Advanced Engineering Science
http://publish.mersin.edu.tr/index.php/ades
e-ISSN 2791-8580

Energy dissipation potential of flow separators placed in spillway flip bucket

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Cite this study: Ulu, A. E., Aydin, M. C., & Isık, E. (2022). Energy dissipation potential of flow separators placed in spillway flip bucket. Advanced Engineering Science, 2, 60-66

Keywords
Spillway
CFD
Energy dissipater
Flow separator

Research Article
Received: 13.01.2022
Revised: 17.02.2022
Accepted: 25.02.2022
Published: 14.03.2022

Abstract

The design of the energy dissipating pools at the downstream of the spillway is an important issue in terms of controlling the downstream flow regime, jet velocities and the scour problem that may occur in this region. In this context, there are many designs for flip-bucket pools for both energy dissipation and minimizing scour problems. In this study, the energy dissipation performance of a flow separator structure placed in an energy dissipation pool was investigated numerically by increasing the shear stresses. As a remarkable result, it has been observed that flow separators are able to reduce flow velocities by up to 55%, while the downstream trajectory increases significantly.

1. Introduction

Spillways are water structures that are widely used in hydraulic engineering. These structures are used to safely transfer the excess water accumulated in the dam reservoirs to the downstream part. After the body part of the dams, they are the most important structures for a dam. Ogee style weirs are also the most important water intake structures from the past to the present. In these weirs, which are known as classical crests, the water taken from the reservoir is passed over an inclined body and delivered to a flip bucket to break its energy. This structure, which resembles a bucket, absorbs the energy it gains during the fall of the flow, and it is important to prevent possible damage to the downstream of the structure. In cases where the spillway design is not done correctly, at the downstream some problems may occur due to scouring, cavitation and energy breakdown at the downstream of the spillway and regulator [1-2]. In this respect, their designs have many differences or shapes, obstacles and sizes that increase the energy breaking potential. There are a number of experimental and numerical studies in the literature for investigating the energy of the high-speed flow that occurs just downstream of the spillway structures [3-7].

Two important problems in spillway chute channels subject to high discharges and velocities are cavitation that may occur on the chute and scour in the downstream. In order to prevent these, measures such as reducing the flow velocities on the chute channels and throwing the water jet away from the downstream are taken. Flip-bucket type chute channels create a jet of water, allowing downstream scours to occur away from the dam body. Thus, the stability of the dam body is not affected. In this case, there are two situations; the first is to reduce the maximum flow velocities in the chute, and the second is to increase the downstream jet trajectory. Although these two situations do not seem possible since they are directly proportional to each other, in this study, these two elements will be examined by using a flow separator. In this study, flow velocities, downstream jet trajectory and the energy dissipation potential of a flow separator structure placed in the flip bucket of a 2D Ogee-style spillway structure was investigated numerically. Possible sediment scour in the downstream region was not taken into account in the study.

2. Material and method

FLOW-3D, a powerful computational fluid dynamics (CFD) program, was used as a method in the study. Flow-3D is a widely used reliable method that can simulate fluid motions [8]. The program determines fluid motion by solving equations such as conservation of mass and momentum. The mass conservation equation used in Flow-3D is presented below [9].

$$V_F\frac{\partial\rho}{\partial t}+\frac{\partial}{\partial x}(\rho uA_x)+R\frac{\partial}{\partial y}(\rho vA_y)+\frac{\partial}{\partial z}(\rho wA_z)+\xi\frac{\rho uA_x}{x}=R_{\mathrm{DIF}}+R_{\mathrm{SOR}}$$

Where;

V_f: Volume ratio of the fluid,
ρ: Density of the fluid,
R_{dif}: Turbulent diffusion term,
R_{sor}: Mass source,
u, v, w are the velocity components in the coordinate directions (*x, y, z*).

Momentum equation of fluid motion:

$$\frac{\partial u}{\partial t}+\frac{1}{V_F}\left\{uA_x\frac{\partial u}{\partial x}+vA_yR\frac{\partial u}{\partial y}+wA_z\frac{\partial u}{\partial z}\right\}-\xi\frac{A_yv^2}{xV_F}=-\frac{1}{\rho}\frac{\partial p}{\partial x}+G_x+f_x-b_x-\frac{R_{\mathrm{SOR}}}{\rho V_F}(u-u_w-\delta u_s)$$
$$\frac{\partial v}{\partial t}+\frac{1}{V_F}\left\{uA_x\frac{\partial v}{\partial x}+vA_yR\frac{\partial v}{\partial y}+wA_z\frac{\partial v}{\partial z}\right\}+\xi\frac{A_yuv}{xV_F}=-\frac{1}{\rho}\left(R\frac{\partial p}{\partial y}\right)+G_y+f_y-b_y-\frac{R_{\mathrm{SOR}}}{\rho V_F}(v-v_w-\delta v_s)$$
$$\frac{\partial w}{\partial t}+\frac{1}{V_F}\left\{uA_x\frac{\partial w}{\partial x}+vA_yR\frac{\partial w}{\partial y}+wA_z\frac{\partial w}{\partial z}\right\}=-\frac{1}{\rho}\frac{\partial p}{\partial z}+G_z+f_z-b_z-\frac{R_{\mathrm{SOR}}}{\rho V_F}(w-w_w-\delta w_s)$$

Where;

(G_x, G_y, G_z): Mass acceleration,
(f_x, f_y, f_z): Viscous accelerations,
(b_x, b_y, b_z): It expresses flow losses in porous media.

3. Numerical modeling and analysis

In the study, a two-dimensional ogee type spillway with a crest elevation of H = 5.28 m and a flip-bucket diameter of 2.0 m was used. Flip bucket design with 3 different types of geometry is used. Type 1 consists of a classic ogee weir without the use of a flow separator. In Type 2 and Type 3 models, a flow separator is placed at α=10 cm and α=20 cm above the flip bucket, respectively (Figure 1). The weir length (B) is taken as 7.7 m. The height of the flip bucket (c) is 80 cm.

In the study, hexahedral 0.05 m cell size was used. Total mesh count is calculated as 130,000 (Figure 2a). Analyzes were continued until the flow became completely stable (120 seconds). Fluid elevation change over time is given in Figure 2b. Analyzes performed using the Renormalized Group (RNG) turbulence model were solved by giving fluid elevation. As the initial fluid elevation, the water level started from 5.38 m and the elevation was increased by 0.1 m till 6.38 m. Since analyzes were carried out in two dimensions, the channel boundary conditions were determined as Symmetry. The channel floor boundary condition has been assigned as Wall, and the inlet and outlet parts have been assigned as Specified Pressure. 1 m downstream water inlet is defined in order to provide downstream conditions and to observe hydraulic jump.

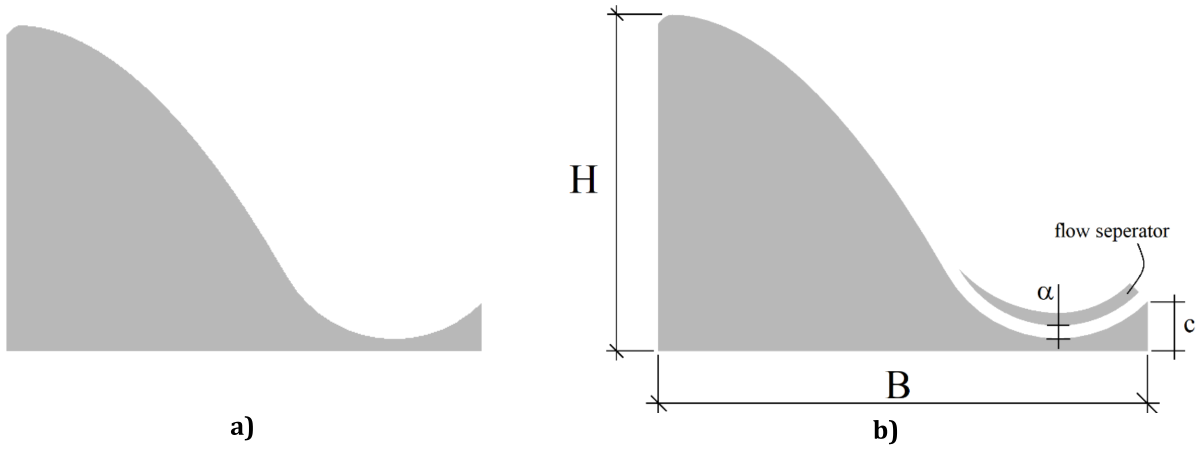


Figure 1. Geometry of the spillway; **a)** Type1 **b)** Type 3

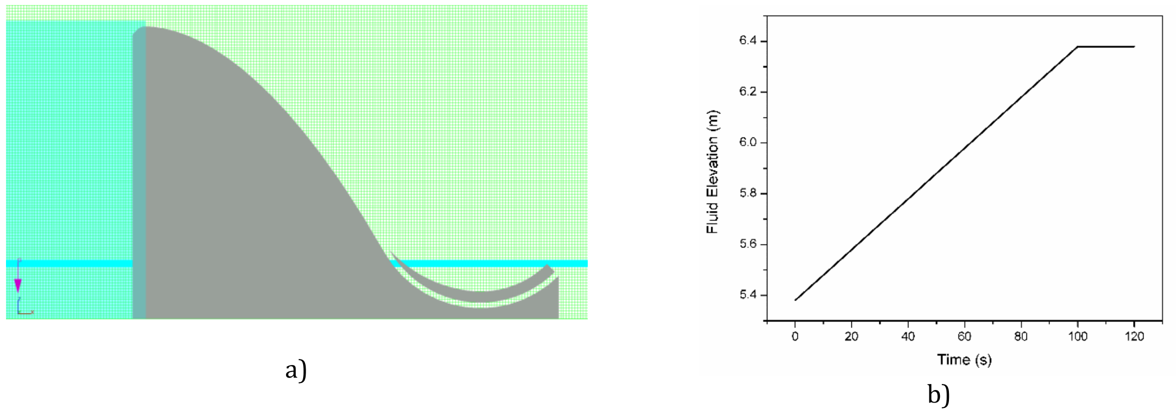
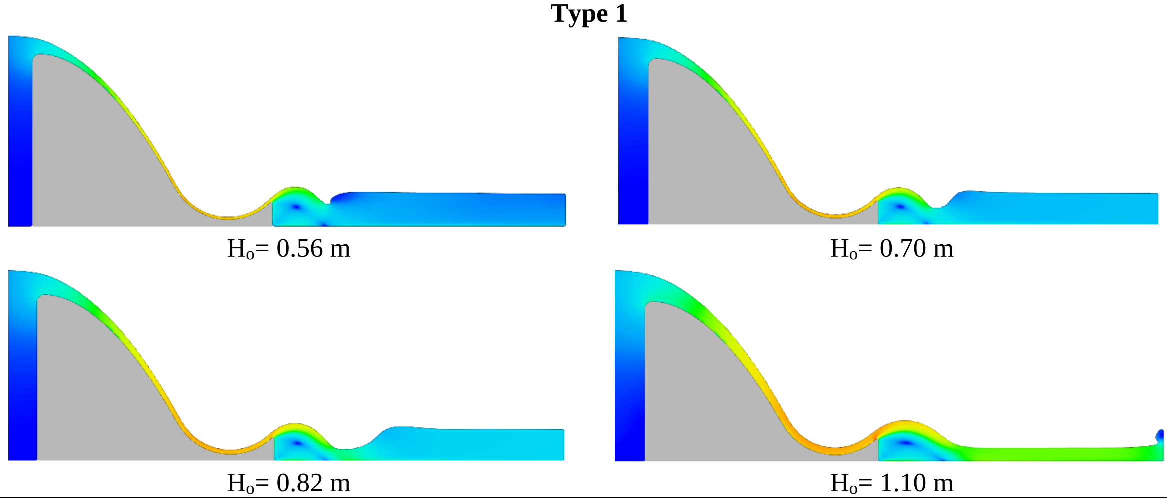


Figure 2. a) Mesh structures of the models (Type 2), **b)** Fluid elevation versus time

3. Results and discussion

In the study, the performance of a flow separator structure placed to increase the energy breaking potential of the spillway flip bucket at different upstream water heads was investigated in a developed CFD software. From analysis results obtained, velocity and pressure contours of some water heads belong to Type 1, Type 2 and Type 3 were presented in Figure 3 and 4, respectively.

Type 1



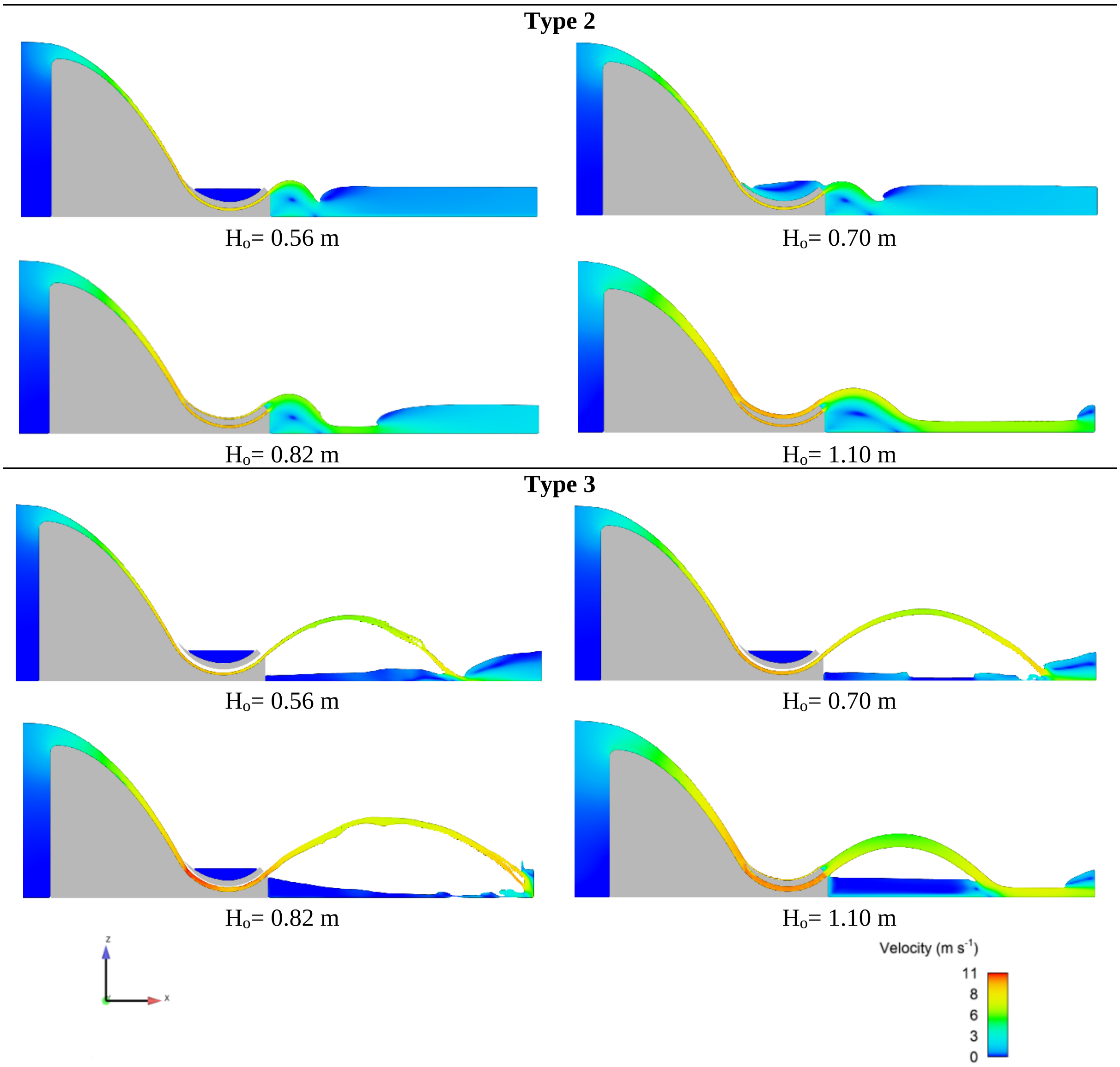
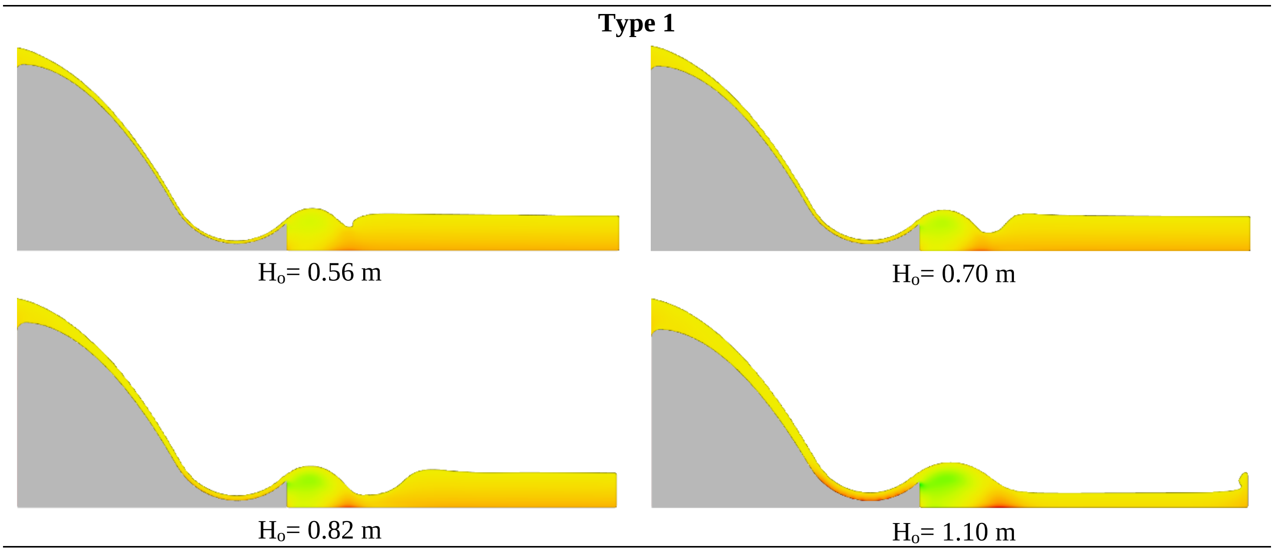


Figure 3. Velocity profiles of the flow



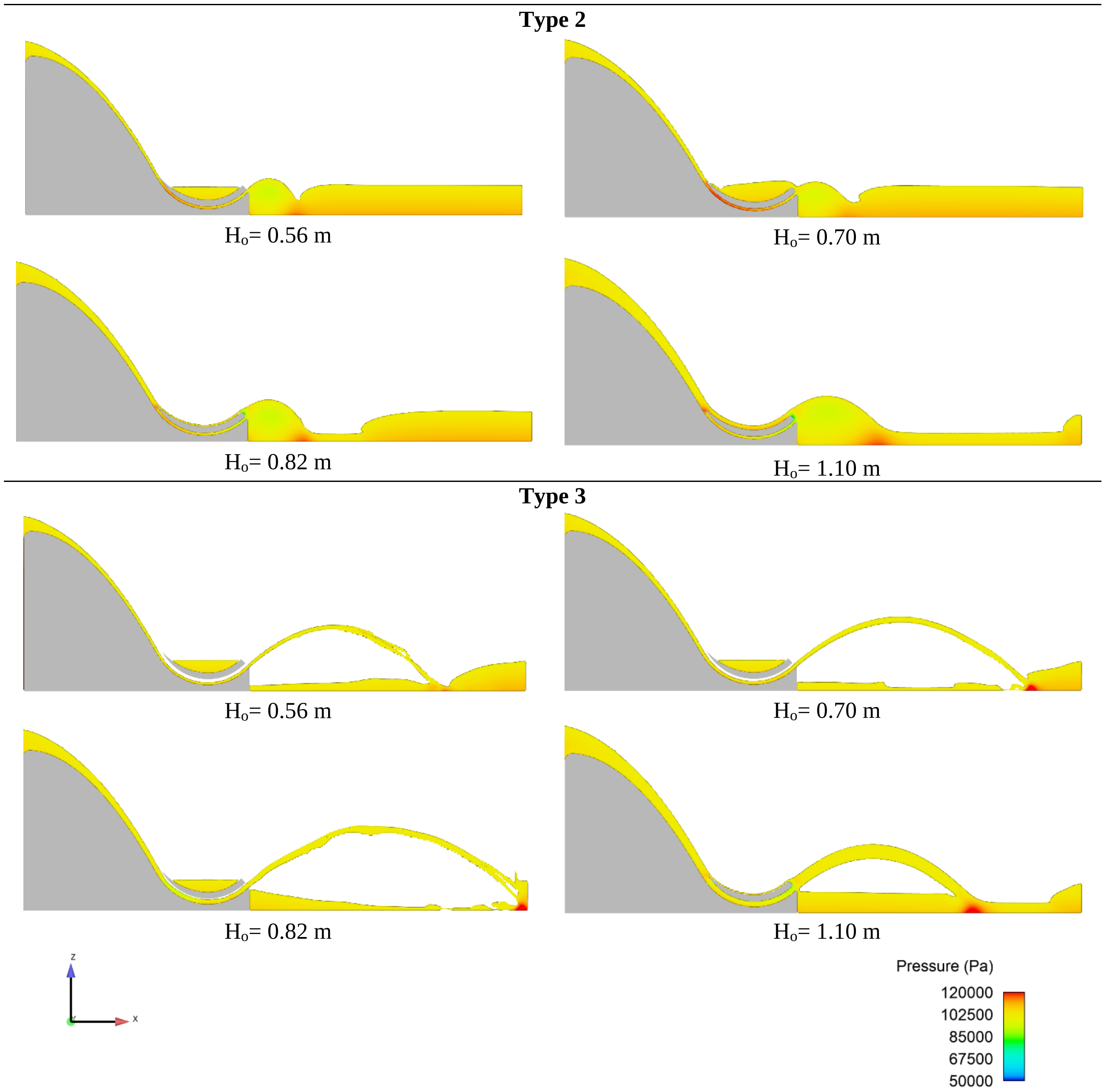


Figure 4. Pressure profiles of the flow

From the figures obtained, it is noticed that similar downstream conditions are obtained in cases of Type 1 and Type 2. However, it is clearly seen that Type 3 is very different from the other two models, it has been observed that the flow is jetted from the flip bucket in all water heads. However, it has been observed that the flow velocity of the Type 3 model, especially at the starting point of the flow separator, is higher in high water heads than in other models. At this point where the velocity increased, it was noticed that the pressure decreased in the Type 3 with H_o = 0.82 m. In this case, it was observed that the flow splash to the farthest point among the Type 3 states. At heads above H_o = 0.82 m, the pressure drop shifted towards the end of the bucket. Also, it is observed that at low water heads of Type 2, the pressure is high at the beginning of the flow separator, but the pressure is balanced as the water head continues to increase.

In the study, how different models affect the flow on the weir was also investigated. For this reason, the average velocity values of the sections A-A and B-B shown in Figure 5a were obtained. In Figure 5b, the velocity distribution of the types for the B-B section is presented. According to the velocity values taken, it was observed that the velocities were very close to each other at each cross-sectional point of the flow in Type 1, which is the model without a flow separator. According to the velocity values taken, it was observed that the velocities were very close to each other at each cross-sectional point of the flow in Type 1, which is the model without a flow separator. The velocity values of Type 1 are the highest values among the investigated models. As can be seen from Table 1, this value is 9.55 m/s. It is seen that the velocities decrease in this section in the models using a flow separator. The lowest average velocity was found in Type 2 with a value of 6.17 m/s.

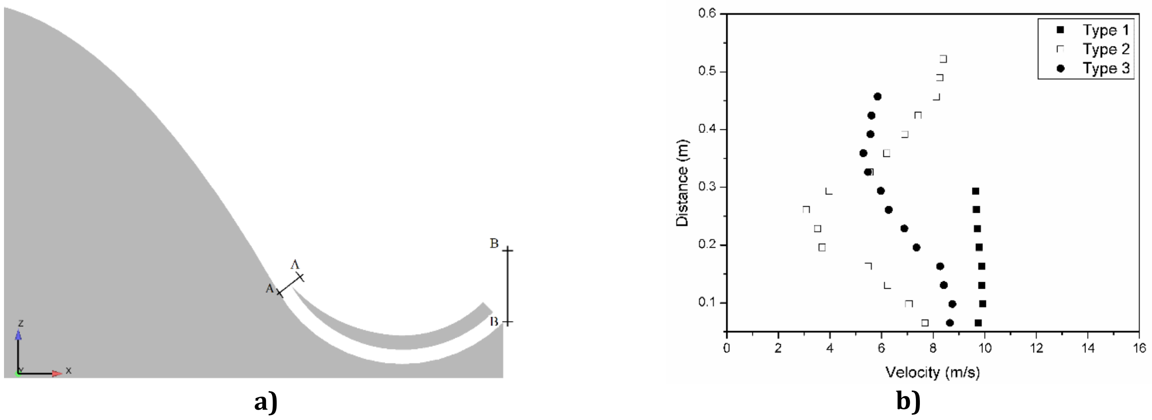


Figure 5. a) Velocity point sections, **b)** Velocities at the B-B section

It is understood from the Froude numbers in Table 1 that the flow has super-critical flow conditions in the A-A section in all three models. It has also been observed as a result of the numerical study that the flow separator has the effect of slowing down the flow passing through this section. This effect was observed mostly in Type 2.

Table 1. Characteristics of the flow

Models	h_{A-A} (m)	V_{avr} (m/s)		$F_{r,A-A}$
		$V_{avr,A-A}$	$V_{avr,B-B}$	
Type 1	0.275	9.24	9.55	5.813
Type 2	0.408	8.71	6.17	3.084
Type 3	0.358	9.02	6.87	3.668

The results showed that the launch significantly increased the jet trajectory, even though the flow separator (Type 3) adjusted at a certain opening reduced the exit velocities (compared to the Type 1). This situation also causes a decrease in the Froude number in the A-A section of the spillway. This will reduce the energy of the flow and increase the length of the water jet formed at the downstream, thus contributing positively to possible cavitation on the surfaces and scours downstream. The reason for this is thought to be due to the changes in pressures under the jet separator, as well as the effect of the flow separator on the shear stresses on the flow (hence the friction resistance / drag coefficient) and the development of the boundary layer. In order to better examine the subject, it is recommended to support it with experimental studies and to analyze it in more detail.

4. Conclusion

In the data obtained from the study, it has been observed that the flow rises by jumping from the flip-bucket structure in the Type 3 model using a flow separator at all investigated water heads. At low head loads, a hydraulic jump has occurred just after the jet throwing region of the models with the flow separator. This situation was not observed in the models without the separator. It has been observed that flow separators reduce flow velocities by up to 55%, especially at the point where the flow leaves the weir structure. The most essential reason for this is that flow separators increase frictional resistance.

In the study, the effect of a flow separator placed in the energy breaking pools (flip bucket) of the spillway structures, which has an important place in the field of hydraulic engineering, on the flow velocities and energy dissipation status was investigated. In future studies, the performance of the flow separator can be evaluated by comparing the different dimensions, the cavitation risk it will create and how it will behave in case of a possible scour in the downstream region compared to the normal situation.

Acknowledgement

This paper was partly presented in 1st Advanced Engineering Days (AED) held on Thursday, December 23, 2021 in Mersin/Turkey [10].

Funding

This research received no external funding.

Author contributions

Ali Emre Ulu: Methodology, Software **M. Cihan Aydın:** Model design, Validation. **Ercan Işık:** Visualization, Writing-Reviewing and Editing.

Conflicts of interest

The authors declare no conflicts of interest.

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