Science Education Collection

Hydraulic Jumps

URL: https://www.jove.com/science-education/10405

Overview

Source: Alexander S Rattner and Mahdi Nabil; Department of Mechanical and Nuclear Engineering, The Pennsylvania State University, University Park, PA

When liquid flows along an open channel at high velocity, the flow can become unstable, and slight disturbances can cause the liquid upper surface to transition abruptly to a higher level (Fig. 1a). This sharp increase in the liquid level is called a *hydraulic jump*. The increase in the liquid level causes a reduction in the average flow velocity. As a result, potentially destructive fluid kinetic energy is dissipated as heat. Hydraulic jumps are purposely engineered into large water works, such as dam spillways, to prevent damage and reduce erosion that could be caused by fast moving streams. Hydraulic jumps also occur naturally in rivers and streams, and can be observed in household conditions, such as the radial outflow of water from a faucet onto a sink (Fig. 1b).

In this project, an open-channel flow experimental facility will be constructed. A *sluice gate* will be installed, which is a vertical gate that can be raised or lowered to control the discharge rate of water from an upstream reservoir to a downstream spillway. The flow rate required to produce hydraulic jumps at the gate outlet will be measured. These findings will be compared with theoretical values based on mass and momentum analyses.

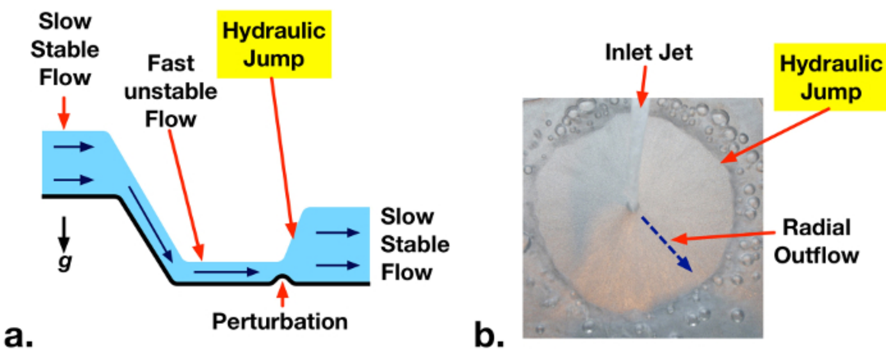

Figure 1: a. Hydraulic jump occurring downstream from a spillway due to a slight perturbation to an unstable high-velocity flow. b. Example of hydraulic jump in radial outflow of water from a household faucet.

Principles

In wide open-channel flows, liquid is only confined by a lower solid boundary and its upper surface is exposed to the atmosphere. A control-volume analysis can be performed on a section of an open channel flow to balance inlet and outlet transport of mass and momentum (Fig 2). If the velocities are assumed uniform at the inlet and outlet of the control volume (V_1 and V_2 respectively) with corresponding liquid depths H_1 and H_2, then a steady mass flow balance reduces to:

$$H_1 V_1 = H_2 V_2 \quad (1)$$

The *x*-direction momentum analysis of this control volume balances forces from hydrostatic pressure (due to fluid depth) with the inlet and outlet momentum flow rates (Eqn. 2). The pressure forces act inward on the two sides of the control volume, and are equal to the specific gravity of the liquid (liquid density times gravitational acceleration: ρg), multiplied by the average liquid depth on each side ($H_1/2$, $H_2/2$), multiplied the height over which the pressure acts on each side (H_1, H_2). This results in the quadratic expression on the left side of Eqn. 2. The momentum flow rates through each side (Eqn. 2, right side) are equal to the mass flow rates of liquid through the control volume (in: $-\rho H_1 V_1$, out: $\rho H_2 V_2$) multiplied by the fluid velocities (V_1, V_2).

$$\rho g \frac{(H_1^2 - H_2^2)}{2} = \rho (H_2 V_2^2 - H_1 V_1^2) \quad (2)$$

Eqn. 1 can be substituted into Eqn. 2 to eliminate V_2. The Froude number ($\mathrm{Fr}_1 = V_1 / \sqrt{g H_1}$) can also be substituted in, which represents the relative strength of inflow fluid momentum to hydrostatic forces. The resulting expression can be stated as:

$$\left(\frac{H_2}{H_1}\right)^3 - \left(\frac{H_2}{H_1}\right)(2\mathrm{Fr}_1^2 + 1) + 2\mathrm{Fr}_1^2 = 0 \quad (3)$$

This cubic equation has three solutions. One is H1 = H2, which gives the normal open-channel behavior (inlet depth = outlet depth). A second solution gives a negative liquid level, which is unphysical, and can be eliminated. The remaining solution allows for an increase in depth

Copyright © 2018

(hydraulic jump) or a decrease in depth (hydraulic depression), depending on the inlet Froude number. If the inlet Froude number (Fr_1) is greater than one, the flow is called supercritical (unstable) and has high mechanical energy (kinetic + gravitational potential energy). In this case, a hydraulic jump can form spontaneously or due to some disturbance to the flow. The hydraulic jump dissipates mechanical energy into heat, significantly reducing the kinetic energy and slightly increasing the potential energy of the flow. The resulting outlet height is given by Eqn. 4 (a solution to Eqn. 3). A hydraulic depression cannot occur if $Fr_1 > 1$ because it would increase mechanical energy of the flow, violating the second law of thermodynamics.

$$H_2 = H_1 \frac{\left(\sqrt{1+8Fr_1^2}-1\right)}{2} \quad (4)$$

The strength of hydraulic jumps increases with inlet Froude numbers. As Fr_1 increases, the magnitude of H_2/H_1 increases and a greater portion of inlet kinetic energy is dissipated as heat [1].

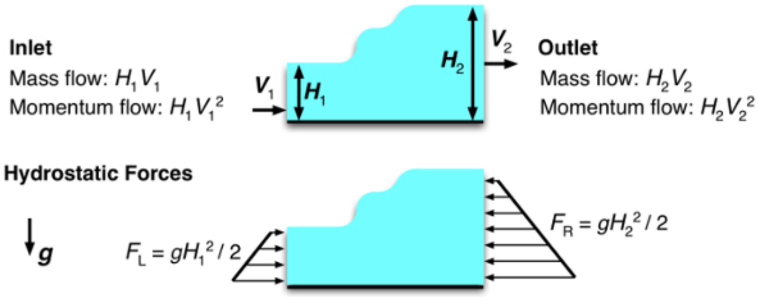

Figure 2: Control volume of a section of an open-channel flow containing a hydraulic jump. Inlet and out mass and momentum flow rates per unit width are indicated. Hydrostatic forces per unit width indicated in lower diagram.

Procedure

NOTE: This experiment uses a relatively powerful submersible pump. The pump should only be plugged into a GFCI outlet to minimize electrical risks. Ensure that no other A/C powered devices are operating near the experiment.

1. Fabrication of open-channel flow facility and tank (see diagram and photograph, Fig. 3)

1. Cut lengths of ~6.0 mm thick × 9.5 cm wide clear acrylic sheet with the following lengths: 2×15 cm, 2×25 cm, 1×34 cm, 1×41 cm (Fig. 3a). It is recommended to use a table saw or laser cutter to ensure that the edges are relatively flat and the sheets have equal thickness.
2. Cut holes in the lower right corners of the two 60 × 45 cm acrylic sheets to mount the flow meter (Fig. 3a). Cut a hole on the upper right side of the front sheet to install the flow control valve.
3. Use acrylic cement (*e.g.*, SCIGRIP 16) to bond the acrylic panels as indicated in Fig. 3a. Ensure adequate ventilation and wear gloves when handling the acrylic cement. It is helpful to apply cement with a needle syringe and use masking tape to position panels during curing. Allow the cement to cure for 24 - 48 hours.
4. Install the flow meter on the front panel and affix with the provided screws. Install 1 NPT to ½ NPT reducing fittings on the flow meter inlet and outlet ports. Install ½ NPT to 0.5 in. inner diameter barbed fitting adapters to those fittings.
5. Install a 0.5 in. ID and a 0.75 in. ID barbed fitting onto the gate valve (flow rate control). Connect the barbed fitting to the submersible pump with a ~20 cm length of tubing so that the valve handle lines up with the hole on the top right of the acrylic enclosure (Fig. 3b-c).
6. Insert the pump into the lower reservoir, and install the valve so that the valve stem passes through the mounting hole and the handle is outside the enclosure (Fig. 3c).
7. Insert a vertical acrylic panel near the inlet portion of the flow facility so that there is approximately a 5.0 mm opening below it (Fig. 3b-c). This component will act as the *sluice gate*, and can be raised and lowered to control flow from the upper reservoir to the channel.
8. Fill the upper reservoir loosely with a stainless steel wool scouring pad. This helps distribute inlet water flow evenly across the channel.
9. Connect the valve outlet to the flow meter inlet with a length of soft plastic tubing. Connect the flow meter outlet to the upper reservoir with plastic tubing. Ensure that the tubing inlet to the upper reservoir is well anchored so that it does not swing out when the pump is turned on.
10. Fill the lower reservoir with water.

2. Performing experiment

1. Measure the gap height underneath the gate using a ruler, and denote the value as H_1.
2. Turn on the pump, and adjust the flow rate using the valve to various flow rates (5 - 15 l min^{-1}). Use a ruler to measure the liquid depth downstream from the gate (H_2) for each case.
3. Qualitatively observe the shapes of the hydraulic jumps that form at different flow rates. Watch for the minimum threshold flow rate for formation of a hydraulic jump. Sharper, greater amplitude (H_2 -H_1), jumps should occur at higher flow rates.

Copyright © 2018

3. Data Analysis

1. For each flow rate case, calculate the inlet velocity, V_1, from the volumetric flow rate. $V_1 = \dot{V}/(H_1 W)$ where $\dot{V}$ is the volume flow rate and W is the channel width.
2. Evaluate the inlet Froude number ($\mathrm{Fr}_1 = V_1/\sqrt{gH_1}$) and theoretical downstream liquid depth for each case (Eqn. 4). Compare these values with measured downstream jump depths.

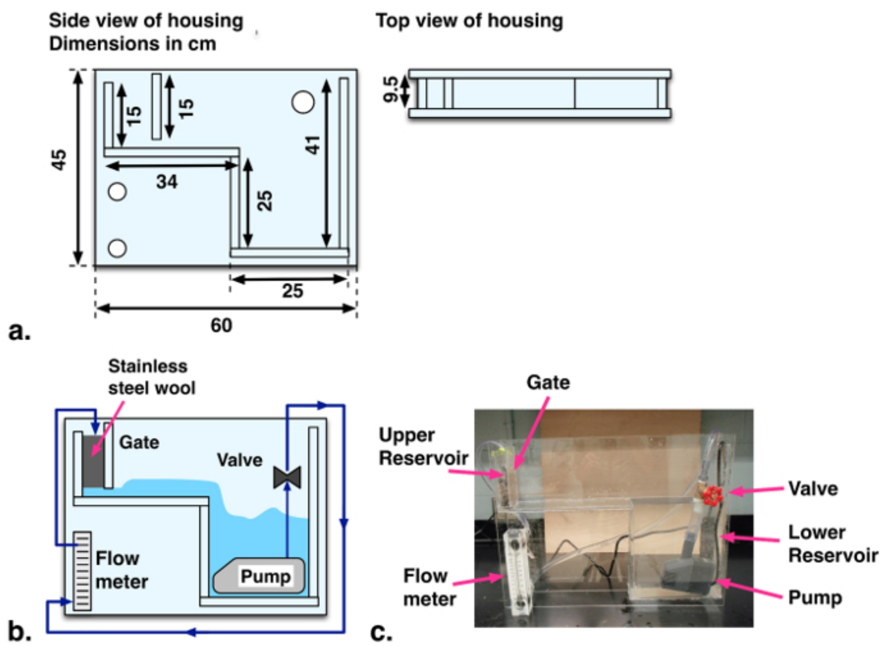

Figure 3: a. Schematic and dimensions of facility structure. b. Flow diagram of hydraulic jump facility. c. Labeled photograph of experimental facility.

Results

Upstream Froude numbers (Fr_1) and measured and theoretical downstream depths are summarized in Table 1. The measured threshold inlet flow rate for formation of a hydraulic jump corresponds to $\mathrm{Fr}_1 = 0.9 \pm 0.3$, which matches the theoretical value of 1. At supercritical flow rates ($\mathrm{Fr}_1 > 1$) predicted downstream depths match theoretical values (Eqn. 4) within experimental uncertainty.

Table 1 - Measured upstream Froude numbers (Fr_1) and downstream liquid depths for $H_1 = 5 \pm 1$ mm

Liquid Flow Rate ($\dot{V}$, **l min^{-1}**)	**Upstream Froude Number (Fr_1)**	**Measured Downstream Depth (H_2)**	**Predicted Downstream Depth (H_2)**	**Notes**
6.0 ± 0.5	0.9 ± 0.3	5 ± 1	5 ± 1	Threshold Froude number for hydraulic jump
11.0 ± 0.5	1.7 ± 0.5	11 ± 1	10 ± 2	
12.0 ± 0.5	1.9 ± 0.6	12 ± 1	11 ± 2	
13.5 ± 0.5	2.1 ± 0.6	14 ± 1	13 ± 2	

Photographs of the hydraulic jumps from the above cases are presented in Fig. 4. No jump is observed for $\dot{V}$ = 6.0 l min^{-1} ($\mathrm{Fr}_1 = 0.9$). Jumps are observed for the two other cases with $\mathrm{Fr}_1 > 1$. A stronger, higher amplitude, jump is observed at the higher flow rate supercritical case.

Copyright © 2018

$6.0\ l\ min^{-1}$ $Fr_1 = 0.9$ | $12.0\ l\ min^{-1}$ $Fr_1 = 1.9$ | $13.5\ l\ min^{-1}$ $Fr_1 = 2.1$

Figure 4: Photograph of hydraulic jumps, showing critical condition (no jump, $Fr_1 = 0.9$) and jumps at $Fr_1 = 1.9, 2.1$.

Applications and Summary

This experiment demonstrated the phenomena of hydraulic jumps that form at supercritical conditions (Fr > 1) in open channel flows. An experimental facility was constructed to observe hydraulic jump phenomena at varying flow rates. Downstream liquid depths were measured and matched with theoretical predictions.

In this experiment, the maximum reported inlet Froude number was 2.1. The pump was rated to deliver significantly higher flow rates, but resistance in the flow meter limited measurable flow rates to ~14 $l\ min^{-1}$. In future experiments, a pump with a greater head rating or a lower pressure drop flow meter may enable a broader range of studied conditions.

Hydraulic jumps are often engineered into hydraulic systems to dissipate fluid mechanical energy into heat. This reduces the potential for damage by high velocity liquid jetting from spillways. At high channel flow velocities, sediment can be lifted up from streambeds and fluidized. By reducing flow velocities, hydraulic jumps also reduce the potential for erosion and scouring around pilings. In water treatment plants, hydraulic jumps are sometimes used to induce mixing and aerate flow. The mixing performance and gas entrainment from hydraulic jumps can be observed qualitatively in this experiment.

For all of these applications, momentum analyses across hydraulic jumps, as discussed here, are key tools for predicting hydraulic system behavior. Similarly, scale model experiments such as those demonstrated in this project, can guide the design of open-channel flow geometries and hydraulic equipment for large-scale engineering applications.

References

1. Cimbala, Y.A. Cengel, Fluid Mechanics Fundamentals and Applications, 3rd edition, McGraw-Hill, New York, NY, 2014.

Copyright © 2018