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Experimental Study of the Effect of Fluid Jet Swirl on Circular Hydraulic Jump

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ABSTRACT: When an axially symmetrical fluid jet impacts on a horizontal plate vertically, a hydraulic jump is formed. Numerous studies are conducted on circular hydraulic jumps. However, the effect of the important and key parameter of fluid jet swirl on hydraulic jumps is not investigated. The main purpose of this study is to investigate the effect of this parameter on the circular hydraulic jump. The results of this study, achieved by using experimental method, show that the higher the angular velocity, the higher the increase in the radius of the jump. Drawing the diagram of the dimensionless radius of jump based on the dimensionless number of swirl shows two categories of lines. The first category is the constant angular velocity lines with a negative slope and the second category is the constant flow rate lines with a positive slope. The results showed that increasing the angular velocity of the swirling jet has less effect on increasing jump radius than increasing the flow rate. Experiments also showed that the hydraulic jumps created by a swirling jet follow the trend results of modified Watson's theory with a non-significant difference.

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1. INTRODUCTION

From the viewpoint of fluid mechanics, when a vertical liquid jet impinges on a horizontal plate, it spreads radially in all directions. At a certain distance from the point where the jet hits the plate, which is called the hydraulic jump radius, the thickness of the fluid increases, and the flow changes from the supercritical state upstream of the jump to the subcritical state downstream of the jump. In this case, a so-called circular hydraulic jump is formed (Fig1.). Among the applications of this phenomenon, we can mention the process of cooling in industrial products.

In 1964, Watson studied the circular hydraulic jump in a viscous manner [1]. He presented this phenomenon as a theory by assuming a boundary layer for the upstream jump to be developed from the liquid jet. In this theory, Watson ignored the effects of surface tension, which is also a defect in his theory.

In 2003, Bush and Aristoff [2] fixed the main defect of Watson's theory. By considering the effect of the key parameter of surface tension on the problem of a circular hydraulic jump, they were able to modify Watson's theory and improved its results analytically. They considered the effect of surface tension by applying the radial component of surface tension force on the jump region and solved the problem by solving the momentum conservation equation.

Pasandideh Fard et al. [3] conducted a parametric study on the effect of various parameters such as flow rate, downstream height, viscosity and gravity on the radius of a circular hydraulic jump and its characteristics. They performed their numerical study using the volume of fluid method considering surface tension and compared numerical and experimental results.

Wang and Khayat [4] presented a simple and coherent model for predicting the position and height of the jump created in high viscosity liquids. They investigated the effect of gravity on supercritical flows. Their results showed that when the gravity effect is applied, the jump position can be determined without the knowledge of the downstream flow conditions, such as jump height and target plate radius. Their results also confirmed recent observations in the field of type I circular hydraulic jump.

By studying the scientific researches, we find that scientists have extensively studied the phenomenon of the circular hydraulic jump and the effect of various parameters on it. However, the effect of the important and key parameter of fluid jet swirl has never been investigated on the phenomenon of a circular hydraulic jump. In this research, the effect of this parameter is investigated for the first time.

2. THEORY

The most important and valid theory in the field of circular hydraulic jumps is Watson's theory [1], which was modified by Bush and Aristoff [2] by applying the effect of surface tension coefficient. They finally proposed the following equations to predict the radius of the circular hydraulic jump

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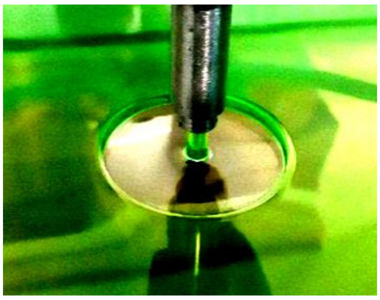

Fig. 1. A circular hydraulic jump generated in laboratory

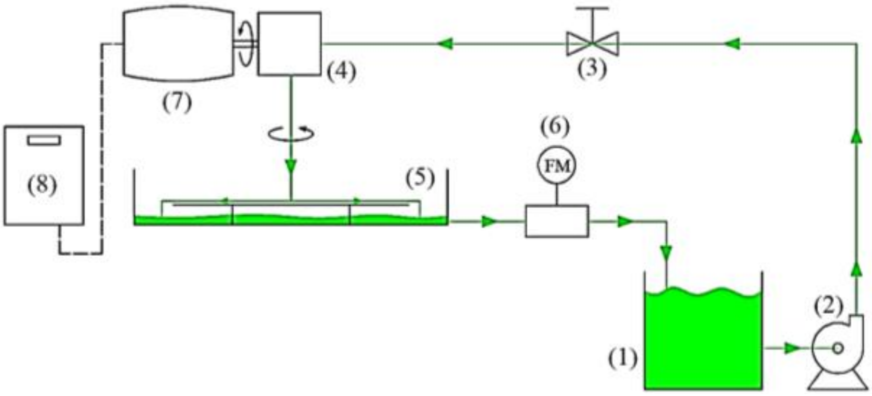

Fig. 2. A schematic of the device designed and constructed to generate hydraulic jumps in the present study; 1) major fluid storage tank, 2) pump, 3) flow control valve, 4) gearbox, 5) overflow tank and target plate, 6) flow meter, 7) electric motor and 8) regulating device of fluid jet swirl velocity.

$$\frac{R_j h_2^2 g a^2}{Q^2}\left(1+\frac{2}{Bo}\right)+\frac{a^2}{2\pi^2 R_j h_2}=0.10132-0.1297\left(\frac{R_j}{a}\right)\mathrm{Re}^{-1/2}, R_j \langle r_o \quad (1)$$

$$\frac{R_j h_2^2 g a^2}{Q^2}\left(1+\frac{2}{Bo}\right)+\frac{a^2}{2\pi^2 R_j h_2}=0.01676\left[\left(\frac{R_j}{a}\right)^3 \mathrm{Re}^{-1}+0.1826\right]^{-1}, R_j \geq r_o \quad (2)$$

In which R_j is the Jump radius, h_2 is downstream height of jump, g is gravity, a is radius of fluid jet, Q is the flow rate, Bo is Bond number, and Re is Reynolds number.

In the present work, for the first time, the effect of fluid jet swirl on the circular jump is investigated. Different definitions are provided for the swirl number. Facciolo [5] presented the ratio between the tangential velocity in the jet tube wall (maximum tangential velocity V_ω) and the mean axial velocity of the fluid (U_b) as the swirl number (S).

$$S=\frac{V_\omega}{U_b} \quad (3)$$

3. EXPERIMENT

Fig. 2. shows a schematic of a laboratory device designed and built for this research. This device is capable of creating hydraulic jumps using a swirling fluid jet that its rotation rate is adjustable using an inverter device.

A digital caliper with an accuracy of 0.01 mm was used to measure the dimensions and geometric parameters accurately. Also, Corel Draw image processing software with an accuracy of 0.01 mm was used to measure the radius of circular jump with high accuracy. The fluid used in this research is ethylene glycol with physical characteristics of ρ=1.1 g/cm^3, υ=11.8 cSt, and σ=47.5 dyn.cm^{-1}.

4. RESULTS AND DISCUSSION

The effect of flow rate on the radius of the circular jump at four angular velocities (for different nozzle diameters) is shown in Fig. 3. By considering this Figure carefully, we find that at a constant flow rate, increasing the angular velocity of the nozzle increases the radius of the circular jump. Because the angular velocity of the nozzle increases the tangential velocity of the fluid exiting the nozzle (centrifugal), forming a circular jump at a greater distance from the center of the fluid jet impact to the target plate.

Accurate analysis of the results shows that the radius of circular jump increases 3.29, 5.89 and 8.34 percent for nozzle angular velocities ω=132.8rpm, ω=266.4rpm, ω=400.8rpm compared to the non-rotating nozzle. In other words, the higher the nozzle angular velocity, the higher the percentage increase in the circular jump radius compared to the non-rotating nozzle. As mentioned earlier, the reason is related to the tangential velocity of the outlet fluid from the nozzle.

Drawing the diagram of the dimensionless radius of jump based on the dimensionless number of swirl shows two categories of lines. The first category is the constant angular velocity lines with a negative slope and the second category

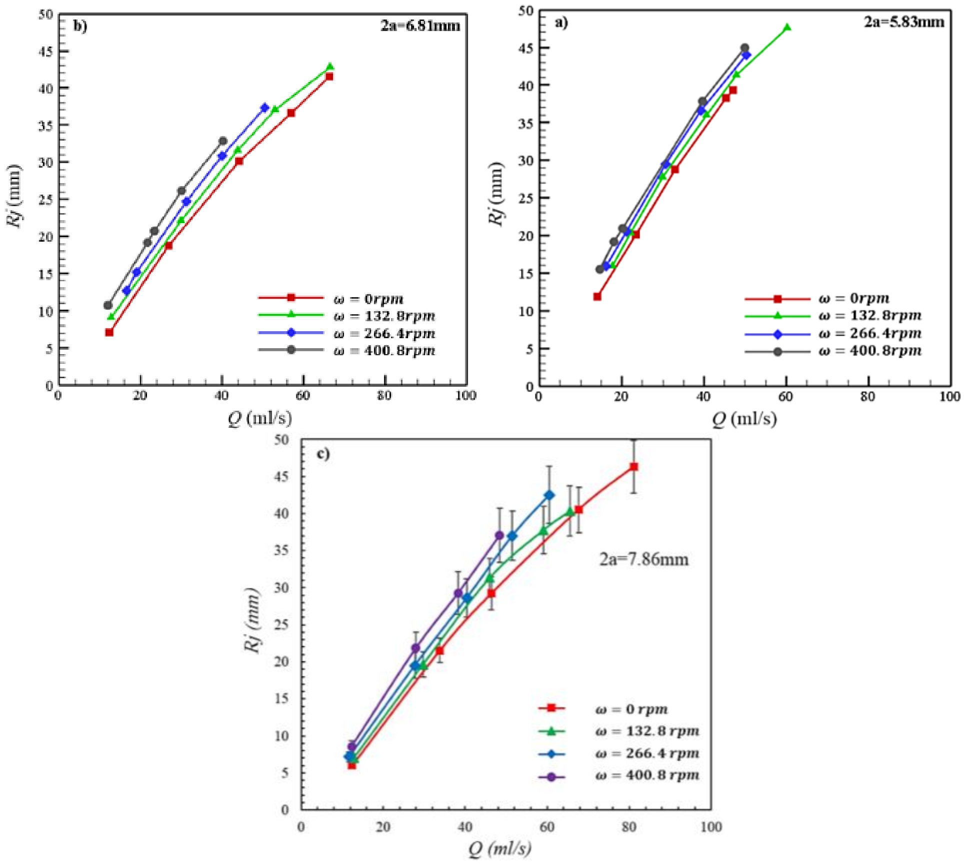

Fig. 3. Variations of the circular hydraulic jump radius against flow rate at different nozzle angular velocities with different diameters

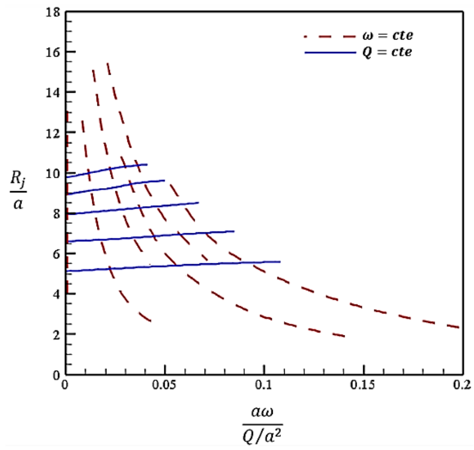

Fig. 4. Variations of the dimensionless radius versus the dimensionless swirl number

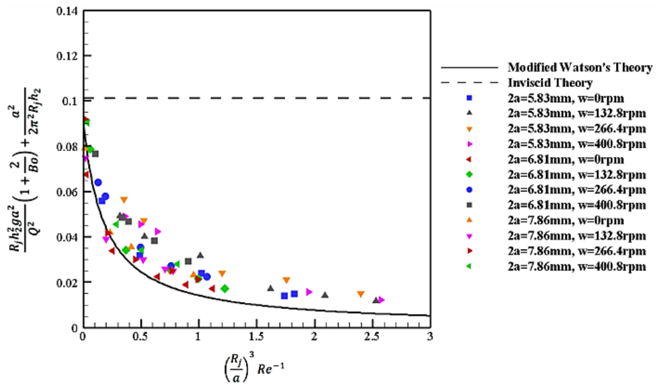

Fig. 5. The comparison of the results of hydraulic jumps generated by a swirling fluid jet with modified Watson's theory

is the constant flow rate lines with a positive slope (Fig. 4).

Fig. 5 shows a comparison of the results of hydraulic jumps formed by a swirling fluid jet with modified Watson's theory (the most important and only theory in the field of circular hydraulic jumps). As can be seen in this Figure, the experimental results of the present study are relatively consistent with the results of modified Watson's theory.

5. CONCLUSIONS

In this research, the effect of the parameter of fluid jet swirl on circular hydraulic jumps was studied experimentally and the following results were obtained:

- Increasing the angular velocity of the nozzle increases the circular jump radius at a constant flow rate.
- The rate of the increase of the radius of circular jump

in the rotating nozzle mode for nozzle angular velocities ω=132.8rpm, ω=266.4rpm, ω=400.8rpm compared to the non-rotating nozzle mode (ω=0rpm) are 3.29, 5.89 and 8.34 percent, respectively.

• The jumps created by the swirling fluid jet follow the results of modified Watson's theory with little difference. This difference is due to the fact that the parameter of fluid jet velocity in Watson's theory is not considered.

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