Measurement of Hydraulic Jump Radius

Group 2: Diya Mehta (22110078), Nishit Mistry (22110172), Shrishti Mishra (22110246), Vatsal Trivedi (22110276), Utkarsh Srivastava (22110278)

Department of Mechanical Engineering, IIT Gandhinagar

Under Professor Dilip Srinivas Sundaram and Professor Uddipta Ghosh for the course ME 207: Fluid Dynamics

1. Introduction

The hydraulic jump is a phenomenon observed in free surface flows during the transition from supercritical to subcritical flow regimes. Before the jump occurs, there's a region characterized by high kinetic energy, with the flow exhibiting high velocity and a thin layer of water. This phenomenon, commonly encountered in daily life, such as when water impacts a sink, presents an intriguing subject for study due to the significant deformation in the fluid's free surface and the subsequent flow separation in the post-jump region. In this experimental study, we aim to investigate the variations in hydraulic jump radius in response to changes in volumetric flow rates.

2. Objectives

The objectives that we hoped to achieve after the completion of all these experiments are:

1. Establish a clear understanding of the relationship between the flow rates of the impinging jet and the subsequent hydraulic jump radius by conducting controlled experiments.
2. Explore the influence of different flow velocities on the formation and dimensions of hydraulic jumps to discern patterns and trends in jump radius variation.
3. Assess the precision and reliability of the experimental setup in regulating flow rates to consistently produce hydraulic jumps of varying sizes, enabling accurate measurement and analysis of jump characteristics.

3. Theory

The foundation of the hydraulic jump lies in the conservation of energy and momentum within fluid flow. When a fast-moving, supercritical flow encounters a slower, subcritical flow, it must shed its excess kinetic energy. This process involves converting kinetic energy into potential energy and turbulence.

The hydraulic jump begins as the high-velocity flow abruptly decelerates upon entering the slower region. This deceleration causes the water depth to increase and the water surface to rise. As the flow slows, its surplus kinetic energy is converted into potential energy, leading to a sudden elevation of the water surface.

This abrupt rise in water disrupts the flow, triggering the formation of turbulent waves and eddies. Turbulence plays a crucial role in dissipating the excess energy and restoring a more balanced flow state. Through turbulent mixing and energy dissipation, the hydraulic jump helps establish equilibrium between the incoming high-velocity flow and the slower, subcritical flow downstream.

In subcritical flow, disturbances propagate upstream against the flow direction, with flow velocities lower than the wave speed. In contrast, in supercritical flow, disturbances travel downstream in the direction of flow, with flow velocities exceeding the wave speed.

4. Applications

Hydraulic jumps find diverse applications across engineering and water management sectors. Here are some key areas where they are commonly utilized:

1. **Energy Dissipation:** Hydraulic jumps are pivotal for dissipating surplus energy in high-velocity flows. They mitigate flow velocities, safeguarding against soil erosion and structural damage in hydraulic constructions like spillways, weirs, and energy dissipators. By converting kinetic energy into potential energy and turbulence, hydraulic jumps ensure the safe dissipation of energy before water proceeds downstream.
2. **Flood Control:** Hydraulic jumps play a crucial role in regulating water flow in rivers, channels, and flood control structures. By dissipating energy and moderating flow velocities, they mitigate erosion risks, reduce the likelihood of downstream flooding, and safeguard infrastructure and communities in flood-prone regions.
3. **Sediment Transport:** Hydraulic jumps aid in managing sediment transport within rivers and channels. By altering flow velocities and encouraging sediment settling, they influence sediment movement and deposition, helping to control sedimentation and maintain desired channel morphologies.
4. **Water Treatment:** Hydraulic jumps are integral to water treatment processes, facilitating efficient mixing of chemicals like coagulants or disinfectants with water. The turbulent mixing within hydraulic jumps enhances chemical-water contact, promoting effective treatment and water disinfection.
5. **Fish Passage Design:** Hydraulic jumps are factored into the design of fish passages and fishways, enabling fish to navigate barriers in rivers and dams. The energy dissipation provided by hydraulic jumps ensures suitable flow conditions for fish passage, minimizing stress or injury.
6. **Recreational Activities:** Hydraulic jumps create whitewater features cherished by water-based recreational enthusiasts like kayakers, rafters, and surfers. The dynamic and turbulent nature of hydraulic jumps offers opportunities for thrilling experiences in outdoor settings.

5. Preliminary theoretical discussion/calculations

Numerous efforts in literature have been dedicated to deriving the scaling laws that govern the relationship between the radius R of the circular hydraulic jump and the various physical parameters that influence this phenomenon. We are going to discuss one such simplified theoretical approach here.

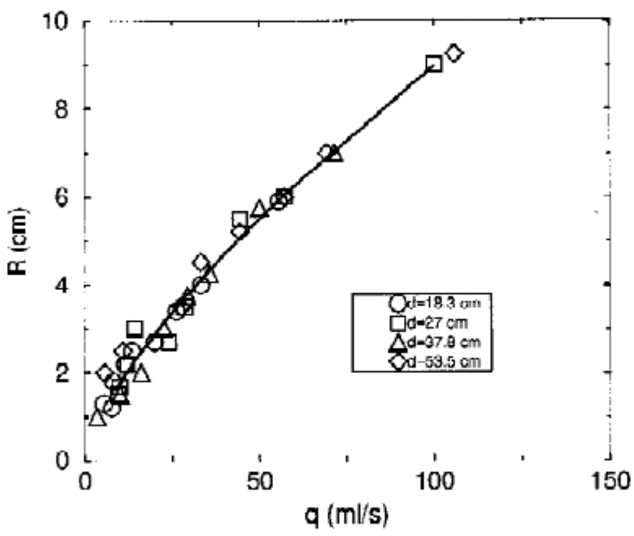

Figure 1. *Hydraulic Jump Radius vs Volumetric Flow Rate*

This theory is based on the role played by the viscous boundary layer. The flow inside the boundary layer can be described as viscous laminar flow, and the flow above it as a laminar flow. Hydraulic jump occurs when the boundary layer reaches the total height of the fluid film.

Making the approximation that the boundary layer is a very small part of the liquid film thickness right upto the hydraulic jump, we get:

$$R \sim q^{2/3} d^{-1/6} \nu^{-1/3}$$

6. Experimental Setup

The experimental setup consists of a sink having water to a certain height to accommodate a submersible pump; it also includes a stand over which we have a target plate of 29cmx29cm. The submersible pump at one end is connected to the plug to receive the AC current supply and, on the other end, to a flexible hose pipe. We have used PVC pipe and connectors to get h shaped stand over which we have mounted hose pipe, and one of the connectors placed just above the middle of the target plate is drilled to pass the hose pipe and accommodate the vertical placement of the nozzle, directing water onto the target plate. The nozzle is placed at a height of 10cm above the target plate. We have attached a scale of 30cm on the other side of the target plate to measure the radius of the circular hydraulic jump. Also, we have used a tank of fixed dimensions to calculate the flow rate of water

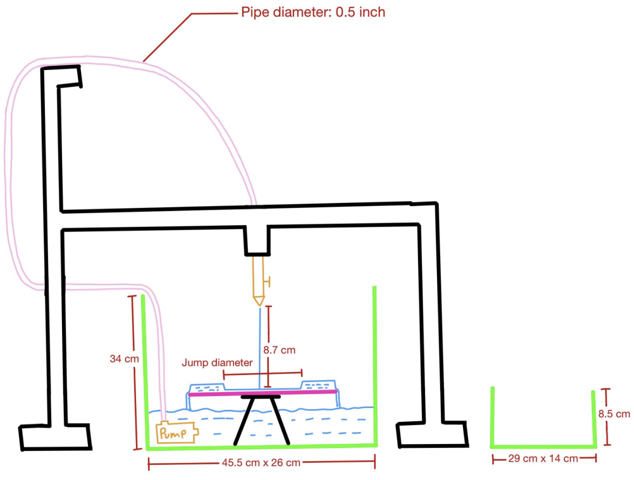

Figure 2. *Schematic of the setup*

coming out from the nozzle.

Figure 3. *Experimental Setup*

Additionally, the sink, equipped with wheels for smooth movement, is shifted, and a tank is positioned. A stopwatch is initiated to record the time taken to fill the tank, facilitating

Readings	Left Scale End where hydraulic jump happens	Centre Point on which the stream hits the scale	Right Scale End where hydraulic jump happens	Time Taken for the contianer to fill to the desired height
1	19.8-20.5		9.5-10.5	
2	19.7-20.2	14.9	10-10.5	115.43
3	22-22.4		8-8.5	
4	20.9-21.4	15	8.8-9.2	70.5
5	23.4-24		6.1-6.7	
6	23.7-24.2	15.1	6.12-6.9	54.14
7	24-24.6		5.4-6.1	
8	23.5-24.1	14.75	5.7-6.5	43.7
9	24.4-24.7		5.4-6	
10	25.1-25.7	15	6.1-6.6	40.59
11	25.4-25.7		4.6-5	
12	24.8-25.3	15	5.2-5.4	34.07

Figure 4. *Collected Raw Data*

flow rate calculation. The readings of six different flow rates have been recorded.

We have verified that the entire setup is aligned precisely both horizontally and vertically, guaranteeing its correct orientation by employing the gyroscope. To prevent inconsistencies in flow rate calculations, we seamlessly move the entire setup and the tank without interrupting the pump operation. Simultaneously, one person records the time required to fill the tank to facilitate flow rate determination.

7. Measurements/Results

To measure the radius accurately, a fixed scale is positioned on the opposite side of the target plate. Upon activating the nozzle, a distinct circular hydraulic jump forms on the target plate after a period of time, although minor fluctuations in the radius are observed. The centre of the circle is noted, along with the range of radii on both its left and right ends. By averaging the lower and upper values of the end range on each side, the mean left and right end measurements are calculated. The difference between the centre position and the average left and right measurement provides the approximate values of the left and right radii, respectively. The following is done two times for each flow rate. This method allows us to have four radii data points for each flow rate, thus mitigating the probable errors in measurement.

Left Scale End Radius	Right Scale End Radius	Left Average Radius	Rigth Average Radius	Flowrate
20.15	10	5.25	4.9	
19.95	10.25	5.05	4.65	29.9
22.2	8.25	7.2	6.75	
21.15	9	6.15	6	48.95
23.7	6.4	8.6	8.7	
23.95	6.51	8.85	8.59	63.74
24.3	5.75	9.55	9	
23.8	6.15	9.05	8.6	78.97
24.55	5.7	9.55	9.3	
25.4	6.35	10.4	8.65	85.02
25.55	4.8	10.55	10.2	
25.05	6.3	10.05	8.7	101.29

Figure 5. *Processed Data used for analysis*

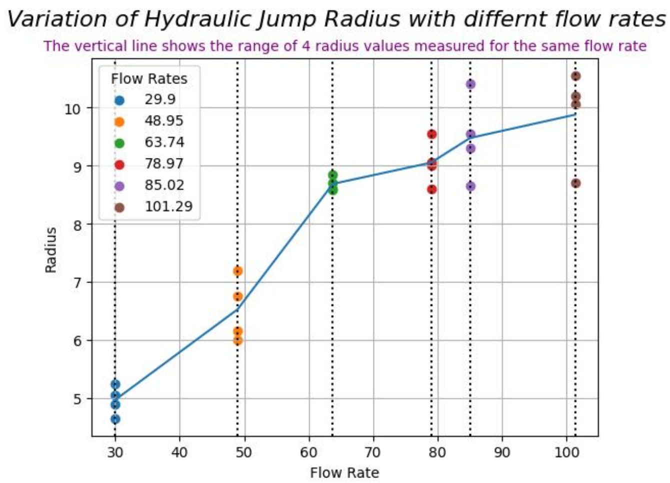

Figure 6. *Variation of Hydraulic Jump Radius with different flow rates*

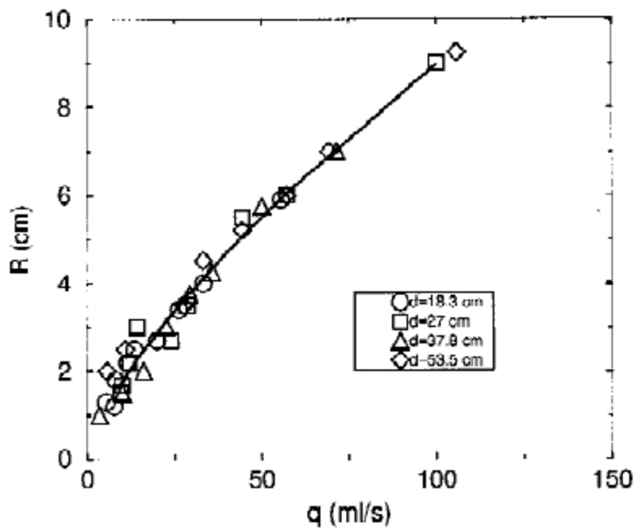

Figure 7. *Hydraulic Jump Radius vs Volumetric Flow Rate*

8. Discussion

On comparing the experiemntal and theoretical results, we see a good agreement of our experimental results with those in the literature.

From the preliminary discussion above, we see that:

$$R \sim q^{2/3} d^{-1/6} \nu^{-1/3}$$

Here, R is the radius of hydraulic jump, q is the volumetric flow rate, d is the distance between the nozzle and the flat plate, and v is the kinematic viscosity. Since, we are only changing the flow rates here, we see a good agreement of our experimental results, which almost shows:

$$R \sim q^{2/3}$$

Thus, as we are increasing the flow rate, we observe increase in the hydraulic jump radius.

9. Errors

1. Reaction Time: While measuring the time it takes for the water to reach the marked height of 8.5cm in the vessel, human reaction time may cause some error.
2. Parallax Effect: If our line of sight is not perpendicular to the marked height, then it can cause an apparent shift in the position of the water level. This condition can cause errors with measuring time.
3. Fluctuating Radius: Hydraulic jump is a dynamic phenomena and keeps fluctuating. These fluctuations may introduce uncertainty into our measurements. To avoid these errors, we can take multiple measurements and calculate an average radius.
4. Viscous Effects: The viscous effects are neglected during the calculations, however, a plate with considerable viscosity can cause errors while calculating jump radius.
5. Least Counts:
   (a) Least count of scale- 1 mm
   (b) Least count of time- 0.01 s

10. Acknowledgements

We would like to extend my heartfelt gratitude to Professor Dilip Srinivas Sundaram and Professor Uddipta Ghosh for their guidance and support throughout the ME 207 course and particularly during our final project. Their expertise and enthusiasm greatly enriched our learning experience.

Additionally, we extend our thanks to all the Teaching Assistants and staff of Machine Shop ‘whose dedication and assistance were instrumental in helping us navigate through the challenges of the final project.

We would also like to thank our institution, IIT Gandhinagar, for providing us with the platform to execute this project.

Thank you once again to everyone who contributed to making this course and project a rewarding and enlightening experience.

11. References

1. https://www.researchgate.net/publication/259225909_On_the_circular_hydraulic_jump
2. https://en.wikipedia.org/wiki/Hydraulic_jump