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A Laboratory Study of a Square Water Intake Cap in Water Extraction from the Sea

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Abstract:
The importance of seawater desalination technology as a supplementary water source or even as the main water source for different countries is increasing. Deep water intake is one of the other methods of water extraction, which has attracted the attention of many researchers due to its various advantages, including the continuous supply of high-quality water from seawater. To reduce the environmental impact and preserve marine animals, a velocity cap is used at the head of the water intake. The common shape of the velocity cap is square. In this research, several physical tests have been done to investigate the effect of the location and height of the openings, the number of blades of the velocity cap, and the Froude number of the flow approaching the velocity cap on the hydraulic performance of the velocity cap. The results showed that by increasing the number of blades as well as increasing the free distance beneath the velocity cap, the discharge coefficient will be decreased. Additionally, increasing the height of the velocity cap will not have much effect on the inlet discharge. An equation was then proposed for the discharge coefficient of the square-shaped velocity caps.

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1. Introduction

With the growth of the population and settling in places far from the river and the need for water for purposes such as agriculture, drinking, and use in industry, people thought of moving and transferring water. In the past, the most common method of extracting water was that the sea water was taken by gravity through a large channel, sometimes with a screening and filter system, and directed to the factory. But now, the use of other methods has become common. Different types of water intake structures can be used according to the project's need. One of the new methods in this field is direct or open intake, which refers to structures that extract seawater directly from the surface or depth of the sea. These intakes are typically designed to draw in large volumes of seawater, making them suitable for high-capacity factories. These intakes are typically designed to extract large volumes of seawater, making them suitable for factories with high capacities. From a technological standpoint, seawater intake is categorized into two types: a) direct (surface) intakes and b) indirect (subsurface) intakes. In Figure 1, the general classification of water intake methods is presented [1].

In the case of deep water intake, the abundance of water resources allows for a more reliable water supply. In storm-prone coastal areas, this intake system mitigates sediment transport from winter storms. To protect the facility from ship impact, the culvert must be installed in an area deeper than the ship's draft [2]. Water intake occurs by guiding a pipe on the seabed, buried or unburied, to the desired depth with suitable water quality. Deep water intake structures typically include a velocity cap serving as an inlet structure (see Figure 2), one or multiple channels (intake pipelines or tunnels), a reservoir or well located on the shore, a debris collector, fine filters, and a pump station.

The shape of the velocity cap affects the flow pattern and the inlet discharge. Only a few studies have been conducted on seawater intake from this perspective. However, given the similarity of the subject, we can draw insights from existing studies that have addressed the hydraulics of flow in common intakes (such as numerous case studies related to river intakes, dams, and pump house intakes). In many hydraulic facilities, it is crucial to determine the flow structure when diverting water from a main channel to a side channel. In recent years, numerous researchers have conducted numerical and experimental studies on this topic. One significant study in this field is the 1993 laboratory

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research conducted by Neary and Odgaard. These two researchers conducted a laboratory study of flow hydraulics in 90-degree intakes. They performed experiments in a flume using a water circulation system. The flume was 18.3 meters long, 1.2 meters wide, and 0.6 meters deep, with a water intake channel that was 0.6 meters wide and 0.6 meters deep. Clearwater was used in the experiments. The main channel had both smooth and rough beds, and the researchers investigated the flow pattern, flow separation line, stillness area, and eddy formation area [3].

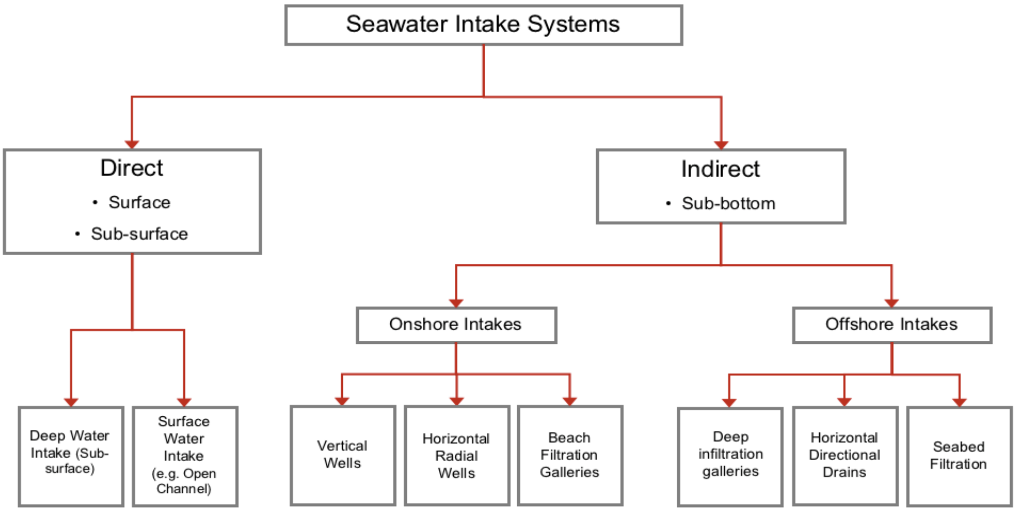


Figure 1. Division of seawater intake systems from the sea [1]

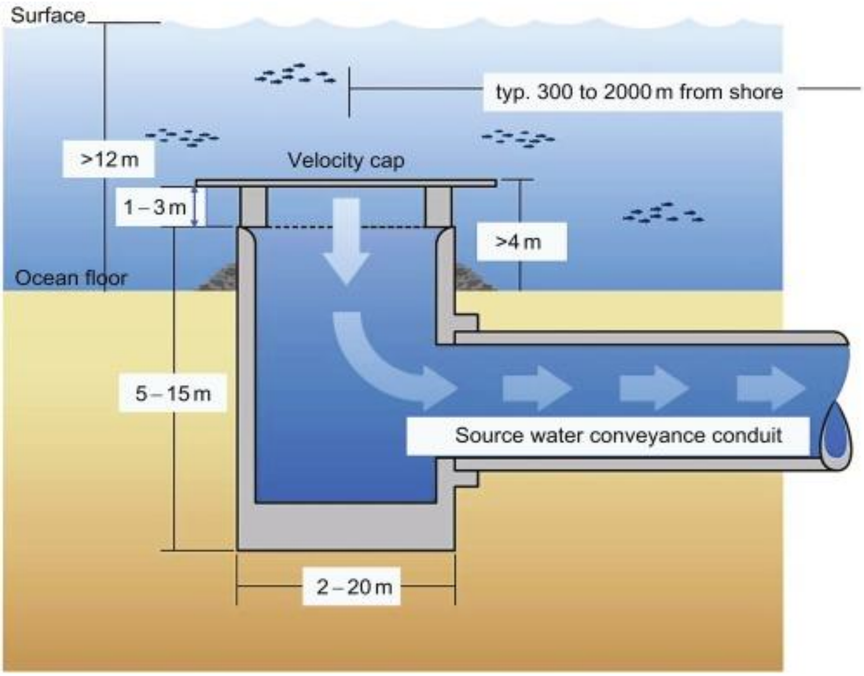


Figure 2. A view of the deep water intake of Bandar Abbas Power Plant [4]

Upon examination of the available sources, it becomes apparent that there has been a lack of extensive research on deep-water intakes within the country and across the globe. Hence, as previously mentioned, a comprehensive standard for the design and implementation of such structures has not been prepared yet. Consequently, only limited information about the structural, construction, hydraulic, and environmental performance of deep-water intakes designed and operated in previous projects has been published and is available from the sources. In 2004, Pankratz revolutionized desalination plants with the introduction of cutting-edge intake technologies. For efficient water extraction, he recommended implementing pre-treatment and filtration systems. These systems are designed to minimize the loss of both large marine organisms and small organisms like eggs and larvae. At the same time, they are capable of meeting the required standards for water quality and capacity [5]. Niazi et al. created a model of the Persian Gulf Star reservoir in Bandar Abbas City in 2012. They conducted a transient analysis using the limited volume method to predict the behavior of the reservoir flow and to assess the potential rise in water level in case of a power failure of the reservoir pumps. It was observed that the water level in the pond began rising at a steady speed of 0.006 m/s after the pump was disrupted by a power cut. Subsequently, after 887 seconds, the water level peaked at 14.8 meters. This outcome revealed that the catchment structure's height sufficiently accommodates all catchment conditions, rendering the maximum water level concerning the pond's edge non-critical [6]. In 2005, Voutchkov conducted a thorough investigation into the practicality of various direct and indirect water intake options for a water desalination plant situated in the coastal city of Huntington. The study involved a comprehensive cost analysis of water production in the desalination plant based on the type of catchment system employed. The results revealed that directional drain intake is a more cost-effective approach compared to other methods. However, it's important to note that this doesn't necessarily make it the optimal method for the desalination plant, as its intake capacity is significantly lower than that of direct intake [7]. In their 2013 studies, Toorang et al. set out to identify the most suitable seawater intake method for desalination plants located on low-sloping beaches. The case study, which focused on Bandar Abbas city, involved an evaluation and comparison of various intake options, considering technical, structural, environmental, and capital cost factors in line with the region's hydrographic and topographic conditions. Ultimately, the surface intake method through the breakwater emerged as the top choice, garnering higher scores [8]. In designing deep water intakes to prevent the entry of fish and large floating aquatic animals, the speed range at the mouth of the intake should be limited to 0.1 to 0.15 m/s [9]. In a 2020 study, Kumar et al. colleagues carried out a comprehensive laboratory investigation on the interaction of waves and structures at the Kisoni intake. The study meticulously examined the impacts of rising and falling waves, as well as fluctuations of the free water level, in both the presence and absence of a curtain wall [10].

In 2015, Naderi studied how sea tide-induced water level changes affect the water intake structure in Sirik City to design a system to supply the Sirik desalination plant. The study involved testing the suction structure and transmission lines of the Sirik aquifer model at Shahid Bahonar University, Kerman. Testing was conducted under various seawater levels and pipe configurations using a tide chart from the Persian Gulf. The optimal operational state was determined, and a predictive model for the loss of the suction structure based on the water intake system's flow rate was developed from the experiment data [11].

In the present research, the effect of the distance of the intake opening from the bottom of the channel, the height of the intake cap, and the number of blades of the square intake cap in the condition of water intake from the bottom of the tank have been investigated in the laboratory, and it has been tried according to the effect of different parameters on the intake of water by the pipe A suitable method for calculating the discharge coefficient should be provided. The current research is complementary to the previous works, and its purpose is to investigate the nature of the parameters affecting the flow coefficient passing through the square-shaped cap.

2. Experimental Setup and Procedures

The hydraulic analysis of the square velocity cap structure was conducted at the prestigious hydraulic laboratory of Tehran University. The laboratory model utilized a flume with specific dimensions (4m length, 0.4m width, and 0.5m height), as shown in Figure 3. To ensure accurate measurements, a sharp-crested rectangular weir was strategically placed at the end of the main channel to regulate flow depth and measure discharges. Furthermore, an ultrasonic flowmeter was employed to calibrate the weir and precisely measure discharge rates, complemented by a high-precision digital point gauge for measuring water levels and head over the weir crests. The collected experimental parameters in this study are summarized in Table 1.

Table 1. overview of the datasets used in the present study

Parameter	Unite	Range of data	
		Minimum	Maximum
Qin	m^3/s	0/0043	0/00552
d	mm	280	360
w	mm	120	160
h	mm	80	160
N		4	8
A	m^2	0/02	
shape		square	

Python was used to analyze and check the data. Additionally, the LIF image processing system has been used to check the flow pattern. In the LIF system, a continuous laser with an output power of 150 MW with a wavelength of 532 nm is used. Also, the camera used has a CMOS sensor and the ability to record pictures with a resolution of 800*600 pixels and a rate of 200 frames per second. In This study, the PIV lab software was used to process and analyze images. Moreover, the experimental data was analyzed using Python code.

3. Calculation of Discharge Coefficient

Aside from side-channel intake, several studies have been conducted on pipes and side-hole intake, as discussed in the study by Heshid et al. [12]. Hussain et al. have conducted studies on circular and rectangular lateral opening intake and provided relationships for the discharge coefficient. They have stated that the discharge coefficient depends on the value of the Froude number, the diameter of the orifice, and the width of the main channel. Finally, they presented Equation 1 for the discharge coefficient [13].

$$C_d = 0.678 - 0.072F_r - 0.130\frac{D}{B} \quad (1)$$

In this relation, Cd is the flow discharge coefficient, D is the diameter of the side opening, B is the width of the main channel, and Fr is the Froude number. Also, Rahmani et al. conducted numerical simulations of lateral pipe intake from an open channel. They examined various parameters affecting the side pipe intake and derived Equation 2 for side pipe intake [14].

$$C_D = 0.126 + 0.296 \times Fr - 0.259 \times \frac{L}{B} + 0.2 \times \theta \quad (2)$$

In this regard, the CD is the discharge coefficient, l is the amount of pipe depression in the main channel, b is the width of the main channel, θ is the angle of the intake pipe in the horizontal plane concerning the main channel, and fr is Froude the number.

There have been limited studies on water abstraction from the sea. However, similar case studies on water abstraction from rivers, dams, and pump houses can provide insight. Previous studies suggest that if we consider the side water intake pipe as a tube with a diameter of D in the wall of the main channel with a width of B (as shown in Figure 4), we can derive the following specifications.

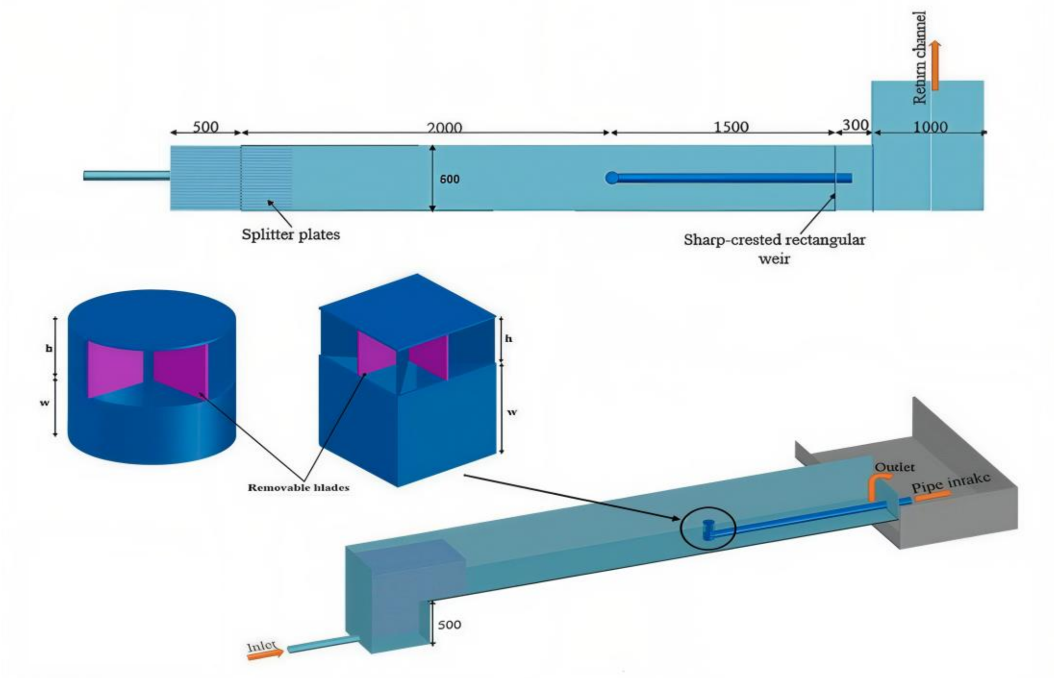
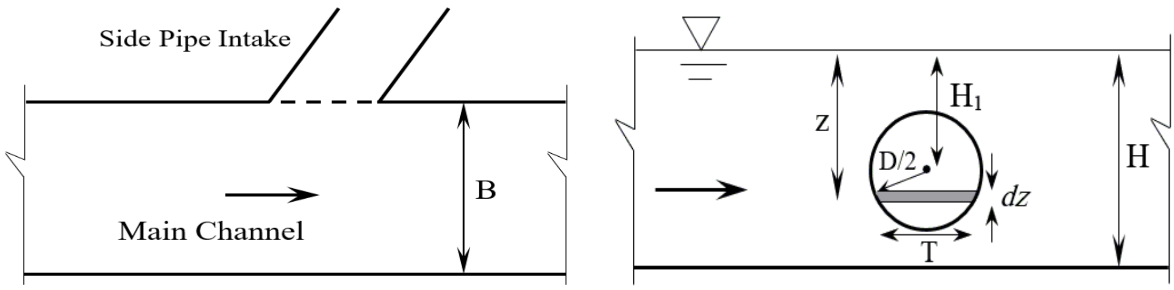


Figure 3. **Scheme of the experimental setup**



a) Plan of the main channel

b) side view of the channel and the side water intake pipe

Figure 4. **Side water intake pipe from an open channel**

According to the specifications presented in Figure 4, Equation 3 is obtained.

$$T = 2 \times \sqrt{(D/2)^2 - (z - H_1)^2} \quad (3)$$

$$dA = T.dz = 2 \times \sqrt{(D/2)^2 - (z - H_1)^2} \times dz \quad (4)$$

$$dQ_1 = V_P.dA = \sqrt{2gz} \times 2 \times \sqrt{(D/2)^2 - (z - H_1)^2} \times dz \quad (5)$$

$$Q_1 = 2 \times C_D \int_{H_1 - D/2}^{H_1 + D/2} \sqrt{2gz} \times \sqrt{(D/2)^2 - (z - H_1)^2} \times dz \quad (6)$$

By integrating equation 6, the following equation is obtained for the actual discharge from the side water intake pipe.

$$Q_1 = C_D \times \sqrt{2gH_1} \times \frac{\pi}{4} D^2 \quad (7)$$

4. Dimensional analysis for C_d

By reviewing previous research on lateral intake, it was found that the parameters affecting the discharge coefficient or C_d in lateral intake with a pipe from an open channel include the average velocity in the main channel upstream of the lateral intake(v), the flow depth entering the main channel(H), the width of the main channel(B), the distance from the bottom of the intake cap to the bottom of the main channel(w), the flow depth in the main channel(d), the height of the intake cap(h), the diameter of the intake cap(D), fluid viscosity(υ), water density(ρ), and gravitational acceleration(g). Therefore, according to Equation 8, we have:

$$C_D = f_1(V, h, B, W, d, D, \mu, \rho, g) \tag{8}$$

Using dimensional analysis, the following relationship is obtained:

$$C_D = f_2\left(\frac{h}{B}, \frac{W}{B}, \frac{d}{B}, \frac{D}{B}, \frac{V}{\sqrt{gB}}, \frac{\rho VB}{\mu}\right) \tag{9}$$

In this regard, $\frac{V}{\sqrt{gH}}$it indicates the Froude number (Fr) in the main channel upstream of the lateral intake. In open channels, the Reynolds number effect of the flow can be ignored and can be removed from the above relationship [13]. Therefore, the final relation of the dimensional analysis for the discharge coefficient of the pipe catchment from the open channel can be written as follows:

$$C_D = f_2\left(\frac{h}{B}, \frac{W}{B}, \frac{d}{B}, Fr\right) \tag{10}$$

5. Description of the Experimental Model

In 2014, Christensen studied the hydraulic performance of a velocity cap-type suction structure using a computational fluid dynamics model. They examined the flow at the inlet and inside the structure, comparing different conditions using dimensional analysis. A schematic representation of the computational geometry and the arrangement of the wall within the cap relative to the flow is shown in Figure 5 [15].

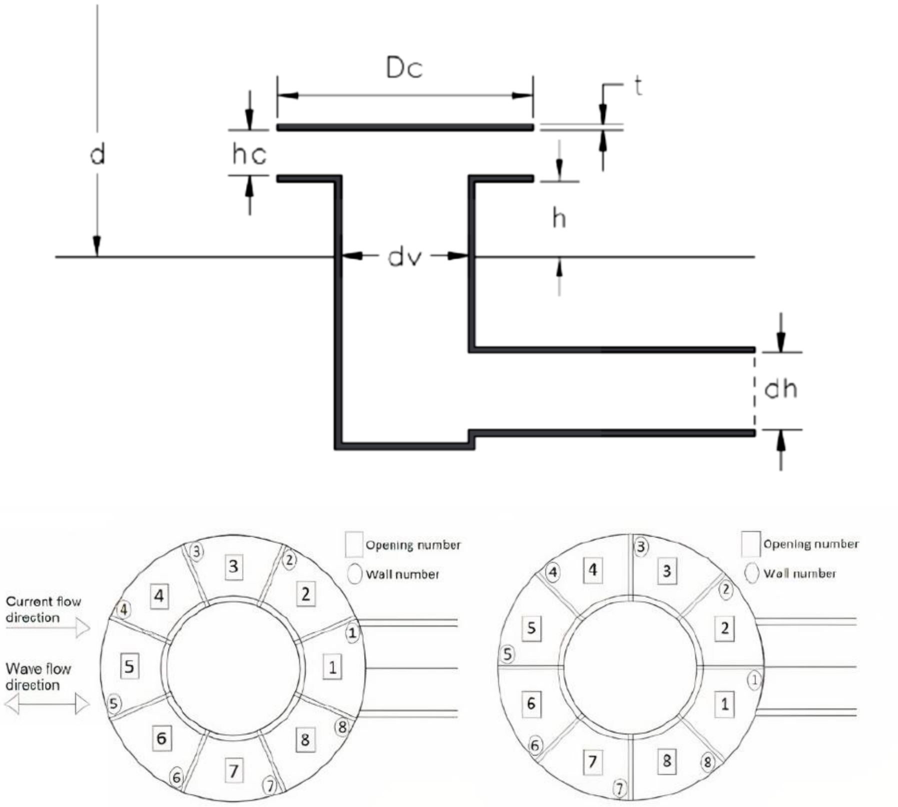


Figure 5. Computational geometry and the arrangement of the wall relative to the flow

By comparing the velocity contour curves for outlets 2 and 3, observations indicated that with an increase in the intake flow rate, the flow velocity in these two areas significantly decreases. As the approaching flow velocity increases, a flow with a velocity of approximately zero forms in front of it, specifically at outlet number 1. Figure 6 illustrates the flow pattern around the velocity cap. As shown in Figure 6, with an increase in the number of blades, the flow pattern around the cap improves, and the high-velocity area around it decreases. This reduction in the high-velocity area will greatly assist in preserving marine organisms, as the incoming flow strength will be reduced, allowing organisms to have a better chance of escaping entering the intake. It is worth noting that the flow pattern around the square-shaped velocity cap will be examined in detail in future studies.

6. Results and Discussion

The correlation coefficient is used to examine the statistical relationship between two variables. This number can indicate whether there is a significant relationship between the two variables. Python was utilized to analyze the correlation of data concerning flow rate. The correlation values of various parameters are shown in Figure 7. According to the figure, the approaching flow Froude number has the most positive impact on the discharge coefficient, while the distance from the cap to the bottom of the main channel has the most negative effect on the discharge coefficient. Additionally, based on the correlation data, as the approaching flow Froude number increases, the discharge coefficient from the intake also increases. This result aligns well with the findings of Rahmani et al. [14] and Hashid et al. [12]. As shown in the figure, the intake cap has little effect on the discharge coefficient, although it seems that if the height of the cap significantly decreases, it could have a noticeable impact on the discharge coefficient due to causing a severe drop at the entrance.

To examine the effect of the distance from the bottom of the cap to the bottom of the main channel, three distances of 80, 120, and 160 millimeters were evaluated (see Figure 8). The results showed that the closer the distance from the bottom, the greater the impact on the flow coefficient. Although it was expected that near the bottom, the bed effect would negatively influence the flow rate, it was found that in cases of lower heights, the head of water on the intake cap increases the discharge coefficient.

The presence of various blades on the intake cap improves flow behavior around the cap. To investigate the effect of the number of blades on the discharge coefficient, velocity caps with 4 and 8 blades were evaluated (see Figure 9).

Observations indicated that as the number of blades increased, the discharge coefficient of the velocity cap decreased.

7. Proposed relationship for discharge coefficient

Based on the flow rates calculated under various laboratory conditions, the following relationship can be proposed:

$$C_d = 0.1229 + 21.86\,Fr + 0.5489Ym\ (m) - 0.01758h\ (m) - 0.1958W\ (m) - 0.000567\,N \tag{12}$$

The coefficients calculated in numerical models and those predicted by the above relationship have been compared in Figure 10. This graph shows that the proposed relationship can predict Cd coefficients with reasonable accuracy. Considering the influence of various parameters on the discharge coefficient in intake structures with caps, this accuracy is acceptable, and future studies should also consider other parameters, such as velocity cap area.

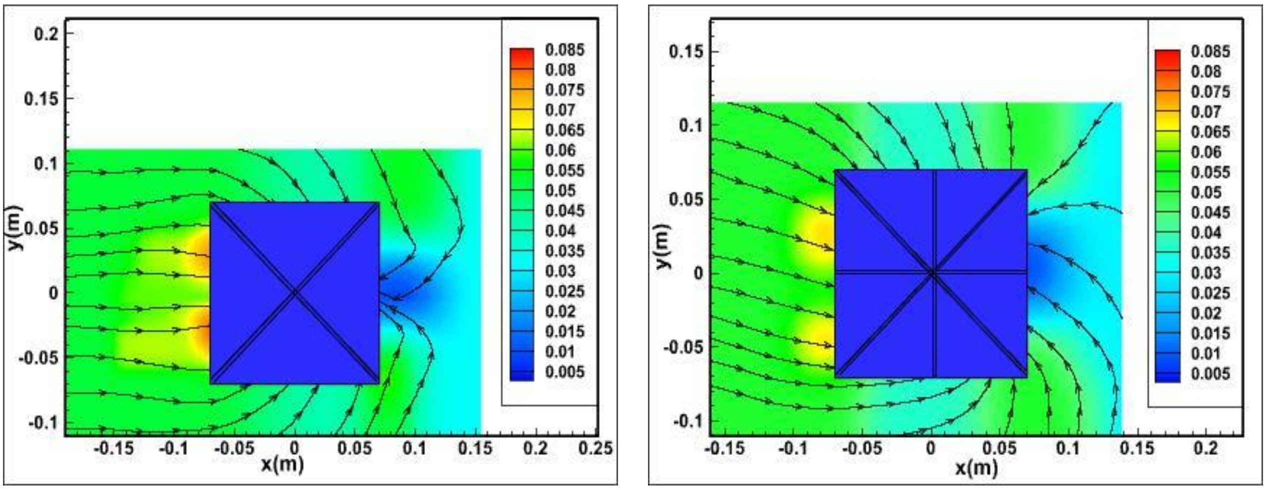


Figure 6. **The impact of the number of blades on the flow pattern around the velocity cap**

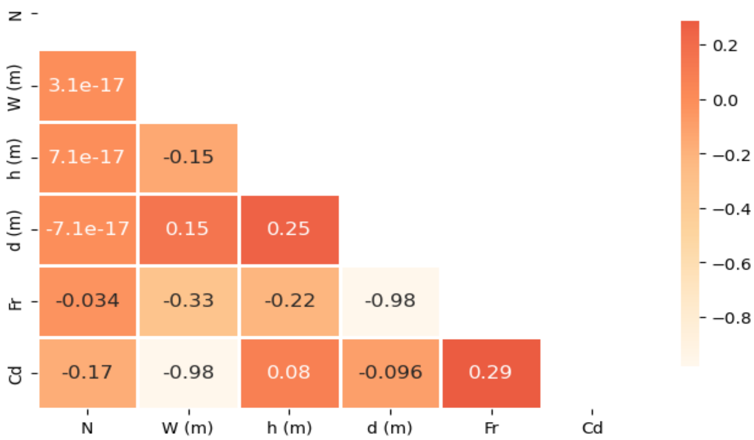


Figure 7. **Correlation of data concerning flow coefficient from the square velocity cap**

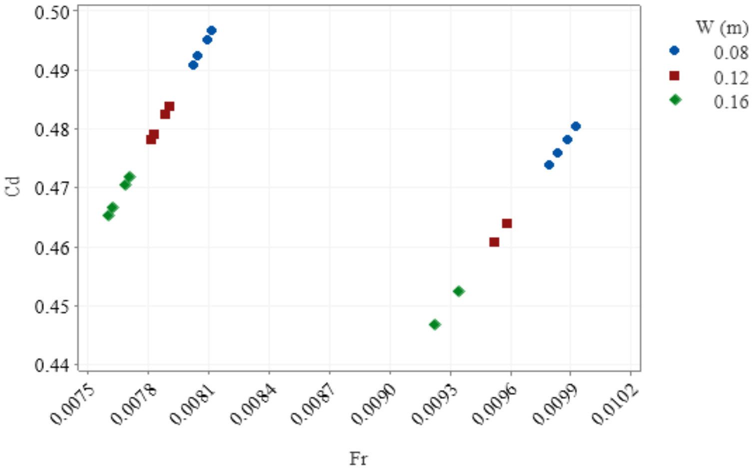


Figure 8. **The effect of the distance from the bottom of the cap to the channel bottom on the discharge coefficient**

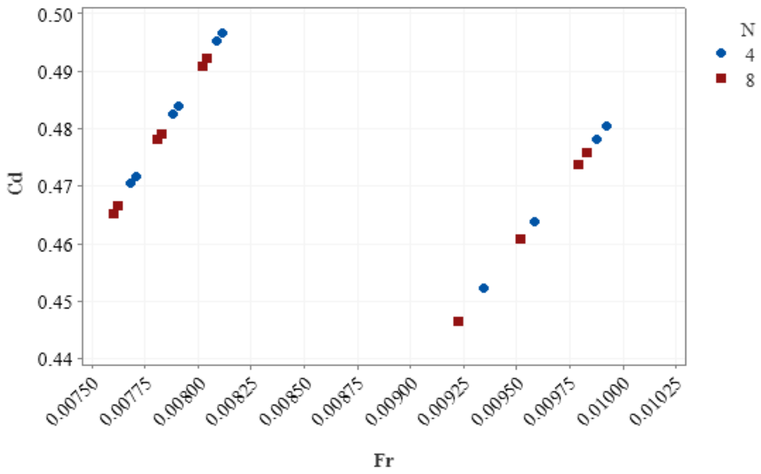


Figure 9. **The effect of the number of blades on the discharge coefficient**

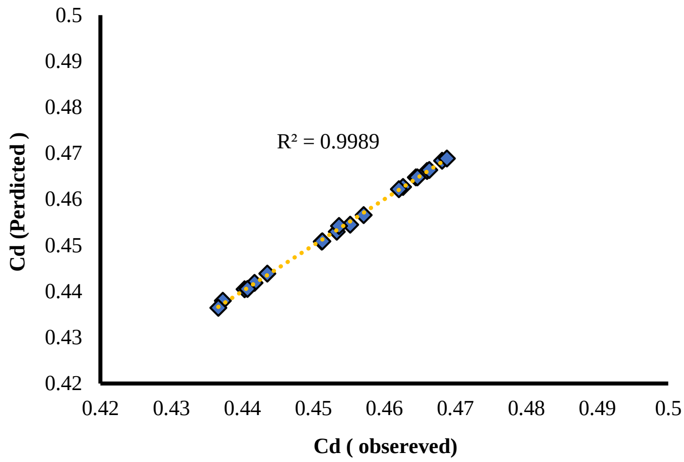


Figure 10. **Comparison of observed values and calculated values of coefficient Cd**

8. Conclusion

Velocity caps are one of the most important components of marine water intake systems. They change the flow pattern from vertical to horizontal, which helps increase the protection of marine life. They are also used to prevent the formation of surface vortices. The experimental research presented complements previous works, and it aims to investigate the nature of the parameters affecting the discharge coefficient of seawater.

Observations showed that the flow Froude number approaching the velocity cap has the most positive effect on the flow discharge coefficient, while the distance from the bottom of the velocity cap to the bottom of the main channel has the most negative impact on the flow discharge. This result is in complete agreement with the findings of

Rahmani et al. [14] and Hashid et al. [12]. Additionally, considering the correlation of the data, the height of the velocity cap has little effect on the flow discharge. The results indicated that the closer the distance to the bottom, the greater the impact on the discharge coefficient. Although it was expected that near the bottom, the bed would negatively affect the flow discharge, in lower height conditions, the water head over the velocity cap increases the discharge coefficient. Furthermore, observations revealed that as the number of blades increases, the discharge coefficient of the velocity cap decreases, although the presence of blades improves the flow pattern around the velocity cap. This research can serve as a fundamental study for future investigations. Future studies will examine the flow pattern around square-shaped velocity caps and investigate the effects of other parameters, including the area of the velocity cap.

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