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A Phenomenological Study of Polygonal Hydraulic Jumps

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1. Introduction

From the viewpoint of fluid mechanics, when a vertical jet of a fluid impinges a horizontal plate, the fluid spreads radially in all directions. At a certain distance from the impingement point of the fluid jet, called the hydraulic jump radius, the thickness of fluid suddenly increases, the flow changes from supercritical to subcritical, and the so-called circular hydraulic jump is formed.

Figure 1 illustrates a schematic view of a circular hydraulic jump. The nozzle radius (a), the nozzle distance from the horizontal surface (h_N), the jump radius (R_j), the jump downstream height (h_2), and other parameters of the circular hydraulic jump are displayed in this figure. This phenomenon can be used for cooling purposes in industrial processes.

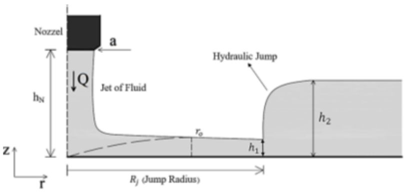

Figure 1. A schematic diagram of circular hydraulic jump

A review of the previous studies indicates that when the viscosity of the fluid is about 11 times more than the water viscosity and a downstream obstacle is considered for a stable circular hydraulic jump, the jump becomes unstable and changes into a polygonal hydraulic jump. The occurrence of this phenomenon has been attributed to the Rayleigh-Plateau instability in the previous studies. However, these instabilities and their effects on circular hydraulic jumps are unknown and the possible reasons for the formation of polygonal hydraulic jumps have not yet been discovered. The present study tried to identify instabilities and the reasons for the formation of polygonal hydraulic jumps. It also tried to respond to the question of why polygonal hydraulic jumps are formed as regular polygons.

2. Theory

The most important theory in the field of circular hydraulic jumps is Watson's theory, which was modified by Bush and Aristoff through applying the effect of surface tension coefficient. Stability is an important factor for classifying circular and non-circular hydraulic jumps. It can be argued that one of the important parameters in the field of stability is the surface tension.

Plateau and Rayleigh found that in a fluid stream pouring out of the nozzle, the surface tension can form curves on the stream surface by radially growing disturbances, which leads to a dropping stream, no matter how much smooth the stream is. The higher the surface tension, the higher the disturbances and instabilities.

With a higher viscosity and lower surface tension, the fluid stream is able to neutralize disturbances and conserve stability more effectively. On the contrary, with a higher surface tension and lower viscosity, the increase in disturbances and instabilities is higher and the fluid progresses towards forming curves and a drop-like shapes. That is why in water, which has a higher surface tension and lower viscosity compared to ethylene glycol, the disturbances increase faster and the hydraulic jump do not show a regular shape. On the contrary, ethylene glycol, as a higher viscosity and lower surface tension fluid, can fairly control disturbances without forming a drop-like shape. As a result, the surface tension reduces the surface, and energy to the lowest level through creating curves on the jump. These curves are the same as the sides and corners of the polygonal hydraulic jump, the number, and length of which changes depending on the flow rate.

Here the questions are: How do the disturbances form the polygonal hydraulic jumps based on the Rayleigh-Plateau instability in the presence of surface tension and viscosity? How do the disturbances enter the system? Does the decrease or elimination of the disturbances form circular jumps instead of polygonal ones? The following sections focus on identifying the disturbances and fluctuations, of the reasons for the formation of polygonal hydraulic and regular jumps.

3. Experimental Details

Figure 2 illustrates the device used in this study. As it is shown, the device includes a main tank for storing the fluid (1), a fluid pump (2), holding legs, pipes with different diameters for regulating the fluid jet diameter, the circular target plate (7), the overflow tank (9), horizontal and vertical levelling mechanisms, exposure and imaging mechanisms, the flowmeter (5), liquid film height measurement system (11), digital caliper, and the thermometer.

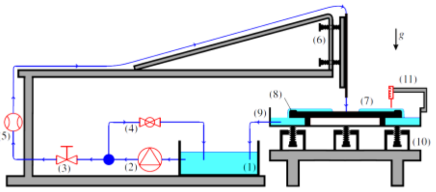

Figure 2. The device used in this study: 1) Fluid storage tank, 2) Pump, 3) Flow control valve, 4) Sub-path valve, 5) Flowmeter, 6) Vertical leveling mechanism, 7) Glass target plate, 8) Downstream obstacle, 9) Overflow tank, 10) Horizontal leveling mechanism, and 11) Fluid thickness measuring system

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4. Results and Discussion

The results of laboratory experiments conducted in the previous studies suggest that when the viscosity of the fluid is high (about 11 times more than the water viscosity) and in the presence of a downstream obstacle with a certain height on the target plate, the hydraulic jump appears in the form of a polygon. As described in the theory section, disturbances create instabilities and convert jumps to polygonal shapes. These disturbances can be divided into several categories: Environmental disturbances, Disturbances caused by moving and vibrate parts, Disturbances caused by the production of bubbles and the phenomenon of cavitation, Disturbances caused by the turbulent flows, Disturbances caused by fluid collisions on the target plate and producing surface waves. In this study, it is predicted that if the disturbances and fluctuations are minimized or reduced, the hydraulic jump remains stable and circular.

The results of various experiments conducted in this study indicate that the predictions made by the authors of the present study were correct and that circular hydraulic jumps can be formed by eliminating or reducing different types of disturbances even in the presence of a downstream obstacle. Figure 3 illustrates the upper and lower views of a stable circular hydraulic jump in the presence of a circular symmetric downstream obstacle with a height of 2.10 mm.

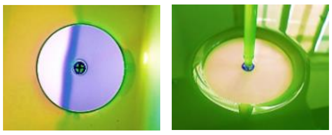

Figure 3. Stable circular hydraulic jump with the structure type IIb in the presence of downstream obstacle at h=2.10mm height (Q=82.23ml/s)

Figure 4 illustrates a comparison of the results of the stable circular jumps obtained in this study with those obtained through modified Watson's theory for fluid jet with three different diameters. The results obtained at different flow rates are consistent with those obtained through modified Watson's theory.

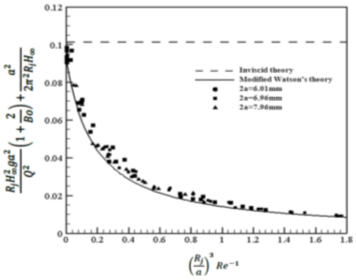

Figure 4. Comparison of the results of the stable circular jumps obtained in this study with modified Watson's theory

By eliminating the disturbances and the fluctuations from the flow, system, and environment, stable circular jumps are formed at low Reynolds numbers to high Reynolds numbers.

Moreover, it should be noted that the hydraulic jump tends to produce the minimum jump surface area due to the presence of the surface tension. The minimum surface area of polygonal jumps with an equal number of sides and the internal area can be found in a regular polygonal jump.

In addition, the reason for the behavior of the polygonal hydraulic jumps and the formation of the stability range can be explained. In the presence of disturbances, the hydraulic jump forms a regular polygon. At low flow rates (low momentum), the shape of the jump is oval or eye-like. As the flow rate increases, which also leads to increases in the flow momentum, the jump size grows and its internal and surface area increases. At the same time, the surface tension force as a resistance force tend to create the minimum surface area. Therefore, it reduces the surface area by adding a corner and one side, and consequently, the jump shape turns into a triangle. The reason is that, at this flow rate, the surface area of the triangular jump is smaller than that of the final oval. This trend will continue with increasing flow rate.

So the upper limit of stability is obtained (path number 1 in Figure 5). The path number 2 in Figure 5 shows the lower limit of stability.

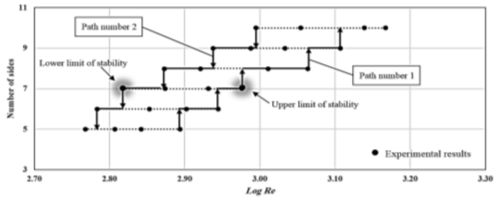

Figure 5. Stability chart for polygonal hydraulic jumps (2a=0.69cm and $H_{obstacle}$=0.25cm)

Nevertheless, it can be discovered from Figure 5, that in a fixed parametric regime (e.g. log Re=3), polygonal hydraulic jumps with 8, 9, and 10 sides can be formed.

5. Conclusion

The present study was an attempt to conduct a phenomenological analysis of polygonal hydraulic jumps, behavior and the possible reasons therefore. The findings of the study can be summarized as follows:

- The true cause of polygonal hydraulic jumps is the presence of disturbances and fluctuations in the flow, environment, or system of the experiment device based on the Rayleigh-Plateau phenomenon and in the presence of surface tension and viscosity effect.
- Increasing the flow rate strengthens instabilities, which leads to unstable circular jumps.
- The stable circular hydraulic jumps were all found to be of type IIb and is fairly consistent with the modified Watson's theory.
- The surface tension of the fluid tries to create the minimum possible surface area in the jump. Since the minimum surface area between different polygons with an equal number of sides is related to regular polygons, the polygonal hydraulic jump is formed in a symmetrical and regular way.