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FLOW AND ENERGY DISSIPATION OVER A CYLINDRICAL STEPPED WEIR

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Mazin S. Jomaa[1], Ahmed Y. Mohammed[1*]

[1]University of Mosul, College of Engineering, Dams and Water Resources Engineering, Iraq

Abstract:
The great economic importance of increasing the energy dissipation flow rate in stepped weirs prompted researchers to make several changes to the geometrical shape. In this study, (36) physical models were constructed to compare cylindrical stepped weirs with traditional weirs. (27) Models of cylindrical stepped weirs and (9) traditional stepped weirs were based on three heights and three diameters of steps. There are three shapes of the weir steps (Fc = all the steps in a circular shape, i.e., without cutting), (Fc & Hc = one round and the other half cut, respectively) and (Hc = all the steps are cut in half). The study showed that the percentage of energy dissipation in weirs increases with the height of the weir (P). Increasing the diameter of the degree (D) and increasing the number of steps (n), and changing the shape of the degrees, as the case (Fc & Hc) was better than the case (Fc). In contrast, the state (Hc) was the best among the other instances in the percentage of flow energy dissipation. The cylindrical gradient weirs are more efficient than traditional stepped weirs by approximately (10%), and the highest value for the energy dissipation of the flow was obtained for stepped cylindrical weirs (67.27%).

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Energy dissipation, stepped weir, cylindrical stepped weir, weir, hydraulics, open channel hydraulic

1. INTRODUCTION

Weirs are water barriers used in rivers and streams and are among the oldest hydraulic installations used. Weirs can be classified according to the shape of the weir's aperture, rectangular aperture weirs, triangular aperture weirs, trapezoidal weirs, and circular aperture weirs. They can also be named according to the shape of the weir such as inclined weirs. The stepped weirs are used for several purposes. The most important purpose is to measure the flow of rivers, raise the water level in rivers and streams, and for navigation in the rivers. The presence of grades in hydraulic installations leads to the provision of dissolved oxygen. It affects the organic materials useful for fish and plants through the ventilation process provided by the steps [1]. Since the geometrical shape of the weirs is with specific dimensions, it is easy to measure the expenditures by applying the equation for each case. The use of the weirs was not recent [2]. It is mentioned that the history of the listed weirs first appeared more than 3,000 years ago, since they obstruct the way of small and large discharges in rivers and streams, exposed to large waves of water energy. Therefore, engineers resorted to designing different forms of weirs, each of which can dissipate energy in proportions that vary from one state to another; since technology development has intervened in all areas of life, researchers have introduced numerical simulation programs in designing and estimating the flow rate dissipation energy, friction coefficient, discharge coefficient.

Increasing the discharge decreases the energy dissipation rate of the stepped weirs and the traditional weirs and increases with the height of the weirs by reducing both the number of steps and the slope of the gradient [3,4]. The setting of the end sill Increases the percentage of dissipation energy of the flow by up to (1.6% - 18.6%) better than the traditional stepped weirs within the

*CONTACT: A.Y. Mohammed, e-mail: a.altaee@uomosul.edu.iq

determinants of the study [5]. The less the number of steps and the slope of the end of the spillways, the amount of energy dissipation of the flow will increase. The stepped spillway is higher than the traditional spillway in the percentage of energy dissipation of the flow [6], that the rough stepped weirs give a higher rate in the energy dissipation of the flow than the traditional weirs [7]. The labyrinth-type spillway is better than the conventional spillway in the percentage of dissipation energy of the flow. As a result of the weir's end's increased slop for the labyrinth spillway, which is in contrast to the traditional spillway, a greater portion of the flow's energy is dissipated [8]. The rough weirs and the weirs with end sill are better in the energy dissipation from flat and cut weirs, and the lower the slope of the downstream stepped face, the greater the amount of energy dissipation [9]. Putting the end sill at the end of each step of the weir increases the percentage of energy dissipation of the flow [10]. The spillways with end sill are more influential than flat spillways in the rate of dissipation energy of the flow. The increase in the number of steps affects the percentage of dissipation energy of the flow [11]. The percentage of flow energy dissipation within the study's determinants is higher for the stepped weir with a circular end sill at the edge of the steps. More degrees than a traditional stepped weir [12], using the triangular end sill's impact at the end of the weir steps is more effective in energy dissipation than the rectangular end sill [13]. The inclusion of barriers in the stepped weirs gives the proportion of flow energy lost better than in traditional weirs; increasing the border's height has a greater effect on the percentage of dissipation energy of the flow [14]. When lost compared using numerical modelling based on program flow-3D, Labyrinth Shaped stepped weirs outperform traditional stepped weirs in flow energy dissipation [15].

The study aims to determine the impact of modifying the height of the weirs and the percentage of flow energy dissipation on the shape of the steps of stepped weirs utilising circular steps with various diameters, conditions, and arrangements of steps.

2. EXPERIMENTAL WORK

Fig. 1 shows that experiments were conducted in the University of Mosul's hydraulic laboratory in a channel with multiple parts. It begins with a feeding trough with a length of 2.25 m, a width of 1.25 m, and a height of 1.2 m, whose function is to calm the water before it enters the canal. The main channel has dimensions of a length of 24.6 m, a height of 76 cm, and a width of 81 cm after the end of the straight section. The main channel is a transverse channel that receives water, with dimensions of a length of 8 m, a width of 0.8 m, and a height of 1.2 m. A pump built at the channel's beginning provides water to the channel Drainage was measured by using a standard rectangular weir (sharp-crested weir) made of iron, with dimensions of the length of 0.5 m, the height of 0.18 m, and thickness of 6 mm, equipped with a notch at an angle 45°. The water depth is measured using a point gauge with an accurate measure with an error rate of (±1) mm.

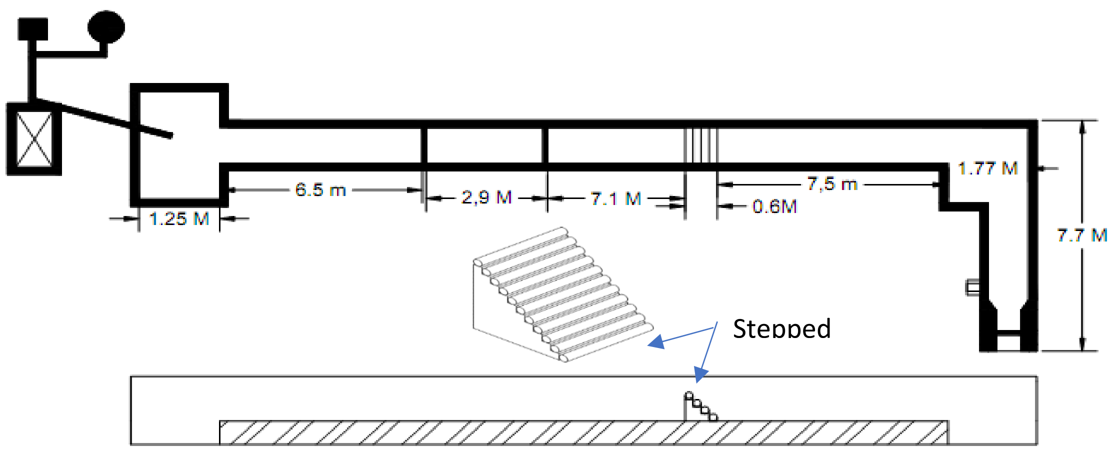

Fig. 1. Laboratory Channel

Three heights of the weirs (p = 60, 45, 30) cm, one downstream slope (ϴ = 45°) and three different diameters (D = 7.5, 5, 2.5) cm were used. Three different shapes of diameters are used in the steps, which are Fc, Fc & Hc, Hc, where (Fc = all steps in a circle without cutting, Fig. 2-a, Fc&Hc = circular step and the other cut in half respectively, Fig. 2-b, Hc = All steps are cut in half, Fig. 2-c. The second group included (9) models of traditional stepped weirs, in which three heights were also used, which are (p = 60, 45, 30) cm and the same downstream slope of the weir (ϴ = 45°) and three heights of steps (h = 7.5, 5, 2.5) cm, as well as three lengths of steps (l = 7.5, 5, 2.5) cm as in Fig. 2-d, a model of the traditional stepped weirs, and all models of the circular and traditional stepped weirs have the same width, which is 81 cm.

a) Model of stepped Cylindrical Weir (Fc)

b) Model of stepped cylindrical weir (Fc&Hc)

c) Model of stepped cylindrical weir (Hc)

d) Model traditional stepped weir

Fig. 2. Models for stepped weire

3. DIMENSIONAL ANALYSIS

In the stepped weirs, in general, there are several constant factors affecting the percentage of dissipation energy of the flow, comprising the structure's height (p), the steps' length (l), their height (h), the weir's downstream slope (ϴ), and the total number of steps (n). This study added a new element to these factors: the diameter of the steps (D) using circular steps of different diameters. Additional factors were used to improve the flow's energy dissipation by using steps cut in half and two different arrangements. Circular step and the other cut in half, respectively, and on the second change all the steps to cut in half, this shape of the steps act as additional improvement end sill at the end of each step. In addition, there are fluid-specific factors which are water mass density (ρ), the dynamic viscosity of water (μ), ground acceleration (g), water velocity downstream of the weirs (v_1), and the depth of the water downstream of the weirs (y_1).

To determine the effect of all these factors on the flow's energy dissipation percentage, we used Buckingham π Theorem in the dimensional analysis known as (π-Theorem), considering the rate of dissipation energy of the flow as a function of all the mentioned factors.

$$\frac{\Delta E}{E_o}\% = f\,(p , D , l , n, y_1 , v_1 , g) \qquad (1)$$

The equation can be formulated according to the pi-theorem used in the dimensional analysis.

$$\frac{\Delta E}{E_o}\% = f\,(\frac{P}{y_1}, \frac{D}{y_1}, \frac{l}{y_1}, n, \frac{g*y_1}{v_1^2}) \qquad (2)$$

The final equation for cylindrical stepped weirs becomes.

$$\frac{\Delta E}{E_o}\% = f\,(\frac{P}{y_1}, \frac{D}{y_1}, Fr_1, n) \qquad (3)$$

And the equation of the traditional stepped weirs.

$$\frac{\Delta E}{E_o}\% = f\,(\frac{P}{y_1}, \frac{l}{y_1}, Fr_1, n) \qquad (4)$$

Where: Fr_1 = is the downstream stepped weir's Froude number.

4. RESULTS AND DISCUSSIONS

To derive an empirical equation for the percentage of energy dissipation in cylindrical gradient weirs based on the trace elements reached through the dimensional analysis process, use the statistical program (Statistical Package for Social Sciences) known by the acronym (SPSS).
An equation with a correlation coefficient R2 = 0.999 can be obtained as follows.

$$(\frac{\Delta E}{E_o})_{SP}\% = 89.911-39.61(\frac{P}{y_1})6.979\ (\frac{D}{y_1})\text{-}7.975\ (n)\text{-}7.977\ (Fr_1)2.099 \qquad (5)$$

Where:
$(\frac{\Delta E}{E_o})_{SP}\%$: It represents the percentage of dissipation energy of the flow for the stepped cylindrical weirs extracted from the statistical program.

Analysing and knowing the factors affecting the percentage of dissipation energy of the flow, which are the weir's height (p), the weir's step diameter (D), and the step's number (n) and three different shapes of diameters used in the steps, which are (Fc = all steps in a circular without cutting) and (Fc & Hc = a circular step and the other cut in half, respectively) and (Hc = all steps cut in half), an increase of three heights (P = 60, 45, 30) cm for the weir and three steps' diameters (D = 7.5, 5, 2.5) cm, the study was done. Studying the effect of this change on the proportion of flow energy lost and other factors with it and making a comparison between stepped cylindrical weirs and traditional weirs; experiments proved that the weir height and the number of steps, and the diameter of the steps increases, the percentage of dissipation energy of flow (E/Eo %) also increases. When all the steps are cut in half (Hc), it is the best form of the steps. Fig. 3 shows the highest flow energy dissipation value obtained from the experiments. It was at the highest weir height, which is P = 60 cm, where the comparison was made between the three forms of steps at this height and the selection of the uniform diameter of the steps D = 7.5 cm. The greatest energy dissipation of flow is achieved when stepped weir steps are cut in half (Hc). When choosing a specific value for (P / y_1) - let it be 30, it is found that the percentage of dissipation energy of the flow increases by 0.8% when converting the form of steps from the state (Fc) to the state (Fc&Hc), and by 5.13% when converting it to the state (Hc).

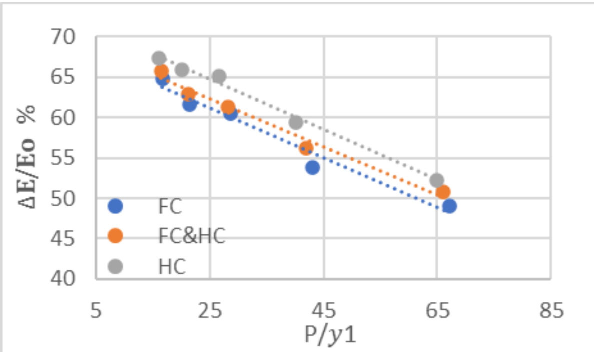

Fig. 3. Links the proportion of flow's energy dissipation and the ratio of the weir's height to the depth of the water downstream of the weir (p=60 cm, D=7.5 cm)

In Fig. 4, the significant effect of increasing the height of the weir from 30 cm to 45 cm and then to 60 cm shows that the height of 60 cm gives the highest percentage of dissipation of the flow energy among the three heights used. Its percentage reaches almost twice the height ratio of 30 cm when relying on the same diameter of the steps for the three heights D = 7.5 cm and the same shape for the steps (Hc). The flow energy increases by 23.51%

when changing the height from 30 cm to 45 cm, and by 40.68% to 60 cm.

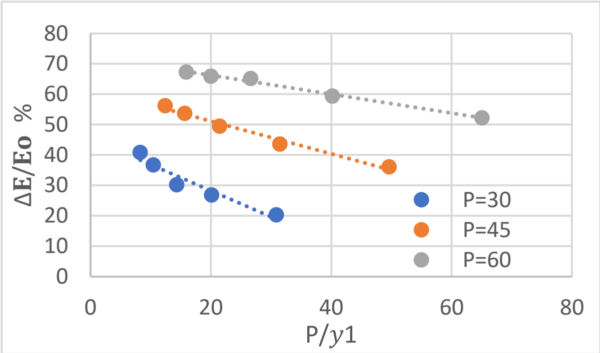

Fig. 4. Link the proportion of flow's energy dissipation and the ratio of the weir's height to the depth of the water downstream of the weir (D=7.5 cm, Hc=condition)

In Fig. 5, the association between the percentage of energy dissipation of the flow for the stepped cylindrical weir (ΔE/Eo%) and the ratio of the diameter steps to the depth of the water downstream of the weir (D/y_1) was drawn as it relied on a uniform height of the weir P = 60 cm with changing the diameter of the steps to the three diameters (D = 2.5, 5, 7.5) cm and the same shape for the steps when all the steps are cut in half (Hc). The graph demonstrated that when increasing the steps diameter increases the percentage of dissipation energy of the flow, as the diameter of 7.5 cm in the state (Hc) was the best. When choosing a specific value for (D/y_1), let it be (2), it is found that the percentage of the flow energy dissipation increases by 7.03% when changing the diameter of the steps from 2.5 cm to 5 cm and by 12.68% when changing it to 7.5 cm.

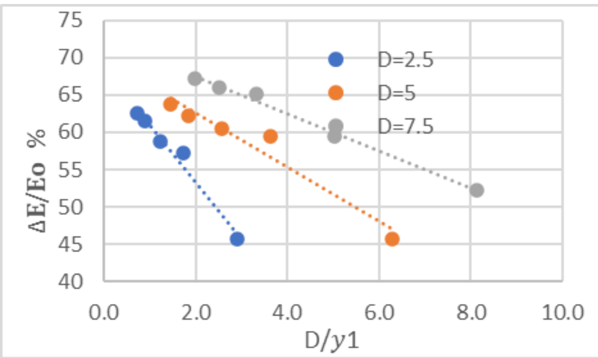

Fig. 5. The proportion of the weir steps' diameter to the depth of the water downstream of the weir and the proportion of flow's energy dissipation (P=60 cm, Hc=condition)

Fig. 6. relied on a fixed height P = 60 cm and a fixed diameter of the steps D = 7.5 cm, with the change in the shape of the steps to the three forms of steps. In the first case, all the steps are in a full circular shape (Fc); in the second case, a circular step and the other are cut in half, respectively (Fc & Hc); and in the third case, all the steps are cut in half (Hc). The drawing shows that the highest percentage of dissipation of the flow energy obtained is for the third case (Hc) relying on a fixed value of (D/y1) -let it be (6), is found that the percentage of dissipation of the flow energy increases by 1.91% when changing the shape of the steps from (Fc) to (Fc&Hc) and by 7.72% when changing it to the shape (Hc).

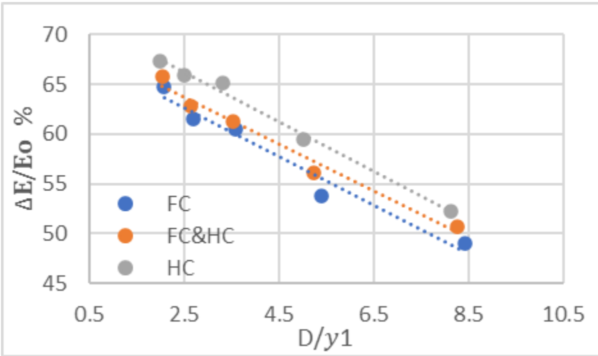

Fig. 6. The proportion of the weir steps' diameter to the depth of the water downstream of the weir and the ratio of flow's energy dissipation (P=60 cm, D=7.5)

In Fig. 7, to determine the impact of the steps on the stepped cylindrical weirs, a link was drawn between the number of steps (n) and the percentage of energy dissipation (E/Eo %). Relying upon three heights of the weir (P = 30, 45, 60) cm and three numbers of steps (n = 4, 6, 8) steps and one diameter of steps D = 7.5 cm and three shapes of steps (Fc, Fc&Hc, Hc), for the percentage of energy dissipation for each of the three steps shapes (ΔE/Eo% Ave), the average was taken, where the percentage of dissipation energy of the flow (E/Eo % Ave) and the number of steps (n) were correlated. The plot demonstrated that as the number of steps increases, the flow energy dissipation percentage also increases. The average percentage of the flow energy dissipation increases by 16.83% when the number of steps is increased from 4 to 6 and by 31.01% when it is increased to 8 steps. Depending on the percentage of the steps, form (Hc) is the best.

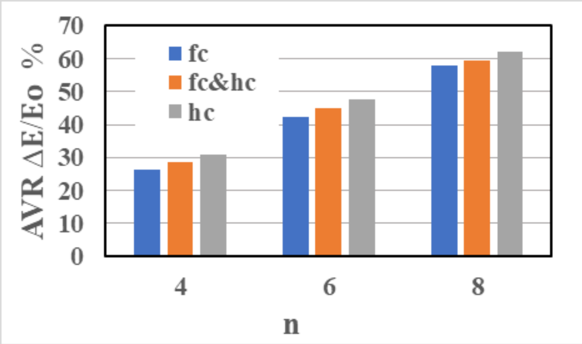

Fig. 7. The proportion of the flow's energy that is lost in the steps and how it relates to the number of steps(P=60 cm, 45 and 30 cm, D=7.5 cm)

In Fig. 8, the average rate of energy dissipation (E/Eo % Ave) and the number of steps (n) were correlated based on three weir heights (P = 30, 45, 60) cm and three numbers of steps n = 6, 12, 9 steps and uniform diameter of steps D = 5 cm and three forms of weir steps (Fc, Fc & Hc, Hc). The plot demonstrated that as the number of steps increases, the percentage of flow energy dissipation also increases. It increases by 16.73% when changing the number of steps from 6 to 9 and by 28.82% when changing to 12. Based on the percentage of the steps form (Hc) is the best.

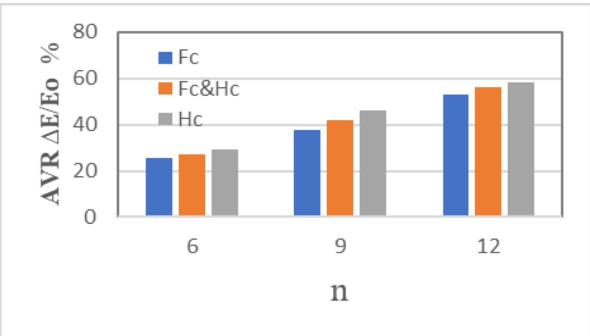

Fig. 8. The proportion of the flow's energy that is lost in the steps and how it relates to the number of steps (P=60 cm, 45 cm and 30 cm, D=5 cm)

In Fig. 9, the relationship between the Froude number downstream of the weirs (Fr1) and the percentage energy dissipation (ΔE/Eo%) was drawn, as it was based on a fixed weir height p = 60 cm and a constant diameter of the weir steps D = 7.5 cm and three forms of steps, which are all steps in a circular without cutting (Fc), a circular step and the other cut in half, respectively (Fc&Hc) and all steps cut in half (Hc). The plotted relationship demonstrated that when the Froude number (Fr_1) declines, the percentage of the flow energy dissipation increases when the shape of the steps is changed from (Fc) to (Fc&Hc) and then to (Hc), with the maximum percentage occurring when the shape of the steps is (Hc).

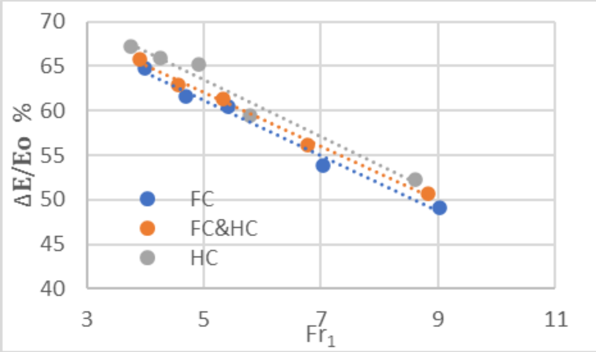

Fig. 9. The proportion of the flow's energy that is lost in the weir and the Froude number downstream of the weir (P=60 cm, D=7.5 cm)

In Fig. 10, a comparison was made between the stepped cylindrical weirs and the traditional stepped weirs in the energy dissipation of flow. There, the relationship was drawn between the energy dissipation of flow (ΔE/Eo%) and the weir height to the water depth downstream of the weir ratio (P/y1) depending on a fixed height of the weir P=60 cm and the same dimensions of the steps D=7.5 cm and h=l=7.5 cm and the shapes of the steps (Fc, Fc&Hc, Hc, h=l). In terms of the percentage of flow energy dissipation, the drawn relationship demonstrated that the stepped cylindrical weirs are superior to the classic stepped weirs. When choosing a specific value for (P/y1) - let it be (30), it is found that the amount of flow energy dissipation rises by 4.47% when the form of steps is changed from the state (h = l) to the state (Fc), by 5.27% when the form is changed to (Fc&Hc), and by 9.6% when the form is changed to (Hc).

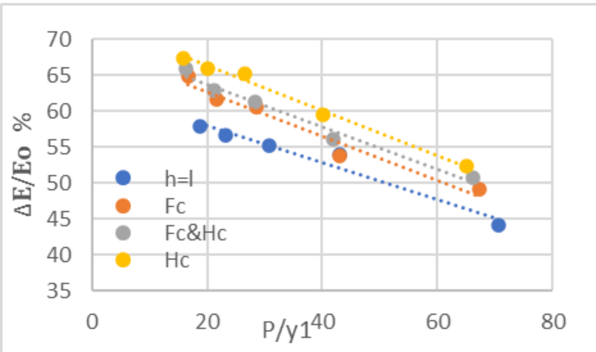

Fig. 10. Relationship between the flow energy dissipation ratio and the weir height to the water depth at the downstream ratio for cylindrical stepped weirs and traditional stepped weirs (p=60 cm)

CONCLUSIONS

The main conclusions of the presented research in this paper are:

1) The flow energy dissipation increases as the weir's height increases, where the highest percentage of dissipation is the flow energy at height P = 60;
2) The steps' diameter affects how much flow energy dissipates, with the diameter D = 7.5 cm having the largest percentage of flow energy dissipation;
3) The percentage of energy lost by the flow increases as the number of steps increases. The height of the weir and the diameter of the steps determine the number of steps. Therefore, each diameter has a specific number;
4) Changing the geometry of the steps leads to an increase in the percentage of dissipation energy of flow, as the shape of a circular step. The other cut in half (Fc & Hc) is better than the shape of all steps in a circular without cutting (Fc). The geometry of the steps (Hc), that is, all steps of the weir cut in half, is better than the two shapes. The former is the percentage of dissipation energy of the flow for all the diameters adopted in the study;
5) The flow energy dissipation percentage increases with the discharge (Q) increase, and it decreases with the increase in the Froude number (Fr_1);
6) The stepped cylindrical weirs are better than the traditional stepped weirs in terms of the flow energy dissipation by about (10%), where the highest percentage of stepped cylindrical weirs was (67.27%) and the traditional stepped weirs (57.84%).

NOMENCLATURE

$\frac{\Delta E}{E_o}$%: Energy Dissipation

$(\frac{\Delta E}{E_o})_{SP}$%: Energy Dissipation extracted from the statistical program

P: Stepped Weir Height (m)

D: stepped diameter (m)

l: stepped length (m)

n: Stepped Number

y_1: Water Depth Downstream (m)

v_1: Flow Velocity Downstream (m/s)

g: Gravity Acceleration (m/s^2)

F_{r1}: Froude Number Downstream

Ɵ: the downstream slope of the weir

Fc: all the steps in a circular shape, i.e., without cutting

Fc & Hc: one circular and the other half cut, respectively

Hc: all The steps are cut in half

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