ISSN 0554-6397
Izvorni znanstveni rad
(*Original scientific paper*)

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Numerical Modeling of Inclined Buoyant Jets for Different Flow Conditions

Abstract

The processes of discharge of higher density effluent into the recipient of lower density occur during the release of wastewater into the sea from desalination process, which is increasingly common today due to the shortage of drinking water. During such discharges, the goal is to achieve the best possible mixing, so that the impact of water with a high salt concentration on the environment is as small as possible. Since the jet returns to the bottom because of the influence of gravity, the use of nozzles at an angle increases the zone in which mixing occurs. In this paper, a numerical model of effluent discharge was made and buoyancy jets inclined at 45° were observed for different flow regimes. The influence of density and velocity on jet characteristics is shown. The numerical model was developed in OpenFOAM, and a comparison with experimental data from previous research is presented.

Keywords: Desalination, Inclined buoyant jets, OpenFOAM, Mixing, Wastewater

1. Introduction

As shortages of portable and freshwater have become a common occurrence, mainly due to the increased demand for drinking water linked to the population growth, desalination processes are of increasing importance. This is especially a problem on islands due to an increase in the population during the summer. Nowadays, ships, submarines and platforms are more frequently applying the desalination process to get drinkable water and reduce the size of the water tanks.

In the desalination process, seawater or brackish water is used to produce potable water by eliminating the suspended matter and the dissolved minerals, mostly salt. A by-product from the process, desalination brine, is discharged using submerged outfalls back to the sea. Since this type of wastewater has a higher concentration of salt than the ambient water, it can potentially have negative effects on marine ecosystems. Increased salinity results in cell dehydration and possibly the death of these organisms [1]. To minimize harmful effects, it is a prerequisite to properly design diffusers and to predict the mixing behaviour of dense jets and assess their environmental impact. Inclined dense jets have many other applications. They also appear during the discharge of cooling water from liquefied natural gas plants, industrial discharges and wastes from mining and dredging operations, so they have been investigated by several researchers.

The earliest experimental study on inclined dense jets was conducted by [2] on discharges for inclinations 30°, 45°, 60° and 90°. The research has shown that the longest trajectory and highest dilution is achieved at an angle of 60°. Later studies [3] have shown the substantial effect of the water surface on dilution rate and mixing for larger discharge angles, so it was proposed to use dense jets inclined at smaller angles such as 45° for shallow coastal waters, where desalination plants are mostly located. Cipollina et al. [4] made an experimental investigation for the inclined dense jet at angles 30°, 45° and 60° for various ranges of Froude and Reynolds numbers, indicating that fluid viscosity has no significant effect on the flow. Shao et al. [5] used a combination of Planar Laser Induced Fluorescence (PLIF) and Particle Image Velocimetry (PIV) to experimentally investigate boundary effects. Vafeiadou et al. [6] applied computational fluid dynamics (CFD) to simulate the behaviour of inclined dense jets using commercial software CFX. Zhang et al. [7] used large eddy simulation (LES) to simulate 45° inclined dense jets with OpenFOAM and compared results with experimental data. Gildeh et al. [8] investigated various RANS turbulence models to study the behaviour of 30° and 45° inclined dense jets and found that both the LRR and realizable k-ε model produce the most accurate results.

In this study, the open-source CFD toolbox OpenFOAM was used to investigate characteristics of the inclined jet for different flow conditions. The results of the numerical model were compared with the experimental results from previous research [7]. Most previous works and experiments focused on ambient freshwater, but in most cases, the desalination effluent is discharged into seawater, where density can vary considerably, especially in the winter-summer seasons. Additionally, the effluent may have a different density, depending on the method used and the setting of the desalination process. As velocity, the density of effluent and brine have a strong impact on dilution rate and mixing, their behaviour has been investigated. Characteristic geometrical features of the dense jet for each case, including return point, centerline peak location and terminal rise height, were observed.

2. Material and methods

2.1. Dimensional Analysis

The main flow characteristics of an inclined dense jet in a stationary environment are shown in Figure 1. The jet is discharged through a round nozzle of diameter d with initial velocity U_0 inclined at the angle θ to the horizontal plane. During the initial vertical momentum flux, the jet is moving upward until it reaches peak height, which can be described with horizontal and vertical locations of the centerline peak x_m and z_m and terminal rise height z_t. Since the brine density ρ_b is bigger than ambient density ρ_a, after reaching maximum height, buoyant forces become dominant and the jet falls over and impacts the seabed. The dashed curved line presents the centerline of the jet, which is defined as the location of time-averaged local maximum concentration or velocity for the various cross-sections. Return point location x_r is defined as a location where the centerline intersects with the initial jet elevation. After reaching the bottom, the plume will continue spreading horizontally as density current at the horizontal direction with smaller speed and dilution.

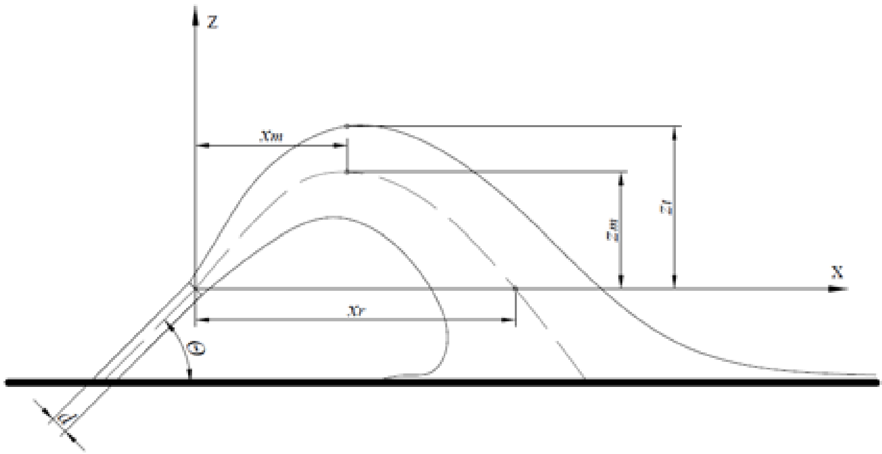

Figure 1: Schematic diagram of an inclined dense jet.

Variables of turbulent jets φ depend on the discharge angle θ, momentum M, buoyancy B, jet kinematic fluxes of volume Q and acceleration due to gravity g. They can be defined as follows:

$$\varphi = f(Q, M, B, \theta) \tag{1}$$

$$Q = \frac{\pi}{4} d^2 U_0 \qquad M = U_0 Q \qquad B = g_0' Q \tag{2}$$

$$g'_0 = \frac{g\left|(\rho_b - \rho_a)\right|}{\rho_a} \tag{3}$$

Previous studies have shown that dilution and jet geometry features mainly depend on densimetric Froude number Fr which is the ratio of inertial and buoyant forces and can be expressed as:

$$Fr = \frac{U_0}{\sqrt{g_0' D}} \tag{4}$$

Momentum-buoyancy length scale L_M is the measure of the distance in which momentum is more significant than buoyancy on the behaviour of the jet:

$$L_M = \frac{M^{3/4}}{B^{1/2}} = \left(\frac{\pi}{4}\right)^{1/4} d\, Fr_d \tag{5}$$

Another relevant dimensionless parameter is Reynolds number Re, which represents the ratio of inertial to the viscous forces is given as:

$$Re = \frac{\rho_b U_0 l}{\mu} = \frac{U_0 l}{\nu} \tag{6}$$

where l is characteristic length scale, ν is kinematic viscosity and μ is dynamic viscosity.

2.2. Numerical setup

In this study, the partial differential equations of fluid flow were calculated utilizing the open-source CFD package OpenFOAM, which is based on the finite volume method. Domain has been shown in Figure 2. with all dimensions in millimetres. The size of the geometry is similar to the experiment in [7]. The origin of the coordinate system was set to the centre of the discharge port.

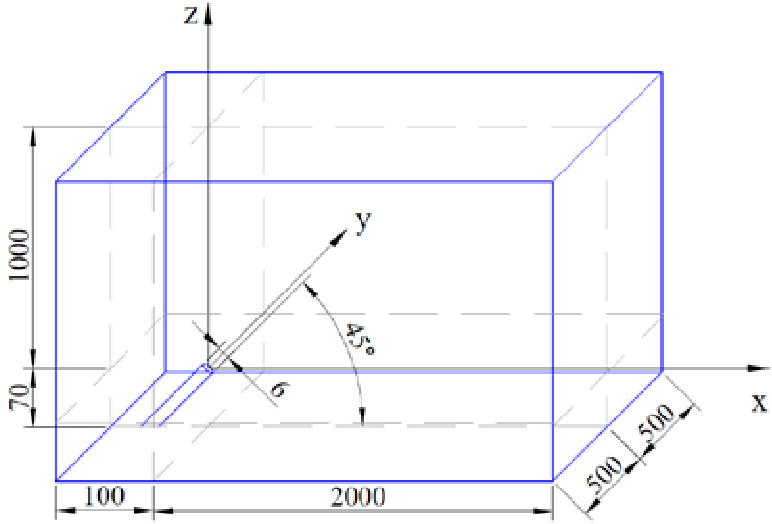

Figure 2: Computational domain

CF-MESH+ software was used to create the mesh. It contains 1962909 elements with refinement in zones near the nozzle. A transient OpenFOAM solver for mixing two incompressible fluids, twoLiquidMixingFoam was used. As suggested by the results from previous studies [8], realizable $k - \varepsilon$ turbulence model was selected. The viscosity of both fluids was set to 10^{-6} m^2/s, while diffusivity and turbulent Schmidt number were 10^{-9} m^2/s and 0.7, respectively. The time step was adaptively varied so as to satisfy the condition that the Courant number is less than 1. The simulation time is 120 seconds.

Boundary conditions were chosen to match the experiment used for validation. Back, front, right and left boundaries were set to be zero gradient open boundaries. The top surface was set to free slip boundary condition. On the bottom side and pipe, standard turbulence wall functions and no slip condition was used. At the inlet of the pipe, uniform discharge velocity U_0 was set at turbulence intensity of 10%.

In Table 1. flow configurations for different cases are shown. Sixteen different cases have been simulated. Brine with density ρ_b and initial velocity U_0 was discharged in homogeneous stationary ambient fluid with density ρ_a. Conditions in case V0 were identical to the experimental study [7]. In experimental cases U1-U5, inlet velocity was changed in A1-A5 ambient density was changed and in B1-B5, brine density was changed.

Table 1: Numerical setup parameters for different cases.

Case	Initial velocity U_0, m/s	Brine density ρ_b, kg/m^3	Ambient density ρ_a, kg/m3	Froude number *Fr*	Reynolds number *Re*
V0	0.515	1034	997	11.21	2987
A1	0.515	1034	1020	18.43	2987
A2	0.515	1034	1022.5	20.36	2987
A3	0.515	1034	1025	23.04	2987
A4	0.515	1034	1027.5	27.15	2987
A5	0.515	1034	1030	34.65	2987
B1	0.515	1030	1025	30.91	2987
B2	0.515	1035	1025	21.86	2987
B3	0.515	1040	1025	17.85	2987
B4	0.515	1045	1025	15.46	2987
B5	0.515	1050	1025	13.82	2987
U1	0.250	1034	1025	11.18	1450
U2	0.750	1034	1025	33.55	4350
U3	1.000	1034	1025	44.74	5800
U4	1.250	1034	1025	55.92	7250
U5	1.500	1034	1025	67.11	8700

Since the brine is usually discharged with salinity less than 5% higher than the density of receiving water, in this study, cases for different densities of seawater and brine were observed. Simulation is also obtained for larger velocity and Reynolds number to show their relations. All simulations were performed on the Bura supercomputer at the Center for Advanced Computing and Modelling at the University of Rijeka.

3. Results and discussion

Previously described problems are transient in nature, hence all results are shown as time-averaged from 50 to 120 seconds when the simulation has no considerable variations. The results from case V0, experimental and LES results from [7] which were used to validate the model are shown in Figure 3.. Length on the axis is divided with the momentum-buoyancy length scale from Eq. (5) to get the dimensionless length since the diameter from an experimental pipe and LES domain are slightly different. While RANS model slightly under-predicts the trajectory from experimental results, LES model gets over-prediction. Results show especially good agreement in the jet-like region where momentum flux is dominant. In Figure 4., contours of the concentration and velocity magnitude for the cross-section of the flow are shown from case V0.

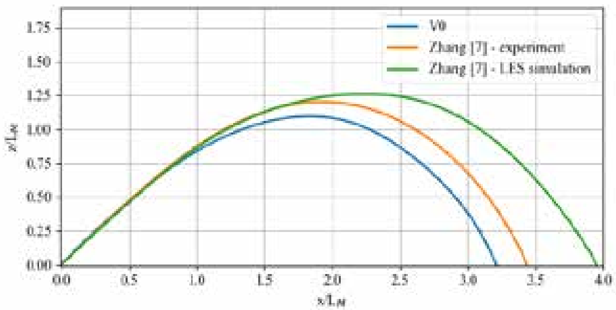

Figure 3: Comparison with experimental data.

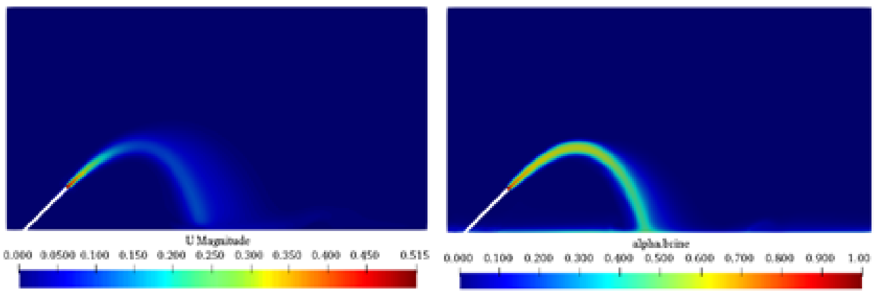

Figure 4: Time averaged velocity (left) and concentration (right) contours at the centre plane for case V0.

The jet centerline or jet trajectory is the main characteristic of the general jet flow. It shows coordinates of the centerline peak and returns point location, which is crucial to understand the characteristic of the flow. The jet centerline is defined from maximum concentration location at different cross-sections. The centre of the coordinate system is in the middle of the nozzle. Figure 5. shows the centerline for starting case and cases A1-A5 for different ambient densities. Case V0 represents freshwater, while other densities represent seawater of different properties. It can be observed that by increasing the density of the ambient water, the centerline will increase and better mixing will occur. In Figure 6. the centerline for different effluent densities are shown. Brine density has the opposite effect. The smaller it is, the centerline is higher and longer. Figure 7. shows the centerline for cases U1-U5 for different initial velocities. It is shown that, that in stationary ambient, larger velocity results in higher momentum flux and better mixing characteristics.

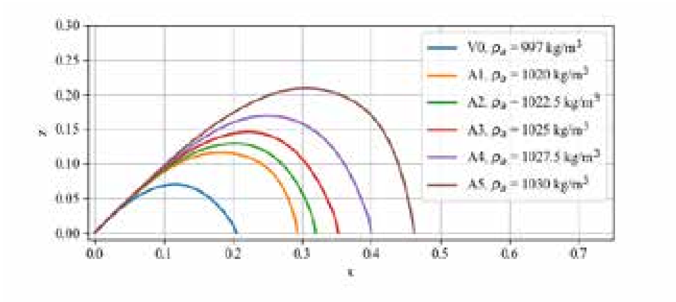

Figure 5: The jet centerline for different ambient densities.

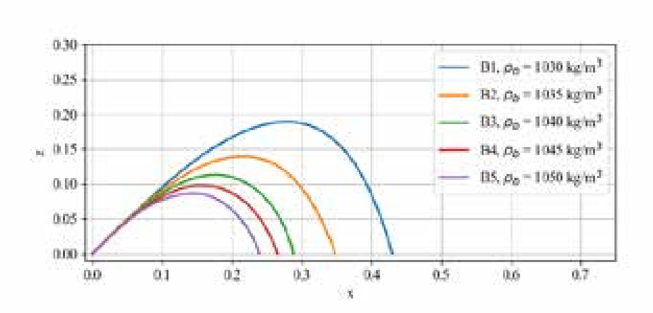

Figure 6: The jet centerline for different brine densities.

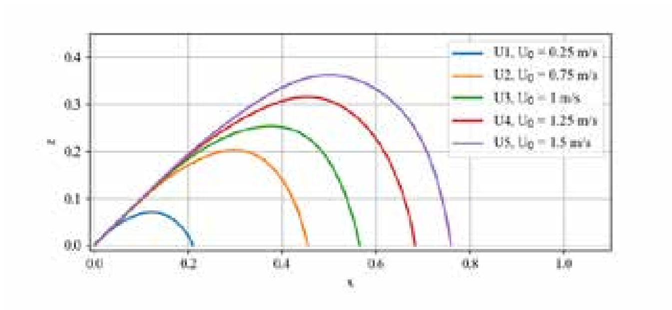

Figure 7: The jet centerline for different velocities.

The geometrical specifications of a buoyant jet, the horizontal and vertical locations of jet centerline peak with coordinates x_m and z_m, the jet terminal rise height z_t and the horizontal location of the jet return point x_r for each case are shown in Tables 2. and 3.. V0 has good agreement with experimental data which can be attributed to the fact they have the same setup. Characteristics from other cases depend on the settings and parameters that have changed.

Table 2: Geometrical specifications for experiment and numerical case V0.

Case	x_m	z_m	z_t	x_r
V0	0.1225	0.07	0.0825	0.205
Experiment [7]	0.119	0.074	0.11	0.212

Table 3: Geometrical specifications for different cases with changed flow parameters.

Case	x_m	z_m	$_z$t	x_r
A1	0.19	0.116	0.15	0.293
A2	0.21	0.129	0.165	0.32
A3	0.23	0.146	0.1925	0.353
A4	0.25	0.17	0.2175	0.4
A5	0.305	0.21	0.2575	0.463
B1	0.288	0.19	0.2525	0.43
B2	0.22	0.139	0.18	0.348
B3	0.183	0.113	0.148	0.288
B4	0.16	0.098	0.123	0.265
B5	0.153	0.086	0.105	0.239
U1	0.125	0.071	0.078	0.21
U2	0.298	0.203	0.263	0.455
U3	0.378	0.253	0.335	0.565
U4	0.466	0.315	0.375	0.683
U5	0.505	0.362	0.435	0.76

4. Conclusions

The aim of this work was to analyze flow characteristics of the inclined buoyant jets for different cases when the density of effluent is larger than the density of ambient water and the effect of buoyant forces are significantly increased. These comparisons focused on the main characteristic of the flow and centerline of the jet for the design of brine discharge and assess effects on marine ecosystems, as well as the environmental impact for regulatory purposes.

The focus of this paper was on diffusers inclined at 45° in stationary ambient. Flow and mixing were assessed in OpenFOAM. Results indicate that OpenFOAM can be successfully applied for predicting jet characteristics. These observations have been validated with previous experimental results. Sixteen numerical cases with different flow regimes have been made and their results have been shown.

The main characteristic of jets is shown with the jet centerline. For a design of desalination systems, it is important to determine the geometrical characteristics of the brine plume, including the horizontal and vertical locations of jet centerline peak, terminal rise height, the horizontal position of the return point.

Numerous cases of jet Froude and Reynolds numbers were observed in this work. Jet centerline and other jet characteristics strongly depend on those numbers, especially the Froude number. Results show as the Froude number increases, the range of the jet also increase.

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