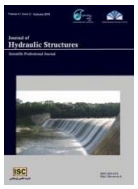
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Design of an Experimental Setup for Free Surface Vortex at Intakes (Including a Review on the Constructed Laboratory Models)

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Abstract

In this study, the laboratory design and construction including: hydraulic, structure and water circulation system of a model for free surface vortex studies at intakes are described in details. Design parameters are considered based on the intake diameter (D) and Froude number (Fr). In order to avoid the scale effects due to the effect of viscosity (υ) and surface tension (σ) in vortex modelling, most criteria are extracted and considered from the previous experimental studies. In structural design of the reservoir and other its components, both stability and construction costs were considered. In order to provide proper visual observation, lighting and imaging; as far as possible, the walls and floor of the reservoir were made of 10mm thick glass. The water circulation system including energy dissipater balls, separator wall, horizontal and vertical intake, butterfly valve, pipe, bend, multiple branch pipe, expansions and contractions, inverter, pump and electromotor, allows formation of vortices at different flow rates and depths and also can keep the water surface at a certain depth. Finally, by considering all design parameters, a rectangular tank with width of 1300mm, length of 2000mm and height of 1500mm was constructed.

Keywords: Free Surface Vortex, Experimental Model, Intake, Hydraulic and Structural design, Water Circulation System.

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Notations

D : intake diameter
Fr : intake Froude Number = $V/(gD)^{1/2}$
g : gravitational acceleration
N_Γ : circulation number =$\Gamma D/Q$
Q : intake discharge
Re : intake Reynolds number = VD/υ

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r : radial distance from surface vortex center
S : submergence of the intake centerline
S/D : relative submergence of the intake
We : intake Weber number $=\rho V^2 D/\sigma$
Γ : circulation of vortex in outer zone
θ : angle of the approach flow
ρ : density of water
σ : surface tension of water
υ : kinematic viscosity of water

1. Introduction

Free surface vortex formation at power intakes is an unpleasant phenomenon that can cause serious problems in the hydraulic systems such as air entrainment, vibration and the deterioration of pump or turbine performance [1,2]. Most investigations of the vortex have shown that the increasing vortex strength led to major negative effects on power generation. Vortices are generally divided into surface and subsurface vortices [1]. According to the studies of Sarkardeh et al., vortices are divided into three categories in terms of risk [3]. Class C is considered safe and weak rotations of flow may be observed in this class. Class B, the rotation of the flow extends down to the intake itself and debris is dragged into the intake. Class A, the strongest vortices, which should be avoided, are included in this category. In this class, air bubbles are trapped and conveyed down from the water surface to the intake. In the strongest state, a stable air core is formed in the center of the vortex and air is steadily entrained into the intake (Figure 1) [3].

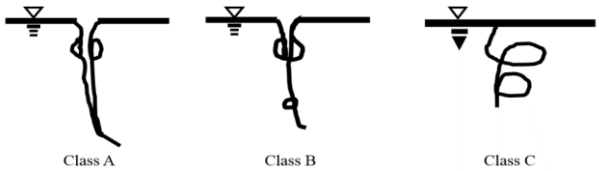


Figure 1. Classification of vortices based on their strength [3]

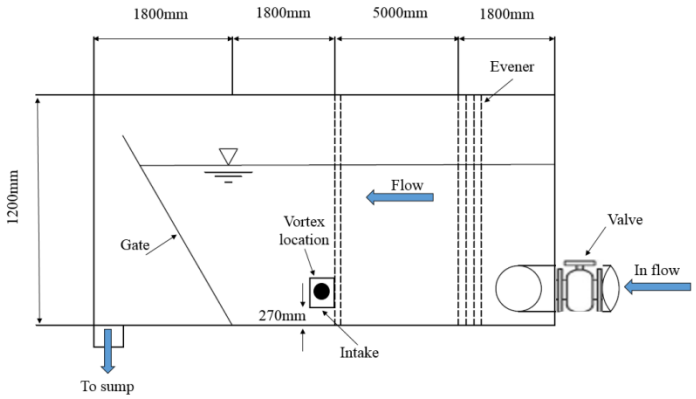
Generally, intakes can be arranged horizontally and vertically. Horizontal intakes are used for river power plants, flood protection structures, and intakes of water supply systems. Vertical intakes are most often used at pump sumps.

One of the most important factors in the formation of the vortex is the asymmetric flow approach to the reservoir [1,4-6] to prevent the strengthening of the vortex phenomenon. Many aspects of forming vortices at intake were discovered using physical models [7-10]. Sarkardeh et al. employed an experimental model to examine the effect of geometric and hydraulic conditions on the strength of free surface vortex in a horizontal intake as well [3,11]. Since the air-core vortex causes reduction in the efficiency of the intake operation, it should be prevented [12-15]. In addition, in shallow basins and low-head intakes, increasing the vortex strength causes increasing the amount of sediment transport into the intake structure [16]. Many studies have been carried out to understand the nature of vortices and the factors affecting their formation. Most published researches are concerned with predicting the critical submergence [3,17-18]. Sarkardeh and Marosi analyzed the free surface vortex formation at intakes analytically [19]. Pakdel et al. investigated the effect of waves on formed vortices in vertical intakes [20]. Wang et al.

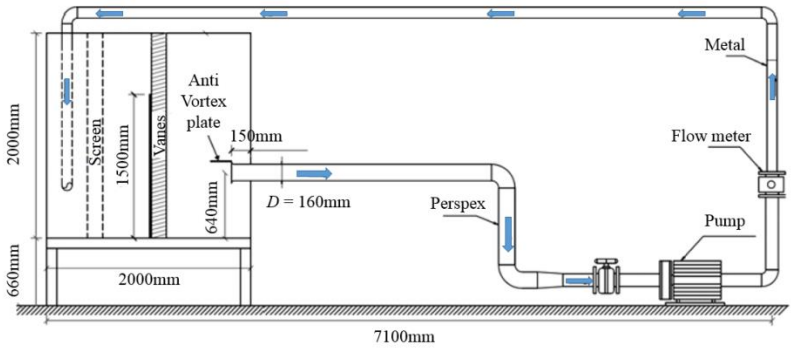
investigated the hydrodynamic properties of the free surface vortices [21]. Aghajani et al. studied the effect of trashrack at entrance of intakes on the formed vortices using an experimental model [22]. Mulligan et al. studied strong free-surface vortices in subcritical flow and concluded that the circulation in this stream was influenced by the approach flow geometry [23]. Amiri et al. also studied vortex prevention, which mainly focuses on using various anti-vortex plates [24]. Camnasio et al. experimentally studied the velocity fields in rectangular shallow reservoirs by ultrasound profiling to evaluate the effect of geometry on the flow fields [25]. Suerich-Gulick et al. presented a model to estimate the key characteristics of free surface vortices at intakes [26, 27]. Monshizadeh et al. compared the structural and hydraulic methods to eliminate the formed vortices at intakes using a laboratory model [28].

Several researchers have introduced various experimental models for vortex study. Anwar et al. made a model with 170*D* length, 12*D* width and 12*D* height. *D* at their study was 76.2mm. Reynolds (*Re*) = 3×10^4, Weber *(We*) = 4×10^3. The distance from the intake to the wall of the flume was 4*D* and the width and depth of the reservoir was more than 12*D* [4]. Hite and Mih's experiments were conducted in an open-water flume with 69*D* long, 8*D* wide and 8*D* deep. The inlet of the intake is located in the side wall, so that the flow must pass through a 90 degree angle to enter. In this study, *D* was 150mm, *We* = 5850 and *Re* = 2.4×10^5. The sidewall of the flume and the closed conduit were made of clear plastic for visual observation. A weir was located at the end of the open return channel for discharge measurements. A diffuser and a flow evener provided uniform approach flow to the test section (Figure 2a) [29]. Constantinescu and Patel built a physical model with *D* = 200mm, a width of 2.6*D* and a depth of 2.75*D* [30]. Hashemi Marghzar et al. Examined the formation of a vortex by constructing a physical model 72*D* long, 6*D* wide and a circular horizontal intake with *D* = 50 mm. In the physical model, the distance from the side wall to the intake is 2.5*D* and the distance from the bottom of the reservoir to the edge of the intake is 1*D*. This model was designed symmetrically to prevent rotation of the current in the channel. For a better visual view, the rectangular channel is made of Plexiglas and the thickness of the walls is 6mm everywhere [31]. Amiri et al. made an experimental model with *D* = 160mm, tank width 8*D*, tank length 12.5*D* and the distance between the side walls and the bed floor to the axis of the intake 4*D* (Figure 2b). In this research, *We* = 1200 and *Re* = 1.2×10^5. Modeling was based on *Fr*. To view the vortices, the tank walls were made of glass and the intake pipe and tunnel were made of Plexiglas. The flow in the tank is calmed as much as possible by the screen and then enters the test range. The intake in the model was horizontal type embedded in the tank. Intake discharge was measured by an electromagnetic flowmeter installed in the closed pipe system. Water surface elevation was measured by reading the scale marked on the reservoir wall and vane angle was measured with a protractor [19]. The experimental model of Moller et al. consists of three main parts: 50m^3 experimental steel tank, 36*D* long pressurized-pipe system, and 130m^3 underground reservoir. In this model *D* = 389mm, tank width 4*D*, intake axis distance to tank bottom 1*D*. The stilling basin was design to promote a uniform velocity distribution in the main tank. In the stilling basin the end fittings of the feeding pipes were perforated to diffuse the incoming jet, homogeneously. The flow was guided through a vertically arranged filter fleece to the main tank. Visual access to the tank was secured by three glass windows at the bottom wall, the right wall, and the head wall. A dimensional analysis conducted by Moller et al. showed that, *Re* with *v*, and *We* with σ, are decisive parameters for scaling the laboratory model. These findings are in line with the Tastsan and Yildirim as well as Suerich-Gulick et al. [32, 33, 34]. Parvaresh and Ghiassi constructed a physical model of Plexiglas with a thickness of 10mm. This tank consists of 44*D* in length, depth 16*D* and *D* = 43mm. In this study; the distance from the intake axis to the bottom of the tank was considered equivalent to 8*D* with 344mm flow laminator perforated plates. Also, the

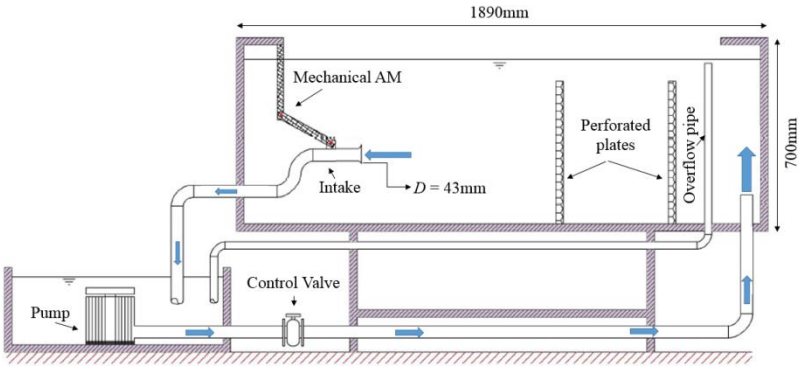
values of $Re = 8.2\times10^4$ and $We = 220$ were used. Two perforated plates are used to smooth the flow. A steel mechanical system is applied to set the angle and height of the intake (Figure 2c) [35]. Sun and Liu experiments were conducted in a cylindrical Perspex tank. D was 19mm, the diameter of the tank was 55D and its height was 24D. The flow exits the tank through a vertical intake at the bottom of the tank. To avoid perturbing the flow field, a Particle Image Velocimetry (PIV) system was used to measure the velocity distribution of the free surface vortex [36]. Laboratory model of Khanarmuei et al. with a dual intake with D = 130mm, a tank with a length of 15D, a width 15D and a height 9D. In this model, the distance from the intake axis to the bottom of the reservoir was more than 4D and the distance from the middle wall to the center of the intake was more than 6D. In this research, We = 800 and $Re = 1.46\times10^5$ are considered [37]. Naderi and Gaskin laboratory model consists of a re-circulating water channel with glass walls, Plexiglas floor and more than 52D long, wide more than 10D with D = 94mm (Figure 2d). The intake distance in this model was 3D from the left plate and 5D from the right wall of the tank. This model used a vertical intake that directed the water leaving the tank to a pump. The water calms down when it hit the energy dissipation plates and enters the test area [2].



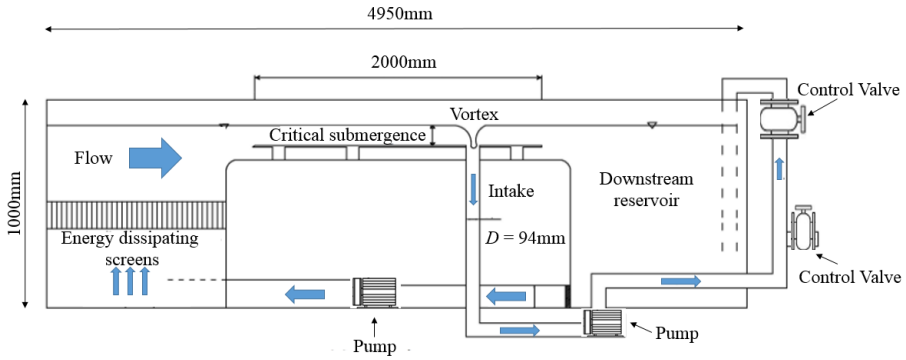
a. Physical model of Hite and Mih [29]



b. Physical model of Amiri et al. [24]



c. Physical model of Parvaresh and Ghiassi [35]



d. Physical model of Naderi and Gaskin [2]

Figure 2. Schematic of physical models [2,24,29,35]

Despite the previous studies, present research in three different sections, including hydraulic design, structural design and water circulation system design, expresses the details of designing an experimental model to study the free surface vortices in horizontal and vertical intakes. Results are presented by considering both technical and economical criteria in designing a laboratory model.

2. Design of the Laboratory Model

2.1. Hydraulic Design

In hydraulic design of a laboratory model for free surface vortex study, researchers have agreed to consider the *Fr* as the base for scaling, and *We* and *Re* should be minimized [3,4,11,14,17]. For better observation of the experimental domain, researchers used glass and Plexiglas to build the model. Also, to measure the flow and water level in the model, a flow meter and a scaled marker should be installed in the model [14]. To prevent the formation of Non-uniform flow, it is suggested that the model be designed, symmetrically [12]. In order to the laminar flow of water to enter the test area, the proximity channel must be long enough. Screens, filter fleece and diffusers can be used to calm the inlet flow to the test area [3,12,13,17,29]. The design of the reservoir and its components is based on the *D* [2,3,4,12-14,17,18]. To reduce the effect of reservoir walls, the proposed width of the reservoir is 8*D* and the minimum distance from the intake axis to the bottom of the channel is 4*D*. Table 1 shows the geometric and hydraulic characteristics of vortex models made by different researchers. Owing to the safety in the design, *Re* and *We* should be considered $Re \geq 1.1\times10^5$ and $We \geq 720$.

Table 1. Geometric and hydraulic characteristics of vortex models made by different researchers

Flume type	Components	*We*	*Re*	*S (mm)*	Width (mm)	Length (mm)	*D (mm)*	Laboratory Model
-	10 guide vanes	4×10^3	3×10^4	920	920	13000	76.2	Anwar et al. [4]
-	Diffuser and a flow evener	5850	2.4×10^5	1200	1200	10400	150	Hite and Mih [29]
-	-	120 - 1000	3×10^4	550	520	1480	200	Constantinescu and Patel [30]
Plexiglass	straightening device from compacted materials	-	-	115-250	300	3600	50	Marghzar et al. [31]
Plexiglass	Vanes and screen	1200	1.2×10^5	2000	1300	2000	160	Amiri et al. [24]
Glass channel	filter fleece	3.2×10^3	6×10^5	2200	1600	5000	389	Möller et al. [32]
Plexiglass	perforated plates and steel mechanical system	220	8.2×10^4	700	–	1890	43	Parvaresh and Ghiassi [35]
Plexiglass	-	-	-	450	–	520 radius	19	Sun and Liu [36]
Plexiglass	-	800	1.46×10^5	1200	2000	2000	130	Khanarmuei et al. [37]
Plexiglass and Glass channel	dissipation plates	-	-	-	1000	4950	94	Naderi and Gaskin [2]

Parameters affecting the vortex circulation can be written as [1]:

$$f\ (\Gamma, \theta, S, V, D, g, \rho, \nu, \sigma) = 0 \quad (1)$$

where θ is angle of the approach flow, S is the submergence of the intake, g is the gravitational acceleration, ρ is the water density, ν the kinematic viscosity of water and σ the surface tension of water. Dimensional analysis of the parameters in Equation 2 yields [1,3-5,18]:

$$N_\Gamma = f(Fr, Re, W, S/D, \theta) \quad (2)$$

where $N_\Gamma = \Gamma D/Q$ is the circulation number, S/D is relative submergence of the intake, $Re = VD/\nu$ and $We = \rho V^2 D/\sigma$. If Re and We are high enough, their effects can be neglected and therefore Equation 3 can be rewritten as:

$$N_\Gamma = f(Fr, S/D, \theta) \quad (3)$$

As can be seen from the Equation 3, N_Γ affected by changing flow rate, intake submergence and approach flow angle.

2.2. Structural Design

The designed model consists of a rectangular reservoir that has a width of 1300mm, length of 2000mm and height of 1500mm, and two horizontal and vertical intakes with a diameter of 152mm. The reservoir has a capacity of about 4m^3 of water. Distance of the horizontal intake to the bottom clearance is 650mm (more than 4D) and the maximum water level in the reservoir is 850mm (more than 5D). Therefore, the critical submergence is seen to be uninfluenced. Also, the distance of the vertical intake to the side walls is 650mm (more than 4D). In this model; the columns of the reservoir are located on six base plates with dimensions of 350×330mm and transfer the load on the columns to the ground. Columns of 80×40mm box type are responsible for transferring the reservoir loads. Moreover, horizontal beams were installed with 80×40mm box type. In order to provide proper visual visibility, 10mm thick glass was used in the walls and floor of the reservoir (Figure 3). Using glass as the wall in laboratory models are usual and many researchers employed it [2,3,12-14,17,18] as well as Vaghefi and Akbari which constructed a hydraulic model with glass walls while supported by steel frames [38]. For distribution of the loads, the glass is divided into small dimensions and placed into the frames of the metal structure. Using ETABS software, the material properties such as grade of steel = ST-37, modulus of elasticity = 2×10^5N/mm^2 and density of steel = 7.86 kg/m^3 were defined initially and then the structural behavior of the model under the designed loads were analyzed. The pressure prism method is used to calculate the applied load to the reservoir walls and the applied hydrostatic force method. The load applied on the walls is non-uniformly hydrostatic. To calculate the water force at the bottom of the reservoir, the weight force of the water column is calculated and a load of 1500 Kg/m^2 was applied uniformly at the bottom of the reservoir. In the Slab Properties, a new glass floor was introduced. Also, due to the lack of knowledge of glass material in ETABS, a new material with an elasticity modulus of 70000 Mpa and a density of 2500 Kg/m^3 were defined. In all designs, in addition to apply a reliability coefficient of 1.4, a full reservoir was provided for greater reliability.

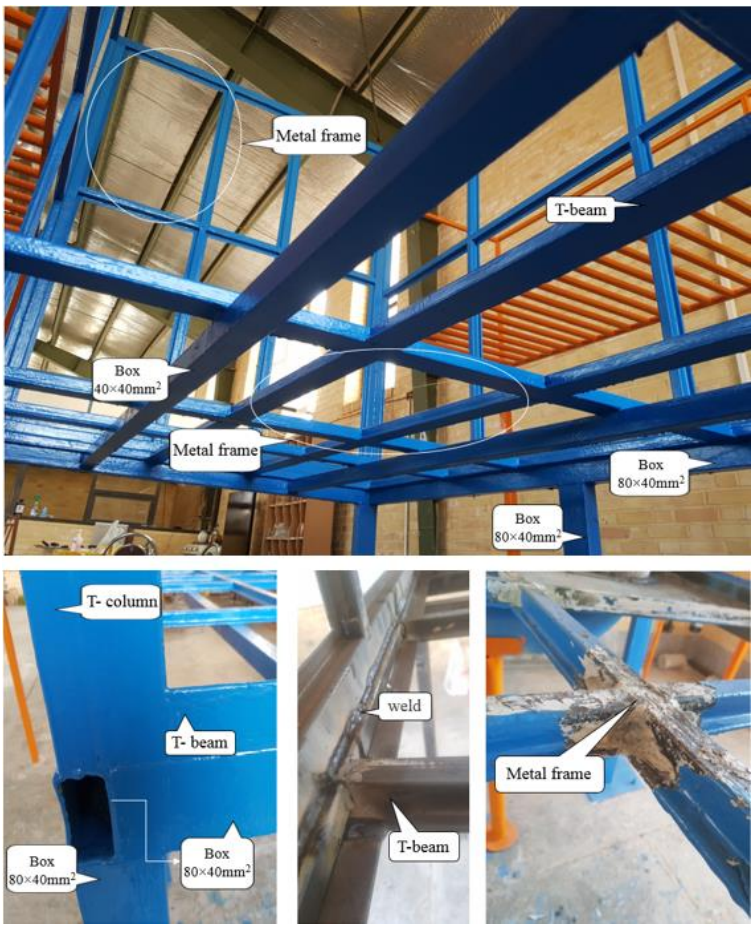


Figure 3. Details of construction

Results according to the Figure 4 show that all elements have the desired capacity to withstand the load of the reservoir.



Figure 4. Structure of the designed model

Figure 5a shows the model moment diagram and the access way to the reservoir for measuring

and image recording and installation of the instruments (Figure 5b). A stair way with a height of 1700 mm and a width of 700 mm were constructed around the reservoir.

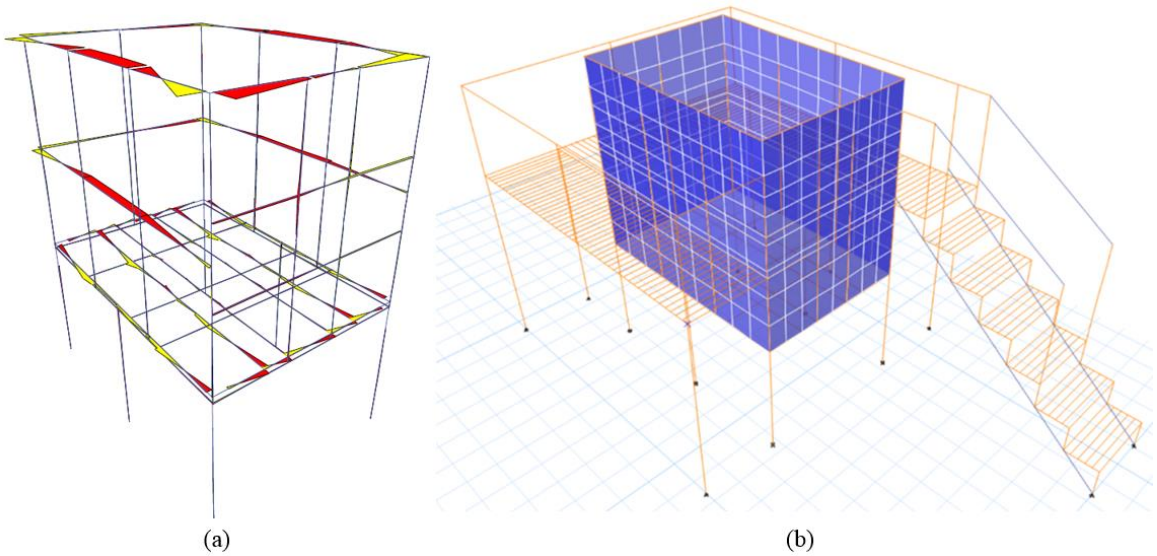


Figure 5. Moment diagram (a) and stair way (b)

As can be seen in Figure 5b, full access to all parts of the reservoir is provided by the constructed stairs. Figure 6 shows the constructed structure of the reservoir and stairs.



Figure 6. Physical model structure

2.3. Water Circulation System

The designed model must be able to form free surface vortices in three different classes. Aquarium glue was used for sealing the reservoir. On all pipe junctions, the flange was installed with a seal weld to allow the connection of additional parts in further (Figure 7a). The outer diameter of the flanges is 270mm and the inner diameter is 152mm. The total number of flanges

used in the water circulation system and inside the reservoir was 152. Also, in order to supply the closed flow cycle, a pipe with a diameter of 152 mm enters the flow to the calming section at the end of the reservoir and returns the water from the pump to the reservoir (Figure 7b). The total length of the used pipes was about 21300 mm.



(a) (b)

Figure 7. Flange connected to pipes (a) and inlet pipe to the reservoir (b)

As mentioned before, the flow with different *Fr* should be able to develop with a constant submerged depth in the reservoir. This condition is not possible in the state of flow under gravitational forces. To solve this problem in the model, the pump must be connected directly to the intake pipe and the reservoir and the speed can be adjusted independently of the water depth of the reservoir so that a constant amount of water was always circulating in the system. The purpose of building a laboratory model is to study and test different hydraulic and geometry scenarios. Therefore, a wide range of *Fr* can be produced and investigated with a suitable pump. The average roughness of the pipes is ε = 0.15mm [39]. As a result, the value of friction coefficient f = 0.0225 is obtained [39]. Therefore by considering both parameters of efficiency and economical, the pump with 5.4 horsepower was selected. In addition to the drop in fluid friction energy, in some places, the flow velocity changes suddenly in quantity and direction. This change in speed can be caused by expansion or contraction of the cross-section, the presence of bends, valves or other connections. For accurately calculating the energy loss of the physical model, it is necessary that the longitudinal and local energy losses in the joints be calculated. According to the calculations, the total energy loss in two pipe paths is less than the head that can be supplied by the selected pump with a flow rate of 50 lit/sec according to the pump specification (Table 2).

Table 2. Pump specifications

RPM 1450	Capacity (m^3/h)					Imp. Dia. (mm)	Pump Flange (mm)		Motor Characteristics			Pipe Dia. (Inch)	
	70	100	130	160	190		Inlet	outlet	Power / A kW	HP	I / Amp	Inlet	outlet
Head (m)	8	7.5	6.8	5.8	4.4	169	125	100	4	5.5	9.15	B	C
	7.1	6.6	5.9	4.8	3.4	169/150			3	4	7.89		
	6.1	5.6	4.9	3.9	-	169/130			3	4	7.89		
	5.1	4.6	3.8	2.8	-	160/120			2.2	3	5.52		

Regarding the required discharges, a centrifugal pump of type 100-160 with an impeller diameter of 169 mm was selected. The diameter of the suction pipe is 127mm and the diameter of the thrust pipe is 101.6mm. The electromotor with 5.4 HP and a maximum variable speed of 1420 rpm and A 4KW inverter device was also selected (Figure 8). The maximum flow of this pump with 1420 rpm is 50 lit/s, in which case the head can be supplied by 4400mm.



(a) (b)

Figure 8. Pump and electromotor (a) and inverter (b)

Three steps were used to create a still flow in the reservoir: A metal cap was installed 500 mm above the water inlet pipe to the reservoir to dissipate a part of energy of flow without applying extra pressure to the pump (Figure 9a), a galvanized plate with dimensions of 1200×1250mm where the distance of 250mm between the plate (Figure 9b) and the bottom of the reservoir is open for the flow passage, using 800 plastic balls filled with water (Figure 9c).

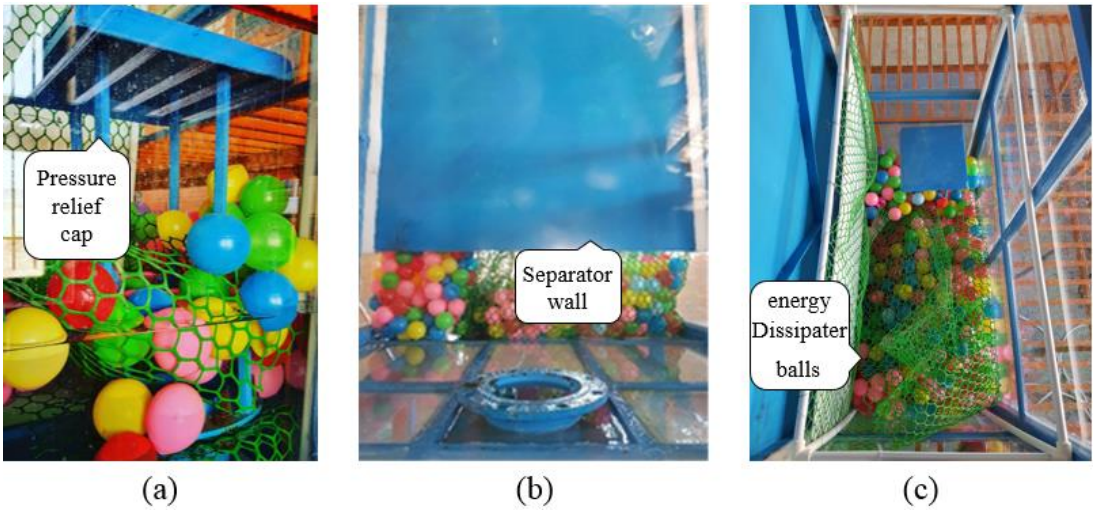
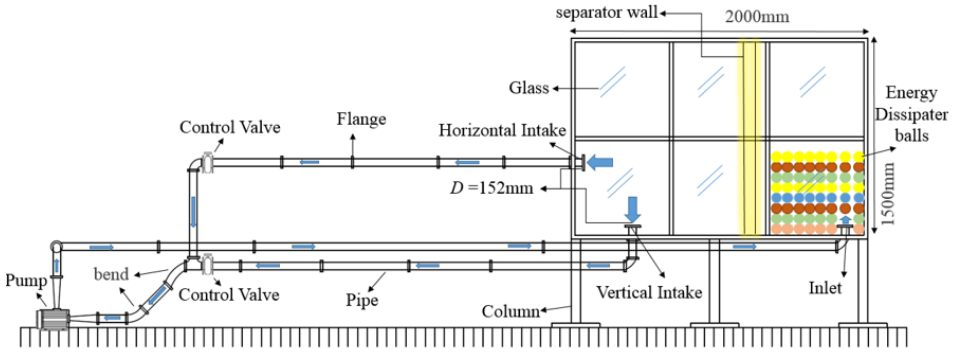


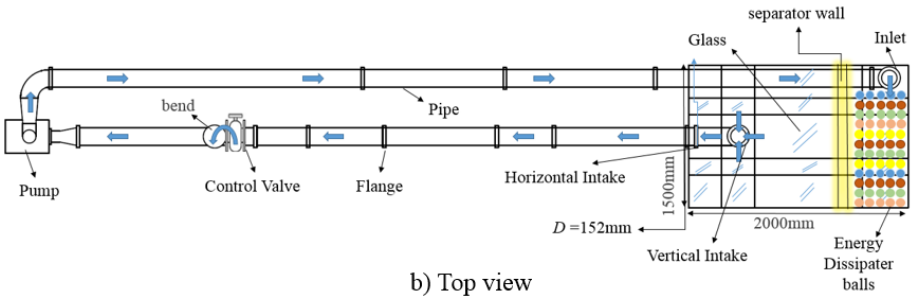
Figure 9. Pressure relief cap of the inlet pipe in the reservoir (a), separator wall (b) and energy dissipater balls (c)

3. Results and Discussions

After assembling all parts of the designed model and finalizing the construction of the model in the laboratory, experiments were conducted to form different classes of vortices. Schematic view of the constructed model and formed different vortex classes are presented in Figures 10 and 11.



a) Side view



b) Top view



c) Side view



d) Front view



e) Up view

Figure 10. Side Schematic view (a), top schematic view (b), side view (c), front view (d) and up view (e) of physical model water circulation system facilities



a) Vortex class C



b) Vortex class B



c) Vortex class A

Figure 11. Vortex formed in the physical model

4. Summary and Conclusions

A vortex is a hydraulic, three-dimensional and complex phenomenon that forms when reservoirs are dewatered. There are different types of vortices and they can form on the surface of the reservoir or subsurface. Formation of vortices can cause some problems in the operation of downstream facilities in critical conditions with the suction of air and suspended trashes and introducing vibration into the system. For this reason, studying and recognizing this phenomenon and strategies to prevent its formation are important for hydraulic engineers. Design and construction of a vortex laboratory model is one of the most common methods for studying and analyzing this complex phenomenon. In the present study, by considering different researches, it

was found that almost researchers agree on modeling based on *Fr*. In this case, *Re* and *We* should be greater than a value which suggested by the different researchers to neglect the effects of viscosity and surface tension. In designing the parameters of the reservoir, *D* plays an important role and based on that, the design of other components is done. To eliminate the effect of reservoir walls, the width of the reservoir 8*D* and the minimum distance from the intake axis to the bottom of the reservoir 4*D* were considered. Also, the length of the reservoir should be such that a uniform flow be provided for the test are. Model was so designed that both vertical and horizontal intakes can be tested. Moreover, in all tests, it is possible to fix the reservoir water level and change the discharge rate. The structure of the model was so designed that be stable according the acted loads. A water circulation system was designed to prepare a closed loop between reservoir and pump. To prepare a still water in the experimental area of the reservoir, three methods were employed to dissipate the extra energy of the inlet water to the reservoir. Finally, three different classes of free surface vortices were formed clearly and distinguished which showed the ability of the model for performing different scenarios of vortex formation at intakes in different geometry and hydraulic conditions.

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