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Radial Hydraulic Jump on Flat Plate

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Abstract—*A hydraulic jump primarily serves as an energy dissipater to dissipate the excess energy of flowing water downstream of hydraulic structures. A vertically impinging jet of water introduced at the centre of horizontal circular plate is forced outward radially and the jump thus formed is called a Radial Hydraulic Jump. The setup prepared for experimental trials was a circular flat plate with no end restrictions. Pressure tapings aligned in straight lines perpendicular to each other along the diameter forming four equal quadrants on the flat plate. The jump observed was unsymmetrical in shape. Pressure readings, discharge, sequent radius ratio and sequent depth ratio were recorded for the entire four axis of the horizontal circular plate. The readings were taken by varying discharge for various heights of jet impingement from the base plate. The following observations were made, the variation of relative energy loss increases with the increase in initial Froude number. The increase is steep initially and gradually attains an asymptotic value of one. The length of the jump was six times the height of the jump for any given initial Froude number. The length of the jump was six times the downstream depth of jump for any given initial Froude number. The location of the jump with respect to height of fall of jet increases linearly with dimensionless head at nozzle's exit.*

1. INTRODUCTION

Hydraulic Jumps occur when open liquid flow transitions from supercritical flow to subcritical flow. When the flow changes from supercritical to subcritical speeds the depth of liquid raises substantially over a short distance and creates an inevitable jump which is called "Hydraulic Jump". This Hydraulic Jump results in relative loss of energy. While certain types of hydraulic jumps can happen in places such as open channels and rivers, the focus of this study is on free jets impinging on flat surfaces.

When a smooth jet of water falls vertically on to a horizontal plane, it spreads out radially in a thin layer bounded by a circular hydraulic jump, outside which the depth of flow is much greater than the depth of flow prior to the jump. Hydraulic Jump has been area of interest for researchers across the world since its first description by Leonardo da Vinci. Since then Radial Hydraulic Jump has been extensively studied in many experimental investigations (Jhon D. Lawson et al. 1983, Thomas Bohr et al. 2006,, A.D.D. Craik et al. 2006).

Different researchers (Bakhmeteff and Matzke, 1936; Bermen, 1990; Khalifa and McCorquodale, 1936; Ranga-Raju, 1993; Afzal and Bushra, 2002) have proposed the computed model for calculating the length of jump. Rajaratnam and Subramanyam (1968), Herband (1973) and Negm et al. (2000) have also proposed the empirical and analytical relations for sequent depth ratio. Jhon D. Lawson et al. (1983) proposed a mathematical model for circular hydraulic jump in which depth of flow at the periphery of the large plate was controlled by means of circular weir. A mathematical equation was developed using linear momentum and continuity equation. In this study variation of relative energy loss, length of jump to height of jump ratio, length of jump to downstream depth ratio and variation of location of the jump to height of fall ratio with respect to dimensionless head at nozzle's exit was plotted and analyzed.

Their practical importance consists of supporting the design of stilling basins and similar hydraulic structures.

2. THEORETICAL APPROACH

The assumptions made are that: i) the liquid is in-compressible; ii) The flow is radial and steady; iii) The pressure distribution is hydrostatic before and after the jump; iii) There is no entrained air within the jump;

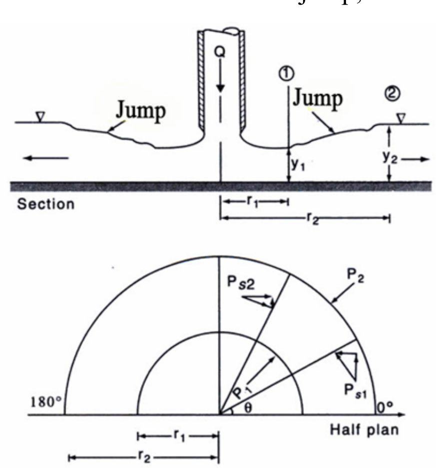

Fig. 1: Definition Sketch for Radial Hydraulic Jump

iv) The profile of jump is linear; v) The frictional shear along the solid boundaries in the region of jump is negligible.

The radial hydraulic jump equation can be obtained by applying the momentum and continuity equation to the element shown in Fig.1 i.e.

$$[1-RY]+\frac{1}{3}(R-1)(1+Y+Y^2)=2F_1^2\left(\frac{1}{RY}-1\right) \quad (1)$$

$$\left[\left(\frac{1}{RY^2}-1\right)+\left\{\frac{1}{3}\left(1-\frac{1}{R}\right)\left(\frac{1}{Y^2}+\frac{1}{Y}+1\right)\right\}\right]=2F_2^2(1-RY) \quad (2)$$

In which R=${r_2}/{r_1}$, the sequent radius ratio; Y=${y_2}/{y_1}$, equation 1 and equation 2 can be solved for F_1 and F_2 between section 1 and section 2 of Fig.1 for any given value of “Y” and “R”.

The energy loss in the radial hydraulic jump can be obtained by apply in the energy and continuity equation between section1 and section2 of Fig. 1, therefore, follows:

$$\Delta H = H_1 - H_2 \quad \ldots\ldots (3)$$

$$\Delta H = \frac{V_1^2}{2g} + y_1 - \frac{V_2^2}{2g} - y_2 \quad \ldots\ldots. (4)$$

$$\Delta H = \frac{Q^2}{8\pi^2 r_1^2 y_1^2 g} + y_1 - \frac{Q^2}{8\pi^2 r_2^2 y_2^2 g} - y_2 \quad \ldots\ldots (5)$$

$$\frac{\Delta H}{H_1} = 1 - \frac{\frac{Q^2}{8\pi^2 r_2^2 y_2^2 g} - y_2}{\frac{Q^2}{8\pi^2 r_1^2 y_1^2 g} + y_1} \quad \ldots\ldots.(6)$$

3. EXPERIMENTAL INSTALLATION

Fig. 2: Experimental apparatus used

The experiment was carried out in Hydraulic Laboratory of Civil Engineering Department at Siddaganga Institute of Technology, Tumakuru. A schematic diagram of the experimental apparatus for impinging water jet is shown in Fig. 3. The setup consists of (1) An overhead supply tank, (2) Feeder pipe with regulating valve, (3) Pipe nozzle of 1cm diameter and 0.9 m length, (4) circular flat plate of 1 meter diameter with no end restriction and pressure tappings at every 4 cm interval along the axes, (5) point gauge with slider, (6) discharge tank.

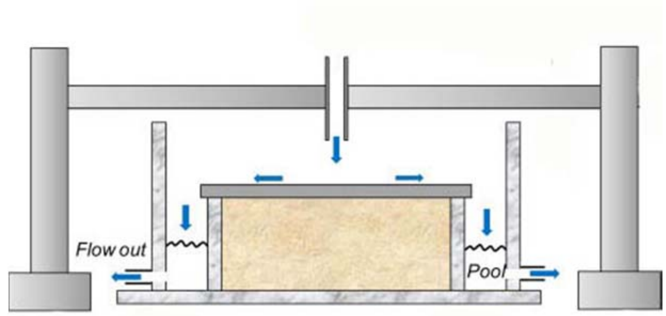

Fig. 3: Schematic diagram of experimental setup

A constant overhead supply tank of volume 5.8m×3.8m×2.5m was used to minimize the error due to change in flow during experimentation. The water from overhead tank flow through the connecting pipe of diameter provided with a regulating valve under Gravitational force. The water jet vertically impinges on a plate. The jet velocity can be readily found from the mass flow rate and the jet diameter. The circular pipe nozzle was fixed on a stand.

The experiments were performed on circular flat plate placed horizontally, with pressure tappings in two perpendicular directions along the diameter so as to form four equal quadrants on the flat plate. Pressure readings on the flat plate due to flow of water was taken through tube connections provided at the base of the flat plate. The impingement surface was elevated above the remainder of the test section. Thus, as the wall jets fell off the impingement surface into the pool, the jet impingement was not influenced by the downstream conditions. Parallel rails were mounted at the top of the side walls for sliding of point gauges to measure the depth at different positions along the jump.

4. EXPERIMENTAL METHODOLOGY

A series of runs at different heights of nozzle from the base plate for different discharge were experimented and the hydraulic jump formed was unsymmetrical in shape. For each run discharge, pressure readings depth at toe, depth at heel, radius at toe, radius at heel of jump for all the four axes were recorded.

The discharge was measured by weighing the amount of water collected for a certain time period. Radius along the four axes was measured using the scale plotted on the flat plate along each axis. Depth of the jump at toe and heel were measured with the help of point gauge.

Fig. 4: Experimental setup used

5. RESULTS

At lower discharge the jump formed on the flat plate was roughly symmetrical as observed in Fig. 5; however at higher discharges the jump formed was un-symmetrical along the axes as observed from Fig. 6.

Supercritical flow is responsible for all hydraulic jump characteristics considered in present work have been computed from the measured data and plotted against the Froude number. In light of the measuring difficulty the scatter of the data is not surprising.

Fig. 5: Symmetrical jump at lower discharge

Fig. 6: Un-symmetrical jump at higher discharge

5.1 Relative Energy Loss versus Froude number

In this study graphs for $\Delta H/H_1$ i.e. relative energy loss with respect to supercritical Froude number has been plotted in Fig.7 . It can be clearly observed from the result of the graph plotted that the relative energy loss increases as F_1 increases. It also suggests that the ability of a radial hydraulic jump to dissipate energies is greater than that of the classical jump. The results obtained from this study is in fairly good agreement with the work of Jhon D. Lawson et al. 1983, who obtained the results using circular weir at periphery of the large plate to increase the depth of the flow. Relative energy loss in terms of sequential Froude number is given based on best fit curve as:

$$y = -2.3063 \times 10^{-9} \times x^6 + 5.0622 \times 10^{-7} \times x^5 - 4.0913 \times 10^{-5} \times x^4 + 1.6246 \times 10^{-3} \times x^3 - 3.443 \times 10^{-2} \times x^2 + 3.8562 \times 10^{-1} \times x - 9.7968 \ldots \quad (7)$$

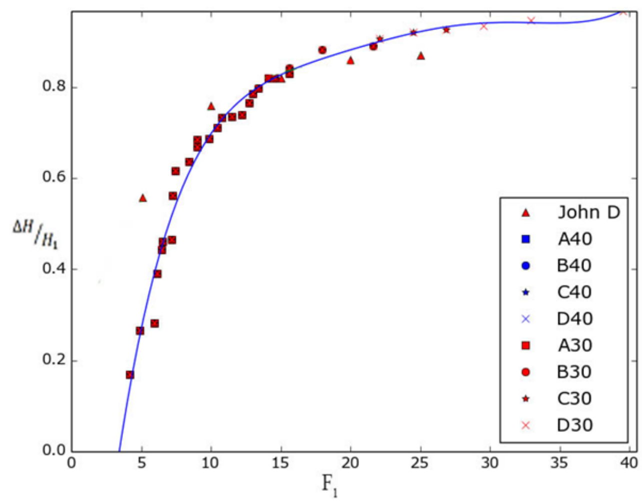

Fig. 7: Relative energy loss versus Initial Froude number

5.2 Ratio of radius at toe to height of fall versus dimensionless head at nozzle exit

The ratio of radius at toe of jump to the height of fall (r_1/H) of the jet was computed and plotted against dimensionless head at nozzle's exit $(V_0^2/2gH)$ as shown in Fig. 8. It can be observed from the plotted data that the location of the jump to height of fall of jet ratio linearly increases with increase in dimensionless head. Equation for location of the jump from the best fit curve is given below:

$$y = 0.00076431x + 0.001034 \ldots\ldots\ldots\ldots\ldots \quad (8)$$

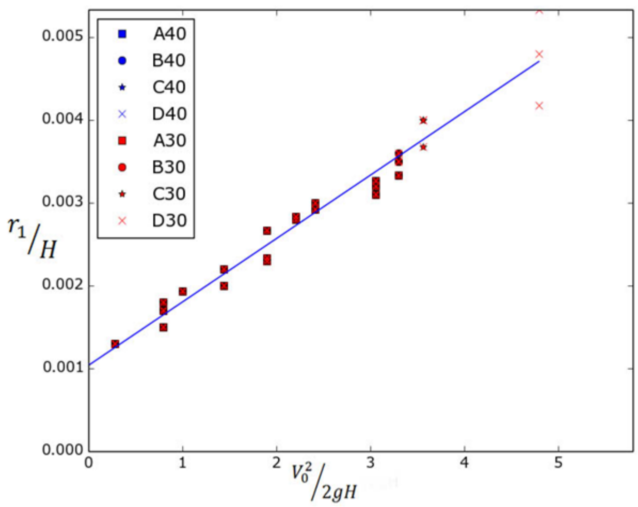

Fig. 8 r_1/H versus $V_0^2/2gH$

5.3 Sequent depth versus initial Froude number

Sequent depth ratio y_2/y_1 is plotted against supercritical Froude number F_1 their relation follows fairly y_2/y_1 proportional to $F_1^{0.3}$ similar to classical hydraulic jump as shown in Fig.9.

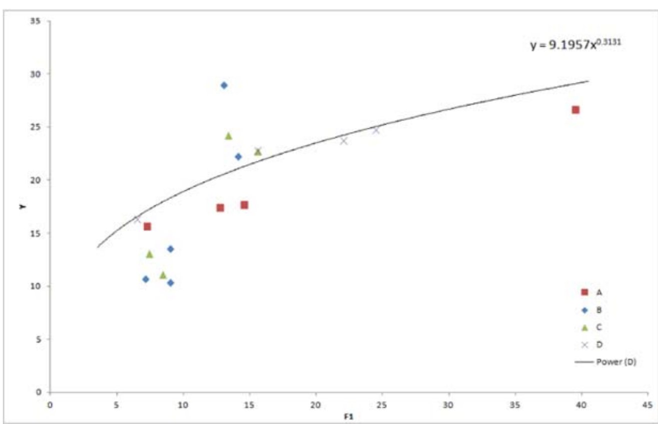

Fig. 9: Sequent depth versus initial Froude number

5.4 Relative Length of Jump versus Initial Froude number

The length of the hydraulic jump was considered to be the distance from the toe of the hydraulic jump to that location where the surface undulations and turbulence appeared to be no pronounced than at any other section further downstream. Using this criterion, the observed jump length ratios,$(r_2 - r_1)/y_2$ are plotted against initial Froude number in Fig. 10. The observed jump length ratios is approximately six times the initial Froude number, which is higher than those reported by Jhon D. Lawson et al. 1983, while is in fair agreement with the results reported by Khalifa et al. 1983.

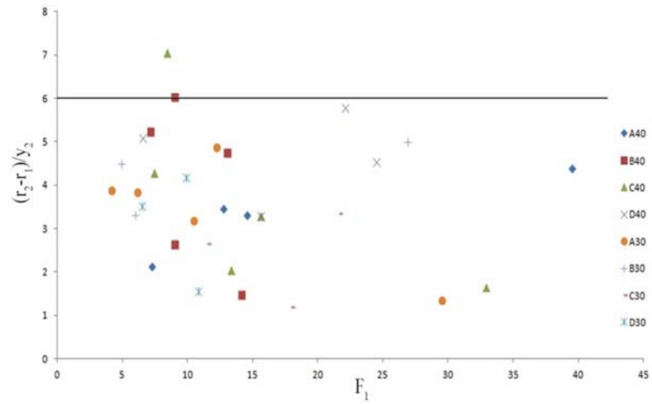

Fig. 10: Jump length ratio versus initial Froude number

5.5 Ratio of length of jump to depth of jump with respect to initial Froude number

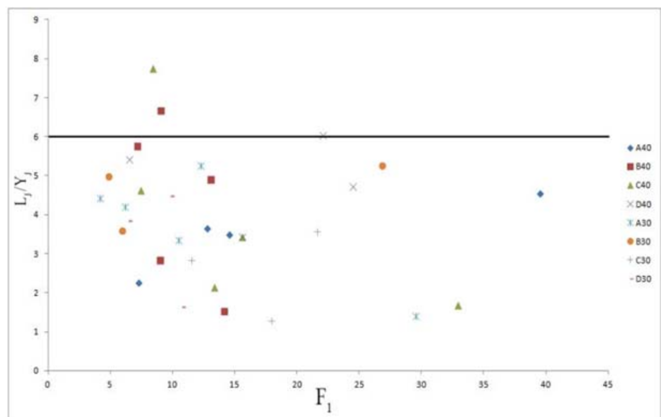

Fig. 11: Jump length to depth ratio versus

The graph plotted in Fig.11 suggests that the length of the jump is approximately six times the depth of the jump for any given value of initial Froude number.

6. DISCUSSION

The asymmetry in the formation of jump on the plate may be due to (i) circular section at the nozzle exit may not be proper (ii) the base plate may be slightly sloped (iii) no control of the flow after the jump leaves the base plate.

The results of energy loss follow a fair agreement with John D Lawson's experimental results. The energy loss is very steep till the value of F_1 around ten, which corresponds to the occurrence of strong jump. For higher F_1 values, energy dissipation increases gradually and reach asymptotically the value of unity. The equation representing the location of the jump increases linearly with relative height impingement. There is a wild scatter in the length of jump values. This may be due to asymmetry in the formation of the jump. The extreme value may be taken as around six.

7. CONCLUSION

Experiments were conducted to study the variation of basic parameter like energy dissipation and location of the jump formation. Equation representing energy loss and location of the jump generates a curve which follows a least scatter path. Energy dissipates considerably high for initial values of Froude number and gradually becomes asymptotic value of one for higher Froude number. Location of jump varies linearly with relative height of jet hitting the plate.

8. ACKNOWLEDGEMENT

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9. NOTATIONS

The following symbols are used in this paper:

A30= readings in the direction of axis A for 30cm height of nozzle from base plate

A40= readings in the direction of axis A for 40cm height of nozzle from base plate

B30= readings in the direction of axis B for 30cm height of nozzle from base plate

B40= readings in the direction of axis B for 40cm height of nozzle from base plate

C30= readings in the direction of axis C for 30cm height of nozzle from base plate

C40= readings in the direction of axis C for 40cm height of nozzle from base plate

D30= readings in the direction of axis D for 30cm height of nozzle from base plate

D40= readings in the direction of axis D for 40cm height of nozzle from base plate

F_1 = supercritical Froude number

F_2 = subcritical Froude number

g = acceleration due to gravity

H = height of nozzle from the base plate

H_1 = total head at toe of jump

H_2 = total head at heel of jump

L_J= length of Jump

P_1 = hydrostatic force at jump toe

P_2 = hydrostatic force at jump heel

P_{S1}, P_{S2}= side pressure forces

Q = discharge through nozzle

r_1 = radius at toe of jump

r_2 = radius at heel of jump

R = sequent radius ratio, = r_1/r_2

v_1 = velocity at toe of jump

v_2 = velocity at heel of jump

V_o = velocity of jet at nozzle's exit

y_1 = depth of flow at toe of jump

y_2 = depth of flow at heel of jump

Y = sequent depth ratio, = y_1/y_2

Y_j= depth of jump

$\Delta H = (H_1 - H_2)$ = total head loss through hydraulic jump

$\pi = 3.141$

Θ = angle, radians

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