systems with environmental risk reductions and potential cost savings due to shorter diffusers with non-uniform jet orientations.

Keywords: Desalination; Brine disposal; Multiport diffuser; Negatively buoyant jet; Laser-induced fluorescence; Discharge inclination.

1 Introduction

The rapid growth population and industrialization of many developing countries have increased the demand for freshwater [1]. This increased demand and climate uncertainty have led freshwater stress and scarcity to become more prevalent globally [2]. Seawater desalination has been introduced as a necessity to overcome these issues [1], and it has become viable as a sustainable solution over recent decades [3][4]. Desalination plants are supplied with seawater and produce freshwater for use and hypersaline water as waste by-products. An efficient disposal method of these by-products, when properly designed, is to eject them back into the source ocean environment [5]. However, brine effluents may reduce water quality and harm marine habitats [6], however, if not discharged properly. To provide rapid mixing of the brine with surrounding water and subsequently protect the marine environment, these by-products are discharged through submerged diffusers in the form of high-velocity turbulent jets [7][8]. Brine discharges, which have a density higher than the receiving environment, are discharged upwards at an angle upon discharging and then turn down and impinge the sea bottom. These discharges are called inclined negatively buoyant jets (INBJs). Understanding the hydrodynamics of desalination discharges is essential to minimize adverse environmental effects resulting from desalination plants.

Discharge mixing and transport processes are affected by the characteristics of the ambient environment and discharge conditions. The former includes receiving water stratification, the topography of the seabed, waves, and currents, which cannot be significantly manipulated by outfall designers. The latter includes port geometry, jet momentum and buoyancy fluxes, and diffuser configuration, which can be optimized by outfall designers to enhance mixing and increase dilution. As the mixing behavior of discharges is significantly affected by the properties of outfall diffusers [9][10][11], the focus of the present study is on the effect of diffuser configuration on the mixing behavior of desalination discharges.

Desalination diffusers can be designed as single port discharges for small rates. Single jets can freely mix with the ambient water without any interactions, and the port angle is an important design feature affecting their mixing behavior. Inclined jets, compared to vertical discharges, result in a higher dilution rate since vertical jets tend to fall back on themselves, which significantly impairs the dilution process [12][13][14]. This interaction of ascending and descending parts of jets and therefore re-entrainment has been reported for nozzle angles to the horizontal greater than 80^{o} [15]. Loya et al. [16] evaluated the effects of installing a 60^{o} single-port diffuser at the Nuevo Canal de Cartagena desalination plant pipeline on the dispersion of the brine. They showed that the dilution rate of samples taken 1 Km from the outfall increased by almost 17 times after the diffuser installation. Although 60^{o} is commonly adopted for diffuser designs to optimize dilution, some studies have reported almost the same dilutions for the port angles over the range 45^{o}-75^{o} [17], 60^{o}-75^{o} [18][19] and 45^{o}-65^{o} [20].

For large discharges, multiport diffusers are the most effective strategy [21]. Although multiport brine diffusers are frequently applied worldwide, e.g., in Sydney, Perth, and Melbourne, there are a limited number of studies on the mixing behavior of multiport diffusers. A conventional multiport diffuser consists of evenly spaced ports oriented at the same angle to the horizontal, and the unidirectional or one-sided diffuser is the most widely employed type [22]. The main issue with multiple diffusers is the port spacing. If they are too close, the jets cannot freely entrain ambient water, as single jets do. Merging causes these jets to have a reduced terminal rise height and to bend inward, with a shorter trajectory compared to a single jet at the same angle [23]. The shortened trajectory further decreases dilution since it diminishes the available surface for entrainment.

The effect of port spacing on the mixing process of multiple INBJs was systematically studied for the first time in 2014 [23]. Before this, most designs of multiport diffusers were based on the investigations of single jets [21]. Abessi and Roberts experimentally studied multiple 60o jets discharging from one or both sides of a diffuser, using the Laser Induced Fluorescence (LIF) technique. The effect of port spacing, s, was found to depend on the non-dimensional port spacing (s/dF), where F is the Froude number and d the nozzle diameter. The influence of port spacing was investigated by varying s/dF between 0.47 and 20.63. The effect of jet merging on geometrical characteristics and dilution rates of closely and moderately spaced ports was quantitatively presented. The significant effect of port spacing on dilution was evident in their results where the impact dilution for diffusers with s/dF=0.47 was about a quarter of those with s/dF>2. They recommended maintaining s/dF>2 to avoid a reduction in dilution rate for multiport designs.

Miller et al. [24] conducted physical model tests for the multiport Perth Stage 2 diffuser and considered one and three nozzles discharging from one side at 60°, using the conductivity probe method. The non-dimensional port spacing was varied between 0.95 and 2.9, and a reduction in impact point dilution was observed as the port spacing was reduced, where s/dF<2. Marti et al. [25] provided field observations on the Perth Stage 1 diffuser, where s/dF was about 1.3 and the ports were 60° inclined. The observations for impact point dilution were close to the impact point dilution presented for single jets [13], noting that the field measurements were conducted in the presence of currents. A recent numerical study proposed that the multiport diffusers with non-uniform port orientations could reduce the negative effects of jet merging on dilution [11]. Two different configurations including a diffuser with 60° inclined ports and a diffuser with alternating 45° and 60° inclined ports were considered; the port spacing was the same, s/dF=0.52, for both configurations. The comparisons indicated that the diffuser with non-uniform port orientation resulted in a 14% higher impact point dilution rate than the uniform diffuser.

The negative impact of jet merging on dilution has also been reported for rosette-type multiport diffusers, where the ports are clustered in rosettes each having multiple nozzles. Some studies showed that for single rosettes with four ports, jet interaction was minimal and there was little reduction in impact point dilution, dilution at the location where the flow impacts the lower boundary, compared to a single jet [26][27]. However, the near-field dilution, dilution at the location downstream of the impact point where the ultimate turbulence collapses, of that type was 27% lower than a single jet [27]. The jets on four-port risers had little interaction before the impact point, but four density currents form on the seabed finally merged, reducing the near-field dilution.

Tarrade et al. [28] reported about a 15% lower dilution rate for six-port compared to four-port risers as a result of jet interaction and competition between jets for clear water to entrain [27]. Miller [29] indicated an approximately 50% reduction in the near-field dilution for a six-port riser relative to a single discharge. Miller and Tarrade [26] and Tarrade and Miller [30] showed that the jets for 9- and 12-port risers were so close that entrainment was mainly from above the jets. The entrainment from the gap between the jets was strictly restricted due to the Coanda effect and significant jet interactions.

While maintaining s/dF>2 has been proposed as a solution to avoid the negative effects of jet merging on dilution [23], it is essential to consider the potential high costs that could be imposed on desalination outfall projects. Discharge facilities can account for a considerable portion of the capital cost of desalination plants [31], and in some cases, they can even exceed 30% of the total costs [32]. Outfall costs may vary considerably depending on factors such as length, diameter, depth, construction technique and material, and local conditions [9][33]. The average investment cost of 200 outfalls worldwide was reported to be approximately 7 million US$ each, with values ranging from 2 million to as high as 3,500 million US$ [9]. Pipe supply and construction costs constitute approximately 90% of the total outfall cost, encompassing construction, design, field studies, operation and maintenance, and monitoring [33]. Chang et al. [34] investigated the database of the construction of outfall pipes in Taiwan and introduced the outfall length and diameter as the major parameters affecting outfall costs. They provided a linear construction cost function in terms of the outfall length and diameter. Maalouf et al. [35] expressed the outfall construction cost as a linear function of the outfall length, port diameter, and the number of ports.

Roberts et al. [33] analyzed the relationship between outfall cost per meter and pipe diameter (in meters) using data for 145 outfalls. While the correlation between diameter and unit cost was found to be relatively weak, they proposed a preliminary estimate of the range of cost range with a linear correlation represented as C=6140D, where C is the cost in US$ (April 2009) per meter, and D is the diameter in meters. For high-density polyethylene (HDPE) outfalls with a diameter less than 1.4 meters, the costs generally fell within the range of 1,000 to 7,000 US$/m. On the other hand, outfalls greater than 2.4 meters in diameter were usually tunneled or concrete, resulting in costs ranging from 10,000 to 20,000 US$/m. For diameters exceeding 3.5 meters, costs could even surpass 30,000 US$/m [33]. The proportion of the diffuser length to the total outfall length can provide some insight into the relative cost of the diffuser section in an outfall, which exhibits significant variation across different projects. For example, the proportion was about 0.1 for the Ipanema outfall in Rio de Janeiro, Brazil, 0.25 for the Perth Seawater Desalination Plant outfall in Australia, and 0.4 for the Berazategui outfall in Buoenos Aires, Argentina. The average values for the characteristics of 200 outfalls reported by Bleninger [9] showed the average diffuser and outfall lengths were 100 m and 1300 m, respectively.

These previous studies have focused mainly on the influence of port orientation on the dilution of single jets, or the port spacing of multiple jets. The adverse effect of merging on the mixing behavior of multiple jets has also been highlighted in prior research. The motivation behind the present study is to reduce the very high cost of construction of diffusers and tunnels by minimizing port spacing and therefore outfall and diffuser length. This study explores the impact of using ports with different angles to the horizontal on a multiport diffuser. The focus is on jet merging and its consequent effect on the mixing process. As a novel approach, this study aims to determine whether this strategy positively influences dilution rates. This idea comes from the observation that different port orientations provide more space for discharges to expand before interacting with their neighboring jets. A series of systematic experiments, simulating typical ocean outfall diffusers, were carried out to determine the effect of non-uniform port orientation on the mixing behavior of multiple desalination discharges.

2 Analysis

A schematic view of typical multiple jets is shown in Figure 1. The dense effluents with a density ρ_0 are discharged into the lighter receiving water ($\rho_a < \rho_0$) at an angle θ with jet velocity U_0 through round nozzles with a diameter d. The initial fluxes characterising the flow behavior include the volume ($Q_0 = \pi d^2 U_0/4$), kinematic momentum ($M_0 = U_0 Q_0$), and buoyancy ($B_0 = g'_0 Q_0$) fluxes. The jets experience a negative buoyancy force due to their higher densities relative to the ambient fluid and therefore turn downward where the initial vertical momentum flux almost vanishes. The overhead view shows the individual jets merging at some distances from the diffuser.

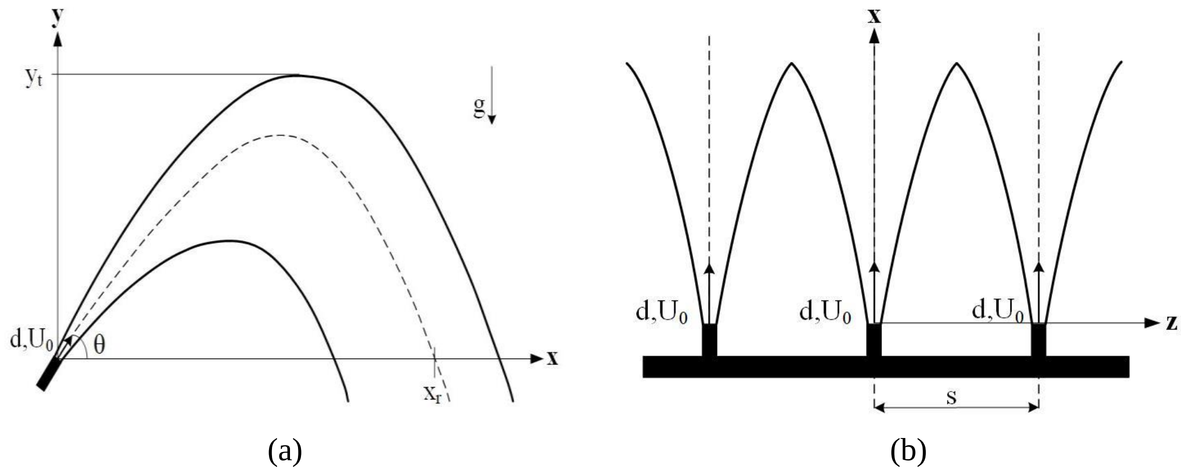


Figure 1 Schematic (a) side- and (b) overhead-view of multiple inclined negatively buoyant jets (INBJs).

The initial conditions affecting the flow behavior include the Froude number (F), port angle (θ), and port spacing (s). The former is a non-dimensional parameter which measures the ratio of inertia to buoyancy and is defined as

$$\mathrm{F} = \frac{U_0}{\sqrt{\mathrm{g}_0' d}} \tag{1}$$

Where g_0' is the initial reduced gravitational acceleration. This term relates the initial density to the ambient density and is expressed as $\mathrm{g}_0' = \mathrm{g}(\rho_0 - \rho_a)/\rho_a$, where g is the gravitational acceleration.

The flow geometry can be mainly characterized by defining the return point distance (x_r) and terminal rise height (y_t). The former determines the horizontal distance between the nozzle tip and the return point, where the flow returns to the nozzle tip level; the latter characterizes the vertical distance between the nozzle tip and the maximum height of the flow. In accordance with previous studies [36][37][38], the boundaries of the jets are defined as the lines with a concentration of $e^{-1}C_{Max}$ along a cross-section of the flow, where C_{Max} is the local centerline tracer concentration. Dilution (S) at any location is defined as the ratio of initial tracer concentration (C_0) to the concentration at that location (C), so dilution at the return point is expressed as $S_r = C_0/C_r$.

The effect of port spacing in dimensional analysis is expressed by the non-dimensional parameter (s/dF).

2.1 $s/dF > \sim 2$

For the case that the ports are widely spaced ($s/dF > \sim 2$), the jets have little interaction and behave as single jets [24]. For these jets, the geometric parameters and dilution are independent of s/dF. The geometric parameters can be normalised by F and d, and dilution by F, to create coefficients that are only a function of θ, as shown below [20].

$$\frac{x_r}{\mathrm{dF}} = f_1(\theta) \tag{2}$$

$$\frac{y_t}{\mathrm{dF}} = f_2(\theta) \tag{3}$$

$$\frac{S_r}{\mathrm{F}} = f_3(\theta) \tag{4}$$

In the presence of a lower boundary, the impact point distance (x_i) can also be considered to characterize the flow geometry. It is the horizontal distance between the nozzle tip and the impact point where the flow impacts the lower boundary. The normalized impact point distance, terminal rise height, and impact point dilution ($S_i = C_0/C_i$) for 60$^{\mathrm{o}}$ jets are constants and can be expressed as [13]

$$\frac{x_i}{\mathrm{dF}} = 2.4 \tag{5}$$

$$\frac{y_t}{\mathrm{dF}} = 2.2 \tag{6}$$

$$\frac{S_i}{\mathrm{F}} = 1.6 \tag{7}$$

The presented value for S_i/F is the maximum reported dilution for multiple dense jets [24].

2.2 $s/dF < \sim 2$

If the ports are not widely spaced ($s/dF < \sim 2$), both θ and s/dF affect the geometrical and dilution characteristics of flows. According to the experiments conducted by Abessi and Roberts on 60$^{\mathrm{o}}$ multiple jets in the presence of a lower boundary, the flow characteristics can be obtained by the empirical equations [24]

$$\frac{x_i}{\mathrm{dF}} = 2\left(\frac{\mathrm{s}}{\mathrm{dF}}\right)^{1/2} \tag{8}$$

$$\frac{y_t}{\mathrm{dF}} = 1.9\left(\frac{\mathrm{s}}{\mathrm{dF}}\right)^{1/2} \tag{9}$$

$$\frac{S_i}{\mathrm{F}} = 0.9\left(\frac{\mathrm{s}}{\mathrm{dF}}\right) \tag{10}$$

Along with θ and s/dF, the present study hypothesizes that the angle difference, φ, between adjacent jets on a multiport diffuser may also play a significant role in the flow behavior, see Figure 2. Considering the angle difference, the flow characteristics can be expressed as:

$$\frac{x_r}{\mathrm{dF}} = f_4\left(\theta, \frac{s}{dF}, \varphi\right) \tag{11}$$

$$\frac{y_t}{\mathrm{dF}} = f_5\left(\theta, \frac{s}{dF}, \varphi\right) \tag{12}$$

$$\frac{S_r}{\mathrm{F}} = f_6\left(\theta, \frac{s}{dF}, \varphi\right) \tag{13}$$

In previous studies on multiport diffusers, the jets were released at the same angle to the horizontal (θ=60^o) [24][25] and therefore (φ=0). This study aims to provide some insight into the effect of φ on the mixing behavior by considering φ=0^o and φ=20^o.

Figure 2 Side-view of multiport diffusers with (a) uniform and (b) non-uniform port orientation; demonstrating main angle (θ) and angle difference (φ).

3 Experimental Procedure

A schematic depiction of the experimental configuration is shown in Figure 3. The experiments were performed in a 2.04 m long, 1 m wide, and 1 m high tank located at the Hydraulics laboratory at the University of Cagliari. The effluent was discharged through diffusers each incorporating five round nozzles with a diameter (d) of 3.25 mm spaced 8 cm apart. Different s/dF values were considered for the experiments by changing the Froude number such that s/dF<1.32, resulting in significant merging effects in all experiments [23]. To investigate the effect of non-uniform port orientation, four diffusers, two with uniform angles (θ=50° and θ=60°) and two with non-uniform angles (φ=20o) were constructed. The diffusers were designated as Type I, II, III, and IV in Table 1. The port angles were chosen to cover the range over which the highest dilution rates had been reported for single dense discharges [17][18][19][20]. The Froude and Reynolds numbers of discharges were higher than 19 and 2200, respectively, to ensure fully turbulent flows. The water depth above the nozzles (H) was about 45 cm and deep enough, dF/H<0.24, for all experiments to avoid surface influence; Abessi and Roberts [39] showed that for dF/H<0.44, the deep-water condition exists and there is no surface effect on the jets' behavior. For the real case of the Perth Seawater Desalination Plant outfall working under its full-flow capacity, dF/H was about 0.31 [25]. The height of nozzles above the tank floor were about 50 cm, preventing bottom boundary effects. The height of nozzles above the tank floor were about 50 cm, preventing bottom boundary effects.

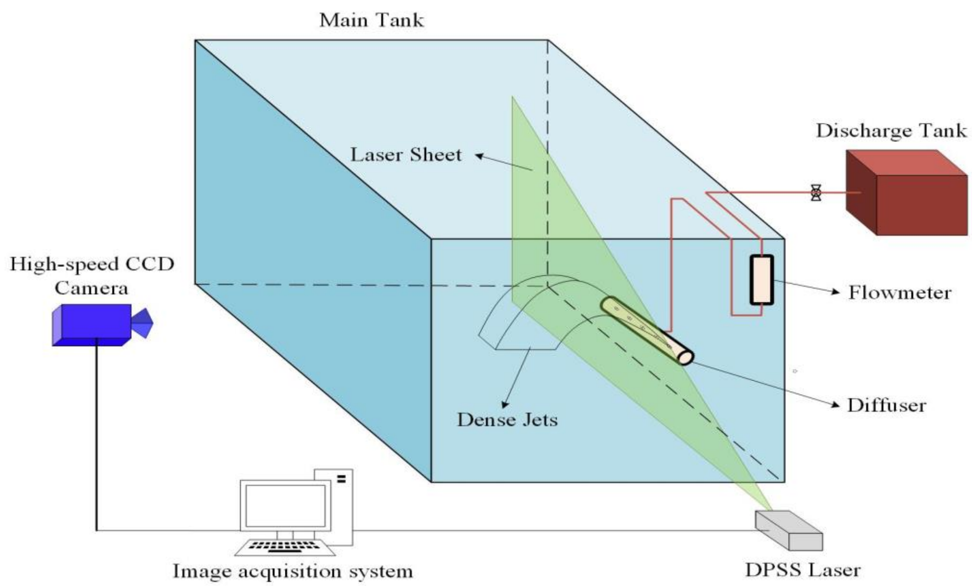


Figure 3 Schematic depiction of the laser-induced fluorescence (LIF) experimental setup.

Table 1 Experimental conditions for uniform and non-uniform diffusers.

Diffuser Type	Configuration	Ports Angle	Number of Experiments	Jet Velocity (m/s)	Brine Density (kg/m^3)	Froude Number	s/dF
I	Uniform	60^o	7	0.746	1016-1049	19-33.1	0.76-1.32
II	Non-uniform	70^o/50^o	7	0.746	1016-1049	19-33.1	0.76-1.32
III	Uniform	50^o	5	0.746	1020-1044	20-29.6	0.84-1.25
IV	Non-uniform	60^o/40^o	5	0.746	1020-1044	20-29.6	0.84-1.25

Concentration fields were obtained using the LIF system. The tank was filled with fresh water, simulating the receiving environment. The discharge tank was filled with effluent consisting of water, a pre-determined amount of salt (NaCl) as a density controller, and a small amount of Titanium dioxide as a tracer. The flow field was visualized using eight vertical laser sheets parallel to the diffuser axes, which were generated by moving one sheet sequentially across the flow, such that there was less space between the sheets closer to the diffusers; they were located at x/d=0, 3, 7, 12, 18, 25, 33, and 41, such that x/d=0 represents the location of nozzles' tip. The sheets created by a 5 W diode-pumped solid-state (DPSS) continuous green laser caused the tracer to fluoresce, and the emitted light was captured by a digital charge-coupled device (CCD) camera, Mikrotron EoSens 4CXP CoaXPress, at 50 frames per second (to ensure that the flow fields on two consecutive frames were uncorrelated) over 1 minute, resulting in about 24,000 images for each test. The concentration fields were obtained from the greyscale images using a calibration process in which each pixel was assigned to a digital number between 0 to 255 based on the captured light intensity, where 0 and 255 represent pure black and white, respectively. Then color-coded time-averaged images of concentration fields were regenerated using a non-commercial MATLAB code, designed for the specific purposes of the present experiment, assuming a linear relationship between the light intensity and concentration [40].

4 Results

4.1 General Flow Behaviour

Figure 4 demonstrates time-averaged concentration profiles at different cross-sections close to and far from the diffusers. Images are shown for uniform diffuser Type I and non-uniform diffuser Type II with the same Froude number of 29.6. The evolution of the discharges and jet merging with distance from the diffusers are evident in these images. Close to the diffusers, e.g., Figure 4 (a and e), the jets for both configurations are separate with high concentrations at their centers. At x/dF=0.41 (b and f), the maximum concentrations are significantly reduced, and the discharges are more diffused, resulting from entrainment of clear ambient water into the jets. The jets are not still wide enough to have significant interaction with their adjacent discharges in both cases. However, there is more space between the jets on the non-uniform diffuser than the uniform one. At farther distances, e.g., Figure 4 (c and g), the jets on the uniform diffuser merge such that there is almost no trace of low-concentrated water between the jets. However, the jets on the non-uniform diffuser are not completely merged and are distinctly identifiable. At x/dF=1.15 (d and h), the jets on both diffusers are fully merged, and there is no evidence of the individual jets. As evident from this section, the non-uniform diffuser results in lower concentrations of brine relative to the uniform one.

Figure 5 shows a snapshot of the concentration profiles at x/dF=0.61, where the jets on both diffusers interact with their neighboring jets. The image shows both the physical mechanisms impairing and contributing to the dilution of the jets. The concentration fields for both diffusers are very patchy, and the fluid motion is chaotic; locally steep concentration gradients and obvious gaps in the flow fields are evident in the images. The lower edges of the jets, under the jet centerline, is more expanded compared to their upper sides, due to buoyancy induced instabilities. At the inner side, the eddies entrain clean water into the jets and continuously dilute the jets. The mixed fluid close to the inner edge is subsequently detrained from the primary flow due to the unstable density gradient. It is evident that this detrainment or separation is more pronounced for 70^{o} inclined jets on the non-uniform diffuser than that for 60^{o} inclined jets on the uniform case.

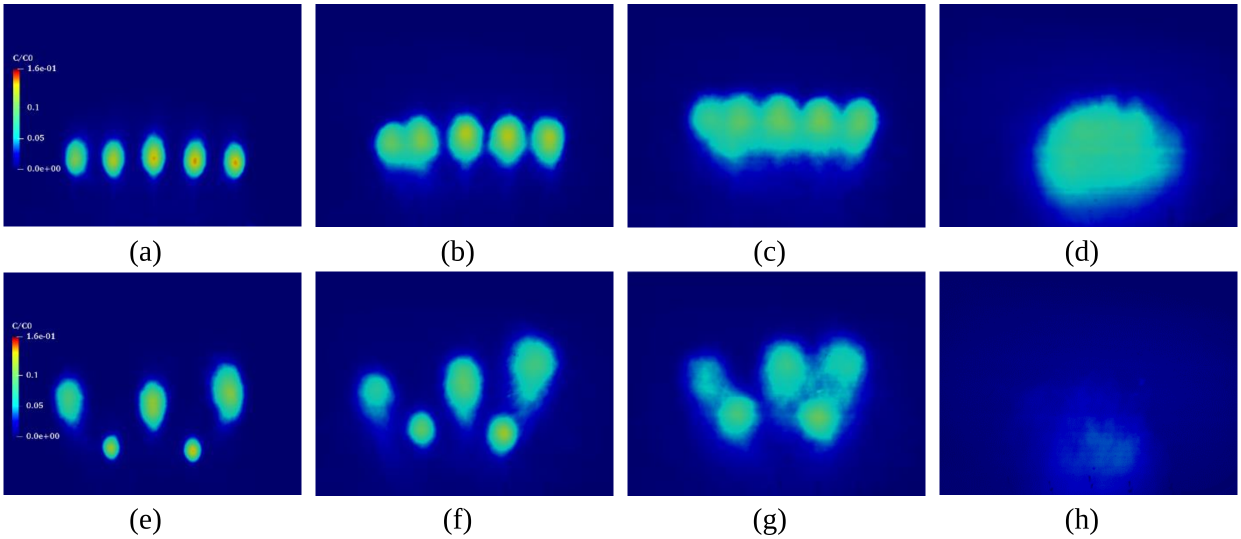
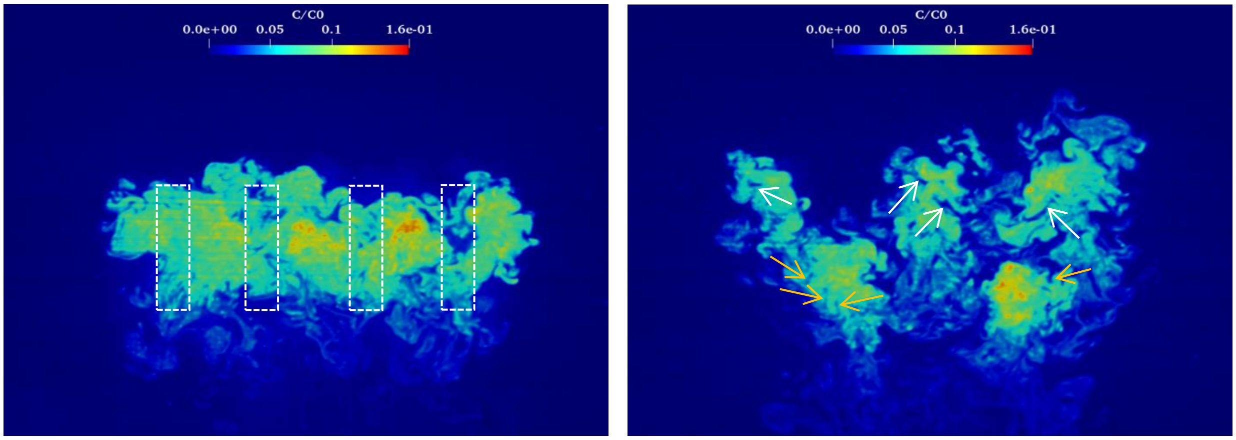


Figure 4 Lateral concentration profiles for the uniform diffuser Type I (a-d) and non-uniform diffuser Type II (e-h) at the cross-sections of x/dF=0.24 (a and e), x/dF=0.41 (b and f), x/dF=0.61 (c and g), and x/dF=1.15 (d and h), F=29.6.

The jets get diluted and expand not only due to the vertical entrainment from the upper and lower sides but also lateral entrainment. Eddies transporting clear ambient water deeply penetrate the 70^o inclined jets on the non-uniform diffuser and some even reach the jets centerline, see the white arrows in Figure 5 (b). This deep penetration of clear water into the jets has a significant contribution to mixing and, consequently, to dilution. These kinds of eddies can be spotted on the 50^o inclined jets too, but they entrain low concentrated brine and do not deeply penetrate them, see the yellow arrows in Figure 5 (b). On the other hand, entrainment for the jets on the uniform diffuser is restricted in the lateral direction. The eddies trying to entrain water into one jet are affected by the motion of neighboring jets. There is a lateral re-entrainment, and eddies transport concentrated brines from one jet to its neighboring jets and the other way around, see the zones shown in Figure 5 (a).



(a) (b)

Figure 5 Snapshot of concentration fields for the (a) uniform diffuser Type I and (b) non-uniform diffuser Type II, F=29.6, x/dF=0.61.

4.2 Major Flow Parameters

The major flow parameters of design interest, including the return point distance (x_r), terminal rise height (y_t), and return point dilution (S_r), were extracted from the concentration fields. To achieve this, we identified the flow parameters of each jet and then presented the mean parameter value over all jets. For uniform diffusers, the mean value of each parameter closely matched the flow parameter value of each jet. However, for non-uniform diffusers, the varying angle of jets led to distinct trajectories and flow parameters.

We explored the maximum concentration of each jet on every vertical plane. In cases where the maximum concentration of jets was not independently distinguishable on the last vertical sheets, we sought that on the line intersection of that y-z (vertical) plane and a plane passing through the nozzle. Utilizing cure fitting techniques with peak concentration points, we obtained the trajectory of each one. The return point was defined as the location where the jet trajectory returned to the average level of nozzles. xr characterizes the horizontal distance between the nozzle tip and the mentioned return point. The definitions of yt and Sr can be found in Section 2. To determine Sr, we focused on the dilution levels at points corresponding to the peak concentrations for each jet and plotted them against the trajectory. By fitting a curve to the data, we analyzed the variation of dilution along the trajectory, enabling us to identify the dilution at the return point. A summary of the experiments and values for the normalized flow parameters is presented in Table 2.

Table 2 Summary of experiments and flow parameters.

Experiment ID	Froude number	s/dF	Configuration	x_r/dF	y_t/dF	S_r/F
Exp1	19	1.32	I	1.70	2.04	---[1]
Exp2	20	1.25	I	1.45	1.99	1.05
Exp3	22.1	1.13	I	1.72	1.95	1.09
Exp4	23.5	1.06	I	1.51	2.05	0.78
Exp5	26	0.96	I	1.77	2.00	1.12
Exp6	29.6	0.84	I	1.62	2.09	0.92
Exp7	33.1	0.76	I	1.55	1.93	1.01
Exp8	19	1.32	II	1.38	2.08	---[1]
Exp9	20	1.25	II	1.40	2.05	1.35
Exp10	22.1	1.13	II	1.31	1.98	1.36
Exp11	23.5	1.06	II	1.45	2.09	1.04
Exp12	26	0.96	II	1.43	2.06	1.13
Exp13	29.6	0.84	II	1.42	2.09	1.27
Exp14	33.1	0.76	II	1.32	2.06	1.30
Exp15	20	1.25	III	1.72	1.71	0.97
Exp16	21.6	1.16	III	1.72	1.73	0.94
Exp17	23.5	1.06	III	1.63	1.75	0.78
Exp18	26	0.96	III	1.71	1.72	0.63
Exp19	29.6	0.84	III	1.72	---[1]	---[1]
Exp20	20	1.25	IV	1.52	1.82	1.31
Exp21	21.6	1.16	IV	1.71	1.81	0.95
Exp22	23.5	1.06	IV	1.51	1.78	1.02
Exp23	26	0.96	IV	1.60	1.77	0.78
Exp24	29.6	0.84	IV	1.64	---[1]	---[1]

[1] Not identified.

The normalized parameters of the return point distance (x_r/dF), terminal rise height (y_t/dF), and return point dilution (S_r/F) are presented versus the normalized port spacing (s/dF) in Figures 6-8, respectively. Previously reported values for uniform diffusers with 60^o inclined jets [25][24], non-uniform diffusers with 60^o and 45^o inclined jets [11], and single 60^o inclined jets [13] are also shown. It is worth mentioning that, unlike the present study, all mentioned studies were conducted in the presence of a bottom boundary. Therefore, in Figures 6 and 8, the values for prior research exhibit the normalized impact point distance (x_i/dF) and dilution (S_i/F) while the results of this study present the normalized return point distance (x_r/dF) and dilution (S_r/F).

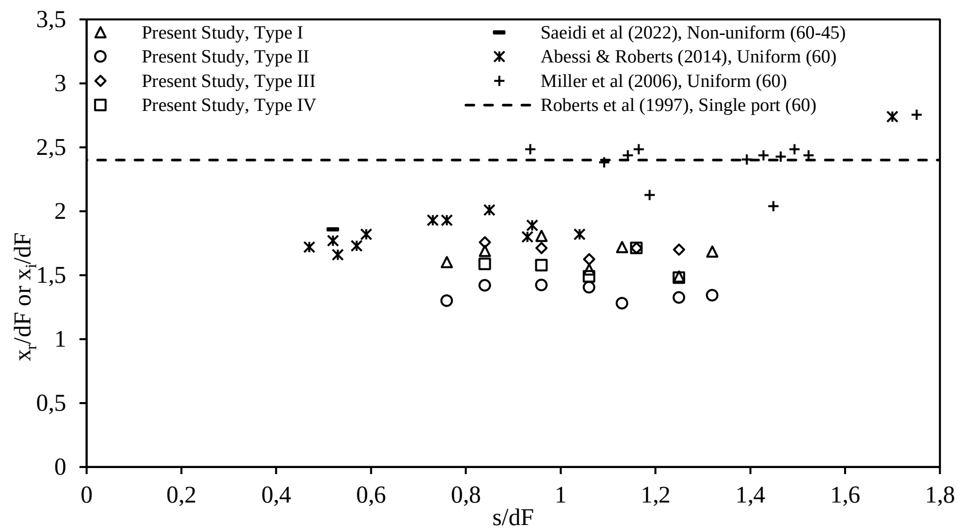


Figure 6 Return or impact point distance versus port spacing for various diffuser configurations.

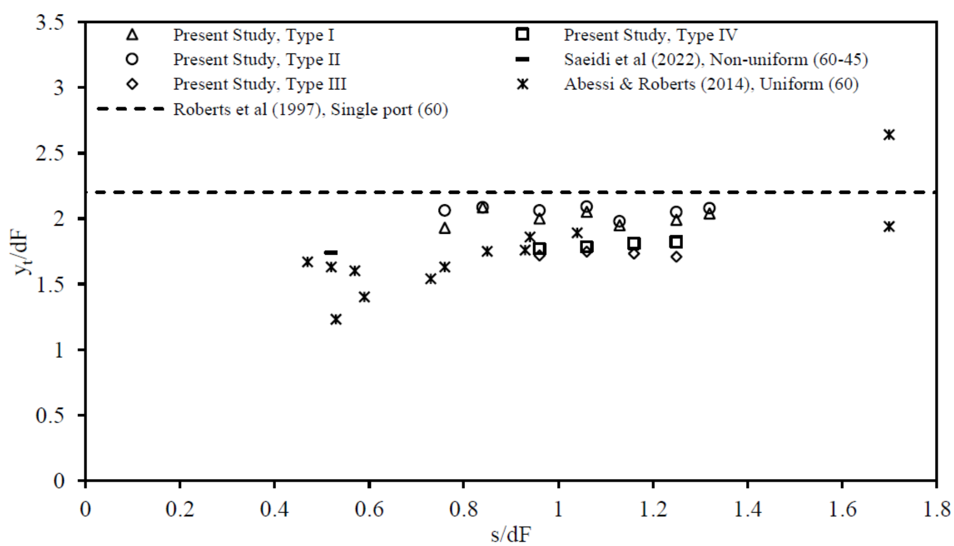


Figure 7 Terminal rise height versus port spacing for various diffuser configurations.

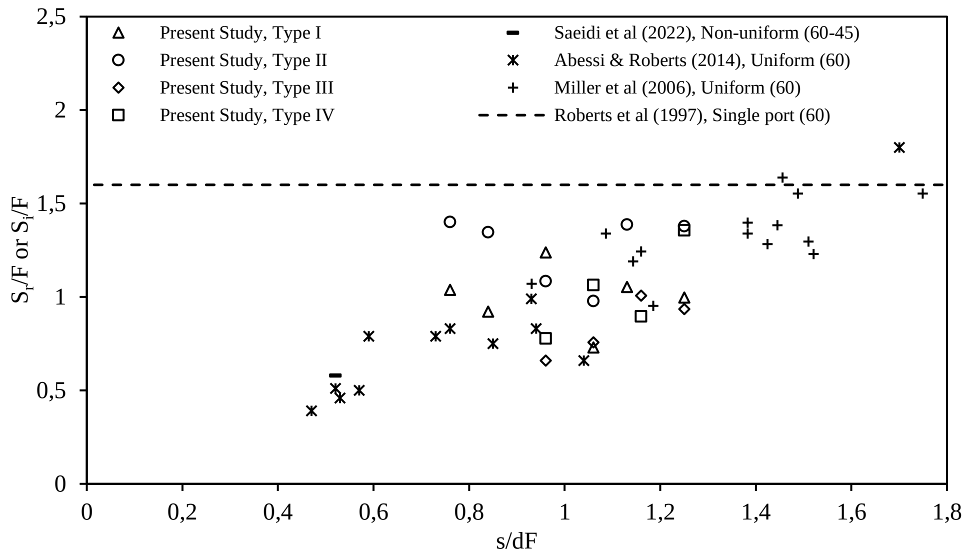


Figure 8 Return or impact point dilution versus port spacing for various diffuser configurations.

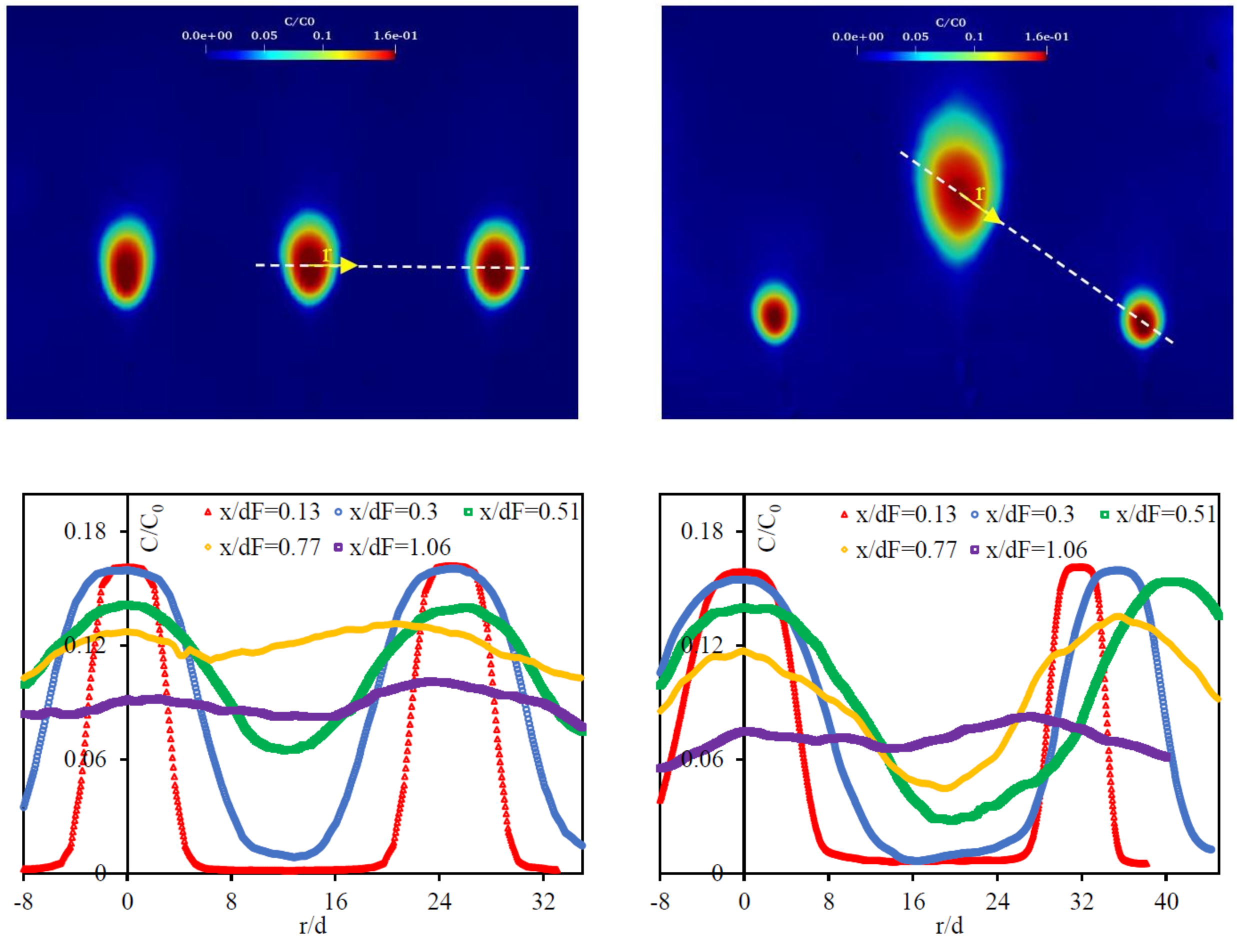
To show the effect of non-uniform port orientation on the physical and mixing properties of multiport diffusers, the average of flow parameter values over all experiments for each diffuser type was obtained and then the mean values for diffuser Type I (θ=60^o and φ=0) were compared to those for II (θ=60^o and φ=20^o), and Type III (θ=50^o and φ=0) to IV (θ=50^o and φ=20^o). The non-uniform diffusers Type II (circle symbol) and IV (square symbol) resulted in on average 14.2% and 6.0% shorter return point distances than the uniform Types I (triangle symbol) and III (diamond symbol) respectively, see Figure 6. At some distances from the non-uniform diffusers, the rising part of shallower-angle jets interact with the falling part of steeper-angle jets, impairing the flow movement in the x-direction. Figure 7 shows that the terminal rise height for the non-uniform diffusers Type II and IV are on average 2.6% and 4.1% higher than those for Types I and III, respectively.

The most important parameter in this study that shows the overall performance of uniform and non-uniform diffusers is the return point dilution. The superiority of non-uniform diffusers in terms of dilution is evident in Figure 8, as the circle symbols are generally located above the triangle symbols and the square ones above the diamonds. The non-uniform diffusers II and IV lead to on average 25.0% and 22.1% higher dilution rates compared to the Types I and III, respectively. This significant difference between dilution rates has its roots in different merging processes of jets for uniform and non-uniform diffusers.

Although previous studies have been conducted in the presence of a bottom boundary, the results of the present study can still be compared. Prior research has mainly focused on 60^o jets, and the outcomes for the 60^o jets of this study are the most applicable comparison with them. The return point distances of 60^o jets are somewhat lower than the impact point distances presented by Miller et al. [24] and Abessi and Roberts [23]. The main source of this difference comes from the comparison of return with impact point distance, as impact point distance is higher than return point distance for 60^o jets. Moreover, the return point distance is extended due to the boundary's presence, resulting from a complex transition from a predominantly vertical flow orientation to a horizontal gravity current [38]. As shown in Figures 7 and 8, measurements for the terminal rise height and return point dilution of 60^o jets are consistent with the previous studies. The better performance of non-uniform relative to uniform diffusers, concluded in this study, aligns with a recent computational study [11] that showed a 14% increase in impact point dilution when applying a non-uniform diffuser with closely spaced 60^o and 45^o ports, as opposed to uniform diffusers with 60^o jets. The comparison of measurements for multiple jets in this study and single ones in prior research [13] confirms the shorter trajectory and lower dilution rates for multiple INBJs compared to single jets, resulting from the Coanda interaction and jet merging effects.

4.3 Merging Process

To investigate the interaction of neighboring jets, normalized concentration profiles (C/C_0) over lines between the central jets and their neighbors were studied. Figure 9 shows the lines and concentration profiles for different cross-sections close to and far from the diffusers, x/dF=0.13, 0.3, 0.51, 0.77, and 1.06; the peak concentration for the central jet was always centered on the chart origin, r/d=0. Along the trajectory, the jets on both diffusers become more dilute due to the entrainment of surrounding water, due to shear induced entrainment at the jets' edges. The maximum concentrations gradually decrease, the jets get more diffused, and the gap between the jets is gradually filled with brine at farther distances.



(a) (b)

Figure 9 Cross-sectional concentration profiles along the lines between the central jets and their neighbouring jets for the (a) uniform diffuser Type I and (b) non-uniform diffuser Type II, F=23.5.

The merging processes were compared by comparing concentration profiles for non-uniform and uniform diffusers at each cross-section. Close to the diffusers, e.g., x/dF=0.13, the central jets for both diffusers have almost no interaction with their neighbors, and therefore there is almost no re-entrainment due to the neighboring jets. At x/dF=0.3, the jets are more diffused, but there is still a small region with almost no jet fluid between the jets for both cases. At x/dF=0.51, the central jets on both diffusers interact with their adjacent discharges. However, the concentration in the region of interaction is much lower for the non-uniform case compared to the uniform one. In other words, there is less exchange of tracer in that region for the non-uniform diffuser. A jet on the uniform case re-entrains more concentrated brine into itself, which significantly hinders mixing. At x/dF=0.77, the uniform jets are almost fully merged, but the non-uniform jets are not yet fully merged. Entrainment for the uniform case is mainly from above and below the cloud since the gap is almost filled with tracer. However, there is still re-entrainment of low concentrated brine into the jets from the jets' gap for the non-uniform case. The lower levels of tracer exchange for the non-uniform case at different sections result in lower concentrations, or higher dilutions, where the jets for both cases are completely merged, e.g., x/dF=1.06.

Investigation of the concentration fluctuations reveals the different nature of mixing in the interaction zone of uniform and non-uniform diffusers. The non-dimensional variance of concentrations (σ^2/C_{Max}^2) at each section is shown in Figure 10, where σ is the concentration standard deviation. Close to diffusers, e.g., x/dF= 0.13 and x/dF=0.3, the variance profiles depict a low peak at the center of the jets and two high peaks beside it. These high peaks show that the jets entrain ambient water and feed themselves from the gap, while the low peaks, with almost zero variance, shows that the centers of jets are not involved in mixing yet. The presence of two well defined, separate peak profiles between two adjacent jets shows that the jets do not re-entrain their neighbouring jets. At some distances from diffusers, e.g., x/dF= 0.51, the difference between the mixing in interaction zones is evident, where there is one peak, point 3, between neighbouring jets for the uniform diffuser and two, points 1 and 2, for the non-uniform case. The presence of one variance peak between the jets means separate jets are still identifiable, but they significantly re-entrain adjacent jets into themselves instead of ambient water. At farther locations, the variance profiles are smoother. The concentration variance exhibits low variation at x/dF=0.77 and x/dF=1.06 for the uniform case, indicating that the jets behave as plane or 2D jets. Notably, as depicted in Figure 10 (a), the trend of concentration variance against distance from the diffuser remains consistently ascending for both individual jets before complete merging (at x/dF=0.13, 0.3, and 0.51) and the formed line plume after merging (at x/dF=0.77 and 1.06). The only instance of a drop in the variance value is observed when comparing x/dF=0.51 and x/dF=0.77, which corresponds to the point when the jets coalesce into a line plume.

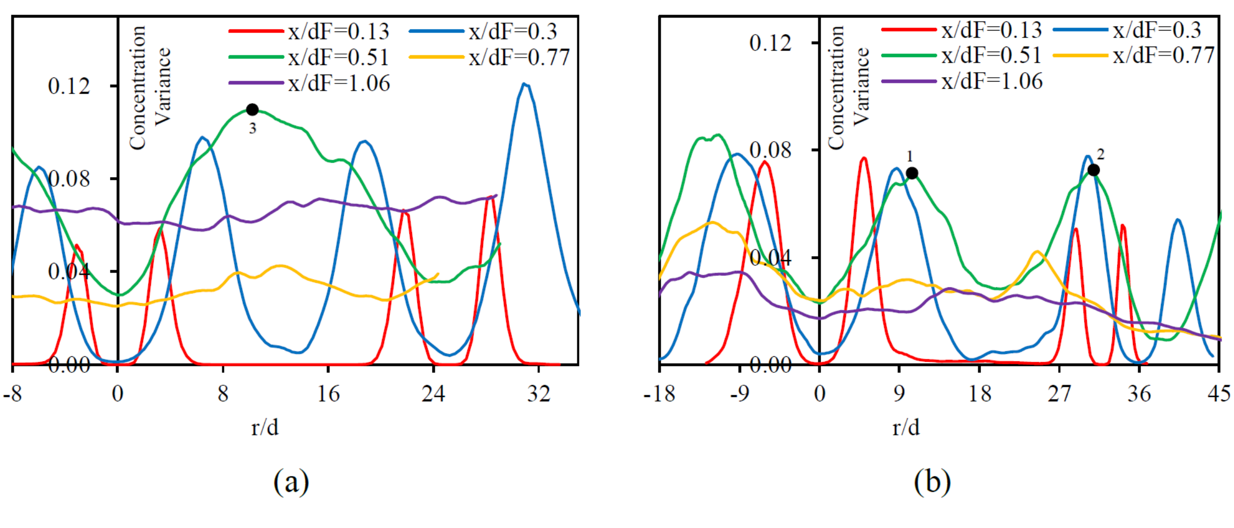


Figure 10 Variance of concentration (σ^2/C_{Max}^2) profiles over the lines presented in Figure 9 for the (a) uniform diffuser Type I and (b) non-uniform diffuser Type II, F=23.5.

The interaction of neighboring jets is significantly affected by the gap between the jets. Previous studies showed that jet merging impaired dilution in multiport diffusers and recommended providing more space between the ports to increase dilution [23]. This study finds that a reduction in this negative impact on dilution may not be solely achieved by increasing port spacing (s). For a uniform diffuser, the distance between the jets' centerline (d_j) at different distances from the diffuser is almost the same as port spacing. However, d_j changes at different distances from a non-uniform diffuser. Uniform and non-uniform diffusers may have the same port spacing, but different d_j at different locations, resulting in different merging processes. Figure 11 indicates how the normalized jet spacing (d_j/d) changes at different distances from diffusers Type I and II. The jet spacing for diffuser Type I gradually decreases as a result of the Coanda effect while that for Type II increases up to a point and then decreases. The reduction in jet spacing originates at the onset of the descending part of the 70° inclined jet. Generally, there is more space between the jets' centerline for diffuser Type II compared to Type I, as the dashed line is located above the solid line. Non-uniform port orientation can be an alternative for port spacing since it provides more space for the jets to expand before interacting with their adjacent jets, the same as the role of port spacing but with a potential lower building cost. It is expected that jet spacing, or non-uniformity, positively affect the mixing process in the angle range over which highest dilution rates have been reported for single jets but not for very steep or gentle angles. Although non-uniformity provides more gap between discharges, the presence of gentle-angled ports on a diffuser may adversely affect the overall performance of it since they result in very short trajectories. The steep-angled jets also fall back on themselves which may reduce the overall dilution.

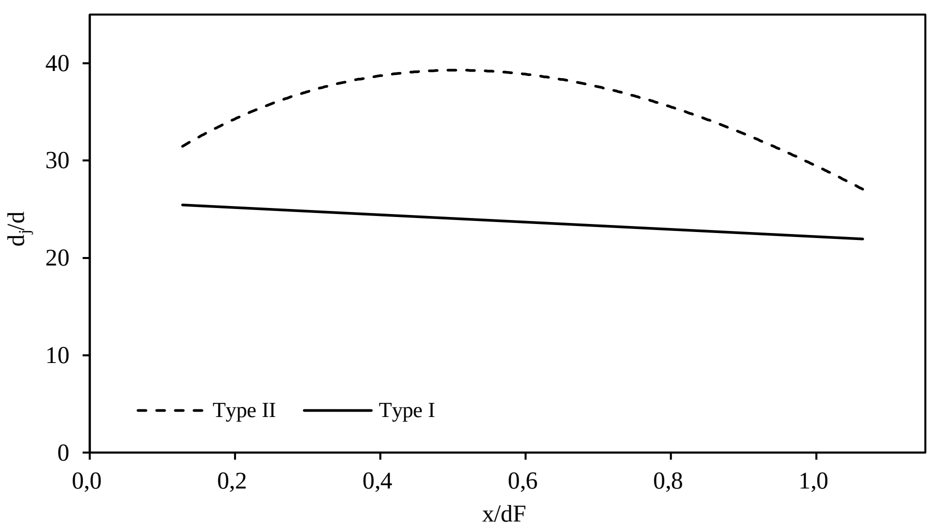


Figure 11 The distance between the jets' centerline versus distance to diffusers for the (a) uniform diffuser Type I and (b) non-uniform diffuser Type II, F=23.5.

5 Conclusions

An issue with multiport diffusers for brine disposal is jet interaction, which can significantly impair the mixing process. This study proposed multiport diffusers with non-uniform port orientations as a means for increasing dilution. A series of experiments adopting the LIF method were conducted for four types of diffusers consisting of two with uniform and two with non-uniform port orientations. The port angles were varied in the range over which the highest dilution rates had been reported for single discharges (40o to 70o). Flow behavior resulting from non-uniform diffusers was quantified using geometric and dilution measurements obtained from LIF and were compared to that of uniform diffusers.

The results revealed better performances of multiport diffusers with non-uniform port orientation over those with uniform port orientation. The non-uniform diffusers resulted in, on average, 6% to 14% shorter return point distance, 3% to 4% higher terminal rise height, and 22% to 25% higher return point dilution relative to the uniform diffusers. This improvement was attributed to different mixing behavior in the interaction zones. The investigations demonstrated that jet merging occurred closer to diffusers for uniform cases compared to non-uniform cases. At some distance from the diffusers, where the jets on non-uniform diffusers had little interaction with their adjacent jets and entrained almost clear water into themselves, there was high exchange of tracer between the jets on uniform diffusers, mixing was restricted in the lateral direction, and significant reentrainment was evident. At the locations where separately identifiable jets on the non-uniform diffusers interacted, there was no trace of separate jets for the uniform cases, demonstrating limited lateral entrainment for the uniform cases and 2D-like (two-dimensional) behavior. Different mixing behavior in the interaction zones and consequently better performance of non-uniform diffusers was due to more space between the jets' centerline at different distances from diffusers for the non-uniform diffusers, compared to the uniform diffusers. Non-uniform port orientation provided more space between the jets to expand before interacting with their neighboring jets, resulting in higher dilution rates. Hence, the application of non-uniform diffusers can result in shorter port spacing and therefore diffuser length while resulting in the same dilution as an equivalent uniform diffuser.

This study questioned the application of formulae obtained from single discharge experiments for multiport diffuser designs and showed that the source characteristics specific to multiport diffusers such as angle difference should be considered for efficient design of desalination outfalls. The new data and analysis provided in this study can benefit the design of desalination outfall systems with considerable potential cost savings, specially for tunneled outfalls. Moreover, the measured higher dilution can help in preventing environmental damages. The present study assumed two port angles, 50^o and 60^o and an angle difference of 20^o between adjacent jets on a multiport diffuser. The assumption of more port angles and angle differences may shed light on the combined effect of port angles and angle differences on mixing efficiency. However, it is not expected to reach more dilution rates by considering port orientations much lower or higher than the investigated angle range. The combined effect of non-uniform port orientation and flowing current on the mixing behavior of desalination discharges may be also of interest. It is suggested to perform optimization studies considering the angle difference as a decision variable, alongside other decision variables previously defined in the literature, such as the number of ports, port and outfall diameters, and outfall and diffuser lengths.

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Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Author Contributions

• Seyed Ahmad Reza Saeidi Hosseini:
Conceptualization, Methodology, Software, Validation, Formal Analysis, Investigation, Resources, Data Curation, Writing—Original Draft Preparation, and Visualization.

• Mostafa Taherian:
Methodology, Software, Validation, Investigation, Resources, Data Curation, Writing—Review and Editing, and Visualization.

• Abdolmajid Mohammadian:
Conceptualization, Methodology, Software, Data Curation, Writing—Review and Editing, Supervision, Project Administration, and Funding Acquisition.

• Simone Ferrari:
Methodology, Software, Investigation, Resources, Data Curation, Writing—Review and Editing, and Supervision.

• Philip J. W. Roberts:
Data Curation and Writing—Review and Editing.