A NEW EFFICIENT WATER ENERGY DISSIPATOR FOR IMPROVING THE IRRIGATION WATER QUALITY

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ABSTRACT

The present experimental study was executed to investigate a new and untested shape of curved dissipators with different angles of curvature and arrangements from the following two points of view: (i) To examine its efficiency in dissipating the kinetic water energy; (ii) To examine the most effective shape and arrangement obtained from the abovementioned step in enriching the flow with dissolved oxygen for enhancing the irrigation water quality. The study was held in the irrigation and hydraulic laboratory in the Civil Department, Faculty of Engineering, Assiut University, using a bed tilting channel 20 m long, 30 cm wide and 50 cm height, using 20 types of curved dissipators with different arrangements. A total of 660 runs were carried out with different discharges. Results, in general, showed that, for the same angle of curvature, the dissipator performance is more tangible in dissipating the water energy when the curvature is in the opposite direction of the flow. Also, the energy loss ratio increases with the increase of the dissipator curvature angle ($\theta$), till it reaches (120$^\circ$), then it decreases again. The study also showed that using four rows of dissipators gives nearly the same effect of using three rows concerning both, the relative energy dissipation and dissolved oxygen content. So, it is recommended to use not more than three rows of the introduced curved dissipator with an angle of curvature equals (120$^\circ$) in the opposite direction of the flow to obtain the maximum percentage of water energy dissipation downstream head structures and maximum dissolved oxygen content. Also, the study showed that, using the new introduced curved dissipator in three rows in the staggered-separate manner gives the best formed hydraulic jump characteristics, less relative depth and less relative length than all other tested dissipators, which reduces the cost of construction of the solid apron on the downstream side of head structure.

Keywords: Energy dissipation, Water quality, Dissolved oxygen, Aeration, Curved sill dissipater

Received 10 May 2016. Accepted 6 July 2016
Presented in IWTC 19$^{th}$

1 INTRODUCTION

The prime goals of this research are, saving, controlling, and improving the quality of the available quantity of water for irrigation. Since saving and controlling of irrigation water can be achieved through some storage and diversion head structures like dams, regulators and weirs, which cause many destructive problems that must be treated to avoid the probable failure of the head structure. At the same time, such structures change the water hydraulic regime behavior owing to raising the upstream water level, gaining a great potential energy, which converts into kinetic energy through falling over the head structure, and produces a large number of eddies and bubbles. These air bubbles entrained in the flow, not only increase the dissolved oxygen content in the water flow, but also prevent the cavitation in highspeed flows downstream head structures. Therefore, with regards to the danger of cavitation attack, forcing aeration of flow is recommended, (Flavey, 1990; Pionto, 1991). Such falling generates a hydraulic jump in the downstream side which must be overcome shortly and as close as possible to the head structure, to keep the structure and its solid apron safe. The most effective method for accelerating the formation of the hydraulic jump to dissipate the falling water energy is using some types of energy dissipators with different shapes and with different arrangements on the solid apron at the downstream side of the structure. The literature on such a topic is rich with many studies for many
shapes and arrangements of such dissipators to test the most effective shape in dissipating the energy downstream head structures. Table 1 introduces the most popular methods investigated by other authors and their predicted equations for determining the percentage of energy dissipation downstream head structures.

Table 1. The most popular investigated methods for water energy dissipation downstream head structures

<table>
<thead>
<tr>
<th>Author</th>
<th>Equation</th>
<th>Definition sketch</th>
<th>Shapes of energy dissipators</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rageh, 1999</td>
<td>$\frac{\Delta E}{E_i} = 1 - \left( \frac{F_r + 2c_yx}{c_yx(F_r + 2)} \right)$</td>
<td><img src="image1" alt="Sketch" /></td>
<td><img src="image2" alt="Sketch" /></td>
</tr>
<tr>
<td>Wafaie, 2001a</td>
<td>$\frac{\Delta E}{E_i} = [A_x \times F_r^2] + [B_x \times F_r] + C_x$</td>
<td><img src="image3" alt="Sketch" /></td>
<td><img src="image4" alt="Sketch" /></td>
</tr>
<tr>
<td>Negm et al., 2003</td>
<td>$\frac{\Delta E}{E_i} = -0.973 - 0.153F_r + 1.031F_r^{1.5} + 0.0066 / y_1$</td>
<td><img src="image5" alt="Sketch" /></td>
<td><img src="image6" alt="Sketch" /></td>
</tr>
<tr>
<td>Habib et al., 2003</td>
<td>$\frac{\Delta E}{E_i} = \frac{c_r'd_r'[2 + F_r^2] - 2d_r'}{c_r'd_r'[2 + F_r^2]}$</td>
<td><img src="image7" alt="Sketch" /></td>
<td><img src="image8" alt="Sketch" /></td>
</tr>
<tr>
<td>Meshkati et al., 2012</td>
<td>$\frac{\Delta E}{E_i} = \left( \frac{V_{r}'^{2}/2g + y_1}{V_{r}'^{2}/2g + y_1} \right)$</td>
<td><img src="image9" alt="Sketch" /></td>
<td><img src="image10" alt="Sketch" /></td>
</tr>
<tr>
<td>Habib, 2012a</td>
<td>$\frac{\Delta E}{E_i} = 1 - \frac{y_1 + 0.5F_r(\rho / \rho_y)}{y_1 + 0.5(\rho / \rho_y)}$</td>
<td><img src="image11" alt="Sketch" /></td>
<td><img src="image12" alt="Sketch" /></td>
</tr>
<tr>
<td>Habib, 2012b</td>
<td>$\frac{\Delta E}{E_i} = 1 - \frac{D_r'(Z + D_r)(e + 2c'^{-})}{D_r'[1 + 0.5F_r^2](e + 2c'^{-})}$</td>
<td><img src="image13" alt="Sketch" /></td>
<td><img src="image14" alt="Sketch" /></td>
</tr>
</tbody>
</table>

Another goal of the present study is facing the challenge of improving irrigation water quality which has a global concern because of the accelerated shortage of the available fresh water. In the light of this fact, we have to reuse the agriculture drainage water once again in the irrigation process after mixing it with the suitable percentage of irrigation water. To keep such mixed water within the safe specification of the irrigation water, the added drainage water must be treated for improving its quality, since the dissolved oxygen (DO) content is considered as a significant indicator of the suitability of the water for the irrigation and agricultural activities, because the dissolved oxygen is considered as one of the most important water quality parameters. To the best of our knowledge, there are limited references in literature for investigating the problem of dissipating water energy downstream head structures, and enhancing water quality by enriching the flow with the dissolved oxygen at the same time. So, in the present study, we introduced a new water energy dissipator for efficient dissipation and using that sill dissipator as one continuous row or more, or as staggered separate dissipators in one or more rows, to examine its efficiency in dissipating water energy, and at the same time, to examine its role in enriching the flow with oxygen through the great aeration of the flow within the dissipating energy distance downstream head structure.
2 THEORETICAL APPROACH

The dimensional analysis is used to define dimensionless variables based on the selection of all relevant variables governing the energy dissipation for curved sill dissipators as shown in the following Figure 1.

![Figure 1. Definition sketch for forced hydraulic jump with curved dissipator.](image)

The variables used in the dimensional analysis of curved sill dissipator are chosen so as to represent all parameters involved in the problem as follows:

**Boundary characteristics**

- \( \Theta \): Curvature angle of the sill dissipator in the direction of the flow or, in the opposite direction;
- \( L_w \): Length of the curved sill dissipator;
- \( L_s \): Position of the curved sill dissipator from the gate;
- \( h_s \): Height of the curved sill dissipator;
- \( D \): Gate opening; and
- \( b \): Width of channel.

**Flow characteristics**

- \( y_1 \): Initial depth of the hydraulic jump;
- \( y_2 \): Sequent depth of the hydraulic jump;
- \( L_j \): Length of the hydraulic jump;
- \( g \): Gravitational acceleration;
- \( V \): Velocity of flow; and
- \( \Delta E \): Dissipation energy.

**Fluid characteristics**

- \( \rho \): Density of water; and
- \( \mu \): Dynamic viscosity of water.

Referring to Figure 1, the following functional form of the dissipated energy in a rectangular basin with a curved sill dissipator could be expressed as follows:

\[
\phi_1 = \left( \rho, \mu, g, D, y_1, y_2, b, L_w, L_s, h_s, \Theta, V, \Delta E \right)
\]

(1)

With the aid of Buckingham's "\( \pi \)" theorem, considering \( y_1, V \), and \( \rho \) as repeating variables, it could be proved that:

\[
\phi_2 = \left( \frac{y_2}{y_1}, \frac{D}{y_1}, \frac{b}{y_1}, \frac{L_w}{y_1}, \frac{L_s}{y_1}, \frac{h_s}{y_1}, \frac{1}{\Theta}, \frac{V_1}{g y_1}, \frac{\mu}{\rho V_1 y_1}, \frac{\Delta E}{y_1} \right)
\]

(2)
b, h, and Ls are constants where the width of the channel (b) equals 0.3 m and the relative height (h/b) was kept constant at the value 0.11 and the relative position (Ls/b) was kept constant at the value 5.83, as recommended by (Wafaie, 2001a and b). So, equation (2) can be written in the following form:

$$\frac{\Delta E}{y_1} = \phi \left( \frac{y_2}{y_1}, \frac{D}{y_1}, \frac{L_w}{y_1}, \frac{L_j}{y_1}, \frac{1}{\theta}, \frac{V_j^2}{g y_1}, \frac{\mu}{\rho V_1^2 y_1} \right)$$

(3)

The term $\left( \frac{V_j^2}{g y_1} \right)$ is the square of Froude number ($F_{11}$), while $\frac{\mu}{\rho V_1^2 y_1}$ is reciprocal of Reynolds number ($Re_{11}$). So the general form may be put as:

$$\frac{\Delta E}{E_1} = \phi \left( \frac{y_2}{y_1}, \frac{D}{y_1}, \frac{L_w}{y_1}, \frac{L_j}{y_1}, \theta, F_n, Re_{11} \right)$$

(4)

In equation (4), the effect of viscosity is assumed of secondary importance in estimating the energy dissipation parameters as the flow is mainly gravitational, and therefore, the effect of Reynolds number ($Re_{11}$) can be neglected. So that, the equation (4) may be expressed as:

$$\frac{\Delta E}{E_1} = \phi \left( \frac{y_2}{y_1}, \frac{D}{y_1}, \frac{L_w}{y_1}, \frac{L_j}{y_1}, \theta, F_n \right)$$

(5)

Where:

- $\Delta E/E_1$: Relative energy loss;
- $y_2/y_1$: Relative depth of the hydraulic jump;
- $L_w/y_1$: Relative length of the sill dissipator; and
- $L_j/y_1$: Relative length of the hydraulic jump.

Since ($\theta$, $L_w$) were kept constants throughout the experimental program, so equation (5) becomes:

$$\frac{\Delta E}{E_1} = \phi \left( \frac{y_2}{y_1}, \frac{D}{y_1}, \frac{L_j}{y_1}, F_n \right)$$

(6)

In this study, we used curved sill dissipators with different angles of curvature, in the direction of the flow and in the opposite direction, to examine its efficiency in dissipating water energy. After that, we used the sill dissipator, which has the most effective angle of curvature as one continuous row or more, or as staggered separate dissipators, also in one or more rows, to examine its efficiency in dissipating water energy. So the number of rows can be included in equation (6) in the form:

$$\frac{\Delta E}{E_1} = \phi \left( \frac{y_2}{y_1}, \frac{D}{y_1}, \frac{L_j}{y_1}, F_n, N \right)$$

(7)

Where: NRows number.

3 EXPERIMENTAL SET-UP

Experiments were performed in a re-circulation rectangular open tilting flume at the Irrigation and Hydraulic laboratory of Civil Engineering Department at Assiut University. As shown in Figure 2.
The flume is 20 m. long, 30 cm. wide and 50 cm. depth with an adjustable slope. A sluice gate made of aluminum was used as a heading-up structure, and tail gate was located at the end of the channel to control the downstream water depth. The discharge was delivered by a pump and measured using a calibrated orifice meter with a manometer. Measurements of the water depths ($y_0$, $y_1$, $y_2$), were recorded using Vernier point gauge. During the experiments, dissolved oxygen measurements upstream and downstream of the curved dissipator were recorded using the calibrated portable VWR brand dissolve oxygen Meter Model 4000.

4 EXPERIMENTAL APPROACH

Twenty different types of sills were tested as energy dissipators downstream a sluice gate with different angles of curvature with respect to the flow direction. Types and arrangements of the tested energy dissipator models are shown in Photos 1 through 5. These models were made of painted timber to be placed separately on the flume bed downstream the sluice gate.

Figure 2. Experimental Set-up.

![Experimental Set-up Diagram]
The experimental runs were categorized into three sets as follows:

**The first set of experimental runs** was carried out without using energy dissipators and its results were used for the comparison purpose with the tested energy dissipators.

**The second set of experimental runs** was carried out using twelve types of curved dissipators (type2 to type13) having curvature angles of 60°, 75°, 90°, 120°, 150°, and 180°, in the same direction of the flow, and in the opposite direction, in addition to the straight one (type 1), as a reference.

**The third set of experimental runs** was carried out using the most effective shape obtained from the abovementioned step in one or more rows of continuous or staggered separate dissipators (type 9 and type 14 to type 20), for examining its efficiency in dissipating water energy, and at the same time for examining its role in enriching the flow with dissolved oxygen within the dissipating energy distance downstream head structure.

In each test, six different discharges ranging between 4.75 and 25.21 L/S were used with five gate openings ranging between 2 and 5 cm (D/b =1/6 and 1/15). The height of the models was fixed so that (h_s/b=0.11) and the position of the models was fixed so that (L_s/b=5.83), as recommended by (Wafaie, 2001a & b). For tangible measurements of the dissolved oxygen content through using our recommended curved dissipator, water of low dissolved oxygen content was used from one of the nearby agriculture drains, instead of the fully dissolved oxygen saturated laboratory water.

5 RESULTS AND DISCUSSIONS

The experiments were carried out, to know the influence of the introduced new curved dissipator, having different angles of curvature and different arrangements downstream head structures on two main important technical positive phenomena. The first is the efficiency of the suggested new dissipator with the examined angles of curvature and arrangements in dissipating the harmful water kinetic energy downstream head structures for more safety of such important structures. The second is the effect of the most efficient curved dissipator obtained from the above technical point of view in improving the quality of the flowing irrigation water by increasing the dissolved oxygen content through the great aeration produced along the protected downstream solid apron. So our analysis and discussion procedures will be done through main four axes as follows:

1) The effect of dissipator angle of curvature on the energy dissipation;  
2) Effect of the introduced new curved dissipator on the relative depth and relative length of the formed hydraulic jump downstream head structure;  
3) Effect of number of rows of the new introduced dissipator on energy dissipation; and  
4) Effect of number of rows of the new introduced dissipator on increasing the flow dissolved oxygen content.

5.1 Effect of dissipator angle of curvature on the energy dissipation

Six angles of curvature were tested, 60°, 75°, 90°, 120°, 150°, and 180° in addition to the straight one, with many discharges (range between 4.75 and 25.21 L/S). Experiments were carried out twice, one when the dissipator curvature is in the same direction of the stream flow, and the other one when the curvature is in the opposite direction of the stream flow. Figures 3 and 4 show the relationship between relative energy loss and angle of dissipator curvature.
Figure 3. Relationship between relative energy loss and angle of dissipator curvature (at $F_{r1}=4.0$)

Figure 4. Relationship between relative energy loss and angle of dissipator curvature (at $D/b=1/6$)

From Figures 3 and 4 it can be noticed that: the curved dissipator with an angle of curvature equals $120^\circ$ gives the best performance in increasing the relative energy loss ($\Delta E/E_1$). Also using curved dissipator with an angle of curvature equals $120^\circ$ in the opposite direction of the flow increases the efficiency of dissipating energy with value ranges between 13% to 42.55% more than that obtained in case of without using any dissipators or ranges between 5.7% to 30.4% more than that obtained in case of using straight dissipator (the discharge ranges between 4.75 and 25.21 L/S, $D/b$ ranges between 1/6 and 1/15, and $F_{r1}$ ranges between 2.68 and 8.76). Based on the experimental data and using the simple and multiple linear regression analysis, the best equation for predicting the relative energy loss in case of curved sill dissipators can be written in the following form of equation (8) as a result of the following Figure 5.

\[
\frac{\Delta E}{E_1} = A \cdot \log\left(F_{r1}\right) - B
\]  

The coefficients $A$ and $B$ are constants depending on the angle of dissipator curvature as shown in the following Table 2.

Table 2. Values of coefficients $A$ and $B$, in Equation (8).

<table>
<thead>
<tr>
<th>Angles of curvature</th>
<th>$0^\circ$</th>
<th>$60^\circ$</th>
<th>$75^\circ$</th>
<th>$90^\circ$</th>
<th>$120^\circ$</th>
<th>$150^\circ$</th>
<th>$180^\circ$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant (A)</td>
<td>0.427</td>
<td>0.439</td>
<td>0.441</td>
<td>0.446</td>
<td><strong>0.439</strong></td>
<td>0.445</td>
<td>0.438</td>
</tr>
<tr>
<td>Constant (B)</td>
<td>0.202</td>
<td>0.208</td>
<td>0.203</td>
<td>0.202</td>
<td><strong>0.184</strong></td>
<td>0.205</td>
<td>0.203</td>
</tr>
</tbody>
</table>
5.2 Effect of the introduced new curved dissipator on the relative depth and relative length of the hydraulic jump.

Figures 6 and 7 show the effect of the angle of dissipator curvature (θ) on the measured relative depth and the measured relative length of the hydraulic jump respectively.

Figure 6. Relationship between the relative depth of the hydraulic jump (y2/y1) and angle of dissipator curvature (at D/b=1/6)

Figure 7. Relationship between the relative length of the hydraulic jump (L2/y1) and angle of dissipator curvature (at D/b=1/6)

Figure 6 shows that, increasing the values of the discharge (Q) increases the value of the relative depth of the hydraulic jump (y2/y1), for all curved dissipator models. Also it is clear that using the curved dissipator with an angle of curvature equals 120° gives the lowest value of the relative depth of the formed hydraulic jump (y2/y1) with value ranging between (2.70% : 15.55%) lower than that obtained by using straight dissipator.

From Figure 7 it is clear that, increasing the value of discharge (Q) increases the value of the relative length of the hydraulic jump (L2/y1) for all curved dissipator models. Also it is of great importance noting that, the curved dissipator with an angle of curvature equals 120° gives the lowest value of the relative length of the hydraulic jump (L2/y1) and decreases the relative length of the formed hydraulic jump (L2/y1) with value ranging between (4.90% : 21.70%) lower than that obtained by using straight dissipator, which means that, for most economic downstream solid apron and shorter one, it is recommended using curved dissipator with an angle of curvature equals 120°.

5.3 Effect of number of rows of the new curved dissipator on energy dissipation.

For testing the effect of using the recommended new curved dissipator as continuous, and as staggered-separate rows on water energy dissipation, the following relations were plotted as shown in Figures 8 and 9 for differentised discharges at (D/b=1/6).

Figure 8. Relationship between the relative energy loss and number of continuous rows (at D/b=1/6)

Figure 9. Relationship between the relative energy loss and number of staggered-separate rows (at D/b=1/6)
From Figures 8 and 9 it is clear that, the relative energy loss (ΔE/E₁) increases with the increase of the discharge, and for the same value of the discharge (Q), the staggered-separate dissipators are more effective than the continuous one, also the relative energy loss (ΔE/E₁) increases with the increase of the number of rows till three. Where using one continuous row of the curved dissipator with an angle of curvature equals 120° increases the efficiency of dissipating energy with value ranges between 5.7% to 30.4% while using three continuous rows increases this efficiency with value ranges between 9.0%: 34.9%, and using three staggered separate rows increases that efficiency with value ranges between 9.3%: 36.0%, more than that obtained in case of using one row of straight dissipator.

5.4 Effect of number of rows of the new curved dissipator in increasing the flow dissolved oxygen content.

Figures 10 and 11 exhibit the relationship between the dissolved oxygen concentration (DO), and the used number of the recommended curved dissipator for different discharges in both cases: if the dissipator is used as continuous, or as staggered-separate rows.

![Figure 10. Relationship between the dissolved oxygen concentration and number of continuous rows (at D/b=1/10).](image)

![Figure 11. Relationship between the dissolved oxygen concentration and number of staggered-separate rows (at D/b=1/10).](image)

From Figures 10 and 11 it is clear that, the dissolved oxygen concentration increases with the increase of the number of rows till three, and for more rows didn't give tangible increase in the dissolved oxygen concentrations, where using four rows of dissipators gives nearly the same effect of using three rows. So, it is not recommended using more than three rows of the curved dissipator to obtain the maximum concentration of dissolved oxygen downstream head structures. Also, it is clear that dissolved oxygen concentration increases with the increase of the discharge for all studied number of rows. For the same value of discharge (Q), the staggered-separate dissipators are somewhat more effective than the continuous one in increasing the dissolved oxygen concentration.

The following Figures 12 and 13 show the distribution of the dissolved oxygen concentration along the stilling basin downstream the head structure. For knowing the distribution of the dissolved oxygen concentrations in the vertical direction, the measurements were taken at three vertical points, the first, near the bottom, the second is in the middle of water depth, while the last is near the water surface. It is worth mentioning that, the dissolved oxygen concentration reaches its maximum value at the end of the hydraulic jump that formed downstream head structure due to the huge aeration through the hydraulic jump, and starts decreasing in the longitudinal direction of the flow till reaching the same recorded values as shown in Figures 12 and 13, from which it is clear that using our recommended new curved dissipator in one, two and three rows behind the hydraulic jump increases the dissolved oxygen content with tangible values.
Figure 12. Distribution of dissolved oxygen concentration along the downstream solid apron using different numbers of rows (at D/b=1/10)

Figure 13. Relation between the measured dissolved oxygen concentrations, and the distance downstream head structure for different number of rows (at D/b=1/10)

6 CONCLUSIONS

Through the present study and the experimental results, the following main conclusions can be obtained:

- A new water energy dissipator for more efficient energy dissipation, and improving the irrigation water quality at the same time was introduced.
- Using curved dissipator with an angle of curvature equals 120° in the opposite direction of the flow increases the efficiency of dissipating energy with a reasonable value depending on Froude number, which is so good for the design of the stilling basin, and decreases the length of the protected solid apron.
- Using curved dissipator with an angle of curvature equals 120° decreases the relative depth of the formed hydraulic jump downstream head structures ($y_2/y_1$). Also decreases in the relative length of the formed hydraulic jump ($L_j/y_1$), which is so good for the design of safe and economic solid apron downstream head structures.
- The staggered-separate curved dissipater is better than the continuous curved dissipater in dissipating the energy and in reaching the flow with dissolved oxygen content.
The optimum number of curved sill dissipator rows for the solid apron downstream head structures is three rows, and more than three rows, didn't give a tangible increase in the relative energy loss.

The dissolved oxygen concentration increases with the increase of the number of dissipator rows, till three and for more rows didn't give tangible increase in the dissolved oxygen concentrations.

According to the obtained results, we strongly recommend using the new curved dissipator, in three staggered-separate rows to obtain the maximum percentage of water energy dissipation and maximum dissolved oxygen concentration.

REFERENCES


