Indian Journal of Geo Marine Sciences
Vol. 48 (12), December 2019, pp. 1941-1948

Numerical simulation research on ecological protection device for marine water intake engineering based on cfd

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Received 11 May 2018; revised 24 July 2018

The ecological protection originated from marine engineering is the key factor for the healthy and sustainable development of marine ecological system. Combined with the tidal dynamic characteristics, a new optimistic ecological protection device concept model is designed for marine water intake engineering to avoid the ecological loss, which following the principles of safe, stable, easy installation and maintenance, unaffected water intake. Based on computational fluid dynamics (CFD), the three dimensional mathematical model of ecological protection device for marine water intake engineering is constructed to simulate and evaluate the feasibility of the proposed device. The flow field and pressure distribution are simulated and analyzed before and after the device installation. The numerical results of flow velocity in the intake, intake box and intake channel show that the ecological protection device has a weak effect on the flow field and the device can provide ecological safeguard for marine intake engineering. The pressure distribution from the ecological protection device would also reflect the underlying reason of the flow velocity change.

[**Keywords:** CFD; Ecological protection; Flow field; Intake; Pressure; Simulation]

Introduction

In seawater intake projects, offshore mushroom intake head is often employed, where seawater flows from the intake channel into the pump room. In particular, the general seawater intake pipeline includes intake head, intake flow channel, front pool, gate, trash rack, rotating filter and pump. These three facilities, namely, intake head grille, trash rack and rotating filter can desirably block suspended substances, aquatic plants and marine life. However,

the pump forefoot due to the relative large grid spacing of the water intake head. As a result, it becomes inconvenient to clean up the marine life. Although this will not introduce too much impact on the project, it is ecologically important to prevent fish, jellyfish and other marine life entering the pump forefoot from intake window and channel. Therefore, it is of significance research and practical value to develop ecological protection device, where loss of marine life resources can be desirably avoided.

From the beginning of net fishing, human have gained thousands of years of experience in fishing, preventing fish, driving away fish, guiding fish and other aspects. The idea of blocking pollution and preventing pollution in marine engineering is derived from those ideas. From initial trash rack, blocking gate[1], to the use of electricity[2,3], sound[4], light[5,6], gas[7-9], heat, odor and water flow biology[10-12], there are various ways to drive away the fish. In addition to the traditional way of driving away fish by using blocking gate, the rest of the seven types of approaches are new techniques, which can make full use of light, odor and water flow principle and characteristics of fish. Therefore, they are considered to be more scientific and potential to develop. However, many methods are still in the initial and preliminary stage so far, such as driving away fish with heat. For example, the previous research results for driving away fish with bubble curtain have shown that fish can adapt to the bubble curtain, where the efficiency of driving away fishing would be compromised[13,14]. There are a variety of marine life resources in the pump. It is often required to design specific parameters for different types of marine life in order to efficiently drive away fish by using light, electricity, sound, gas, heat or smell. However, there is no existing parameter setting criterion for reference. Meanwhile, these parameters would become ineffective due to the adaptability of marine and other marine organisms. In this paper, an anti-fish block is designed and developed outside the water intake head as an ecological protection approach, by combining the characteristics of the existing seawater intake projects. As a result, this method has a characteristic of economy and reliability compared to other methods. Meanwhile, a reasonably designed mesh distance can desirably intercept various marine lives, where complex characteristics investigation of biological diversity is not required to be carried out.

Computational fluid mechanics is based on theoretical fluid mechanics and computational mathematics. After years of development, a variety of software models have been successfully developed and widely applied in many fields such as port construction, water conservancy and hydropower engineering, aerospace, civil engineering and turbine design[15]. For example, a model to discharge wastewater into deep sea was established, where the influence of jet angle on the flow characteristics is investigated in their study[16]. Liu et al.[17] employed the fluent calculation software to simulate the hydrodynamic characteristics of the square artificial reef.

Based on computational fluid dynamics (CFD), a three-dimensional mathematical model is constructed for ecological protection device in marine water intake project. The flow field and pressure field before and after the ecological protection project of intake, intake box and intake channel are simulated and analyzed. By comparing the flow velocity before and after installing the device, scientific evaluation on the feasibility of the ecological device can be provided. These results can be used as a technical support for protecting ecological system.

The structure of the remainder of this paper is as follows. In section 2, the basic CFD model is introduced. The ecological protection device and its detailed structure are described in section 3. In section 4, the flow field and pressure field is simulated by the CFD model, the numerical results are analyzed by the cases of non-installation and installation of ecological protection device in section 4, and finally, the conclusions are presented in section 5.

Materials and Methods

Basic governing equations

The flow field characteristics are studied by using the computational fluid dynamics model[17,18]. The basic governing equations are as follows:

Continuity equation:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{u}) = 0 \qquad \ldots (1)$$

Momentum equation:

$$\frac{\partial(\rho u_i)}{\partial \mathrm{t}} + \frac{\partial(\rho u_i u_j)}{\partial x_j} = \rho f_i - \frac{\partial p}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_j} \qquad \ldots (2)$$

where, ρ is the fluid density. p is the pressure of fluid micelles. u_i, f_i, x_i is the velocity, body force of unit mass and coordinate of i direction. u_j, x_j is the velocity and coordinate of j direction. τ_{ij} is the surface viscous shear of fluid micelles.

Turbulent model

An Anisotropic algebraic stress model is applied to close the basic governing equation, as described below.

Turbulent kinetic energy equation:

$$\frac{\partial}{\partial x_j}[\rho v_j k - (\mu + \frac{\mu_t}{\sigma_k})\frac{\partial k}{\partial x_j}] = \rho(p_k - \varepsilon) \qquad \ldots (3)$$

Dissipation rate of turbulent kinetic energy equation:

$$\frac{\partial}{\partial x_j}[\rho v_j \varepsilon - (\mu + \frac{\mu_t}{\sigma_\varepsilon})\frac{\partial \varepsilon}{\partial x_j}] = \rho\frac{\varepsilon}{k}(C_{1\varepsilon}p_k - C_{2\varepsilon}\varepsilon) \qquad \ldots (4)$$

Where, μ_t is the vortex viscosity coefficient, $\mu_t = C_\mu \frac{k^2}{\varepsilon}$. p_k is the turbulent kinetic energy production term, $p_k = \frac{\mu}{\rho}(\frac{\partial v_i}{\partial v_j} + \frac{\partial v_j}{\partial v_i})\frac{\partial v_i}{\partial v_j}$. Empirical coefficient: $C_{1\varepsilon} = 1.44$, $C_{2\varepsilon} = 1.92$, $C_\mu = 0.09$, $\sigma_k = 1.0$, $\sigma_\varepsilon = 1.3$.

Boundary conditions and near wall treatment

The boundaries of the computational district are consist of inlet, outlet and wall. The basic wall function is used to simulate the boundary layers in this paper.

Inlet: $u = u_{in}$, $v_{in} = 0$, $w = w_{in} = 0$,

$k = k_{in} = 0.058(u_{in}^2 + v_{in}^2 + w_{in}^2)$,

$\varepsilon = \varepsilon_{in} = k_{in}^{3/2}/(0.4h)$, $c = c_{in}$.

Outlet: $w = 0$, $\frac{\partial}{\partial x}[u,k,\varepsilon,c] = 0$.

Free surface: rigid-lid hypothesis is used. $w = 0, \frac{\partial}{\partial z}[u,k,\varepsilon,c] = 0$.

Side: $\frac{\partial}{\partial y}[u,v,w,k,\varepsilon,c] = 0$.

Wall (Launder and Splanding (1974))[19]:

$u = v = w = 0$, $k = 0$, $\varepsilon = 0$, $\frac{\partial c}{\partial y} = 0$, $\frac{\partial c}{\partial z} = 0$.

Numerical method

In this paper, the finite volume method is used to discretize the three dimension Navier-Stokers equations. The Green-Gauss cell based method is applied to estimate the gradients[20]. SIMPLEC algorithm is used to solve the pressure and velocity with the coupling at the every time step[21]. The discrete momentum, turbulent kinetic energy and turbulent dissipation rate are formulated by the second order upwind scheme.

Conceptual Model of Structure for the Ecological Protection Device in Water Intake Project

Basic design principles for ecological protection device

For the sea water intake project, especially those completed project, the basic design principles of ecological protection device, such as safe and stable, convenient installation, no interference on water intake and easy maintenance, should be satisfied. It is also important to consider the tidal flow dynamics of the water intake project region. In particular, the structure of the device should be based on relevant research results[22,23], norms[24] and biological status quo, where the pressure of environmental dynamic can be reduced. In addition, the mesh size should be designed to prevent fish, jellyfish and other marine organisms from entering the pump house through the water intake window and water channel. Therefore, the loss of marine living resources can be avoided.

Overview of project area

In this study, the seawater intake project is located in the south coast of Caofeidian in Tangshan, which is 100 meters away from the south side of the seawall. More specifically, Caofeidian is located in the northeastern part of Hebei Province, which is 55 km southeast of Tangshan City, the north of Luannan, east of Laoting, west of Fengnan, south of Bohai Sea in Figure 1. The geographical coordinates of the island is latitude of 38°55'N, longitude of 118°30'E. The coastline is around 80 km and the sea area is about 2000 km^2. Originally, Caofeidian is a band shaped island in the south of Luannan County, where the area of the sand island is around 4 km^2 in climax and 20 km^2 with low tide. There exist a large area of shallow beach underwater between the sand island and the mainland coastline, where the depth can reach 25 m in the beginning 500 m and the depth can reach 36 m at deep groove[25]. In recent years, jellyfish and other marine organisms has significantly increased in

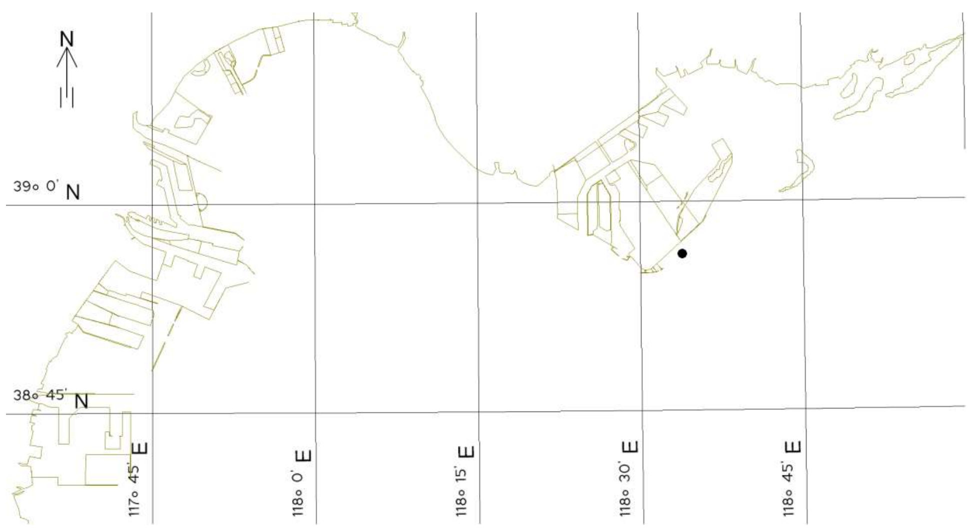

Fig.1 — Engineering location of Caofeidian, Tangshan in China (● engineering location)

coastal waters of Caofeidian[26]. Therefore, it is of significant research and practical value to investigate ecological protection device for seawater intake project, where loss of jellyfish, fish and other marine biological resources can be desirably avoided.

Structure of the ecological protection device

The conceptual model of structure for ecological protection device can be constructed by combining with structure size of the original water intake project, the natural conditions such as tidal flow in the project area and basic design principles for ecological protection device, which can be shown in Figure 2.

In Figure 2, geometric size diagram is given for the water intake and ecological protection device. In this figure, the original water intake diameter is 7.2 m, the distance between the water intake window and the water surface is 3.7 m, height of water window is 2.5 m, and a roof is used for the top. The piping is buried underground, where the center of the pipeline is 9 m from the top of the water intake. Based on the reciprocating flow characteristics of the tidal flow in the project area, the conceptual model for the structure of ecological protection device can be obtained as shown in blue ellipsoid of the figure.

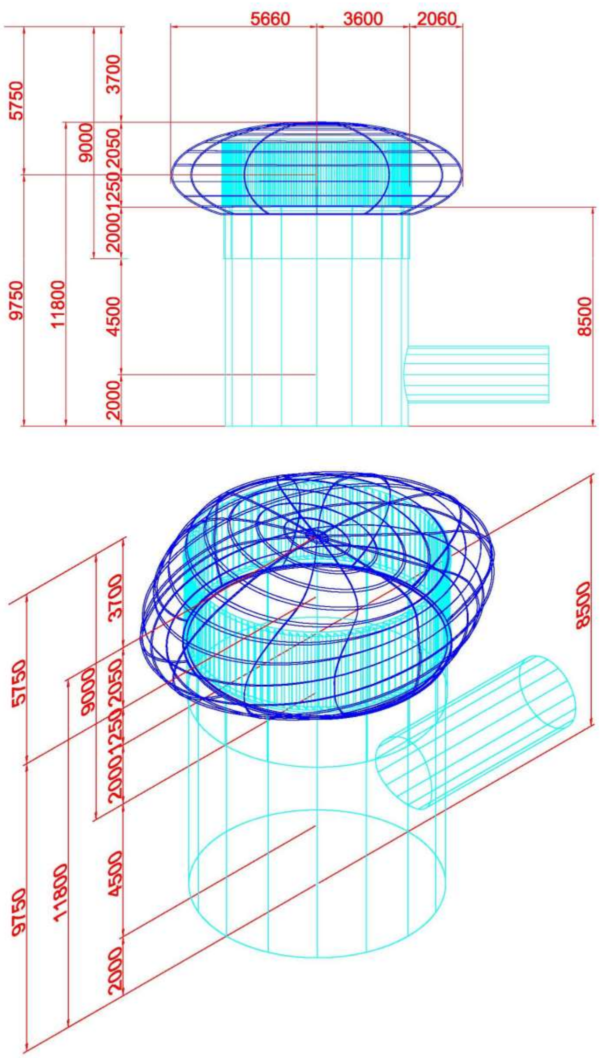

Fig. 2 — Geometry size diagram of intake and ecological protection device (Unit: mm)

Numerical Simulation of Computational Fluid Dynamics for Ecological Protection Device

The computational domain and division of grid

The ocean water intake project locates in a wide area, where an area of 70 m × 105 m centered on the water intake in Figure 3 is used for calculation and the influence of the boundary on the water intake is ignored. In particular, the computational domain is divided into grids as shown in Figure 4. To obtain the calculation with high accuracy, the local grid is refined as shown in Figure 5, where a total number of 6262906 grid cells are used.

Numerical simulation and comparative analysis before and after installing the ecological protection device

Assuming the flow velocity is 0.66 m/s and the flow flux is 6.67 m^3/s, the flow field before and after installing the ecological protection device can be calculated by using the computational fluid dynamics model, where the results are shown in Figure 6 to Figure 7.

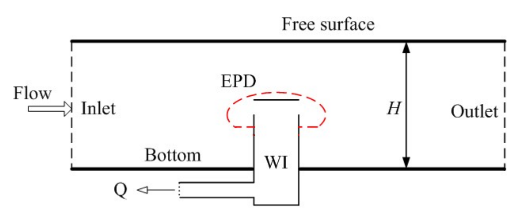

Fig. 3 — Diagram of computational domain (EPD: ecological protection device. WI: water intake)

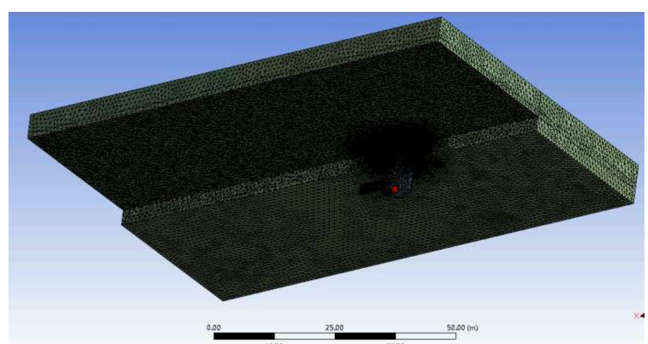

Fig. 4 — Diagram of the whole mesh generation

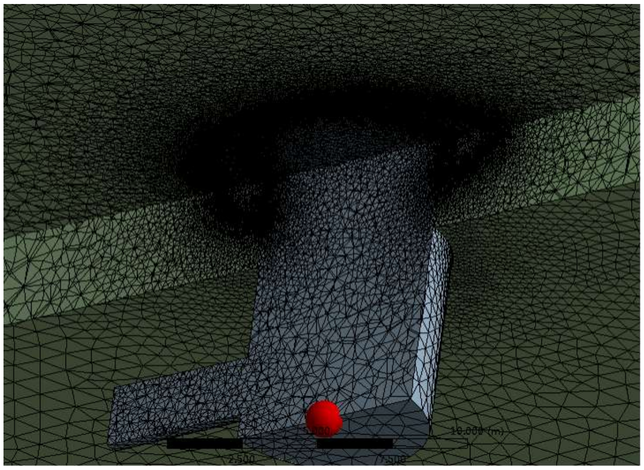

Fig. 5 — Diagram of local mesh generation

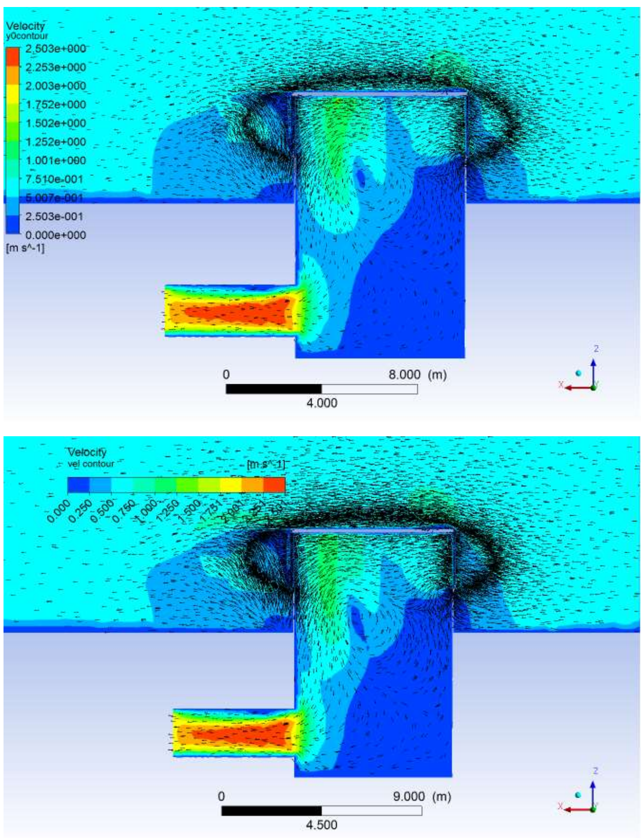

Fig. 6 — The whole flow field of intake region

From Figure 6 to Figure 9, the water flow field maps are presented, which are obtained from the whole water intake area, vertical window, horizontal and the bottom, respectively. It can be seen from Figure 6 that a recirculation zone vortex would be formed in the bottom when the water flows into the water intake. By comparing the flow field before and after the installation of ecological protection device,

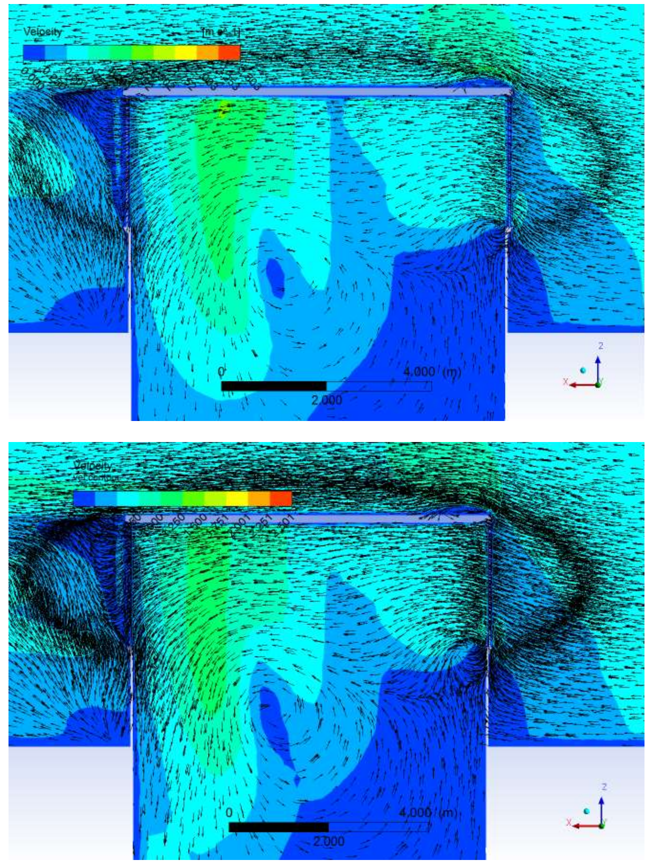

Fig. 7 — Local flow field of intake window in vertical

it can be seen that the flow velocity inside the water intake has increased. The reason is that the water inside of the intake window would spirally move down along the axis with increased speed, which indicates the vertical speed would increase as shown in Figure 7. In Figure 8, it shows the local flow field of the water in the horizontal plane of the water intake window. It can be seen from this figure that a horizontal vortex would be formed by the directing effects of the water intake window grid when the fluid enters the water intake window. By comparing the fluid fields before and after installing the protection device, the internal water flow distribution becomes more uniform after the installation, which is caused by the rectifying effects of ecological protection device. In Figure 9, the local flow field of the bottom of the water intake is shown. By comparing the flow fields before and after installing the ecological protection device, it can be seen that the overall flow does not change dramatically.

To compare the changes of velocity flow near the seawater intake before and after the installation of the ecological protection device, comparison points are

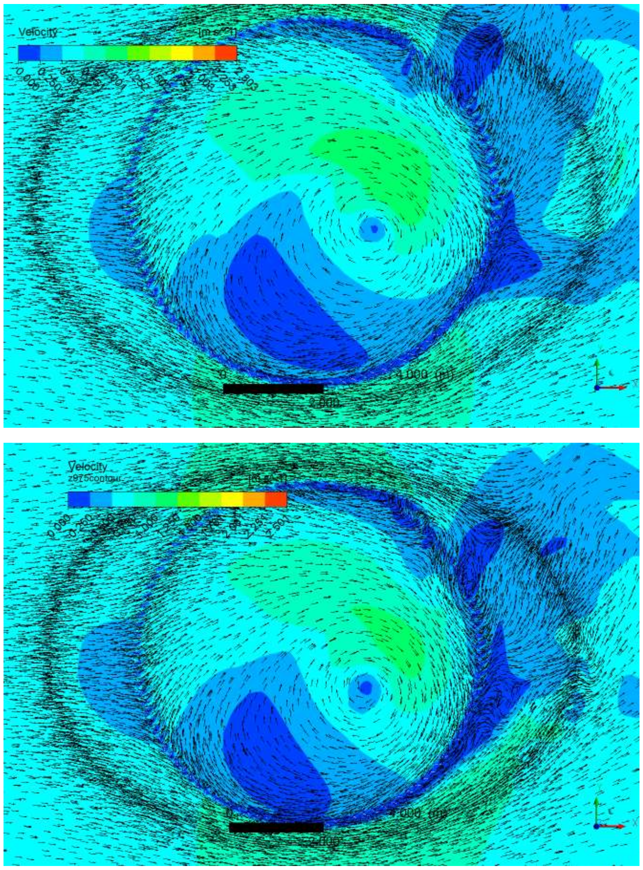

Fig. 8 — Local flow field of intake window in horizontal

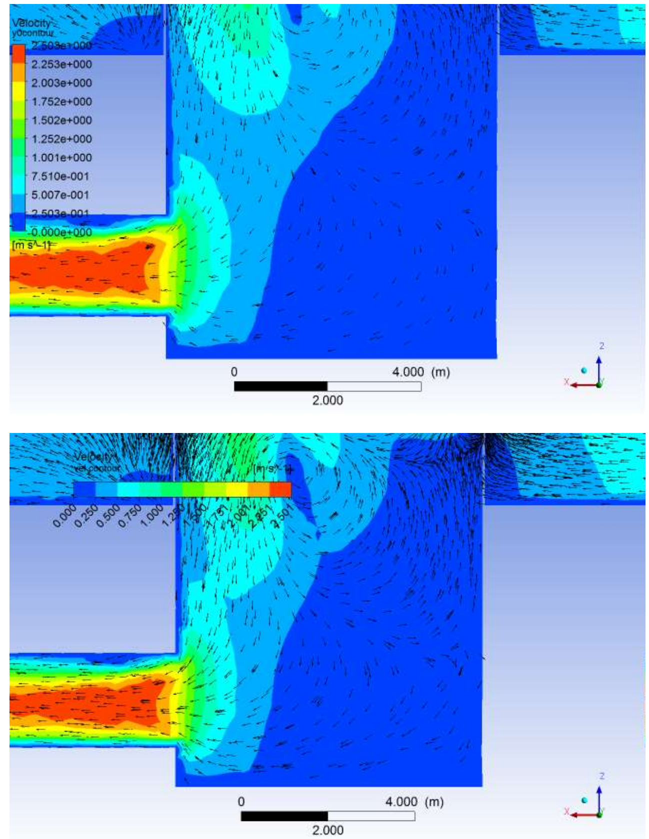

Fig. 9 — Flow field of the intake in the bottom

selected in the water intake area as shown in Figure 10. The comparison results are shown in Table 1.

In Table 1, the flow velocity before and after installation of ecological protection device are compared. It can be seen that the overall change of flow velocity is slight and the water flow velocity in the top of the device, inside the water intake window and inside the flow channel are slightly increased, while the water flow velocity in both front and back of the device are slightly decreased. The reason is that sedative effects on water would be caused by the ecological protection device. Moreover, the pressure distribution from the ecological protection device would also reflect the underlying reason of the flow velocity change, which can be shown in Figure 11 and Figure 12.

In Figure 11, local pressure field distribution map for horizontal section is presented. The central negative pressure is strengthening from the installation of ecological protection device.

In Figure 12, the pressure distribution map inside and outside the ecological protection device is presented. It can be seen from the figures that

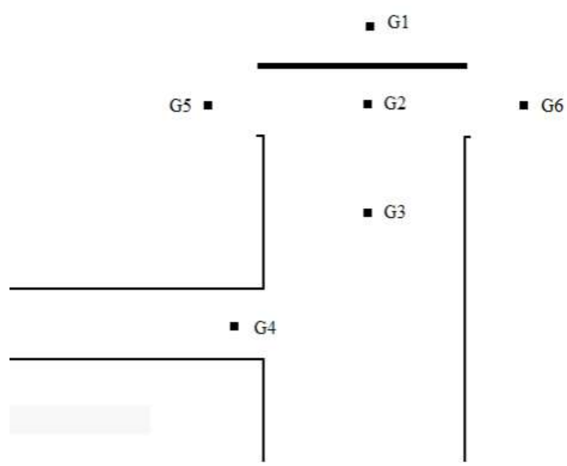

Fig. 10 — Contrast position of flow velocity

installation of the device would increase the static pressure in the head area, and result in pressure both sides of the device due to the pressure step near the device.

The central negative pressure is increasing, owing to the installation of the ecological protection device, which is same as the increase of flow velocity in position G1 and G2. The flow velocity increase of

Table 1 — Contrast of flow velocity before and after ecological protection device installation

Position	Non-installation (m/s)	Installation (m/s)	Change of flow velocity
G1	0.73	0.74	0.01
G2	0.52	0.59	0.07
G3	0.20	0.20	0.00
G4	2.46	2.48	0.02
G5	0.56	0.54	-0.02
G6	0.64	0.58	-0.06

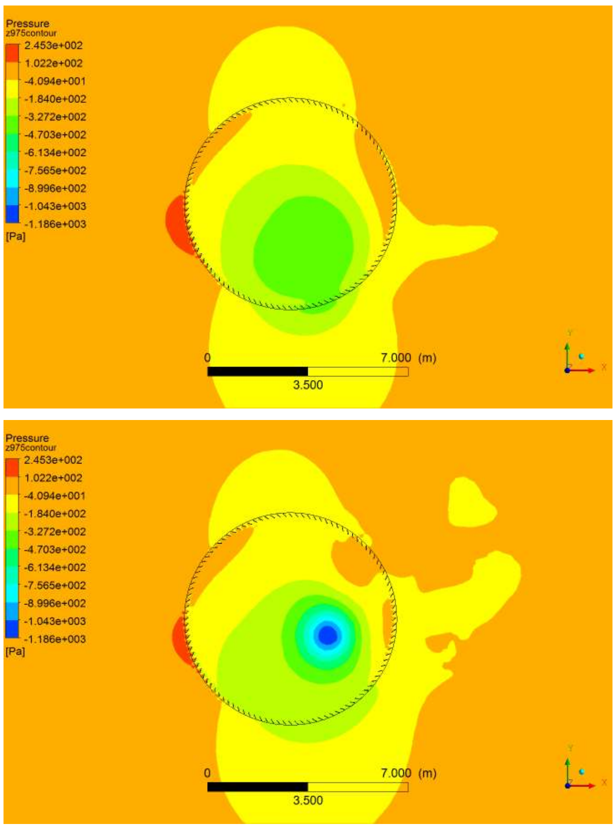

Fig. 11 — Local pressure field distribution map for horizontal section

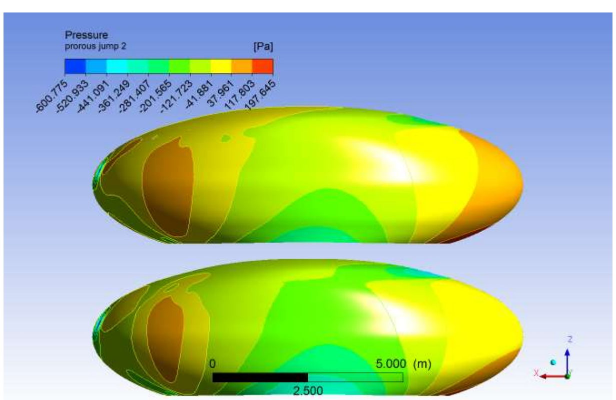

Fig. 12 — The pressure distribution map inside and outside the ecological protection device

local district around the ecological protection device has advantages of ensuring the engineering water intake and scouring the potential attachment.

Conclusion

In this paper, the conceptual model of ecological protection device for seawater intake facility is optimized through ellipsoid design to reduce the resistance, which can fully consider the flow characteristic near the region of water intake project and can also satisfy basic design principles such as safety, no interference on water intake tasks and easy maintenance. In particular, the three-dimensional mathematical model of ecological protection is established based on the CFD. The simulation results have shown the flow field of the water intake, the intake tank and the water intake channel before and after the installation of the device. By comparing the flow velocity before and after the installation of the device, it can be concluded that the influence of the ecological protection device on the water intake project is rather small which ensure the water flux for the intake engineering. The pressure distribution would also reflect the underlying reason of the flow velocity change.

Acknowledgement

This work was supported by the National Major Research Plan for Water Pollution Control and Treatment of China (2017ZX07107-004), the National Natural Science Foundation of China (No.51209110), the Research Foundation of State Key Laboratory of Coastal and Offshore Engineering Dalian University of Technology (LP1108) the project of Science and Technology for Development of Ocean in Tianjin (KJXH2011-17) and the National Nonprofit Institute Research Grants of TIWTE (TKS090204, TKS100217, TKS130215, TKS160227, TKS180401 and KJFZJJ2011-01).

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