Numerical Simulation of Near Field and Far Field Brine Discharge from Desalination Plants (A Case Study in Persian Gulf)

Ahmad Rezaee Mazyak[1], Mehdi Shafieefar[1], Alireza Shafieefar[2]

Abstract— Seawater desalination has gained importance in coastal countries where conventional water sources are insufficient or overexploited. Seawater desalination contributes to mitigate water scarcity. Brine is a sub-product of desalination plants and is usually discharged into seawaters, with potentially negative effects on marine ecosystems. The process of desalination is not per se environmentally friendly and seawater desalination plants also contribute to the wastewater discharges that affect coastal water quality. Therefore, modelling of the brine discharge dispersion is crucial in the design of coastal desalination plants.

In this paper, the salinity dispersion pattern of discharged saline water from the outfall pipeline of SAKO desalination facilities is studied to check the possibility of recirculation and fulfilment of environmental criteria. The SAKO desalination plant has a production capacity of 1,000,000m3/day and is located in northern coast of Persian Gulf, Bandar Abbas, Iran. The salinity dispersion process of a brine jet with ambient water includes near and far field regions. In this research, CORMIX II was used to model the near field process and then check the environmental criteria. The environmental criterion indicates that the excess salinity in a 200 meter diameter from the outfall should be less than 10% of the ambient salinity. Near field simulations indicate that salinity increment in 18 meter distance from the outfall will be about 4.17 PSU which is less than the 42 PSU ambient salinity. Hence, the environmental criteria are thoroughly met.

The results of the near field model have been used as input data for the far field model (HD model). The far field model covers north of Qeshm Island and is set up to check recirculation criteria. Results of this simulation have been extracted in the intake location and they show that there is no salinity increment trend at the intake. Consequently, recirculation problem will not happen. Also, results show that the optimization of near field dilution of brine discharge plays an extremely important role in checking the possibility of recirculation and environmental criteria.

Keywords— seawater recirculation, desalination plant outfall, near field simulation, far field simulation.

I. INTRODUCTION

Water scarcity is a serious problem around the word. Since the world's fresh water sources become more and more meagre, the world's attentions diverted towards the oceans and seas as an immediate resource for fresh water. Seawater desalination has gained importance in coastal countries where conventional water sources are insufficient or overexploited.

A large part of Iranian central plateau suffers from sustainable access to safe drinking water. Seawater desalination has the potential to help to alleviate this problem, but the desalination process has negative environmental impacts. Hence, modelling of brine discharge dispersion plays a key role in designing of coastal desalination plants.

Dilution and dispersion of a brine jet with ambient water can e processed in the near or the far field. In the coastal environment, simulation of brine discharge is strongly influenced by the wide range of temporal and spatial scales phenomena. So it is generally not feasible to obtain all of these conditions in one numerical model. Therefore, individual numerical models are employed for each phase and the models are coupled. Some researchers have focused on the near field process and the others have evaluated the long term diffusion, environmental criteria and coupling the near and far field process.

The research of Zeitoun et al. (1972) and Pincince and List (1973) were pioneer and helped to initiate development of near field studies [8,7]. More numerical studies about the negatively plume indicate that the numerical modelling is a reliable tool to evaluate the brine discharge behaviour in the near field region [4,5]. More recent studies on numerical modelling of desalination effluent discharge have concentrated on the optimization of outfall diffusers to achieve demanded dilutions in the near field [1]. In some other studies, capabilities of commercial software packages have been compared for modelling of near field process of negatively buoyant jets [11].

Some other researchers have focused on the long-term effect of effluent discharge from desalination plant. Simulation results illustrated the sensitivity of far field numerical model to coastal parameters such as bathymetry, ambient current structure, etc. [3]. Some studies have shown that individual modelling of the near field process and far field effects is not optimal for design considerations [2]. Therefore, in order to comply with the design requirements, it is essential to model near and far field simultaneously [10].

This paper provides comprehensive simulation results for

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the dispersion of the submerged brine discharges into the sea from the SAKO desalination plant. The main goals of this study are: a) meeting the environmental requirements, and b) coupling near field results with the far field model for assessment of water recirculation. This study will provide valuable results on salinity dispersion and its recirculation in the study area. This will help on determining the best schemes for dealing with this phenomenon.

II. Study Area

The SAKO desalination plant is located on the northern coasts of the Persian Gulf, near Bandar Abbas, Iran. It consists of desalination units with total product capacity of 1,000,000m3/day, i.e. 42,000m3/hr. The site of the project is located on the Khuran Strait, a narrow strait separating the Qeshm Island from the Iranian mainland. It is the much smaller counterpart to the Strait of Hormuz. The project location is shown in Figure 1.

Figure 1 Location of SAKO desalination plant

III. Study Methodology

The methodology of this study contains three main steps (Figure 2). The first step is to assess and evaluate hydrodynamics conditions. The second step is developed to evaluate behaviour of brine discharge in near field. In the final step, far-field region was investigated.

The numerical modeling for the salinity distribution process of SAKO desalination plant is performed according to the stated methodology with the goal of better understanding and improving the distribution conditions and also to mitigate environmental effects.

IV. Hydrodynamic Modelling

Due to the extent of the study area, numerical simulation is required to determine the hydrodynamic characteristics.

Most hydrodynamic models have been two-dimensional (depth-averaged) which is probably adequate for fairly shallow unstratified waters. Previous studies in this area shows the changes of temperature and salinity in depth is negligible [9,12].

Therefore in this study MIKE 21 Flow Model (FM)-HD has been used for hydrodynamic modelling in the Strait of Khuran. This model simulates the water level variations and flows in response to a variety of forcing functions in oceans and coastal areas. The model is based on the three-dimensional incompressible Reynolds averaged Navier-Stokes equations, subject to the assumptions of Boussinesq approximation and hydrostatic pressure.

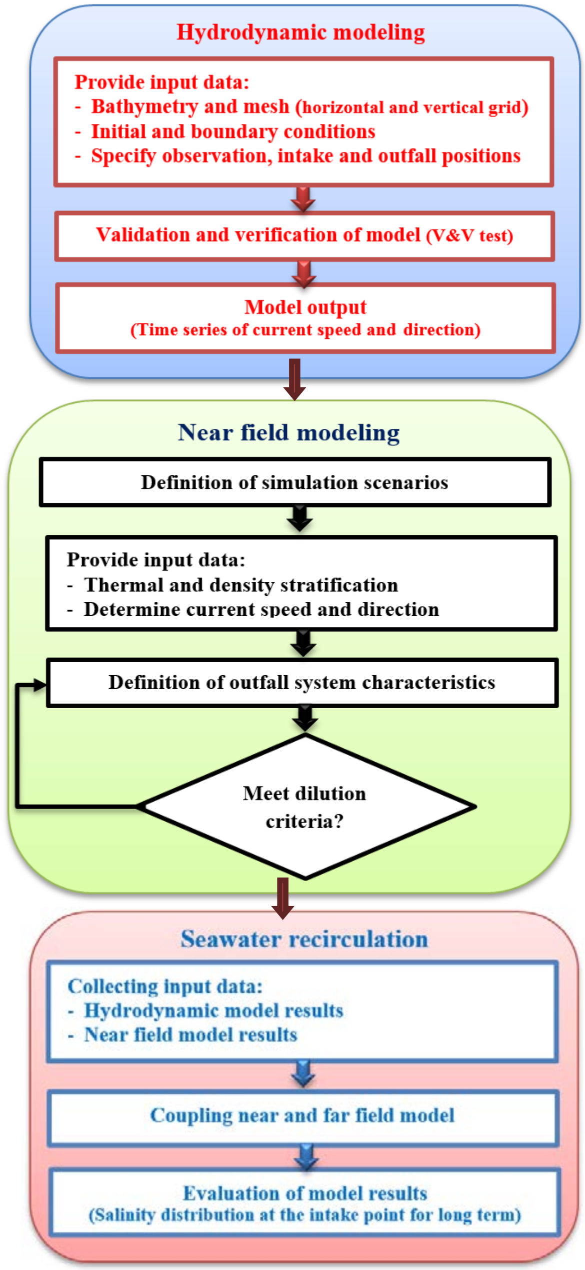

Figure 2 Flow chart of the study methodology

A. Boundary Conditions

As shown in Figure 3, there are two open boundaries in the west and the east side of the modelling area. For producing the boundary conditions in the west and east side of the modelling area, tidal elevation time history have been predicted based on the Basaidu and the Bandar Bahman tidal information (N.C.C Station) for year 2015. Figure 4 shows the surface elevation time series at the mentioned stations.

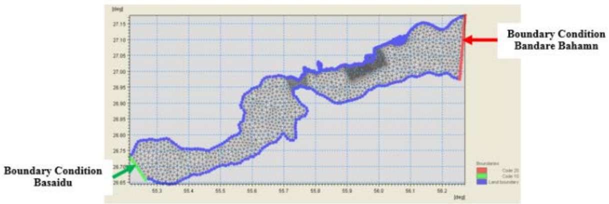

Figure 3 The open boundaries of the model.

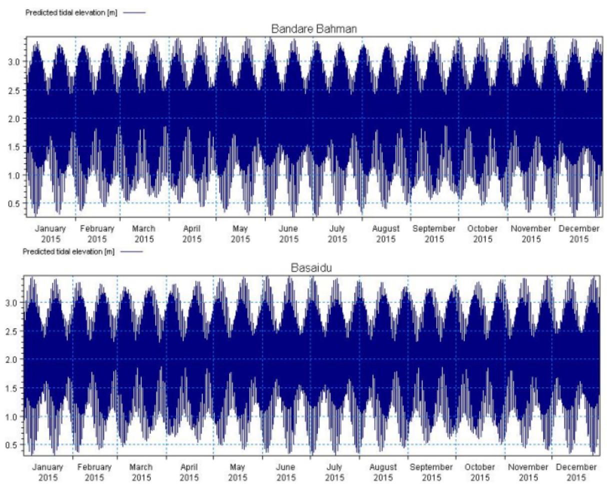

Figure 4 Time history of predicted tidal level at the station of (up) Bandare Bahman (down) Basaidu.

B. *Field Measurements*

For model verification, the current velocity and direction and surface elevation were measured in the study area. Current velocities and directions were recorded with Acoustic Doppler Current Profiler (ADCP) at 2 stations for 3 month (June-August 2015). The RBR is located in the ISOICO port and records surface elevations. The ADCPs scatter data and location and the RBR position are shown in Figure 5.

C. *Validation and Verification*

The calibration is achieving the best fit between simulated results and available measured data by changing the empirical parameters such as bed resistance. The comparisons between the measured data and calibrated model results, including current speed and surface elevation for one month duration (23 Jun- 22 Jul), are illustrated in Figure 6 and Figure 7.

Moreover for better comparison between modelled and measured data the statistical parameters including Bias, Root Mean Square Error (RMSE), Scatter Index (SI) and correlation coefficient (CC) have been calculated and presented in Table 1. The results of numerical modelling demonstrate that the selected model can accurately reproduce all the critical features in the study area.

D. *Results of Hydrodynamic Modelling*

For near field modelling, the results have been extracted at the outfall location. The time series and current speed rose is shown in Figure 8. Based on the numerical modelling results, the average current speed is 0.6 m/s and direction of the tidal current is along the shoreline.

Figure 5 (up) Measurement positions (down) Scatter plot of ADCPs data.

V. Near Field Modelling

High flow velocities of the discharged outfall jet and salinity differences of the outfall with the ambient water causes stratified flow pattern formation around and near the outfall location. In this region which is called "Near field zone", flow velocity and water salinity do not have a homogeneous distribution in depth and then, 2D models would not be applicable.

Discharged saline water from desalination systems into the sea, may lead into two problems including major environmental pollution (water salinity increment should not exceed 10% in 200 m distance from the outfall location) and recirculation problem (discharged saline water should not affect the intake water).

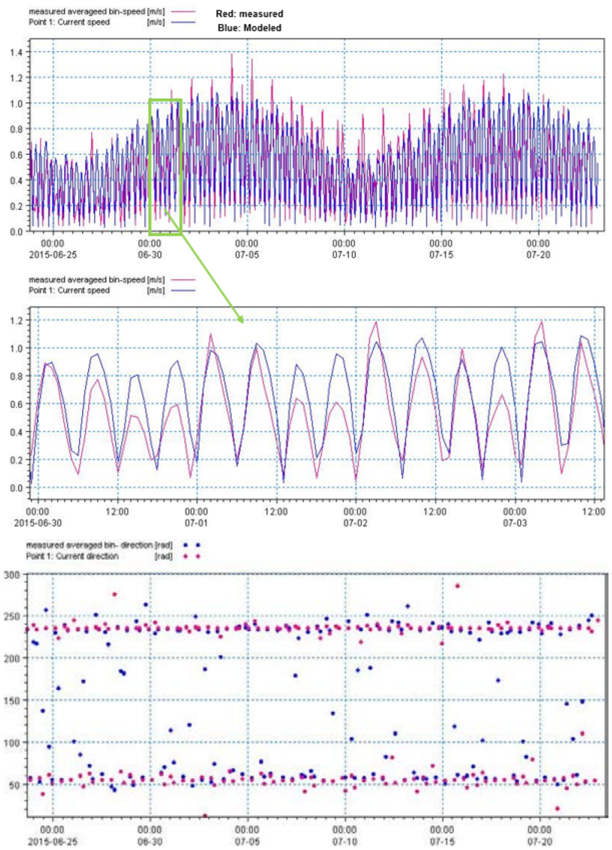

Figure 6 Measured and modelled current speed and direction (Jun- Jul) (ADCP1)

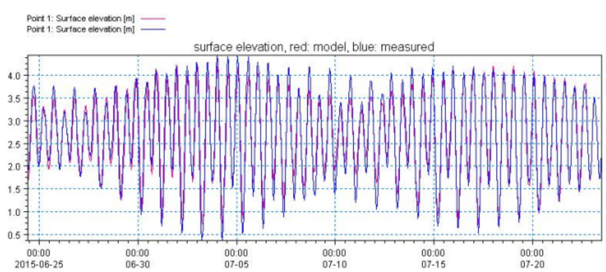

Figure 7 Measured and modelled surface elevation (Jun- Jul)

Table 1 Statistical parameters used for comparing modelled and measured data

Time duration	parameter	Bias	RMSE	SI	CC
Jun- Jul	Current speed	0.07	0.19	0.38	0.79
Jun- Jul	Surface elevation	0.005	0.24	0.09	0.97
Jul- Aug	Current speed	0.09	0.19	0.37	0.81
Jul- Aug	Surface elevation	0.04	0.59	0.23	0.80

A. Simulation Scenarios

The near field modelling is considered for environmental pollution and water recirculation;

Scenario 1 (environmental criteria): the full amount of discharged water from desalination and power plant is brine with concentration similar to the RO outfall salinity by high recovery rate (41.67 %).

Scenario 2 (water recirculation): the recovery rate of desalination is 41.67% and fully salinity mixing of saline RO discharged water and power plant outfall in weir box is considered. The salinity of outfall is calculated by the mean salinity according to Equation 1.

$$S_O = \frac{S_{RO} \times Q_{RO} + S_{PP} \times Q_{PP}}{Q_{RO} + Q_{PP}} \qquad (1)$$

where S_{RO}, Q_{RO}, S_{pp} and Q_{pp} are salinity and flow rate of RO and power plant outfall respectively.

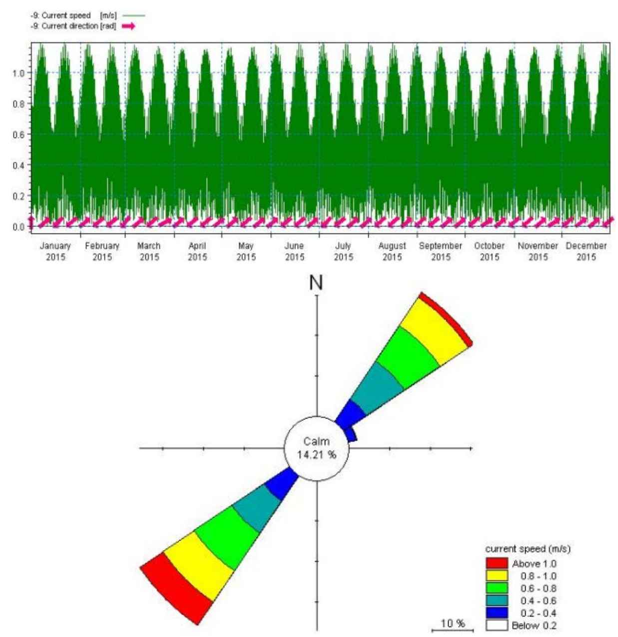

Figure 8 Time series and current rose at outfall location

B. Software Description [6]

In this study Cornell Mixing Zone Expert System (CORMIX II), has been applied for the near field analysis. It computes the plume characteristics in the initial mixing zone within which the fluid motion, turbulent field and salinity dispersion are dominated by the discharge properties such as the mass flux, and buoyancy flux of outfall jet. Results of CORMIX II will be extracted at the end of near field which can be defined where brine plume characteristics are fully mixed vertically. It is assumed that the ambient flow as environmental hydrodynamic currents have negligible effects on the discharged flow pattern in the near filed zone.

The dilution parameter is defined as a representative for pollutant material concentration (water salinity in this study) in CORMIX II outputs and is calculated by Equation 2.

$$S = \frac{C_0}{C} \tag{2}$$

where C_0= water salinity of discharged flow in outfall position and C= water salinity in a specific distance from outfall along the plume centreline

In this study, C and S are extracted at the end of the near field zone and then the plume velocity and discharge is calculated there and applied as the input data for the far field model.

C. Input Data

The required model inputs for defining the diffuser discharge conditions include bathymetry, ambient water temperature and salinity concentration, ambient wind speed, current velocity, discharge rate, discharge temperature and salinity concentration, discharge velocity or flow rate, and diffuser characteristics (port diameter, number of ports, port orientation, port spacing, and port layout for a submerged diffuser).

The required input data for modelling near field are summarized in Table 2. The typical arrangement of the outfall riser for each pipeline is presented in Figure 9.

D. Results of Near Field Modelling

The negative buoyancy of the jet causes it to reach a terminal rise height and then falls back to the lower boundary where it spreads as a density current. The results of CORMIX II for two scenarios are presented as below.

Scenario 1 (Environmental Criteria): The variation of excess concentration and dilution parameter along the centreline of brine plume has been shown in Figure 10. The excess salinity at 22m distance from the outfall is less than 10%, therefore the environmental criteria is satisfied.

Scenario 2 (Water Recirculation): The variation of dilution and vertical thickness of the plume along the centreline are shown in Figure 11. Two regions with a different effluent behaviour should be considered when studying the discharge of brine into the receiving water body: the near and the far field regions.

The near field region is located in the vicinity of the discharge point and is characterized by initial mixing, which mainly depends on the brine discharge configuration design and the effluent and ambient properties. The far field region is located further away from the discharge point, where the brine turns into a gravity current that flows down the seabed. Mixing depends on the ambient conditions (bathymetry, currents, waves, etc.) and the differences in density between the hyper saline plume and receiving waters. Therefore, based on the numerical modelling, the edge of near-field is located at the distance of 45m from the outfall (Figure 11). The salinity increment at this point is 1.39 PSU.

Table 2 Summary of ambient and discharge characteristics used as input to the near-field model

Description	Scenario	
	1	2
Ambient Characteristics		
Density (kg/m^3)	1027.5	
Average Depth (m)	9	
Current Velocity (m/s)	0.62	
Bottom Slope (°)	0.96	
Wind Speed (m/s)	2	
Darcy- Weisbach Coeff.	0.025	
Discharge Characteristics		
Density (kg/m^3)	1050.2	1039.67
Effluent flow rate (m^3/s)	10.03	
Salinity (PSU)	72	58.15
Concentration (Excess)	71.4	38.45
Discharge Geometry		
Diffuser Length (m)	20	
Port Height (m)	1.2	
Port Diameter (m)	0.8	
Vertical Angle (°)	45	
Horizontal Angle (°)	Perp. to current: 90	
Contraction Ratio	1	
Total Number of Openings	5	

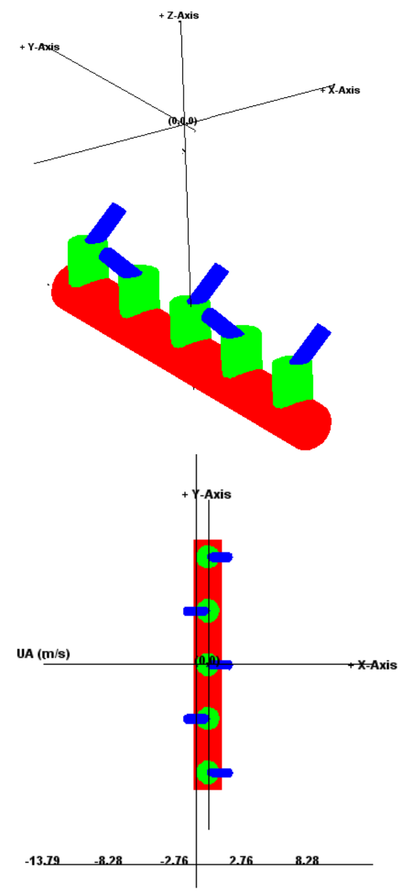

Figure 9 A typical arrangement of outfall riser per pipeline

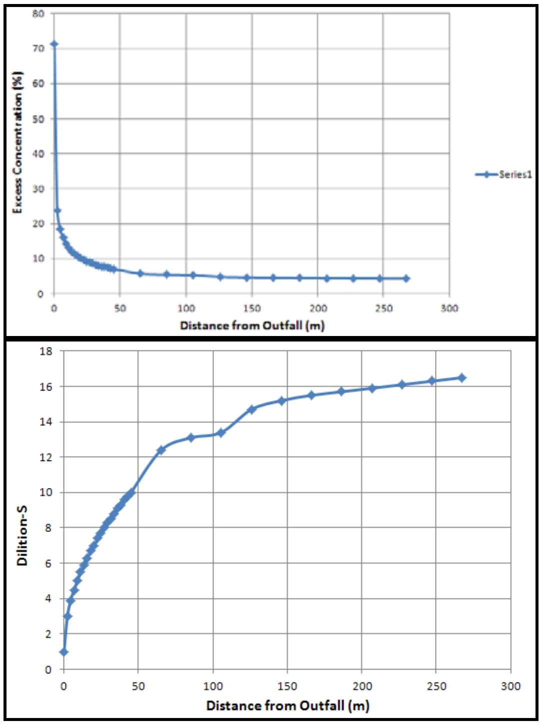

Figure 10 Variation of excess concentration and dilution parameter along the centreline of plume

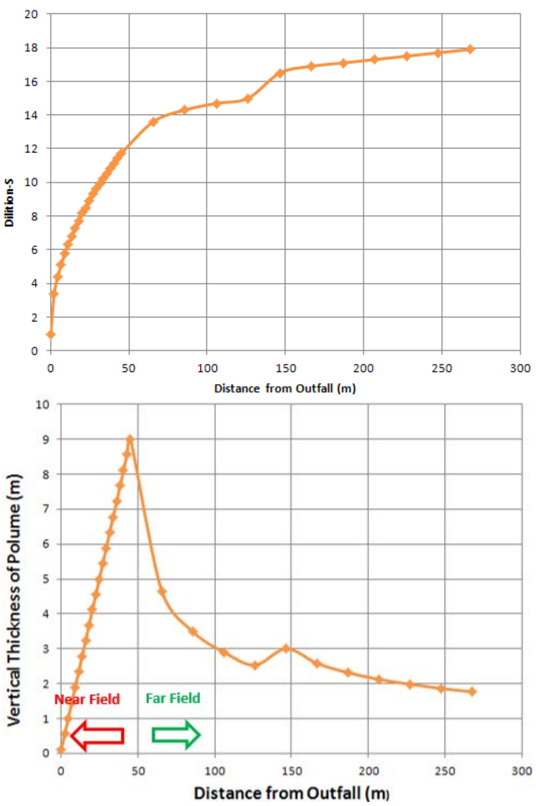

Figure 11 Variation of dilution along the centreline of plume trajectory

VI. Far-Field Modelling

In order to analyse saline water recirculation criteria, the results of near-field models, are applied into the far-field model as input data. The far-field hydrodynamic and salinity dispersion modelling is executed for the proposed intake and outfall locations.

A. Near-Field & Far-Field Coupling

Water salinity at the end of near-field is one of the CORMIX II outputs and can be applied directly as far-field model inputs. But, discharge and velocity are not determined in near-field model outputs.

A mass-balance box model is used for evaluating the far-field model inputs. The mass-balance box model is a volume control between outfall and the edge of near-field (Figure 12). Considering the mass, momentum, and buoyancy fluxes conservation equations, and with regards to Figure 12, plume characteristics at the edge of near field are calculated based on Equation 3.

$$Q_0 C_0 = QC \rightarrow Q = Q_0 S \qquad (3)$$

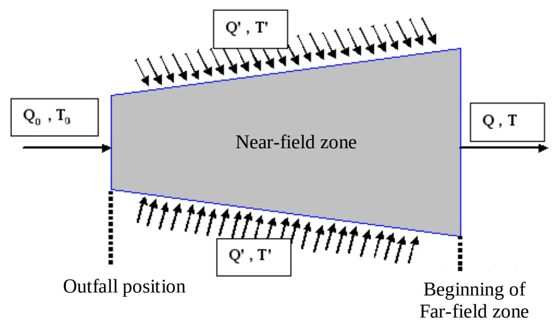

Figure 12 Volume control between the outfall and the first of far-field zone

The specifications of source point and the strength of artificial sinks (Q') are calculated for the far-field modelling as follows:
C = 1.39 PSU (input in far-field model)
Q = 117.351 m^3/s for each pipeline (input in far-field model)
Q'= -107.321 m^3/s for each pipeline (artificial sink)

B. Set-up of the Numerical Model

The hydrodynamic model is used for seawater recirculation study. Outfall (source) data is extracted from the near field modelling results. Specifications of outfall and intake based on calculations in the near field studies are:

Discharge of source (Q) = 352.05 m^3/s
Salinity of discharged water = 43.39 PSU
Discharge of sink (intake) (Q) = -41.655 m^3/s

It should be mentioned that for satisfying the mass conservation equation, an artificial sink has been defined. Discharge of this sink is equal to 321.963m^3/s.

C. Results of Far-Field Modelling

Salinity dispersion result for a sample time step is presented in Figure 13, showing intake and outfall locations. The intake water should not be affected considerably by the salinity plume of the outfall. For this purpose, the salinity increment values at the intake point are extracted and presented as time series charts (Figure 14).

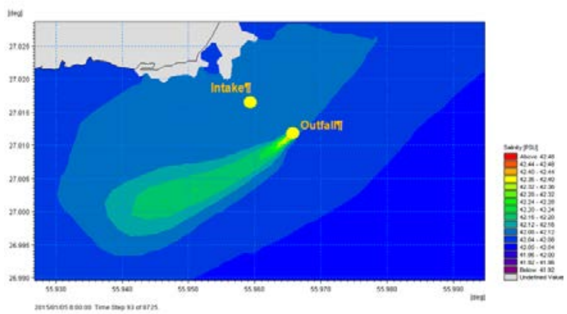

Figure 13 Salinity dispersion pattern (sample time step)

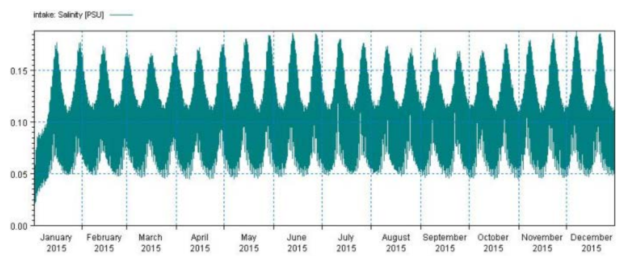

Figure 14 Salinity increment at the intake location

Maximum salinity increment in the intake location is about 0.2 PSU. In addition the mean salinity increment is about 0.1 PSU. This increment would be acceptable since the salinity of the ambient water is about 42 PSU and the plant works properly in the range of 40 to 44 PSU. Figure 14 indicates that in this project, recirculation problem is not an issue.

VII. Conclusions

In this paper salinity dispersion studies were performed by numerical modelling using MIKE21-FM and CORMIX II. Intake and outfall points are located in the depths of -12m.CD and -9m.CD respectively. These locations are selected based on environmental permission and water quality test results. Recirculation and environmental criteria have been checked for this intake and outfall system considering two different scenarios. These scenarios include two different situations; i.e. (1) considering the environmental criteria and (2) recirculation criteria. In this study, CORMIX II is executed to simulate near field characteristics of effluent dispersion. The model considers 3D turbulence effects in the mixing area. For the first scenario, salinity increment in the 22.5 meter distance of the outfall will be 4.07 PSU which is less than 10% of the primitive salinity (42 PSU) in 200 meter distance. Hence, the environmental criterion is thoroughly met. For the second scenario, salinity increment in the 45 meter distance of the outfall is 1.39 PSU.

The results of the near field model have been used as input data of far the far field model that is Mike21 FM. This model covers north of the Qeshm Island, aiming to check recirculation criteria and has been executed for one year duration. Results of this simulation have been extracted at the intake location and shows that there isn't any salinity increment trend at the intake location. Maximum and mean salinity increment at the intake location is about 0.2 PSU and 0.1 PSU respectively, which is acceptable since the plant works properly in the range of 40 to 44 PSU.

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