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Experimental Study of the Interaction of Hydraulic Jumps Caused by an Inclined Jet and a Vertical Jet

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Abstract

The present work investigates the effect of hydraulic jump interaction between an inclined nozzle and a vertical nozzle experimentally. Water is used as the test fluid, and the flow is laminar. First, the experimental setup used in this study was validated with the results of an inclined nozzle and two vertical jets. Previous studies have shown that there are boundaries (far, distance, and near regions) in the interaction of two vertical jets, which change with an increase or decrease in flow rate and distance between the nozzles. The results of this study show that in the interaction of hydraulic jumps from an inclined and a vertical nozzle, the boundary between the far and distance regions increases linearly by about 20% with an increase in inclination angle. Additionally, with a fixed distance between the nozzles, the ratio of the jump radius of the vertical jet at 0 degrees to 180 degrees ($R1_{\pi}/R1_{o}$) increases with an increase in inclination angle, but this ratio decreases for the inclined nozzle ($R2_{\pi}/R2_{o}$). These ratios increase linearly with an increase in flow rate. Moreover, at a constant flow rate, the ratio $R1_{\pi}/R1_{o}$ decreases with an increase in inclination angle, and this ratio approaches 1, as the nozzles move away from each other. This trend is vice versa for the inclined nozzle.

Keywords: Hydraulic jump interaction; jet inclination angle; inclined jet; vertical jet; image processing.

1. Introduction

When a vertical fluid jet impinges on a horizontal plate, the fluid spreads radially in all directions of the plate. The jump radius is a specific distance from the point of impact of the jet on the horizontal plate, at which the flow changes from supercritical to subcritical, and the fluid thickness increases suddenly. This hydraulic jump has many applications in industry, including chemical mixing, coating, cooling, etc.

As the radius of the hydraulic jump increases, the heat transfer surface area increases. The high fluid velocity before the jump creates a high heat transfer rate, but this rate decreases rapidly with distance from the jump. Therefore, the distribution of net heat flux around the impact region is non-uniform. To overcome this drawback, multiple jets (nozzles) are used in many industrial applications.

In 2007, Kate et al. [1] were the first to experimentally investigate the interaction of hydraulic jumps formed by the impact of two vertical circular liquid jets (with equal and unequal strength) on a horizontal surface.

When multiple nozzles are used, the jump regions become wider and merge due to the proximity of the jumps. This creates a more uniform heat transfer surface compared to the jump created by single jets, which improves the surface cooling efficiency. This protects the surface from being subjected to severe temperature gradients. In 2016, Kate and Gorde [2] studied the hydraulic jumps resulting from the interaction of multiple vertical jets impinging on a horizontal surface. They demonstrated that in this case, the circular hydraulic jumps deform and lose their symmetry. The total effective area of the circular hydraulic jumps also decreases due to the deformation of the jumps caused by their interaction.

Given that inclined nozzles are more commonly used in industry due to their more superficial placement, a review of the research [3-6] shows that most studies on inclined jets have focused on single-angled jets. No study has yet been conducted on the interaction of hydraulic jumps caused by an inclined jet and a vertical jet. The present study aims to investigate such interactions experimentally.

2. Methodology

For the present study, a hydraulic jump creating device was used. This device can create inclined and vertical hydraulic jumps with one or two nozzles. In this device, the nozzles are installed by a unique mechanism so that they can move horizontally and angularly**.** When a single inclined nozzle with a diameter of d impinges on a horizontal surface, the angle of impact of the fluid is greater than the angle of inclination of the nozzle due to the effect of gravity and is calculated using Equation 1.

$$\phi = tan^{-1}\frac{(V^2}{V}\frac{sin^3\phi_n + 2g * H)^{\frac{1}{2}}}{cos\,\phi_n} \qquad (1)$$

Where ϕ_n is angle of the nozzle with the horizontal surface, θ is the circumferential angle of the hydraulic jump, H is height of the nozzle from the target plate, V is the exit velocity of the fluid from the nozzle orifice, $R_j(\theta)$ is the radius of the hydraulic jump, ϕ is the angle of impact of the jet with the horizontal surface, g is acceleration due to gravity.

The radial position of the non-circular hydraulic jump is also predicted according to Equation 2, by analyzing an external inviscid flow combined with the boundary layer approximations.

$$R_j(\phi,\theta) = C\left[\frac{{r_o}^2}{2}\frac{sin^3\phi}{(1+cos\phi cos\theta)^2}V\right]^{\frac{5}{8}}\vartheta^{-\frac{3}{8}}g^{-\frac{1}{8}} \qquad (2)$$

Where ϑ is the kinematic viscosity of the fluid and C is the constant equal to 0.73.

Figure 1 shows a schematic diagram of the impingement of hydraulic jumps from two inclined and vertical nozzles. This figure is drawn in a case where the hydraulic jumps do not effect on each other (far region). Other cases, such as the impingement of hydraulic jumps in the distance and near regions, can also occur. Nozzle number 2 can be rotated relative to the vertical axis. It can also be displaced longitudinally relative to nozzle number 1. When the fluid impinges on the surface, the hydraulic jumps created by the two nozzles can interact with each other, and for this reason, the radius of the jump at two angles of 0 and 180 degrees are considered the important measured factors. S and H are the distances between the nozzle outlets and the height of the nozzles from the target plate, respectively. $R1_o$, $R1_\pi$, $R2_o$, and $R2_\pi$ are the radii of the jumps created at angles 0 and 180 degrees for nozzles 1 and 2, respectively. The fluid used in the experiment is purified water with a hardness of about 50 ppm and a volume of 70 liters. Therefore, the thermophysical properties of the fluid with reasonable accuracy are like distilled water and with the properties mentioned in the text at temperature of 25 degrees Celsius with the specifications $\sigma = 0.073\,\frac{N}{m}$, $\rho = 998\,\frac{kg}{m^2}$ and $\vartheta = 0.001003\,\frac{kg}{ms}$. the maximum flow rate through the nozzles in this work is about 6 liters per minute, which corresponds to a Reynolds number (considering the inner radius of the nozzles) of about 2000. Therefore, all experiments performed are in the laminar flow regime. To better observe the radius of the jumps, food coloring was injected into the fluid. H is considered equal to 10 cm. All experiments were extracted for angles 0, 10, 20, and 30 degrees for nozzle number 2 (Figure 1)**.**

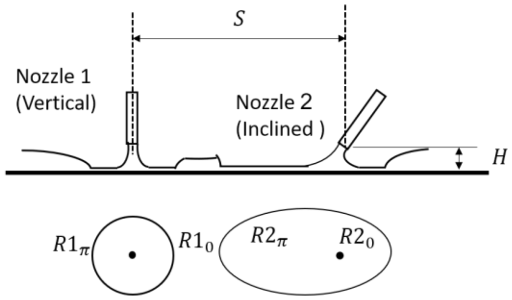


Figure 1 - Schematic of hydraulic jumps created by two impinging inclined and vertical jets on a surface

The combined uncertainty for measuring the fluid flow rate, including the uncertainty of the measuring instrument and the uncertainty of the repeatability of the experiment, (obtained using the Klein-Macline equation), is 2.0%.

A digital caliper with an accuracy of 0.01 mm was used to measure the radius of the hydraulic jump. A YF-401 Hall effect sensor with a flow rate range of 1 to 6 liters per minute and an error of 0.1 to 0.5 percent was used to measure the flow rate. This sensor is suitable for general and laboratory applications. The results of the calibration of this sensor with a TFM3100-F1 ultrasonic sensor and also with the flow meter available in the device under the same flow conditions and the same fluid and nozzles, indicate very good accuracy of this sensor. The experiments were repeated several times at different time intervals and the same results were obtained.

3. Results and Discussion

The results will be presented in three sections. first, the effect of the jet inclination angle on the far, distance, and near regions will be investigated. Then, the effect of this parameter on the formed radii of two nozzles at a constant flow rate and S/D will be discussed.

4. Effect of Inclination Angle on the Regions Created by the Interaction of Jumps

When the jumps from two vertical nozzles interact, three regions are formed: the far, distance, and the near regions. The definition of this regions depend on the distance between the jets and their flow rates. In this study, since one of the nozzles is inclined, it is expected that the nozzle angle will affect the size of the three formed regions. The boundary between the far and distance region is the threshold at which the hydraulic jumps interact and deform. As can be seen in Figure 2, this boundary increases with increasing the inclination angle.

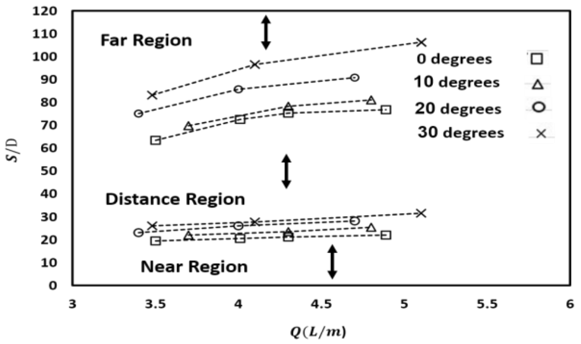
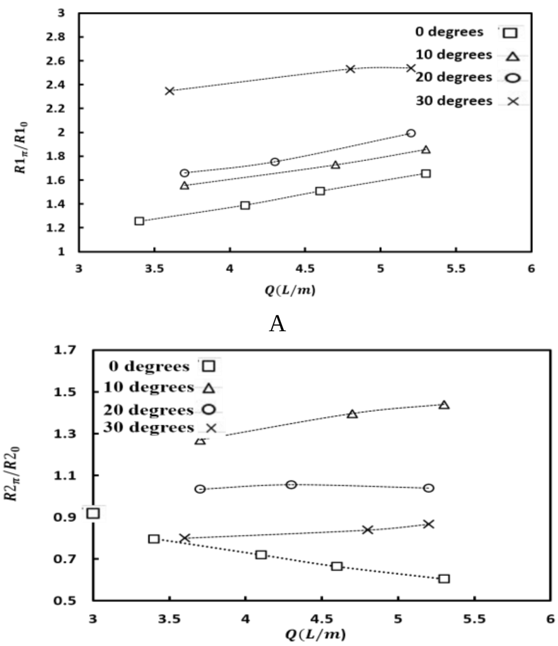


Figure 2 - Effect of the inclination angle of a nozzle on the boundary of the regions formed by the jumps of two fluid jets

5. Effect of Nozzle Inclination Angle on the Radius of Hydraulic Jumps Formed at S/D Constant

When two vertical jets impinge a surface, the shape and size of the resulting hydraulic jumps depend on factors such as flow rate and S/D [1]. In addition to the above factors, it seems that the angle of nozzle 2 can also affect this parameters (Figure 3).



B

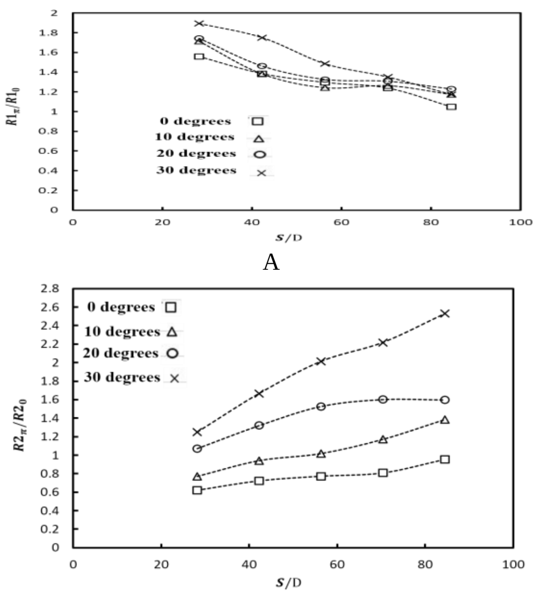
Figure 3. (A) Variations of the $R1_\pi/R1_o$ to flow rate for different nozzle angles 2, (B). Variations of $R2_\pi/R2_o$ to flow rate for different angles of nozzle 2 ($S/D = (20)$)

Physically, when the distance between the two nozzles is constant, with increasing flow rate, the radii of the hydraulic jumps of nozzles 1 and 2 in the interaction zone are affected by each other, so that the ratio $R1_\pi/R1_o$ increases and the shape of the jump deviates from the circular shape. With increasing the inclination angle of nozzle 2, due to the increase in $R2_\pi$, the ratio $R1_\pi/R1_o$ increases and the shape of the jump of nozzle 1 also deviates more from symmetry, and it becomes more elliptical in shape (Figure 3 (A)).

In the case of nozzle 2, with increasing inclination angle, the ratio $R2_\pi/R2_o$ decreases due to the ellipticity of the jump shape when it interacts with the jump of nozzle 1, which is the opposite of what happens with nozzle 1(Figure 3 (A)). as a result, the shape of the jump tends towards a circular shape due to the interaction of the jumps of nozzles 1 and 2. The ratio ($R2_\pi/R2_o$) increases with increasing fluid flow rate due to the increase in the radius of the jumps (Figure 3(B)).

6. Effect of Nozzle Inclination Angle on the Radius of Hydraulic Jumps Formed at Constant Flow Rate

According to Figure 4(A), since $R1_\pi$ and $R1_0$ are behind and in front of the interaction point respectively, therefore $R1_\pi$ is much more affected by the jump of nozzle 2 than $R1_o$. Increasing the nozzle angle increases the momentum of the flow at the point of jumps interaction from the nozzle 2. as a result, $R1_o$ is more affected by the interaction and $R1_\pi/R1_o$ increases. This effect is more significant, by bringing the 2 nozzles closer together (When nozzle 2 is inclined).



B

Figure 4. (A) Variations of $R1_\pi/R1_o$ to S/D for different angles of nozzle number 2, (B). Variations of $R2_\pi/R2_o$ to S/D for different angles of nozzle number 2 ($Q = 4.4$ Lpm)

When nozzle 2 is completely vertical, Reducing the distance between the two nozzles decreases the ratio of $R2_{\pi}/R2_{o}$. Because, the jump radius of nozzle 2 ($R2_{\pi}$) at the interaction point is affected by the jump radius of nozzle 1 ($R1_{o}$). As the nozzles move away from each other, this ratio increases due to the reduced effect of the jumps on each other (Figure 4(B)). Also, at a constant distance between the two nozzles, increasing the inclination angle of nozzle 2 increases $R2_{\pi}$ more than $R2_{o}$. Therefore, when the jump interacts to jump of nozzle 1, the $R2_{\pi}$ is less affected by the $R1_{o}$ and the $R2_{\pi}/R2_{o}$ increases. Finally, as the nozzles move away from each other, the ratio $R2_{\pi}/R2_{o}$ increases due to the reduction of interaction strength between the jumps.

7. Conclusion

the boundary between the far and distance regions changes as the nozzle inclination angle increases, such that the hydraulic jumps interact at a farther distance compared to the vertical case. However, the boundary of the near and distance regions is not significantly affected by the nozzle inclination angle.

When the distance between two nozzles (S/D) is constant, the inclination of one nozzle affects the symmetry of the hydraulic jumps and increases the ratio $R1_{\pi}/R1_{o}$. However, this inclination decreases the ratio $R2_{\pi}/R2_{o}$.

At a constant flow rate (varying S/D), the ratio $R2_{\pi}/R2_{o}$ increases with increasing inclination angle due to the interaction of the inclined nozzle jump on the vertical nozzle hydraulic jump. This ratio increases as the nozzles move further apart.

8. References

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