A Laboratory Study on Stilling Basin with Semicircular Rough Bed Elements

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ABSTRACT

In this research, a laboratory study of hydraulic jump properties was conducted by making small semicircular rough elements, which covered the stilling basin floor downstream of spillway. The objective of this research was to introduce and make a comparison of roughed bed hydraulic jump stilling basin by using semicircular rough elements. To reach such an idea, a new expression was first developed for sequent depth and hydraulic jump length. Then, hydraulic jumps were conducted on a bed of prismatic roughness elements in a rectangular flume in order to investigate the jump effect on the characteristics of stilling basin. The rough elements are positioned on the bed of the flume downstream of an Ogee spillway in such a way that the incoming water jet is just skimming above the elements' top surface. Each rough element shape was tested under different Froude numbers, ranging from 4 to 11. In each test, the water surface profile, the roller length and the jump length were measured. The experimental results showed that the presence of a rough element increases the shear force and consequently reduces the jump length and the sequent depth of flow. Comparison of the results with those of previous studies showed that using beds roughed with semicircular shaped elements can decrease the length of the stilling basin by 56% of any regular basin and the sequent depth of the jump by 25% of a comparable one occurring on a smooth bed. Also, the average value of energy dissipation was computed and found to range between 68.1% and 60.4% of stilling basin of type I developed by Peterka (1978).

KEYWORDS: Stilling basin, Hydraulic jump, Semicircular rough bed elements.

INTRODUCTION

Hydraulic jump stilling basins are types of irrigation structures which are constructed downstream of chutes, gates and spillways to dissipate excess energy. The dimensions of such structures depend on the jump length and the sequent depth of the jump. During the past decades, many attempts have been made to reduce the size of such structures by forcing the jump to occur within a short distance of the apron using baffle blocks and end sills. According to a classification introduced by Peterka (1978), there are five categories of hydraulic jumps depending on Froude number at the upstream side of the jump. He conducted extensive experimental tests and introduced four types of hydraulic jump stilling basins; USBR types I, II, III and IV. In addition, a SAF stilling basin similar to USBR type III basin has been tested. In these types, the main problem which is caused by the flow impacting the floor block is the cavitation problem which causes the damage of the basin. Bestawy (2013) studied the effects of various shapes of baffle piers downstream of a spillway model on the dissipating water energy downstream and the scour hole. Results showed that the models with concave surfaces had better performance than other models discussed in his research, where this model had low turbulence intensity in recirculation zone downstream baffle piers and dissipated more energy than other models, which led to

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a stable hydraulic condition and shorter stilling basins.

In an attempt to develop economic stilling basin structures, Hughes and Flack (1984) carried out experimental tests on hydraulic jumps over a bed of block elements and found that boundary layers would develop faster and the jump dimensions would decrease considerably. Mohamad Ali (1991) performed a series of experiments on a rough bed using cubed block elements and found that the hydraulic jump length is reduced, ranging from 27.4% to about 67.4% for F1 ranging from 4 to 10. Alhamid (1994) conducted experiments on a horizontal rectangular channel bed using rough wooden blocks over a fixed length with different densities. Ead et al. (2000) performed tests on turbulent open channel flow and coducted hydraulic jump tests on a bed of trapezoidal-shaped corrugated roughness. Their results indicated that the integrated shear force in rough bed is ten times that in smooth bed. However, the studies of Ead et al. (2000), Ead and Rajaratnam (2002) and Izadjoo and Shafai-Bejestan (2007) indicated that if the rough elements are placed on the bed, the jump occurs above the rough elements. In other words, if the crest of the rough element is just below the lower level of the incoming jet, the elements would not protrude into the flow and will not cause any cavitation. Therefore, it is the purpose of this study to investigate the effects of semicircular shapes of artificially rough elements on the sequent depth and length of hydraulic jumps.

MATERIALS AND METHODS

Dimensional Analysis

Based on the resultant hydraulic jump produced by the overflow coming from the Ogee spillway as shown in Figure 1, we can assume that the functional relationships f_o and f_l of the sequent depth of jump (y_{2R}) and the length of hydraulic jump (L_{jR}) on a roughed bed with semicircular baffle blocks are dependent on the flow depth of pre-jump (y_1), the incoming flow jet velocity (v_1), the fluid characteristics such as fluid density (ρ) and fluid viscosity (μ) and the acceleration of gravity (g). In this study, only the shape effects on the hydraulic jump properties are studied with constant dimensions and distances of the roughing elements were used, so the spacing between them, as well as the arrangement, are not included in the dimensional analysis. In mathematical form, the functions f_o and f_l can be written as:

$$y_{2R} = f_o(y_1, v_1, \mu, \rho, g) \quad \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

$$L_{jR} = f_1(y_{2R}, y_1, v_1, \mu, \rho, g) \quad \ldots\ldots\ldots\ldots\ldots\ldots (2)$$

Buckingham's π-theorem was used to develop a dimensionless equation, in which repeated variables y_1, g and ρ were selected. The dimensionless form of equations (1) and (2) is:

$$\frac{y_{2R}}{y_1} = f_o(F_{r1}, R_e) \quad \ldots\ldots\ldots\ldots\ldots\ldots (3)$$

$$\frac{L_{jR}}{y_{2R}} = f_o(F_{r1}, R_e) \quad \ldots\ldots\ldots\ldots\ldots\ldots (4)$$

where F_{rl} and R_e are the Froude and Reynolds numbers at the upstream section of the jump, respectively. In this study, the Reynolds number during the experimental tests was made greater than $2.4*10^6$; therefore, the effect of Reynolds number can be assumed negligible. So, the final expressions for sequent depth and length of the basin can be written as:

$$\frac{y_{2R}}{y_1} = f_o(F_{r1}) \quad \ldots\ldots\ldots\ldots\ldots\ldots (5)$$

$$\frac{L_{jR}}{y_{2R}} = f_o(F_{r1}) \quad \ldots\ldots\ldots\ldots\ldots\ldots (6)$$

Equations (5) and (6) are general expressions for the sequent depth and length of hydraulic jump for the stilling basin over the roughed bed with semicircular elements. To determine the coefficients of these relations, experimental tests were conducted which are discussed later.

Experimental Work and Program

For the purpose of this study, an experimental work was carried out using a rectangular laboratory flume at the hydraulic laboratory of Faculty of Engineering/Kufa University (An-Najaf, Iraq) in winter 2015. The flume was 15 m long, 0.3 m wide and 0.4 m deep, with plexiglas sides and stainless steel bed. An Ogee spillway was installed at 4.5 m from the upstream end of the flume to produce a hydraulic jump in the downstream. Figure 2 (a & b) shows a plan view and cross-section of the experimental facilities. The semicircular roughness elements were glued to the bed of flume downstream of the spillway in such a way that the crests of elements were at the same level as the downstream end of the spillway as shown in Figure 1. The first line of bed elements in all testes was positioned at 25 cm from the toe of the spillway to control the jump position before the bed elements in order to use the pre-jump depth (y_1) in calculating the post-jump depth (y_2) for the smooth stilling basin type I from the classical sequent depth ratio. This means that the roughness elements are not acting as blocks and are not directly subject to the incoming jet. The roughness elements act as depressions in the bed to create more turbulent eddies which will increase bed shear stress. The semicircular roughness element shape was tested under different Froude numbers ranging from 4 to 11. Figure 1, Figure 2 (a & b) and Figure 3 show the arrangement of the semicircular roughness elements which have been studied. These elements were made from PVC pipe with a height of 27 mm and outside and inside diameters of 25mm and 16mm, respectively.

A movable calibrated sharp crested weir was used to measure the flow discharge at the end of flume in each experiment. A tailgate was used to control the tail water depth in the flume. In all tests, the tailgate was adjusted so that the jumps occurred either at the start of rough elements or at the downstream end of the spillway for smooth bed case.

The experimental procedure was started by letting water enter the flume gradually. When the desired discharge was achieved, the tailgate was gradually closed until the water reached the desired depth. This situation was kept constant for enough time to take the required data. Usually, the water surface profile along the jump, the roller length and the jump length were measured in each test. Hydraulic length is the horizontal distance from the beginning of the jump to the section beyond which the water surface is horizontal. The roller length is the horizontal distance from the beginning of the jump to the roller end that can be determined by a float to recognize the stagnation point.

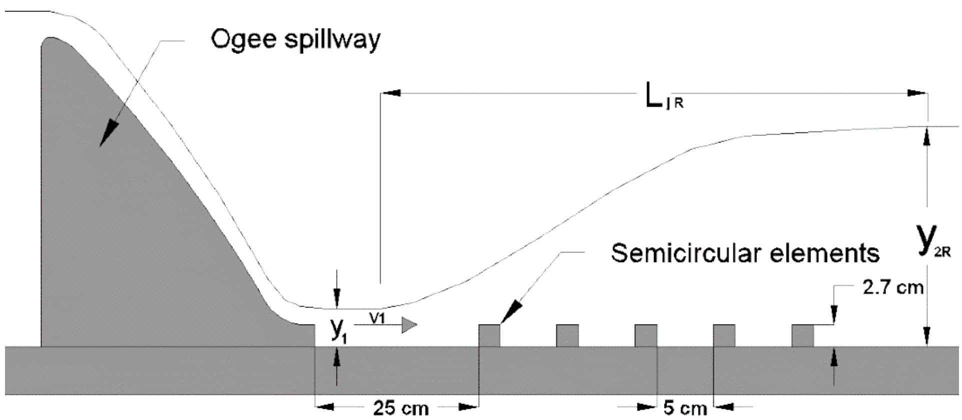

Figure (1): Longitudinal section in the region of hydraulic jump over semicircular roughness elements

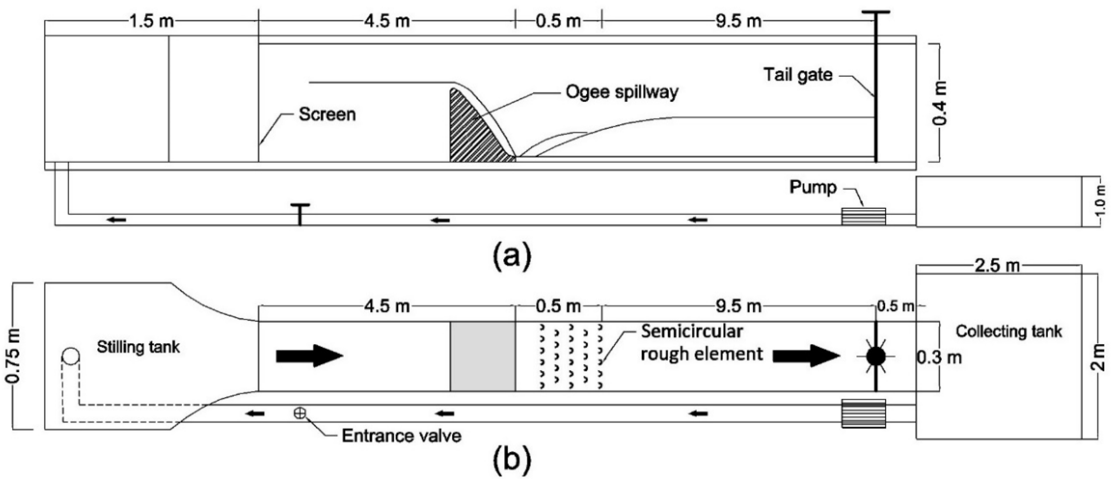

Figure (2): Experimental flume (a) longitudinal section view and (b) plan view

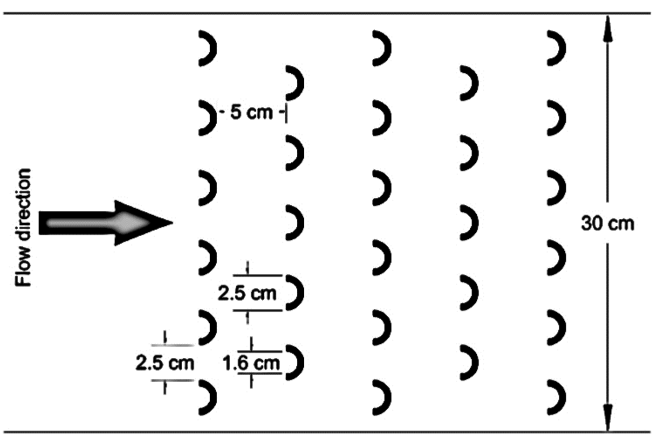

Figure (3): Arrangement of semicircular elements in this study

RESULTS

The required tail water depth and hydraulic jump length are the two main variables, which must be determined for the design of hydraulic jump basin. Using the experimental data, relations for computing these two variables for the new stilling basin were developed and are presented below.

Sequent Depth Ratio

Figure 4 shows the variation of sequent depth ratio *versus* Froude number. The best fitted expression which can be developed by regression analysis is as follows:

$$\frac{y_{2R}}{y_1} = 0.787F_{r1} + 1.2579 \qquad \ldots\ldots\ldots\ldots\ldots\ldots (7)$$

with $R^2 = 0.9817$. Equation 7 is limited to Froude numbers ranging from 4 to 11.

In Figure 4, the sequent depth to initial depth ratio of the classical hydraulic jump equation is plotted. Using equation 7, the required tail water depth for proper occurrence of jump in the new stilling basin can be determined. In addition, the results obtained were compared with those of Lozenge type rough bed elements, which were used by Mahmood and Neisi (2009). The variation of sequent depth ratio (y_{2R}/y_1) *versus* Froude number in this research showed a lower ratio of (y_{2R}/y_1) for the same Froude number value than for Lozenge type bed elements as shown in Figure 4. This indicates that semicircular elements have better performance than Lozenge type elements.

Jump Length

Figure 5 shows the variation of ratio of hydraulic jump length to sequent depth *versus* Froude number. The best-fitted equation from the experimental results is:

$$\frac{L_{JR}}{y_{2R}} = 3.7377\ \ln F_{r1} - 3.2462 \qquad \dots\dots\dots\dots\dots (8)$$

with $R^2 = 0.9783$. Equation 8 is limited to Froude numbers ranging from 4 to 11.

In Fig. 5, the variation of the ratio of hydraulic jump length to sequent depth for the USBR type I stilling basin has been plotted.

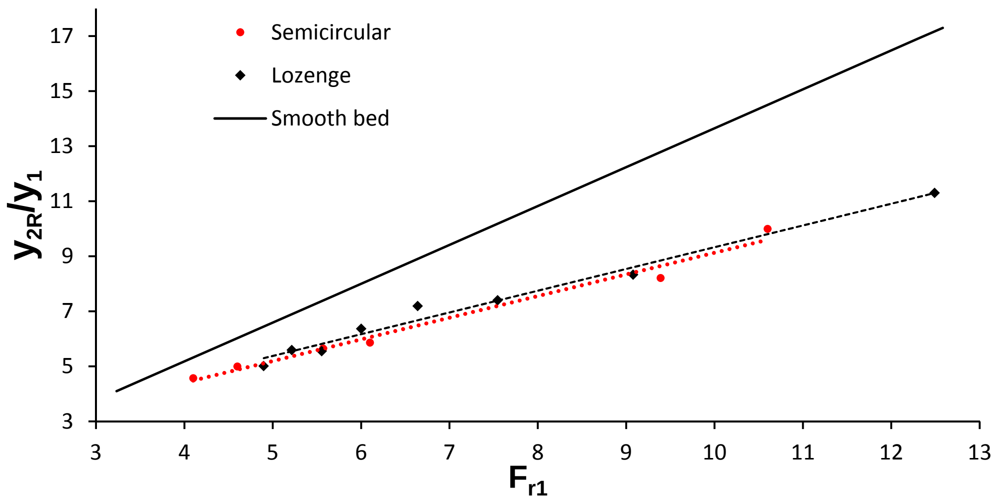

Figure (4): Sequent depth ratio *versus* Froude number

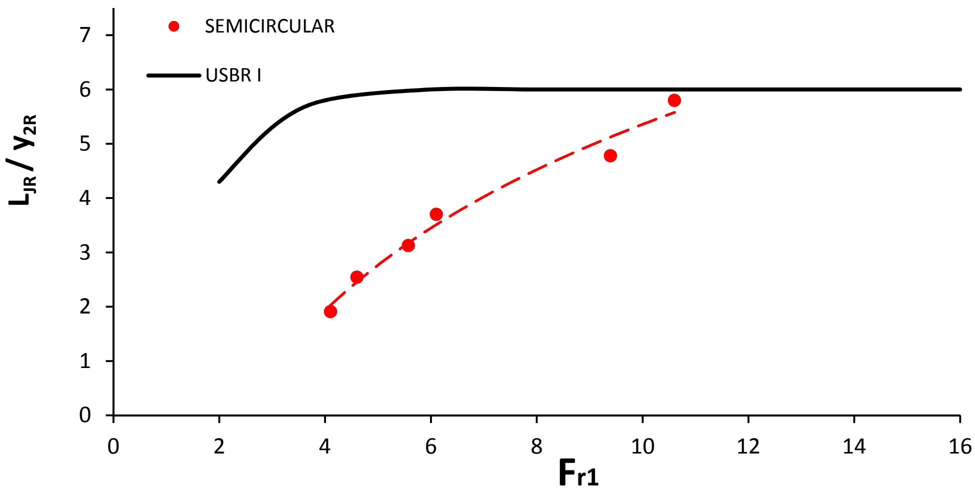

Figure (5): Stilling basin length *versus* Froude number

DISCUSSION

The main goal of this study was to introduce a new modified stilling basin using semicircular rough elements on the bed and make a comparison with other new stilling basin types with Lozenge rough bed elements studied by Bejestan and Neisi (2009). Generally, the dimensions of the new basin are found to be smaller than those of the existing basins. More discussion on the new basin is presented below.

1. Sequent Depth Ratio

As can be seen from Figure 4, the experimental data are located under the classical jump equation, which means that the sequent depth ratio in new stilling basin is always smaller than in classical jump. The amount of reduction depends on the Froude number. To see to what extent such reduction can occur, the magnitude of reduction was computed from the following equation:

$$D_* = \frac{y_2 - y_{2R}}{y_2} \qquad \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (9)$$

where y_2 and y_{2R} are the sub-critical depth of flow for smooth and rough beds, respectively. The average value of D_* was computed and found to be 24.9%. This means that the required tail water depth for proper hydraulic jump in new stilling basin with semicircular rough elements can be described as y_{2R}=0.751y_2. Comparison of the results of this study with those of previous studies shows that the required tail water depth for stilling basin type II is 0.83y_2 (Peterka, 1978), which means that semicircular shape rough elements introduced in this study can create more shear force than the blocks on type II USBR stilling basin. The D_* value of 0.249 found in this study is close to the D_* values obtained by Bejestan and Neisi (2009), Ead and Rajaratnam (2002) and Lzadjoo and Shafai-Bejestan (2007) for corrugated bed. D_* values found by these researchers were in the order of 0.24, 0.25 and 0.20, respectively. However, the main significance of using semicircular rough elements introduced in this study lies in that they are not subjected to the inflow water jets and therefore, cavitation will not occur.

2. Hydraulic Jump Length

As can be seen from Figure 6, the experimental data are located under the classical jump equation, which means that the jump length for jump of stilling basin with semicircular rough elements is always smaller than in stilling basin type I. The amount of reduction depends on the Froude number. To see to what extent such reduction can occur, the magnitude of reduction was computed from the following equation:

$$L_* = \frac{L_J - L_{JR}}{L_J} \qquad \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (10)$$

where L_J and L_{JR} are the jump length for stilling basin type I and the stilling basin with semicircular rough elements, respectively. The average value of L_* was computed and found to be 55.67%. This means that for hydraulic jump over semicircular rough elements, the length is reduced by approximately 56%. To compare the length of the stilling basin with semicircular rough elements introduced in this study with the lengths of four types of existing basins, such as USBR (Peterka, 1978) and SAF stilling basin, Figure 6 was plotted. As can be seen from this figure, the semicircular rough elements stilling basin length is shorter than the USBR type II when Froude number is between 4.0 and 6.5. For Froude number more than 6.5, the stilling basin length will be less than the USBR type I. The main difference of this semicircular rough elements stilling basin is that cavitation is no longer a problem in the stilling basin of the present study, since the semicircular rough elements are not subjected to the incoming flow jet.

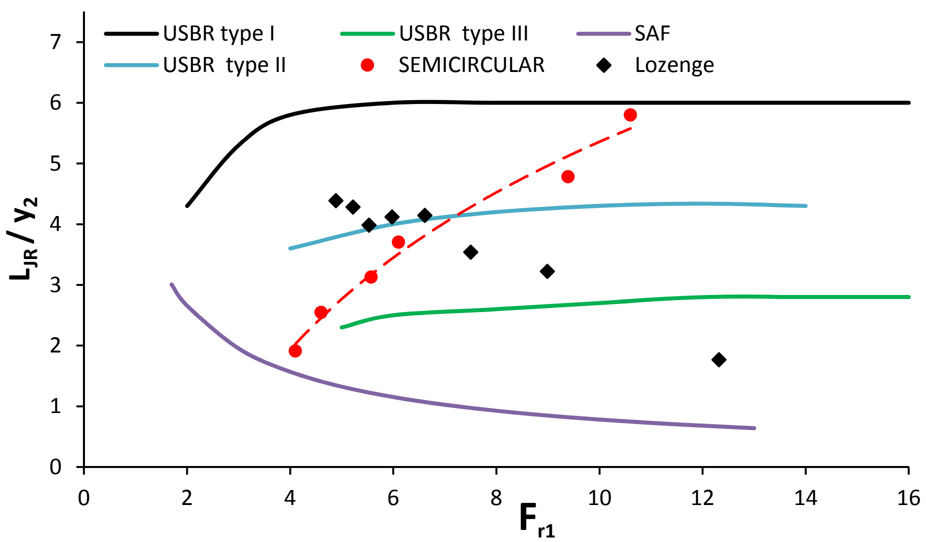

Figure (6): Length of semicircular rough element stilling basin compard to USBR, SAF and Lozenge stilling basins

3. Energy Dissipation

Discharge has a reverse effect on the behavior of semicircular elements in terms of energy dissipation. Figure 7 shows that when the Froude number increases, energy dissipation increases for smooth bed and semicircular roughed bed. It is obvious that energy dissipation by semicircular rough elements is always greater than energy dissipation in stilling basin type I. The magnitude of reduction in energy dissipation was computed from the following equation:

$$E_* = \frac{E_1 - E_2}{E_1} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (11)$$

where, E_* is the percent of energy dissipation, E_1 and E_2 are the energy of flow for pre-jump and post-jump depth in stilling basin type I and stilling basin with semicircular rough elements. The average values of E_* were computed and found to be in the order of 68.1% and 60.4% for semicircular rough elements and stilling basin type I, respectively. This means that energy dissipation for hydraulic jump over semicircular rough elements is higher than in stilling basin type I. The semicircular elements model M1 gave good results of reducing the scour-hole and consequently has good energy dissipation compared to most of the other models tested by Bestawy (2013).

CONCLUSIONS

In this study, developing and comparing of a hydraulic jump stilling basin with semicircular rough bed elements covering the basin floor downstream of Ogee stilling basin have been carried out. The results of experimental tests showed that the tail water depth and hydraulic jump length of stilling basin with semicircular rough bed elements are lower than in the comparison basins (USBR TYPE I, II, III, IV and SAF type). The reduction of required tail water depth is about 25% and the hydraulic jump length is reduced by about 56%. The aeration of water at the transition of flow from super-to sub-critical flow where jump occurs is very high because of very high shear stress at the rough bed boundary. The semicircular rough bed elements do not create any cavitation, since the semicircular rough elements are not subjected to the incoming flow jet. Also, in this study, the reduction in the hydraulic jump length is greater than 15% compared to that of the Lozenge type with the same conditions of Froude number range which was used by Bejestan and Neisi (2009).

Also, the average values of energy dissipation were computed and found to be 68.1% and 60.4% for semicircular rough elements and stilling basin type I, respectively.

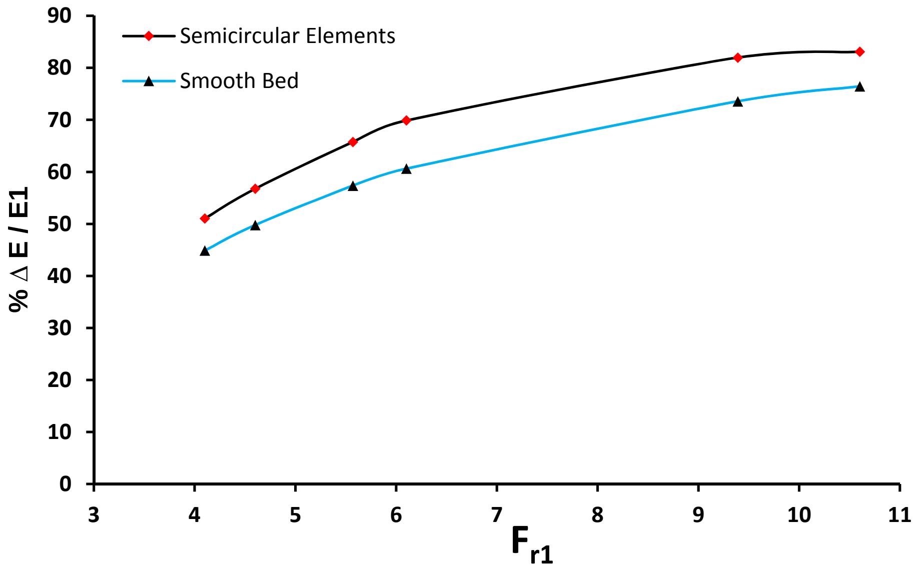

Figure (7): Variation of energy dissipation with flow rate

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