Instrumentation Mesure Métrologie
Vol. 23, No. 1, February, 2024, pp. 55-61
Journal homepage: http://iieta.org/journals/i2m

Experimental Study of Energy Dissipation in Sudden Contraction of Open Channels

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https://doi.org/10.18280/i2m.230105

Received: 19 December 2023
Revised: 24 January 2024
Accepted: 2 February 2024
Available online: 26 February 2024

Keywords:
dissipated energy, sudden contraction, non-linear model, open channel, statistical analysis, dimensional analysis, hydraulic structures

ABSTRACT

The study of energy dissipation in hydraulic structures has an essential role in providing safety to these structures and providing plans to protect them during different releases of flow. The purpose of this research is to determine the impact of sudden constriction that occurs in open channels on the dissipated energy. Therefore, experimental work was conducted on models that were built based on dimensional analysis for the parameters impacting the dissipated energy in an open channel. Eighty experiments were conducted on these models. In each experiment, several readings for water depth were measured along the contraction zone. Through analyzing the laboratory results, several findings were established. First, it was found that the contraction length has an inverse effect on energy dissipation, with the energy dissipation increasing at the smallest contraction length. Second, the results obtained in the laboratory showed that the dissipation of energy increases with the increase in the discharge. Third, the greatest energy dissipation was obtained at the greatest amount of contraction, and the least energy dissipation was obtained at the lowest amount of contraction in all cases of flow and length of contraction. Finally, an empirical equation was built based on the experimental outcomes statically using the non-linear regression analysis in SPSS software. The calculated dissipated energy by the empirical equation showed a great fitting with experimental findings, and this was confirmed by statistical measurement of the Coefficient of Determination (R^2) and Nash-Sutcliff Efficiency (*NSE*), which they found 0.995 and 0.986, respectively.

1. INTRODUCTION

Flow control structures are frequently used to keep the kinetic energy under control; in certain situations, they even get some profit from it, like hydropower generation [1, 2]. These control structures should be able to safely deliver the design discharge and dissipate enough energy to safeguard the hydraulic structure and downstream channel from localized erosion and scour, among other functional criteria [3]. Energy dissipaters are crucial hydraulic structures that can be used wherever needed to reduce the surplus kinetic energy of the flow in a waterway. Energy dissipaters can take different types and shapes based on the need and utility of the hydraulic structure [4]. However, kinetic energy reduction in waterways can be achieved by utilizing several techniques and apparatuses [5]. A transition is a part of an open channel where a change occurs in a cross-section of a channel geometry and bed slope while keeping the flow transferred smoothly. This change in a channel section can be caused by changing the channel's width (contraction or expansion) or by raising or lowering the bottom of the channel [6].

Many laboratory experiments and theoretical approaches have been conducted to study the energy dissipation resulting from sudden contractions in open channels [7]. An early study addressed the impact of thin plate contraction positioned vertically in the channel axis. The observations of this study covered data involving several flow regimes. However, several key findings from the study were established; for instance, the increase in flow speed was due to contractions and caused an increase in turbulence [8]. The effects of contraction inlet angle and contraction ratio were investigated experimentally. The experimental work was implemented under the status of asymmetric contraction. The flow condition upstream of the contraction was subcritical, and the flow passed through critical flow through the length of the transition. The research results showed that reducing the contraction ratio and increasing the contraction inlet angle from 30 to 90 degrees decreased the contraction coefficient. The exit contraction angle had a small effect on the contraction coefficient [9]. A study of the effect of relative contraction on the discharge coefficient, which is the ratio of the amount of real fluid flow to the theoretical amount of fluid flow through the contraction zone, of subcritical flow during short contraction was performed experimentally. It was found that the discharge coefficient decreases with increasing relative contraction. The drop in discharge coefficient with higher relative contraction can be explained by the rise in cross-sectional area available for flow [10]. An experimental study was conducted to investigate the energy loss due to sudden contraction over the length of the transition period in inclined open channels. It turns out that the energy loss increases with increasing layer steepness. Lower contraction rates also lead to a higher reserve depth ratio and more energy loss [11].

Also, the study considered the energy dissipation of supercritical flow in sudden contractions. The different range of contraction was inspected experimentally. Experimental and numerical results show that as the Froude Number value increases, the energy dissipation increases. As standing water and flow depth grow downstream, the rate of relative energy contractions increases [12]. The analysis of flow characteristics through varied Channel contractions (Sudden, Transitional, and Radial) was studied experimentally. The results of this study showed that the water flowing through the constriction undergoes a certain energy change. It has been found that the maximum specific energy occurs during a sudden contraction compared to another two types of contraction in this study [13].

In summary, previous studies have highlighted the significant influence of sudden contractions on the dissipated energy in open channels. Therefore, the main aim of this study is to measure the change in energy due to the sudden change in the cross-section of the waterway. The current study is, in a way, a continuation of previous studies on the energy dissipation of different models of open channel contraction. However, some specific objectives of research questions could be addressed in this area to fill the gap from previous studies, like how does the contraction ratio affect the amount of energy dissipation? Can theoretical models and numerical simulations accurately predict the amount of energy dissipation in sudden contractions?

2. DIMENSIONAL ANALYSIS

Dimensional analysis is one of the most powerful mathematical tools for addressing complex scientific issues, especially when combined with experimental work. Dimensional analysis gives a guide to aspects that significantly impact the researched phenomenon [14]. The basic principle of dimensional analysis is that physical quantities can be broken down into fundamental dimensions such as Length (L), Mass (M), and Time (T), among others. Each physical quantity can then be expressed as a product of powers of the fundamental dimensions. Dimensional analysis can also help compare and generalize the results across different experimental or computational studies [15]. Identifying the most relevant dimensionless parameters makes it possible to perform parameter sweeps and determine the effect of various factors on the dissipated energy in open channels, as shown in Figure 1, with sudden contractions.

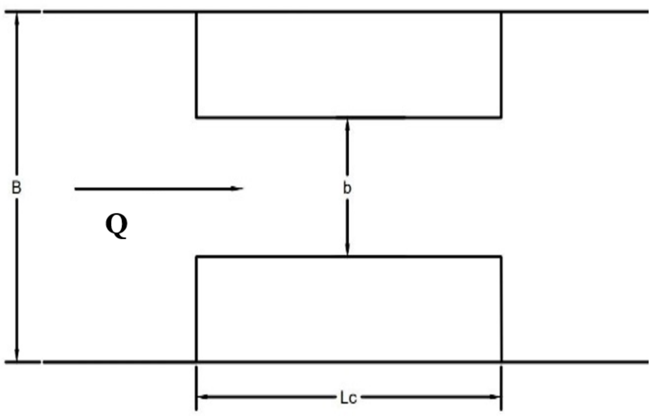

Figure 1. Definition sketch of the contraction area

In this research, using Buckingham's π-theorem technique will allow finding the relationship between variables and their effect on energy dissipation. Table 1 lists the dimensions for each variable that impacted the energy dissipation in this study.

Table 1. The dimensional analysis parameters in the MLT system

Variable	Definition	Dimension
Q	Discharge of water	$L^3 T^{-1}$
ρ	Mass density	$M L^{-3}$
g	Acceleration due gravity	$L T^{-2}$
B	Channel width	L
b	Contraction width	L
ΔE	Energy dissipation	L
L_C	Contraction length	L
y	Water depth	L

The general relation for important parameters on energy dissipation can be written as:

$$f_1(\Delta E, L_c, b, B, Q, y, \rho, g) = 0 \quad (1)$$

So, the number of variables is equal to 8. In contrast, the number of dimensions is equal to 3, which are M, L, and T. Thus, the number of $\pi = 8 - 3 = 5$; and if the variables (Q, ρ, B) are repeated variables that can be written the formula:

$$f_2(\pi_1, \pi_2, \pi_3, \pi_4, \pi_5) = 0 \quad (2)$$

$$\pi_1 = B^{a_1} Q^{b_1} \rho^{c_1} b \quad (3)$$

$$\pi_2 = B^{a_2} Q^{b_2} \rho^{c_2} L_c \quad (4)$$

$$\pi_3 = B^{a_3} Q^{b_3} \rho^{c_3} y \quad (5)$$

$$\pi_4 = B^{a_4} Q^{b_4} \rho^{c_4} g \quad (6)$$

$$\pi_5 = B^{a_5} Q^{b_5} \rho^{c_5} \Delta E \quad (7)$$

By performing a dimensional analysis of π_1

$$\pi_1 = B^{a_1} Q^{b_1} \rho^{c_1} b$$

$$\mathrm{M^0 L^0 T^0} = (\mathrm{L})^{a_1} (\mathrm{L^3 T^{-1}})^{b_1} (\mathrm{ML^{-3}})^{c_1} (\mathrm{L})^1$$

For M: $c_1 = 0$
For L: $a_1 + 3b_1 - 3c_1 + 1 = 0$; $a_1 + 3b_1 + 1 = 0$
For T: $-b_1 = 0$; $b_1 = 0$; $a_1 = -1$

$$\pi_1 = \frac{b}{B} \quad (8)$$

In the same way as the rest of the variables of the non-dimensional parameters are produced:

$$\Delta E = f(F_r, B, b, y, L_c) \quad (9)$$

Since the flow is considered a subcritical flow during the experimental work and the depth of flow upstream of the contraction portion (y) is a function of the total flow (Q), and the width of the channel (B) is constant during the experimental work; thus, the dissipated energy correlation in Eq. (10) can be rewritten as follows.

$$\Delta E = f(Q, b, L_C) \tag{10}$$

3. EXPERIMENTAL WORK

Laboratory experiments are conducted according to the need and type of research work to be completed. First of all, the Open Channel used in laboratory experiments is a typical open channel made of 4 mm thick iron for the base, and the channel walls are made of 10 mm thick plexiglass. Figure 2 represents the entire setup rig for the open channel and the contraction model in the laboratory channel and its attached parts and their dimensions.

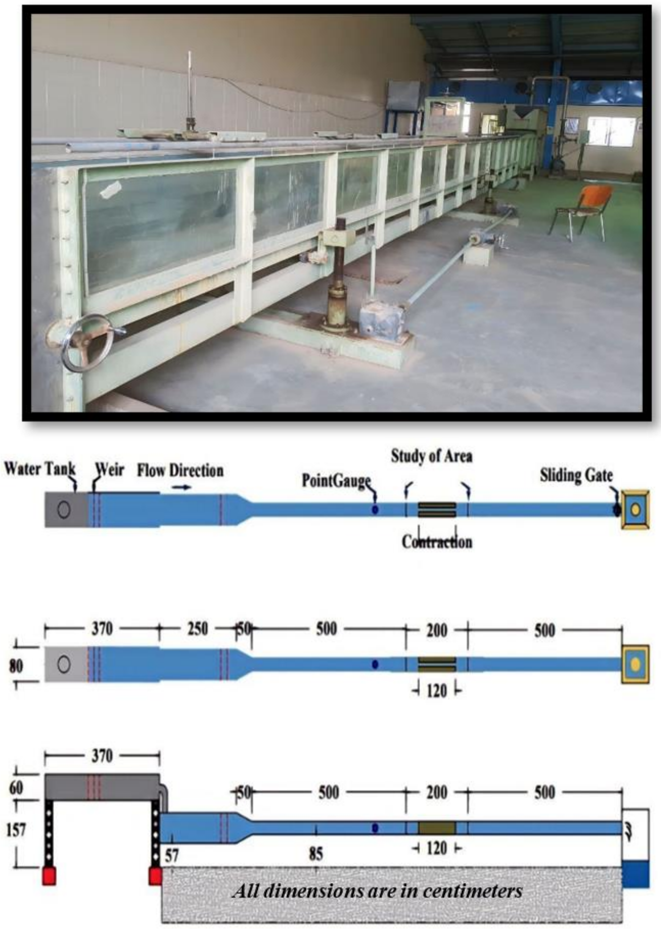

Figure 2. The channel's horizontal and lateral view and the contraction area's location

This study conducted the experiments using four different lateral contraction widths (b) of 25, 30, 35, and 40 cm. The model length (Lc) was changed four times for each contraction ratio as 120, 90, 60, and 30 cm. Then, a prototype, as shown in Figure 3, was locally manufactured and made from marine wood for the purpose of reducing the width of the channel cross-section. The contraction ratio is defined as the channel width at the contraction section to the original channel width. Thus, the prototype model is placed in the middle of the original channel during the test.

Eighty experiments were conducted on these models. In each experiment, several readings for water depth were taken. The depth of flow in the contraction area was measured using a measuring point gauge placed on the top of the channel. Readings were started to be taken 40 cm upstream until 40 cm downstream of the contraction zone. The depth of flow readings was taken every 10 cm along this distance. These readings were repeated three times, and the average of these readings was taken to make the results more accurate.

Furthermore, a connected flow meter to the pipes supplied the water to the open channel was used to measure the discharge that passed through the channel accurately. However, the flow meter is already validated by measuring the flow by a triangular weir installed at the outlet of the upper reservoir of the used open channel in this study. Figure 4 shows the flow meter and triangular weir that were used to measure the flow in this study.

Figure 3. The reduction of channel cross-section at the contraction area's location

Figure 4. The instrument for measuring the discharge

For all models, the total number of readings was around 280. Table 2 lists the dimension range for the variables investigated to check their impact and influence on the dissipated energy under sudden contraction status.

Table 2. The dimension range of effect variables

Contraction Width (b) (cm)	Contraction Length (Lc) (cm)	Discharge (Q) (m^3/hr)
40, 35, 30, 25	30, 60, 90, 120	55, 75, 95, 115, 135

4. RESULTS AND DISCUSSION

The pattern and nature of water flow inside the open channels vary due to the change in the cross-section of the convey channels. This variation in cross-section may occur gradually or suddenly along the waterway. Unlike the gradual contraction in the cross-section, the sudden contraction of the waterway significantly influences flow energy at this location of contraction in open channels. Therefore, the flow behavior, especially energy characteristics, must be investigated individually to understand the nature of this influence.

4.1 The influence of contraction width

The contraction width is defined as the channel width at the contraction region. Through the results obtained in the laboratory, it was observed that there is a clear impact on the energy dissipation produced by changing the width of contraction. Figure 5 shows a relationship between the percentage of energy dissipation and contraction width under different discharge scenarios.

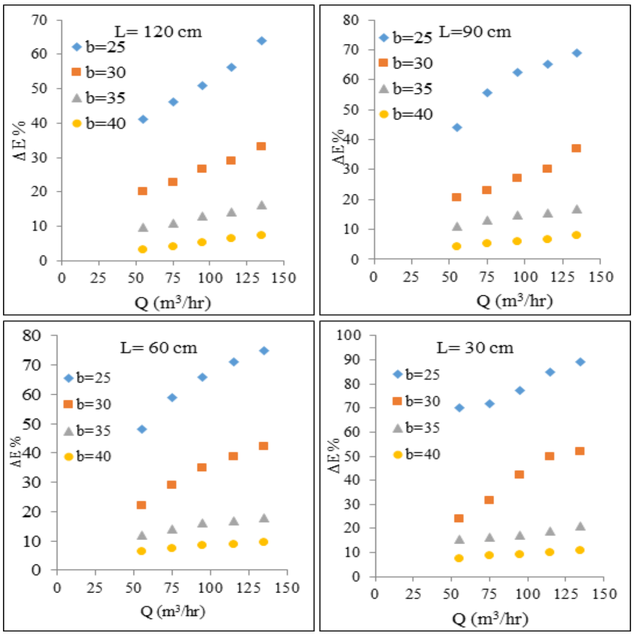

Figure 5. The dissipation energy due to different contraction width

The section contraction process in the open channel is accompanied by a change in the water motion resulting from the water trying to pass through the contraction portion with the same amount of discharge. Therefore, there is an acceleration in flow that will occur in this area. This acceleration is accompanied by a decrease in the water level within and along the contraction zone. Thus, the need for adequate energy to push the water will increase to achieve and maintain the law of conservation of mass. According to these results, the greatest energy dissipation was obtained at the greatest amount of contraction, and the least energy dissipation was obtained at the lowest amount of contraction. The greater the percentage of contraction, meaning that the width of the constriction area becomes smaller compared to the original width of the channel, will lead to a need for tremendous energy consumption to pass the water. This loss of water energy while trying to pass through the constriction area is required to ensure that the phenomenon of chock does not occur.

4.2 The influence of discharge

The results obtained in the laboratory shown in Figure 6 showed that the dissipation of energy increases with the increase in the discharge. The highest values of energy dissipation are at the maximum discharge (135 m^3/hr), and the lowest values of energy dissipation are at the minimum discharge (55 m^3/hr). It has been proven that energy losses are directly proportional to passing discharges; energy losses increase with increased discharge.

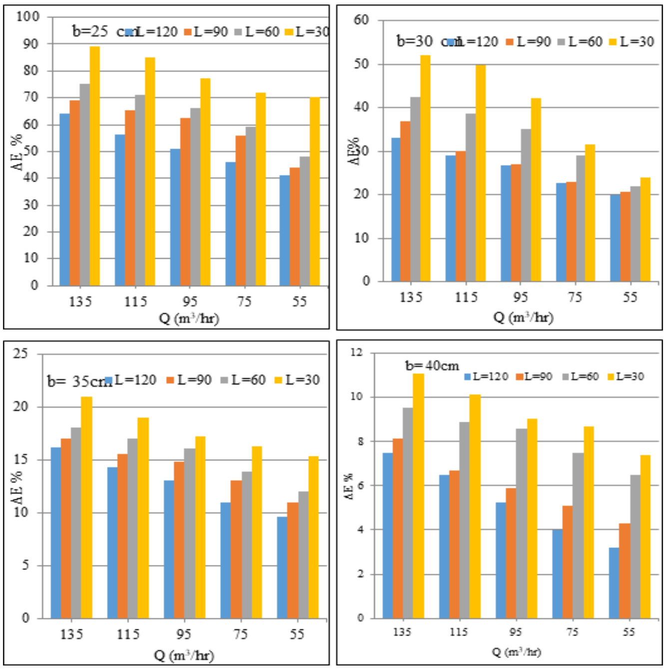

Figure 6. Dissipation energy under different discharges

Obviously, it is very clear in the diagrams, as mentioned in Figure 5, that the amount of flowing discharge plays an essential role in the energy loss process. It is noted that for all cases of sudden contraction of the flow cross-section and different lengths of the contraction zone area, there was a tangible and clear decrease in the values of energy losses with a decrease in the values of passing flow. This is due to the fact that the shear stresses between the water and the contraction zone area begin to decrease as the flow decreases, which is accompanied by a decrease in the height of the water inside the channel.

4.3 The influence of contraction length

Through laboratory results, it was found that the contraction length has an inverse effect on energy dissipation. It was found that energy dissipation increases at the smallest contraction length. In contrast, energy dissipation decreases at the largest contraction length, as illustrated in Figure 7 the relationship between energy dissipation and contraction lengths.

The phenomenon of eddy currents that occur at the entrance to the sudden contraction area requires longer paths to disappear. Also, these vortexes are generated when water is released from the contraction zone into the main open channel portion. Therefore, the shorter distance between the inlet and the outlet of the contraction length will lead to higher turbulence in the water stream. As a result, the amount of energy dissipated will be greater.

On the contrary, when the length of the contraction length zone increases, the water will have a chance to flow more smoothly, providing a stable environment for less energy losses and dissipation.

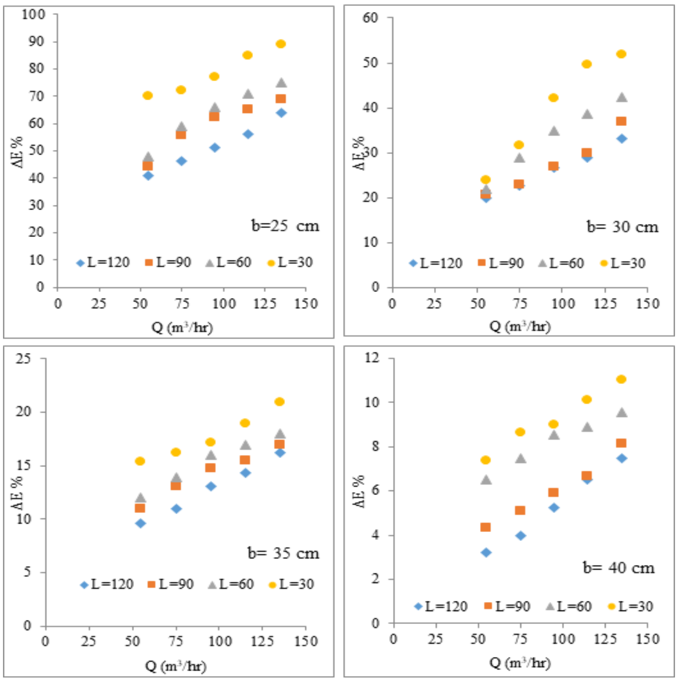

Figure 7. Dissipation energy of different contraction lengths

5. STATISTICAL ANALYSIS

The process of collecting data and then analyzing and interpreting the results of these data is called statistical analysis. Statistical analysis is a wide scientific branch of applications involved in academia, business, the social sciences, genetics, population studies, engineering, and many other fields. It has several functions, and one can use it to make forecasts, conduct simulations, and establish models to reduce risk, time, and cost [16].

Usually, Statistical analysis applies estimations by utilizing a huge amount of data that may take a while to be computed by hand. In order to achieve a relationship between the amount of dissipated energy at the contraction zone with parameters established from the dimensional analysis earlier (Flow, Length of contraction, Width of contraction), a regression analysis was carried out based on the extracted and reliable results from experimental work. A very brief description of the Non-linear regression method is stated in this section because it can take many different forms, however, further details can be discovered in numerous previous research and books [17, 18].

$$Y = f(X, \beta) + \varepsilon \tag{11}$$

where, X is the vector of predictors, β is the vector of parameters, and ε is the error term.

Several software programs have been developed to help study data effectively and efficiently. The most common software is the SPSS, which is used in this study to establish a correlation between the influencing parameters on the dissipated energy in sudden contraction in open channels. The analysis using the SPSS was based on the parameters established from the dimensional analysis earlier.

$$\Delta E \propto f(Q, b, L_c) \tag{12}$$

The data collected in this study was divided into two parts randomly. The first part was equal to 70% of the entire collected data. These data are used to establish an equation for estimating the dissipated energy using the regression analysis. The Non-Linear regression analysis was used in SPSS software to establish Eq. (13) as shown as follows:

$$\Delta E(\%) = 15.45 * 10^6 \left(\frac{Q^{0.47}}{L_c^{\ 0.285} * b^{4.144}} \right) \tag{13}$$

where Q in m^3/hr, L_C in cm, and b in cm.

The performance of the Regression Model for dissipated energy presented in Eq. (13) was evaluated by using quantitative statistical metrics, such as the coefficient of determination (R^2) and the Nash–Sutcliffe efficiency (NSE) [19, 20].

$$NSE = 1 - \frac{\sum(\Delta E_o - \Delta E_s)}{\sum(\Delta E_o - \overline{\Delta E_o})} \tag{14}$$

where ΔE_o is the measured dissipated energy experimentally, ΔE_s is the calculated dissipated energy from the regression model, $\overline{\Delta E_o}$ is the average measured dissipated energy experimentally.

The second part of the data, which is 30% of the entire data, was used to validate the accuracy and efficiency of the equation to measure the dissipated energy through the R^2 and NSE, as shown in Table 3. The results for both parameters are close to 1, which indicates a high accuracy for the energy dissipated prediction.

Table 3. The statistical parameters results

The Statical Parameters	
R^2	NSE
0.995	0.986

Finally, Figure 8 shows the fitting between the predicted dissipated energy from the regression analysis model with those measured experimentally.

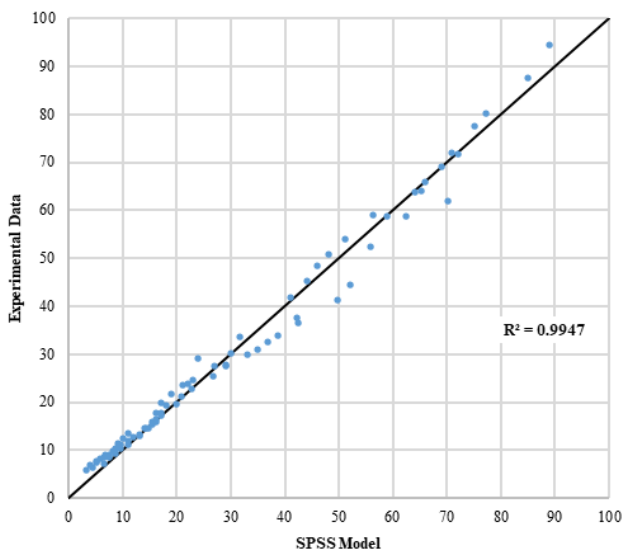

Figure 8. Fitting of experimental dissipation energy and SPSS Model

6. CONCLUSIONS

The importance of investigating the influence of sudden contraction on the dissipated energy in open channels is twofold. First, it can help to understand the energy dissipation mechanisms in open channels. Second, it can help to predict the amount of energy dissipation in a particular channel under specific conditions. Therefore, in this study, by considering these research aims, a deeper grasp of the effect of sudden contraction on dissipated energy in open channels can be gained, leading to more effective and sustainable design and operation of open channel flow systems. Dimensional analysis of the main parameters of sudden contractions on the dissipated energy in open channels was held using the Buckingham π-Theorem. The relevant variables in this problem, including the geometric parameters of the sudden contraction, the fluid properties such as mass density, and the upstream flow conditions, were combined with experimental work. Therefore, experimental work was conducted on models that were built based on dimensional analysis for the parameters impacting the dissipated energy in an open channel. Eighty experiments were conducted on these models. In each experiment, several readings for water depth were measured along the contraction zone. The main finding of this study can be summarized as follows:

- The influence of contraction width showed a clear impact on the energy dissipation produced by changing the width of contraction under different discharge scenarios. The results showed that when increasing the contraction width, the dissipated energy will increase. The greater the percentage of contraction, meaning that the width of the constriction area becomes smaller compared to the original width of the channel, will lead to a need for tremendous energy consumption to pass the water. This loss of water energy while trying to pass through the constriction area is required to ensure that the phenomenon of chock does not occur.
- The influence of discharge was obvious, which showed that the dissipation of energy increases with the increase in the discharge. This is due to the fact that the shear stresses between the water and the contraction zone area begin to decrease as the flow decreases, which is accompanied by a decrease in the height of the water inside the channel.
- The influence of contraction length gives an indicator that the contraction length has an inverse effect on energy dissipation. The relationship between energy dissipation and contraction lengths was found that energy dissipation increases at the smallest contraction length. In contrast, energy dissipation decreases at the largest contraction length. The shorter distance between the inlet and the outlet of the contraction length will lead to higher turbulence in the water stream. As a result, the amount of energy dissipated will be greater.

Although a solid basis for addressing the impact of sudden contraction on dissipated energy in this study, pursuing other interesting impacts and additional investigation efforts can take many directions. For example, studying the impact of the variations in bed slope and the impact of flow condition (Supercritical) scenarios upstream of sudden contraction. Also, addressing the surface roughness could be investigated to add more knowledge to the concept of dissipated energy in rough contraction zones compared to smooth surfaces.

ACKNOWLEDGMENT

The authors would like to acknowledge the support provided by Mr. Ahmed Ashour Al-Faoury from the Upper Euphrates Developing Center at the University of Anbar in terms of help and guidance during the laboratory work.

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