Libyan Agriculture Research Center Journal International 3 (3): 104-110, 2012
ISSN 2219-4304

DOI: 10.5829/idosi.larcji.2012.3.3.1202

# Dissipation of Energy of Water Falling on Inclined Surfaces Using Cross Jet

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**Abstract:** The present work is intended to study the dissipation of energy of water over inclined surfaces. A reversed cross jet flow is developed to dissipate the energy of flow over an ogee weir spillway, since its back face is an inclined surface. The reverse jet, issuing from a slot in the solid floor, transversely strikes the main flow, falling over the weir resulting in a formation of a forced hydraulic jump. The flow jet issuing from the slot is fed from the headwater side, therefore, both the main and the cross jet flows are acting under the same head. The main parameters affecting the characteristics of the forced jump, either perfect or drowned, were investigated such as ; the location, direction and width of slot, in addition to the Froude number of the main flow. The problem was dealt with analytically and experimentally. In the analytical study, equations rendering the conjugate depth ratio, the loss of energy for jet-forced hydraulic jump and the limiting condition of perfect free hydraulic jump were developed. The accuracy of these equation was checked by the experimental measurements using a physical model for the suggested dissipator. In the experimental study, the effect of the main parameters, involved in the problem, on the characteristics of the forced jump either perfect or drowned was investigated. Results showed that the developed dissipator possesses high efficiency, since reduces the length of stilling basin to a great extent compared with the case without dissipator. The study is completed by a design procedure, to fix the proper dimensions of the cross jet ; position, width and direction, to be used in the practical applications.

**Key words:** Hydraulic structures · Dissipation of Energy of Water.

## INTRODUCTION

Hydraulic structures such as dams,weirs, spillways,….etc. are constructed to satisfy many functions.

To efficiently perform their functions, hydraulic structures should be characterized by : (1) safety and stability against various effects caused by the acting forces, (2) minimum cost in both construction and maintenance and (3) rapid response to any abrupt variation in both discharges and water levels.

Hydraulic structures are commonly constructed in streams having alluvial bed materials. The downstream bed of such structures may be lowered locally due to movement and transportation of soil particles in the high velocity zone, very close to the stream bed, as a result of the hydraulic jump formation. The lowering of bed is referred to the interaction between the high velocity of the issuing jet and the loose material of bed. Such a process is called a local scour, as shown in Fig. 1. Successive scouring process can undermine the foundation of hydraulic structures leading to a whole failure. Therefore, erosion or scouring process in the downstream bed of hydraulic structures presents a very dangerous effect on the stability of such structures.

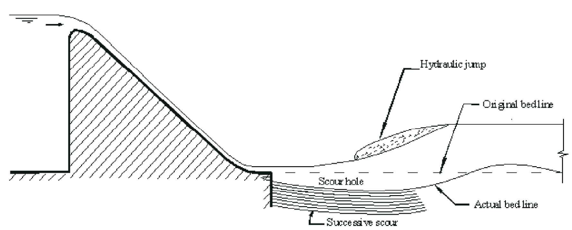

Fig. 1: Scour Process Downstream a Hydraulic Structure

To ensure both safety and durability of functioning such structures, the downstream bed should carefully protected against erosive effect.

Protection is generally made of concrete blanket laid on the downstream bed to a certain length. The length of bed protection, generally, depends on the permissible amount of scour ( length and maximum scour depth ) and the geotechnical structure of soil involved (densely or

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loosely packed sand ) [1]. Scour dimensions, length and depth, mostly depend on the energy of the falling flow as well as on the tailwater depth.

To protect the stream bed against scour, it is recommended to extend the structure apron to a distance equals the length of scour hole [2]. Such a protection length, however, reduces scour dimensions, it will not prevent scour. This may refer to that elimination of scour hole effect increases the required length of protection, since acts as a tranquilling water cushion. Based on the critical velocity equation [3], the safe length of protection was defined as that length extends to section at which the bed velocity of flow is less than the critical velocity.

Protection length, based on the critical velocity criteria gives 50% increase than that based on scour hole geometry [4]. The critical velocity, here, is defined as that velocity of flow below which scour will not occur. On the other hand, the formed jump and eddies should completely finish within the solid floor so that the velocity may regain its normal distribution.

Thus, to protect the downstream bed against scour, according to the above conditions, the structure floor will be too long. From the practical point of view, it was so expensive to construct long concrete aprons to guarantee safety against scour. Therefore, investigators focused their attention to weaken the flow velocity and inturn reduce its energy, using energy dissipators, to shorten the floor length required for protection.

The operation of energy dissipators mainly depends on expending a part of the flow energy by creating external friction between the flow and channel boundary or between water and the air and by the internal friction and turbulence. To achieve this purpose, different methods have been used such as; stilling basin provided with some appurtenances, counter flow and jet diffusion. Stabilizing the formed hydraulic jump, as possible close to the structure, may decrease the floor length. This refers to that the hydraulic jump is a useful mean to dissipate energy in supercritical flow passing over spillways, chutes and weirs or below sluices. To stabilize the hydraulic jump, stilling basins may be constructed to improve its performance. To increase its efficiency, stilling basins should be provided with some appurtenances such as; chute blocks, baffle piers, intermediate and end floor sills. From one hand, such precautions may increase the turbulence of flow and inturn decrease its velocity. On the other hand, these appurtenances may locally elevate the tail water to control the jump very close to the structure or even to drown it.

**The above Methods, However, May Ensure Dissipation of Energy to a Certain Extent, Some Defects May Arise as Follows :**

- Concrete blocks may be subjected to cavitations and abrasion at high values of velocity or when heavy sediment, debris or ice is existed in the flow. Where cavitations pressures are present, conditions are most severe on the sides of baffle. In addition, it may cause erosion to the top surface of the floor.
- JEt diffusion may be used only for small discharges. In addition, such process may need to very complicated mechanisms which increase total costs.

Therefore, a good design of a stilling basin should satisfy the following requirements: (i) high efficiency in dissipating energy, (ii) necessity of low tailwater level, (iii) compactness and economical design of structure, (iv) stability of the process under variable discharge and (v) safety against cavitation and erosion. For structures having great water energy, specially dams, chutes and weir spillways, the above traditional methods may not be efficient and more costs would be paid. Therefore, in the present study, a reversed cross jet flow dissipator is presented to dissipate the energy of flow falling over inclined surfaces of structures having high potential head of water and shallow tail water depth. Flow over inclined surfaces may met its application in dams,ogee weir, or chute spillways, since the back face of such structures has an inclined surface. In the present study, the ogee weir spillway is chosen to satisfy this purpose and to be handled in both analytical and experimental studies.

The presented technique,in the present work, mainly depends on dividing the headwater flow into two jets ; the first is the main flow which flows over the inclined surfaces, while the other passes through a water way, connected to the transverse slot, so that water can flow upwardly through the slot, creating a reversed cross jet, to hammer the main flow, as shown in Fig. 2. This leads to decrease of the main flow velocity and in the same time increasing the tailwater depth resulting in a formation of perfect forced jump instead of free repelled jump. Thus, the length of floor can be reduced to a large extent.

The problem presented here was handled analytically and experimentally. In the analytical study, both the energy and the momentum as well the continuity equations were used to develop theoretical equations for the conjugate depth ratio and the relative energy loss as well as the limiting condition of a perfect hydraulic jump. The experimental study was behaved to study the effect

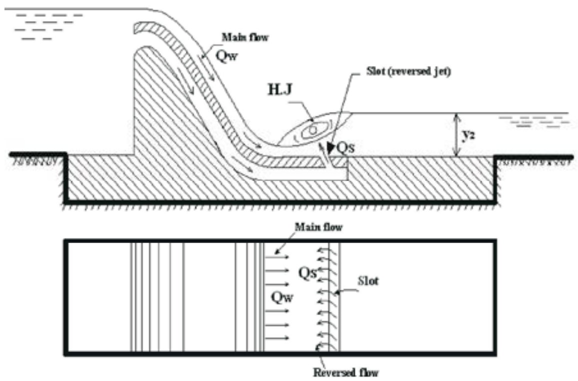



Fig. 2: Definition sketch for the proposed cross jet dissipator

of the considered parameters on the characteristics of the forced hydraulic jump either perfect or drowned. The experimental measurements was used to check the developed equations and to estimate some coefficients included in these equations. Results of the present study showed that the suggested cross jet dissipator possesses a good efficiency in dissipation water energy. It can reduced the stilling basin length to a large extent compare to case without cross jet. In addition, the cross jet dissipator creates a loss in the flow energy but to a small extent.

**Analytical Study:** This section deals with the theoretical treatment of the problem under consideration concerning with the energy dissipation of flow over an ogee weir spillway.The analytical solution aims at predicting theoretical equations including the parameters involving in the problem.These equations may give an estimation for the conjugate depths relation in the case of a forced hydraulic jump. To get the conjugate depths equation, the contracted depth at the toe of the ogee weir as well as the discharge of the slot should be priory found. The basic equations of flow ; energy, momentum and continuity equation were used to develop the theoretical solutions. The back face of an ogee weir spillway represents an inclined surface. Therefore, the cross jet dissipator is applied to dissipate the energy of flow downstream the ogee weir spillway.

**Determination of the Contracted Depth:** The flow depth at the toe of a weir, or the toe depth, is the contracted depth behind the spillway. The toe depth should be accurately estimated since influences various downstream conditions, such as ; flow velocity, Froude number, the characteristics of the formed jump and the design of any required measures for energy dissipation. The depth of flow at the toe is usually obtained using graphs for certain values of the velocity coefficient $C_v$. Some procedures solve the energy equation using trial and error technique for assumed values of the coefficient $C_v$ which causes difficulties, [5]. Other techniques used the energy equation but neglecting the energy loss ($C_v$=0) which leads to a great mistakes in determining the contracted depth.

In the following, the procedure presented by Abourohim, [5] to determine the toe depth, is illustrated.

The contracted depth ($y_c$) can be obtained by applying the energy equation (Bernoulli's equation) between the approaching section 1-1 and the contracted section 2-2 at which the contraction of flow occurs we get the contracted depth in submerged and free flow condition respectively as follow ;

$$y_c = \frac{H_0}{3}\left[1 + 2\cos\left(\frac{\gamma}{3}\right)\right], \text{gives values of } y_1 > y_c \qquad (1)$$

$$y_c = \frac{H_0}{3}\left[1 - 2\cos\left(\frac{\gamma}{3} + \frac{\pi}{3}\right)\right], \text{gives values of } y_2 < y_c \qquad (2)$$

Where: $\cos\gamma = \left(1 - \frac{6.75}{C_v^2}\left(\frac{y_{c_r}}{H_0}\right)^3\right)$

Using the experimental data, Abourohim [5] presented an empirical formula to estimate the velocity coefficient $C_v$ in the form ; for values $C_v = 1.0 + 0.07 \ln\frac{H_w}{p}$ of $0.05 < \frac{H_w}{p} \le 1.0$ .

**Experimental Study:** The problem of energy dissipation is of a great importance since concerned with the protection of hydraulic structures constructed in various practical situations. The nature of problem, the various parameters involved in the problem, the tailwater condition and the shape of the used dissipator dictate the experimental procedure to be nearly the best solution, which is confirmed through the above literature review. Dissipation of energy using the cross jet, in the present study, is based on dividing the flow into two portions ; the main flow flowing over the spillway $Q_w$ and the cross flow jet issuing from the slot $Q_s$. Both the two flows are affected by the same headwater depth.

The reversed flow, $Q_s$, transversely strikes the main flow falling over the spillway, $Q_w$, in the tailwater channel downstream of weir toe and hence decreases its velocity.The problem, however, is theoretically handled, some coefficients are to be determined using the experimental data.In addition, the effect of the cross jet; width, location and angle of slot must be experimentally studied to obtain the proper design values of slot dimensions; width, angle and location. Therefore, the problem will be treated experimentally on a physical model of a spillway having an inclined surface. The ogee weir spillway is chosen to satisfy this purpose, since it's back face is an inclined surface. The model was installed in the experimental set up prepared at the laboratory of fluid mechanics, Faculty of Engineering, Al-Mergheb University, Al Khoms, Libya.

**Experimental Set-up and Arrangement:** Experimental work was conducted in the experimental set-up specially prepared to study the effect of the main parameters concerned with the cross jet on the characteristics of the formed hydraulic jump considering the following three cases :

- Free perfect jump, without cross jet,
- Forced perfect jump, with cross jet and
- Drowned jump, with cross jet.

**Water Depth Measurement:** The headwater depth, $H$,was measured using a piezometric tube, fixed on a vertical scale of 0.50*mm* accuracy and connected to the bottom of the testing flume by a rubber tube. The contracted depth $y_c$ or the initial water depth, $y_1$,was measured using a point gauge provided with a vernier to obtain an accuracy up to 0.10*mm*, as shown in photo 3.

**Discharge Measurement:** The discharge was measured by a sharp edged rectangular weir of width 17.0*cm* and height 5.0*cm*.The measuring weir is connected to the moulded channel which has 70*cm* long and 25.0*cm* wide, The head above the weir was measured using a point gauge having vernire of accuracy up to 0.10*cm*, as shown in photos 4, 5. The weir was calibrated using the volumetric method. As a result, the obtained discharge equation may be expressed as,

$$Q = 0.27485 * h^{1.578} \qquad (3)$$

Where ;

$Q$ =discharge, (*lit/sec*) and
$h$=head over weir

**The Experimental Procedure**

**Case of Perfect Free Jump:** The pump is turned and the control valve is opened to a certain limit to obtain a constant values of the discharge passing over the weir spillway, where $Q_w$= 0.5,1.0,1.50,2.0 and 2.50cm, corresponding to a headwater depth $H$= 45.70, 46.98, 48.05, 48.98 and 49.85*cm*, respectively. For every discharge the contracted section is singed and the contracted depth and its distance from the weir toe, $x_c$, were measured. The length of the jump, $L_J$, was measured using a horizontal scale.

**Case of Drowned Jump:** Considering a constant values of both slot width b=0.15*cm* and inclination angle $\theta$= 15°, the slot location was fixed at distances $x_s$=5, 10, 15, 20, 25 and 30*cm*. Considering $x_c$ =5.0cm the pump is turned and the control valve is adjust to give the same headwater depth, $H$, used in case of free jump. In this case, the discharge passing over the weir spillway, $Q_w$, remains constant as considered in case of free jump. Due to the effect of the discharge issuing from the slot, $Q_s$, the tailwater depth increases creating a drowned jump. Then, the tailwate depth, $y_2$ and the length of the drowned jump, $L_D$, were measured.

**Case of Perfect Forced Jump:** Using the tail gate, the tailwater depth was gradually reduced until the jump front is being immediately at the contracted section. Here,the initial depth, $y_1$, (or the contracted depth, $y_c$) still at the same value found in case of free jump since, $Q_w$ , is not changed. The tailwater depth, $y_2$ and the length of forced jump, $L_J$, are then measured. The head on the rectangular weir is measured and the discharge, $Q_T$, is then estimated using Eq. (3). The discharge issuing from the slot, $Q_s$, is then found since $Q_s$=$Q_T$-$Q_w$. Steps above are repeated for other values of the headwater depth, $H$. Considering another values of the slot distance, $x_s$, steps above are repeated. Fixing the slot location at distance $x_s$=15cm and considering slot width b=0.15cm, the inclination angle of the slot, $\theta$, is taken equal to 15°, 30°, 45°, 75°, 90°, For each of the above values of, $\theta$, the procedure is repeated. Fixing the slot location at distance $x_s$=15*cm* and considering the inclination angle of slot, $b$= 0.15*cm*, the width of slot, $\theta$, is varied as $x_s$=0.15, 0.20, 0.25, 0.30. Considering each of the above values of slot width, $b$, steps above are repeated. It should be noticed that, a sufficient time was allowed to satisfy a steady state condition of flow before recording the measured values.

Fig. 3, shows the parameters affecting the hydraulic jump characteristics.

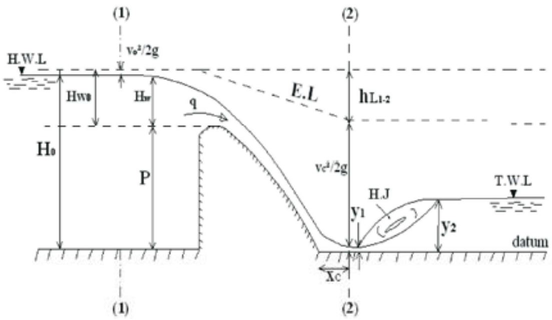



Fig. 3: Determination of the contracted depth.

**Photo (1)**

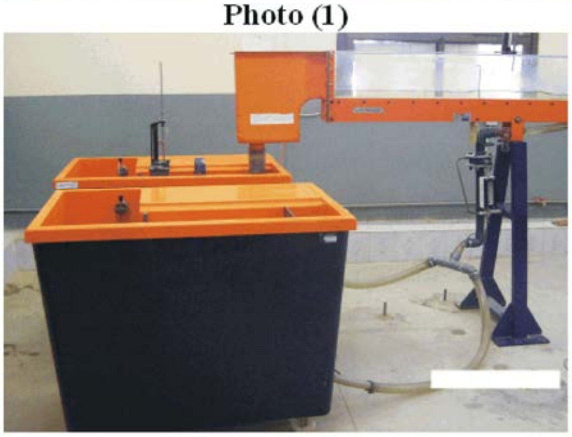


**Photo (2)**

Photos (1 . 2 , 3 ) components of the experimental set up.

**Analysis of Results and Discussion:** This section deals with the analysis and discussion of the obtained experimental results that describe the effect of various parameters on the characteristics of the hydraulic jump formed downstream of an ogee weir spillway. Referring to Fig.4, cases of perfect free, perfect forced and drowned jump have the same conditions of flow upstream the contracted section, wherever; $x_s > x_c$ the head water depth $H$, the head over the weir crest $H_W$ and discharge passing over the weir $Q_w$.

Photo(3)

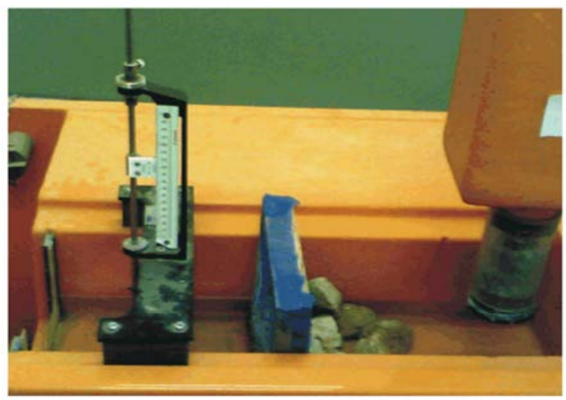


**Photo (4)**

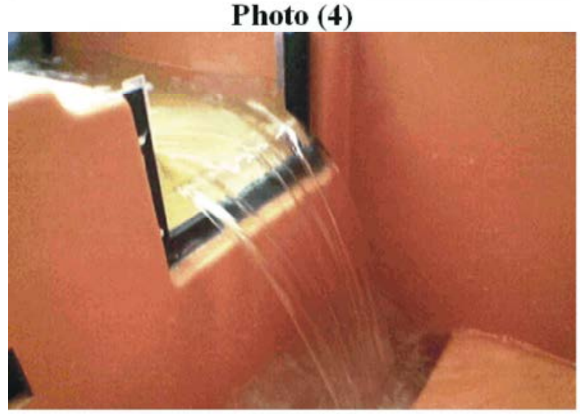


**Photo (5)**

Downstream the contracted section, the above cases have different conditions ; the total discharge $Q_T$ and the tailwater depth $y_2$. In case of free jump, where $Q_T$= 0.0, the total discharge $Q_T$ equals the weir discharge $Q_w$, or $Q_T = Q_w$ while $Q_T = Q_w + Q_s$ in case of forced jump, where $Q_s$ is the discharge passing through the slot.

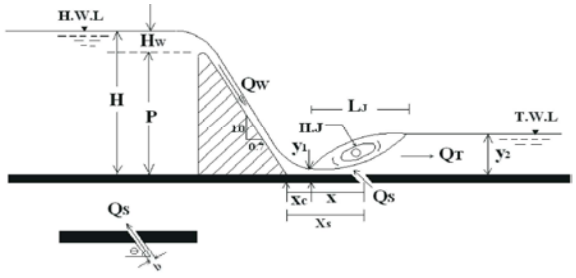
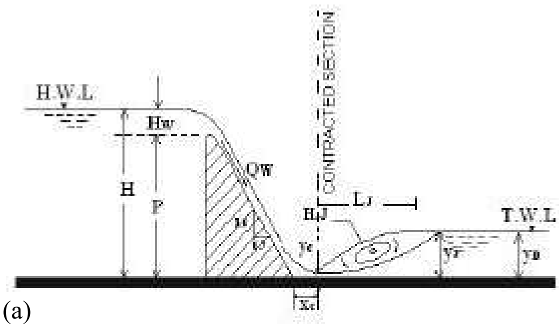
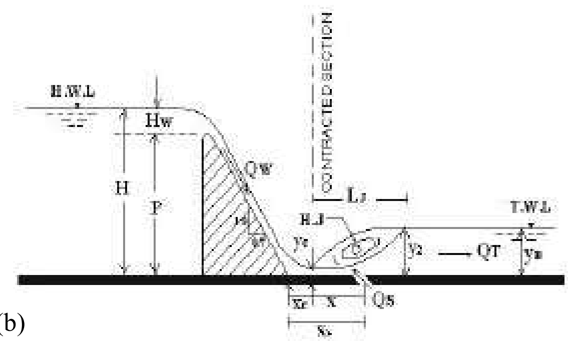


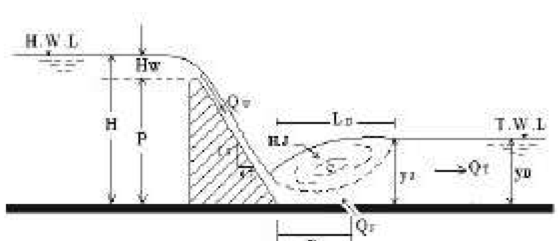

Fig. 4 details of dissipater model




(a)




(b)




(c)

Fig. 4: Definition sketch for the formed hydraulic jump; (a) free perfect jump, (b) forced perfect jump , and (c) drowned jump .

**Analysis of Results, in this Section, Includes the Following Items :**

- Characteristics of the perfect free jump,
- Effect of the considered parameters on the characteristics of the perfect forced jump,

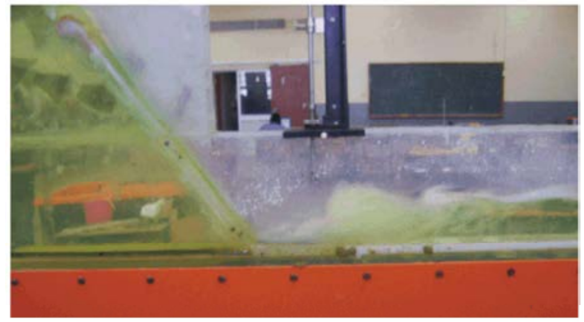


Photo (6)

Photo (7)

- Effect of the considered parameters on the drowned jump,
- Effect of the considered parameters on the discharge characteristics of the slot.
- Comparison between analytical and experimental results,

## DISCUSSION

It is found, from the analysis of the obtained results, that the reversed cross jet can create a forced perfect jump starting at the contracted section. The efficiency of the cross jet is being maximum when the cross jet is located within the jump length, as possible close to the contracted section. This may refer to that concentrating the jet close to the contracted section will increase the slot discharge and in turn increase the horizontal component of the momentum of the cross jet which hammers the main flow since directed against the main flow. Therefore, the slot distance $x_s$ should exceed the location of the contracted section $x_c$, but with small extent to avoid existence of splashing jump. Concentrating the cross jet at the contracted section or before it will create a splashing jump, as shown in Photo 6. On the other hand, when the cross jet is located behind the jump end a negligible effect is obtained on the jump characteristics.

It is also noticed that increasing the slot width beyond the tested values will produce an over head jump, as shown in Photo 7. This is because that increasing the slot width will increases the jet discharge which in turn increase the horizontal component of the jet momentum, acting against the main flow. This makes the momentum resultant of the two flows to be directed upward causing an over head jump which increases the length of jump compared to those obtained for lesser widths.

From the obtained results the maximum relative width of slot $b/y_1$, beyond which an overhead jump is formed, is found as $b/y_1 \approx 1$. Therefore, the jet width $b$ should not exceed the contracted depth to avoid occurrence of the overhead jump.

## CONCLUSIONS

A comprehensive analytical and experimental study had been conducted, in the present work, on the cross jet flow when used to dissipate the energy of the flow falling over an ogee weir spillway since it's back face presents an inclined surface. The obtained results insure that control of the hydraulic jump, formed downstream of an ogee weir spillway, is possible using the reversed cross jet dissipator. The suggested cross jet dissipator can be used to convert the repelled hydraulic jump not only to a perfect jump but also to a drowned jump and hence reduces the length of solid floor to a large extent. In addition, the tailwater depth could be reduced to about 77% of its original value at the same Froude number $F_1$ and the same initial depth $y_1$, of the falling flow, using the reversed cross jet.

Based on the analysis and discussion of both analytical and experimental results, obtained in the present study, the following conclusions may be given as follows :

- The suggested cross jet dissipator can create a perfect forced jump starting at the contracted section.
- Locating the cross jet flow within the length of the forced perfect jump, as the possible close to the contracted section, gives the minimum values of both the conjugate depth ratio and jump length and the maximum values of the energy loss.
- Location of the cross jet with an inclination angle $\theta = 45°$ gives the minimum values of both conjugate depth ratio and jump length and the maximum values of the energy loss.
- Increasing the slot width results in a decrease in the conjugate depth ratio, a decrease in the jump length and a slight increase in the energy loss. The value of the jet width should not exceed the value of the contracted depth otherwise on overhead jump will occur.
- The cross jet flow shortens the length of the solid floor, required for a repelled jump, by 79% while the reduction in the jump length itself amounted to 19%.
- The cross jet flow results in a slight increase in the energy loss, about 5% when $\theta = 45°$.
- The cross jet flow gives a decrease in the conjugate depth ratio up to 23% of it's original ratio.
- The cross jet flow can shorten the length of the solid floor, by creating a drowned jump instead of a free perfect jump, to about 65%.

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