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Research Article / Araştırma Makalesi

EXPERIMENTAL INVESTIGATION OF HYDRAULIC JUMP CHARACTERISTICS IN CONTRACTIONS AND EXPANSIONS

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ABSTRACT

Hydraulic jump is one of the most important phenomena in a rapid changing flow. It occurs when flow change from supercritical into subcritical and there is an increase in the depth over a small distance. In the present study, the characteristics of hydraulic jumps in contractions and expansions with curved walls were investigated for five Froude numbers in the range $5.8<Fr_1<9.1$. The values of the depths and instantaneous velocities were measured at different locations in the hydraulic jumps throughout the transition. The results of the study indicated that energy dissipation in the contraction compared with the expansion decreased on average by 8.74%. On the other hand, the values of the second depth and the jump length increased by 1.8 and 2.5 cm in average. Also, the findings of the study revealed that as the longitudinal distance from the beginning of jump increased, the maximum amount of Reynolds intensions increased in the contraction and decreased in the expansion.
Keywords: Contraction, expansion, hydraulic jump, instantaneous velocity, reynolds stresses.

1. INTRODUCTION

A hydraulic jump is characterized by a dissipative mechanism through which the state of a flow can be converted from the supercritical state to a subcritical state. As a result of the hydraulic jump, flow depth increases within a relatively short distance along the flow, and the flow velocity decreases as a result of the increased area and the energy dissipation. Due to these characteristics, hydraulic jumps are often used to dissipate energy in supercritical high velocity flows at the stilling basin constructed downstream of structures such as dams, chutes, and waterfalls. A stilling basin is one of the common structures used for depreciation of energy in high speed flows. One of the methods of lowering the costs of building stilling basins for hydraulic jumps is to change the profile and the plan of the stilling basin without the use of transformation structures, in order to coordinate with upstream and downstream sections. On the

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other hand any change in the geometry of the basin affects the conditions of the jump and its hydraulic characteristics.

Changes in geometric parameters of the (channel) bed including roughness and invert slope, as well as cross sectional changes and their effect on hydraulic jump characteristics have been subject of numerous studies. Mauris (1955), Rajaratnam (1968), Lothauser and Schiller (1975), Hughes and Flack (1984) were among the first researchers to conduct systematic studies on hydraulic jump over rough beds [1]. To prevent cavitation which normally occurs during hydraulic jump over rough beds, Aide and Rajeratnam (2002) suggested that corrugated beds should be used [2]. Gohari and Farhoudi (2009) conducted experiments at different Froude numbers (between 3 and 10) on a rough bed fitted with rectangular rough strips for different heights and intervals. Their results showed that, on the roughened bed, the secondary depth of the hydraulic jump would decrease compared with that on the smooth bed, and that the value of this decrease would increase with increasing the spacing between the roughness strips. They also found that the primary depth and the roughness height variations had little effect on the hydraulic jump characteristics [3]. Ebrahim and Chezy (2010) studied hydraulic jumps over five different bed types, namely, sinusoidal, triangular, trapezoidal (with two different side slopes), and rectangular for Froude numbers between 3 and 7.5. In all the experiments, the roughness height and wavelength were 1.8 and 6.5 centimeters, respectively. They concluded that relative roughness and roughness shape had no considerable effect on the relative conjugate depth [4]. Fathi and Sunn (2012) conducted experiments to study the effect of two roughness types, namely, zigzag and strip, on the secondary depth in the hydraulic jump for a Froude number range of 2.98 – 11.5. According to their results, the zigzag and strip roughness types reduced the secondary depth by approximately 14-40 % and 30 % respectively [5]. In their study, Aziza *et al.* (2012) used U-shaped roughness types in addition to the implemented blocks in the stilling pool and compared the corresponding results with those obtained from smooth floors. Their results showed that U-shaped roughness had a positive effect on hydraulic jump energy dissipation for specific arrangements [6]. Ebrahimi et al. (2013) used Fluent to simulate a two-dimensional hydraulic jump over a roughened floor (consisting of both rectangular and triangular roughness types). Upon running 16 different cases for Froude numbers between 3 and 7, they compared the obtained secondary depths, jump length, and energy dissipation with corresponding laboratory experiments. The numerical model produced acceptable results when compared with the experimental results [7].

Hydraulic jump over sloped surfaces has been studied in the course of the 19^{th} and 20^{th} centuries by many researchers including Basyan (1865), Bibb (1917), Elms (1927), Yaranel (1934), Bachmetov and Matzec (1938), Kinswater (1944), Kenyson (1944), Bradley and Petroka (1957), Wigham (1958), Rajartenam (1965), Huggar (1988), and others. [8]. Nikmehr and Tabbordbar (2009) studied hydraulic jump over floors with inverted slopes [9]. They examined smooth and rough beds with four inverted floor slopes of -0.00125, -0.0025, -0.00375, and -0.005. Their results showed that, under identical slopes and Froude numbers, the hydraulic secondary depth and length in the smooth bed were more than those obtained for the rough bed. They also found that the rough bed produced higher energy dissipation than the smooth bed.

Laboratory experiments conducted on the effect of stilling pool wall expansion on hydraulic jumps in rectangular sections showed that increasing the expansion angle in rectangular stilling basins with expanding walls would reduce the length and secondary depth of the jump and increase energy dissipation compared with the jump formed in stilling pools with straight walls [10, 11]. As a result, construction costs for stilling pools with expanding walls would be much less than those of straight walled stilling basins. The studies also showed that increasing contraction in stilling basin walls would reduce the scouring pit depth in the downstream channel [12]. In spite of the long history of laboratory research of hydraulic jumps, numerical simulation of hydraulic jump is relatively new. The use of numerical models in order to lower the costs and simulate the flow in different states can play an important role and familiarize the designers with the flow's condition after execution. Study of hydraulic jumps in convergent and divergent sections with lateral tilt or different shaped of walls with the use of analytical methods is difficult due to the marginal conditions of this phenomenon and the complexity of turbulent flows and the process of diffusion between the flow's direction and the walls, the floor and the rolling surface of the water. Since turbulent flow occurs at the interface of water and air when hydraulic jump occurs, so simulation of this phenomenon using turbulence models can lead to more accurate results.

Although there are several studies in the literature, there is a paucity of information related to hydraulic jumps when channel walls are formed as expanding or contracting curved surfaces. In other words, hydraulic jump in the curved walls of contracting or expanding sections are not considered significantly. The aim of this study is an experimental examination of hydraulic jump characteristics formed in such open channels with curved walls at five different supercritical approaching Froude numbers ranging from 5.9 to 9.1.

2. MATERIALS AND METHODS

As shown in Fig. 1., the experiments were conducted in a laboratory flume with the following dimensions of 6m (length), 1m (width), and 0.7m (height). To provide the necessary head, a 1.75m x 1.65m x 1.20m tank was installed upstream of the flume. Water entered the flume upon being pumped from the underground reservoir and passing through the tank adaptor. Water flow was regulated by a valve installed on the pump drive pipe. At the flume inlet, a steel slide gate (thickness=3mm; height=1.2m) was installed to control water surface and produce the required Froude number. To control the hydraulic jump, A sliding gate was fitted downstream of the channel to fix the hydraulic jump at a specific distance from the upstream gate. At the flume outlet, a tail tank was installed to direct water to the drainage channel and then into the underground reservoir.

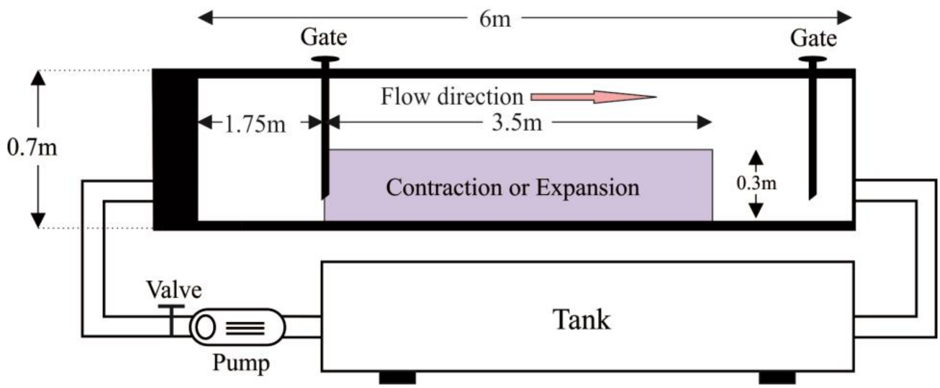


Figure 1. The schematic figure of flume

During the experiments, four Plexiglas sheets (thickness=6mm; length=1m; height=30cm) were used to form the upstream and downstream channel adaptors. The adapter walls were made from two plexiglass sheets (thickness=6mm; length=1.5m; height=30cm). To install the adapter walls and upstream/downstream channels, a compressed polyethylene false floor (thickness=1cm; length=3.5m; width=1m) was positioned at the inlet to the flume. To maintain supercritical flow at the contracted sections, the sliding gate opening and the corresponding upstream and downstream channel widths were set at 2, 80, and 40 centimeters respectively (contraction ratio = 0.5).

For the expansion experiments, the sliding gate opening and the corresponding upstream and downstream channel widths were set at 3, 80, and 40 centimeters respectively (expansion ratio = 0.5). The adaptor walls radius of curvature was 0.63m. Figures 2 and 3 present photographs of the adaptors. The flume flowrate was measured via an acoustic flowmeter (Model UFM610P; accuracy= ±0.02 l/s) the sensors of which were installed on the flume inlet pipe. A point depth gage (accuracy=±0.01mm) was used to measure corrugation heights. To measure flow velocity at different points, a 2D electromagnetic tachometer for horizontal surfaces was implemented (Model ACM2-RS; accuracy= ±0.5cm/s).

Figures 3 and 4 show photographs of the hydraulic jumps for a representative contraction and expansion, respectively.

Figure 2. The flume with contractions

Figure 3. The flume with expansions

the contractions and expansions at Fr_1=7.3. The Froude number definition is provided in Eq. (1) where V is the velocity of flow and y is depth of flow.

$$Fr = \frac{V}{\sqrt{gy}} \tag{1}$$

Table 1. The characteristics of experiments of the contractions

Q (lit/s)	H (m)	Fr_1
32.0	0.91	5.8
34.2	0.95	6.2
40.3	1.02	7.3
40.8	1.09	8.0
46.3	1.15	9.1

Table 2. The characteristics of experiments of the expansions

Q (lit/s)	H (m)	Fr_1
32.4	0.94	5.8
34.5	0.98	6.2
40.5	1.06	7.3
42.0	1.12	8.0
47.8	1.18	9.1

Figure 4. The hydraulic jump in the contractions for Fr_1= 7.3

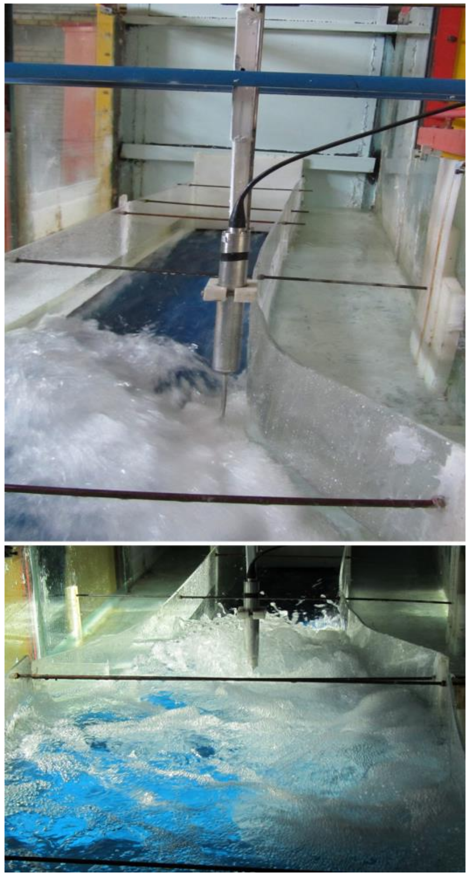


Figure 5. The hydraulic jump in the expansions for Fr_1=7.3

Once the hydraulic jump had formed at a distance of 40cm from the start of the jump, the instantaneous velocities along the vertical direction at 30cm longitudinal distances were measured at five different sections. At the first vertical direction, the data were measured at vertical distances of 1cm and at the other sections, at vertical distances of 3cm.

3. RESULTS AND DISCUSSION

Figures 6 and 7 show sample velocity profiles obtained for contraction and expansion adaptors at four different Froude numbers. In these figures, parameters y and d represent the vertical distance from the bed and the gate opening, respectively. Parameters u and u_1 are the measured instantaneous velocity and the velocity passing through the sliding gate at the respective Froude numbers.

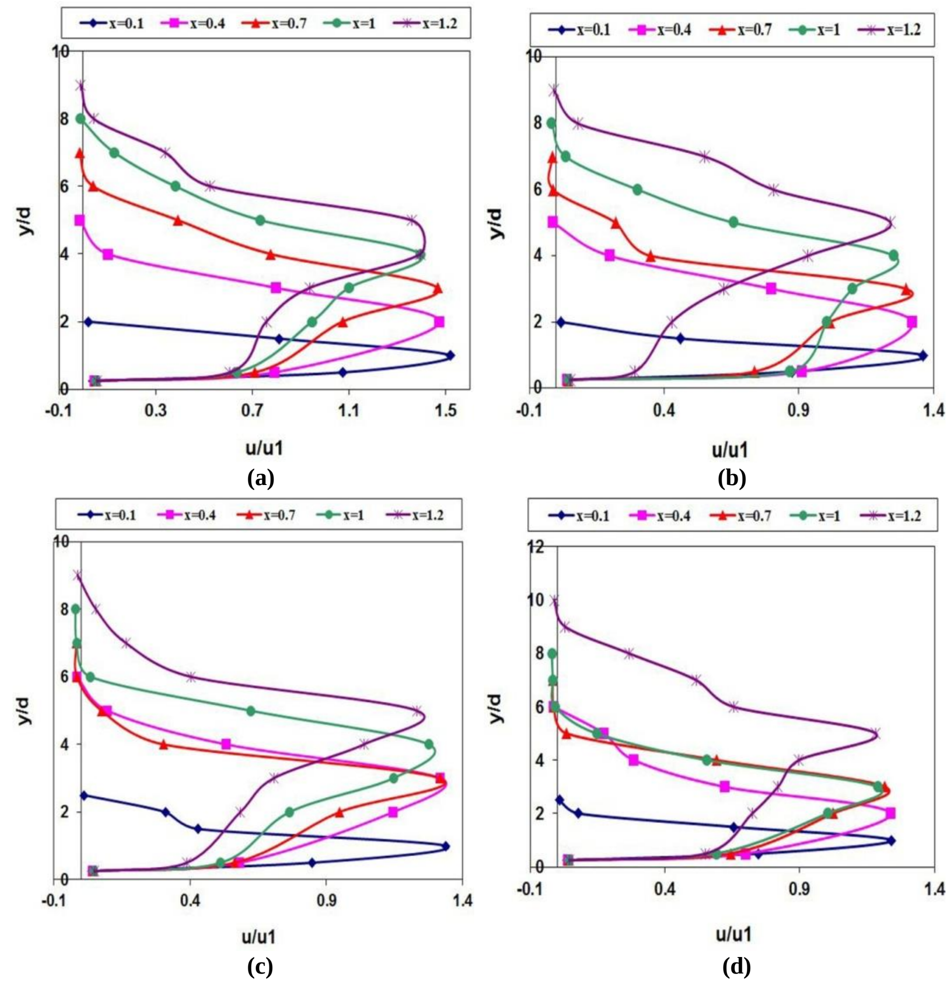


Figure 6. The profiles of velocity of the hydraulic jump in contractions, a) Fr_1= 6.2, b) Fr_1= 7.3 c) Fr_1=8 d) Fr_1=9.1

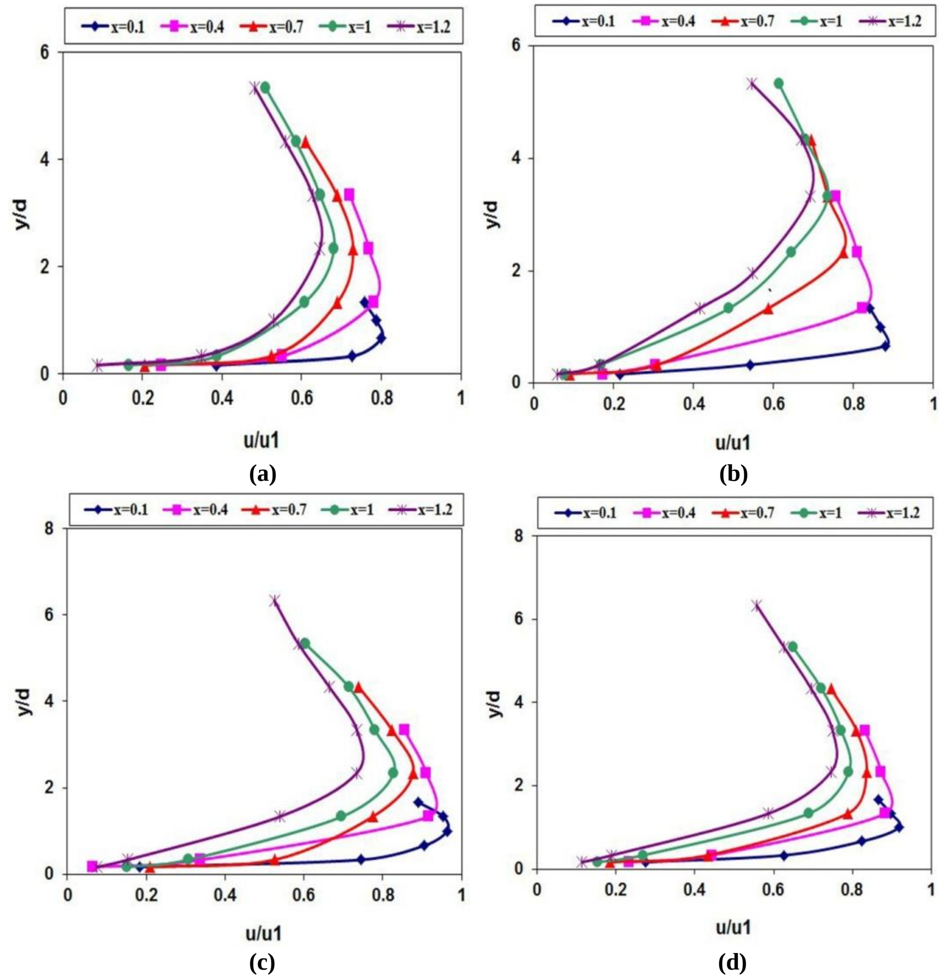


Figure 7. The profiles of velocity of the hydraulic jump in expansions, a) Fr_1= 6.2, b) Fr_1= 7.3 c) Fr_1=8 d) =9.1

It can be observed that, at all the measured sections, velocity initially increases with increasing distance from the bed until it has reached its maximum value, and thereafter, it starts decreasing. In fact, the occurrence of the hydraulic jump leads to intense mixing of water and air near the water surface, which results in energy dissipation and reduced velocities. It can also be observed that as the distance from the start of the jump increases, the boundary layer grows and the maximum velocity values decrease. The contraction the velocity profiles show negative values for velocity near the water surface. This is due to the return flows dominating the main flow in the channel (near the surface). In fact, as the hydraulic jump enters the contraction section, water-air mixing is intensified, leading to this phenomenon. Increasing the Froude number intensifies this condition. However, at a constant Froude number, the maximum velocity at a given vertical measurement point is larger in the contraction as compared to the expansion.

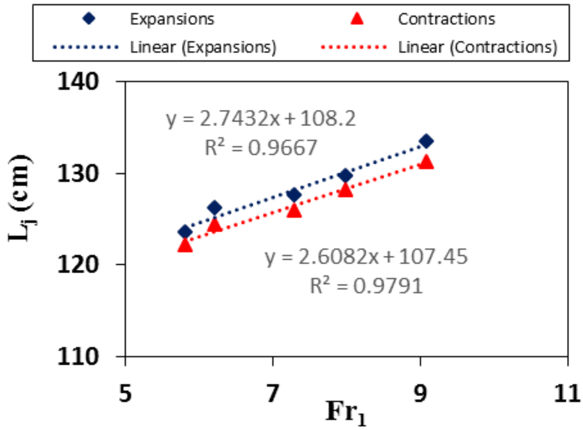


Figure 8. Changes in length of the jump for the different Froude numbers in the contractions and expansions

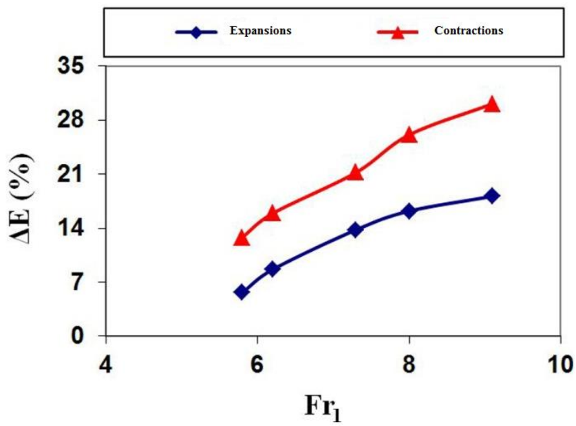


Figure 9. Changes in energy dissipation for the different Froude numbers in contractions and expansions

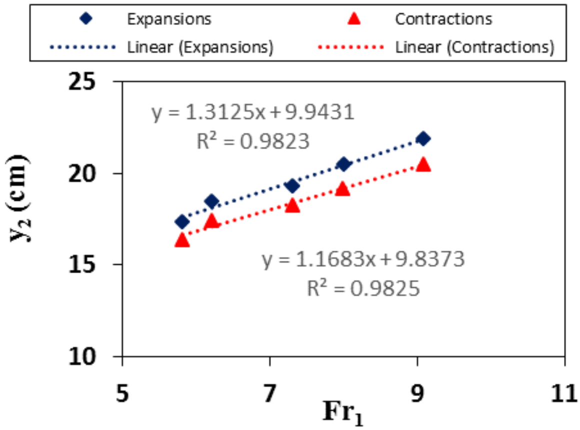
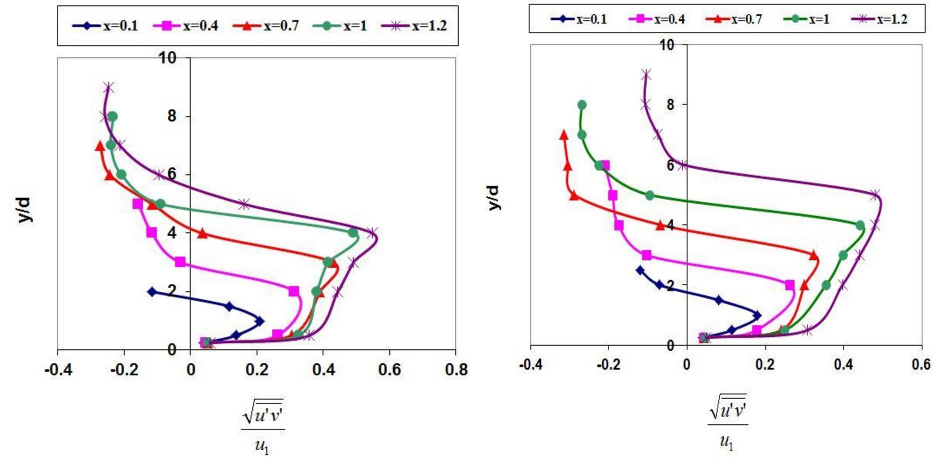


Figure 10. Changes in the secondary depth of the jump for the different Froude numbers in contractions and expansions

$$\Delta E = E_1 - E_2 = (y_1 + \frac{V_1^2}{2g}) - (y_2 + \frac{V_2^2}{2g}) \tag{2}$$

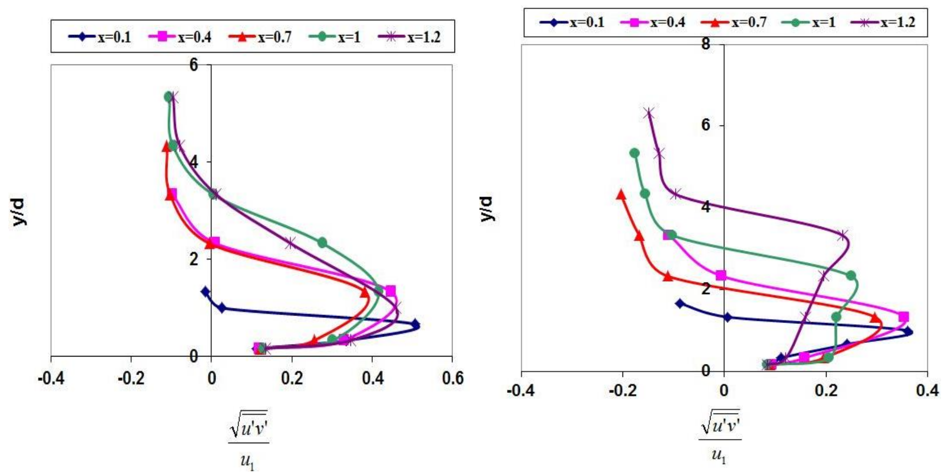
Figures 8-10 show the experimental results obtained for contraction and expansion adaptors in the form of the relative energy dissipation (ΔE) described in Eq. (2), the hydraulic jump length (Lj), and the secondary depth of the jump (y_2) diagrams against Froude number. Also some linear equations with R^2 are fitted and plotted to the hydraulic jump length and secondary depth of jump in Figs. 8 and 10.

As can be observed, increasing the Froude number leads to an increasing trend in the mentioned parameters. The results also show that, at constant Froude numbers, larger values are obtained for the secondary depth and the length of the jump for contractions. However, for energy dissipation the situation is reversed. In fact, in the contraction stage, the widening section would lead to energy dissipation in the flow, whereas during the expansion stage, gradual reduction of width would prevent complete energy dissipation. As a result, energy dissipation (i.e., transition from super to subcritical flow) would take place at a greater length, leading to increased secondary depth and jump length. Our measurements show that energy dissipation in expansions is, on the average, 8.74% less than that of the contractions. Instead, the secondary depth and hydraulic jump length increase by 9.7% and 2.1% respectively as compared with the expansion channels. Figures 11 and 12 show the vertical Reynolds stress distributions obtained for the contractions and expansions at the longitudinal measured distances at two different Froude numbers.



(a) (b)

Figure 11. The vertical distribution of Reynolds shear stress in contractions, a) Fr_1=3.2, b) Fr_1=8



(a) (b)

Figure 12. The vertical distribution of Reynolds shear stress in expansions, a) Fr_1= 3.2, b) Fr_1= 8

As can be observed, stress suddenly drops upon reaching its maximum value and assumes negative values. The negative values occur in reversed flows that are in accord with the results of Zhao and Misra (2004). As Reynolds stresses are directly proportional to instantaneous velocity fluctuations, this sudden drop can be attributed to the intense mixing of water and air at the jump and the subsequent reduction in the instantaneous velocity amplitude. Thus, along the contractions, there would be more negative values due to air-water mixing as compared with expansions. In both expansions and contractions, the greatest negative values were obtained in the middle part of the jump. On the other hand, in the contractions, increasing the distance from the start of the jump would lead to a corresponding increase in Reynolds stresses. In other words, as the jump progresses along a contraction, instantaneous velocity fluctuations and, consequently, stress intensity would increase, whereas the reverse would occur in an expansion. On the other hand, comparing the corresponding vertical velocity distributions reveals that, in both contractions and expansions, the maximum velocity approximately coincides with maximum stress at different sections of the hydraulic jump.

4. CONCLUSION

The characteristics of hydraulic jumps formed in contractions and expansions with curved walls were determined by conducting laboratory experiments at five different Froude numbers (5.8–9.1). To this end, the depth and instantaneous velocity were measured at different sections along the jump within the contractions and expansions. The results showed that, in both contractions and expansions, different vertical velocity profiles were obtained along the vertical direction to the jump, so that velocity would increase with increasing distance from the bed until it reached its maximum. Thereafter, velocity would start decreasing due to air-water mixing. In both expansions and contractions, increasing the Froude number along the jump increases the air-water mixing intensity and surging, leading to more rapid decrease in velocity. Due to the more intense air-water mixing, these results were more readily observed in the expansions, so that at the top surface of the jump, negative velocities were observed. The results also showed that, at constant Froude numbers, the secondary depth and jump length were greater in contractions as compared with expansions. However, energy dissipation of the hydraulic jump formed in the contraction was less than that of the expansion. Vertical distributions of Reynolds stresses were also similar to velocity profiles, i.e., stresses increased until they reached a maximum, and began decreasing thereafter until they adopted even negative values. It was also observed that increasing the longitudinal distance from the start of the jump would lead to increased and reduced maximum Reynolds stresses in the contracting and expansions respectively.

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