HYDRAULIC JUMPS AND THEIR INTERACTIONS DUE TO MULTIPLE IMPINGING JETS

Kate R. P.* and Gorde R.P#.
*Author for correspondence
Department of Mechanical Engineering,
Dr. Babasaheb Ambedkar Technological University Lonere Raigad,
Maharashtra 402103,
India
E-mail: rpkate@dbatu.ac.in
and
#Department of Mechanical Engineering,
Jayawantrao Sawant Polytechnic, Hadapsar Pune,
Maharashtra 411028,
India

ABSTRACT

Impingement cooling is a mechanism of heat transfer by means of collision, and can be achieved when a fluid jet strikes a surface. Multiple impinging jets increases rates of heat transfer considerably in comparison with single impinging jet. If the colliding fluid is a liquid, the flow of the thin film often gives rise to the formation of a complicated fluid dynamic phenomenon of circular hydraulic jump. The interaction between the hydraulic jumps formed due to multiple impinging jets creates interesting hydraulic jump interaction patterns. Depending on the spacing between the jets, their configuration, and their relative strengths, different kinds of hydraulic jump interactions are possible, resulting in a variety of flow patterns such as 'upwash' formation due to two closely spaced impinging liquid jets. The present study experimentally elucidates the jump–jump interactions formed due to normal impingement of two, three, and four liquid jets simultaneously on a flat horizontal surface. In case of more than two impinging jets, multiple stagnation lines are formed and these stagnation lines interact with each other giving rise to interesting flow patterns.

INTRODUCTION

Normal impingement of jets on surfaces is an established technique for providing high local heat/mass transfer rates in a variety of applications, including glass manufacturing, paper drying, gas turbine cooling and electronic packaging. The circular hydraulic jump following the impact of a liquid jet on a flat horizontal surface is a very common example of a free boundary problem in fluid mechanics[1]. It is observable in everyday life as one opens a water tap into a kitchen sink. When a vertical jet hits the horizontal surface, it first spreads out radially into a thin layer. At some distance, however, the height of liquid suddenly jumps to a higher value. Detailed quantitative estimations for position of the hydraulic jump, based on flow rate and viscosity of the liquid, were obtained by Bohr *et al.*[2] as

$$RJ = c\, q^{5/8} \nu^{-3/8} g^{-1/8} \qquad (1)$$

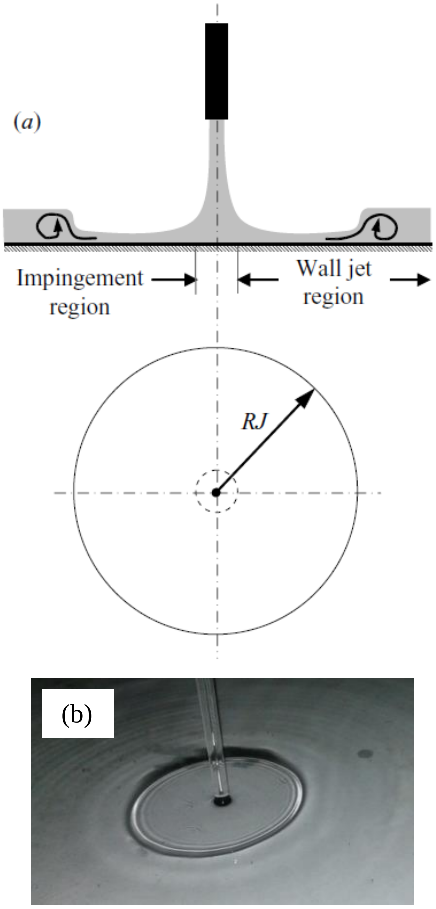


Figure 1(a) Sketch of the circular hydraulic jump, and (b) the circular hydraulic jump captured in laboratory experiments[8].

Where, the constant *c* depends on the velocity profile chosen in the analysis. For a parabolic profile, for example, *c* turns out to be approximately 0.73.

Physics of flow patterns of the circular hydraulic jump obtained under these conditions have been relatively well studied [2-7]. Figure 1(a) illustrates a typical circular hydraulic jump due to a normal impinging jet, while the corresponding experimental visualization is depicted in Figure 1(b).

Though very high heat transfer rates can be achieved in the vicinity of the impingement point region with a single jet, the heat transfer rate decreases sharply as the distance from the impingement point increases. To overcome this limitation of a single impinging jet, multiple impinging jets are used in a heat transfer applications. Each jet, in multiple impinging jets, striking on a flat horizontal surface gives rise to a circular hydraulic jump. The radially spreading films of multiple impinging jets collide and interact with each other. The studies on such hydraulic jump interactions are very rarely reported in the literature. Kate *et al*.[9] in their experimental study on interaction of hydraulic jumps formed by two normal impinging circular liquid jets have discussed in detail jump–jump interactions formed in such cases, for different values of inter-jet spacing and for different strengths of the individual jets. Analogous flow fields associated with the interactions between a single impinging jet and a fence are also studied to allow convenient experimental flow visualizations. This study is restricted to hydraulic jump interactions due to twin impinging liquid jets.

Studies on hydrodynamics of multiple impinging jets, widely accepted for cooling applications, and the subsequent hydraulic jump interactions are yet to be reported in the literature. The aim of the present work, therefore, is to investigate experimentally the flow field due to multiple impinging jets, with the primary intention of elucidating the mechanism of the associated hydraulic jump interactions.

The outline of the remaining part of this paper, is as follows. To begin with the experimental facility for multiple impinging liquid jets is discussed. Then the flow field due to two normal impinging liquid jets is described, both for distant and adjacent impinging jets (covering hydraulic jump interactions due to equal impinging jets), followed by hydraulic jump interactions due to two and three normal impinging circular liquid jets. At the end concluding remarks based on the present study are outlined.

NOMENCLATURE

d	[mm]	Nozzle diameter
g	[m/s^2]	Acceleration due to gravity
q,*Q*	[lpm]	Volume flow rate of water
S	[mm]	Jet spacing
RJ	[mm]	Radius of the circular hydraulic jump
ν	[m^2/s]	Kinematic viscosity of fluid

DESCRIPTION OF EXPERIMENTAL FACILITY

Experiments were performed for the characterization of hydraulic jumps and their interactions corresponding to both single and multiple impinging jets. A schematic diagram of the experimental setup is shown in Figure 2. The experimental set-up consists of a closed-loop water-jet system, comprised of a centrifugal pump four independent rotameters, for measurement of volume flow rate of water, calibrated in the required range of water flow rates, and circular tubes of brass and aluminum (in the diameter range 5–10 mm). These tubes can be used as nozzles having a length to diameter ratio of 150–200, so as to ensure a fully developed flow condition at the exit. The jet issuing from the nozzle is made to fall on a square glass plate of dimensions 600 mm × 600 mm, and a thickness of 10 mm, mounted on four levelling screws. The edge of the glass plate is chamfered with a radius of approximately 4mm on the top face, for smooth drainage of the liquid.

The set-up is fabricated such that that the jump can be viewed and photographed from underneath of the glass plate. Calibration of the experimental set-up has been performed by employing benchmark (experimental) data available in the literature for circular hydraulic jumps.

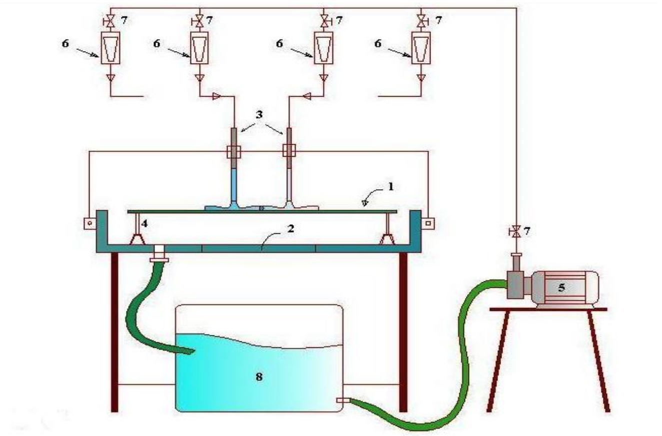


Figure 2 Experimental setup: circular liquid jets impinging on a flat horizontal plate (1– glass plate, 2– water collecting tray, 3– nozzle tubes, 4– levelling screws, 5– centrifugal pump, 6– rotameter, 7– flow control valves, 8– storage tank)

DESCRIPTION OF THE PHENOMENON

Various fluid dynamic aspects of interactions of the hydraulic jumps, formed as a consequence of the interaction between the jet and a target plate have been investigated. Hydraulic jump interactions due to two equal and unequal jets are well described by Kate *et al*. [9] in their experimental study. In their study, the impinging jets are termed 'jets of equal strength' or 'equal jets' when the nozzle diameters and the jet velocities of both the jets are the same, and 'jets of unequal strength' or unequal jets' when nozzle diameters and/or the jet velocities are not the same. This study deals with hydraulic jump interactions due to vertical multiple impinging equal jets. The multiple jets, in general, are grouped into three categories as far-distant impinging jets, distant impinging jets, and adjacent impinging jets.

Two far distant, distant and adjacent impinging jets are shown in Figures 3(a), 3(b) and 3(c) respectively. As the distance between the jets is reduced far from the critical spacing an upwash is formed as can be seen in Figure 3(d). Figure 4(a) depicts interacting jumps captured in the laboratory experiments.

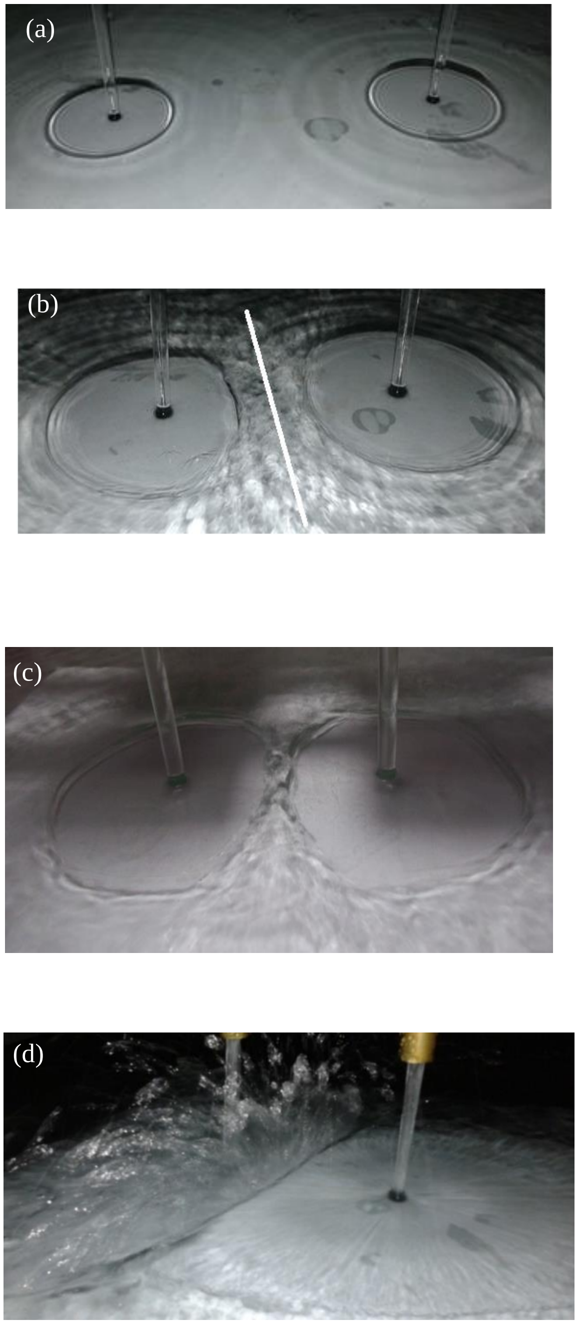


Figure 3 (a) Two far-distant impinging jets indicating no jump interactions. (b) Two jets spaced at a critical distance (c) formation of upwash (d) Upwash fountain flow.

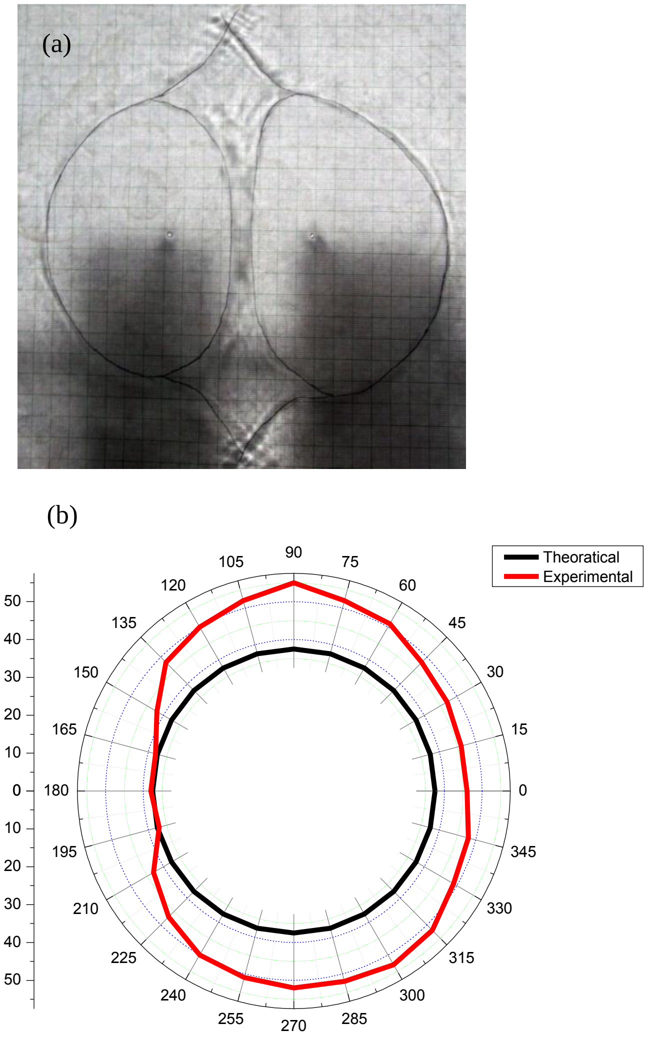


Figure 4 (a) Hydraulic jump interaction captured on a graph paper, (b) Deformed hydraulic jump shape due to two impinging jet (*Q* = 3 lpm, *S* =75 mm, *d* = 6 mm)

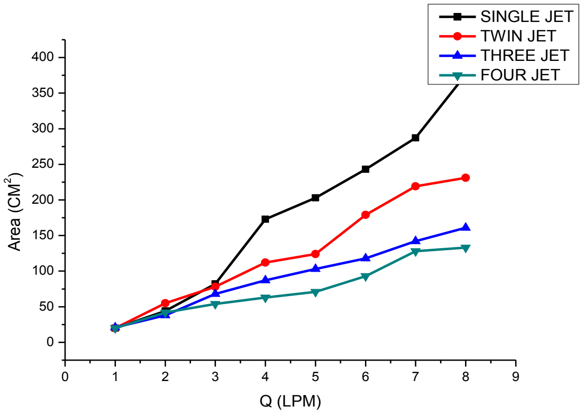


Figure 5 Effect of jump interaction on effective area of the hydraulic jump.

The graphical representation of reacting hydraulic jump is shown in figure 4(b). As can be seen from the figure the circular hydraulic jump gets deformed and loses its symmetry. It has been observed that the total effective area of the circular hydraulic jumps gets reduced as the jumps gets deformed due to their interactions. The effect of volume flow rate of liquid *Q* on effective hydraulic jump area due to hydraulic jump interactions is depicted in Figure 5. As can be seen from the figure, the effective jump area gets reduced as the number of jets are increased. This effect is more dominant at higher volume flow rates of the liquid as the hydraulic jump interactions are more intensive at high volume flow rates.

HYDRAULIC JUMP INTERACTIONS DUE TO THREE NORMAL IMPINGING JETS

Hydraulic jump interactions due to three equal and normal impinging jets are shown in Figures 6 (a) and (b). The contour of the jumps and their interactions traced on a graph paper is depicted in figure 7. Sketches of various interactions of hydraulic jumps due to three impinging jets are shown in Figures 8 (a) and (b). The deformed hydraulic jump, due to three equal and normal impinging jets is presented on a radial plot in Figure 9.

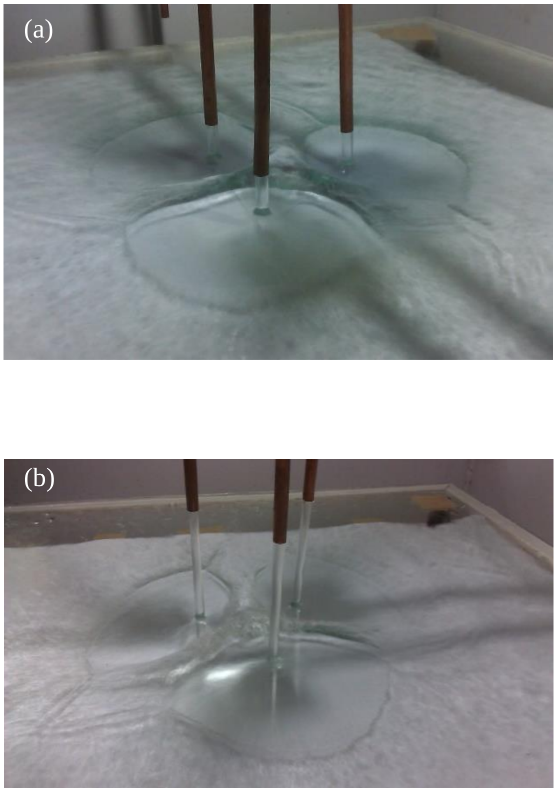


Figure 6(a) and (b) Hydraulic jump interactions due to three normal impinging circular liquid jets

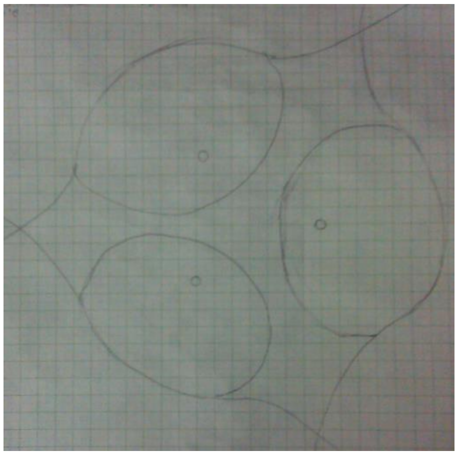
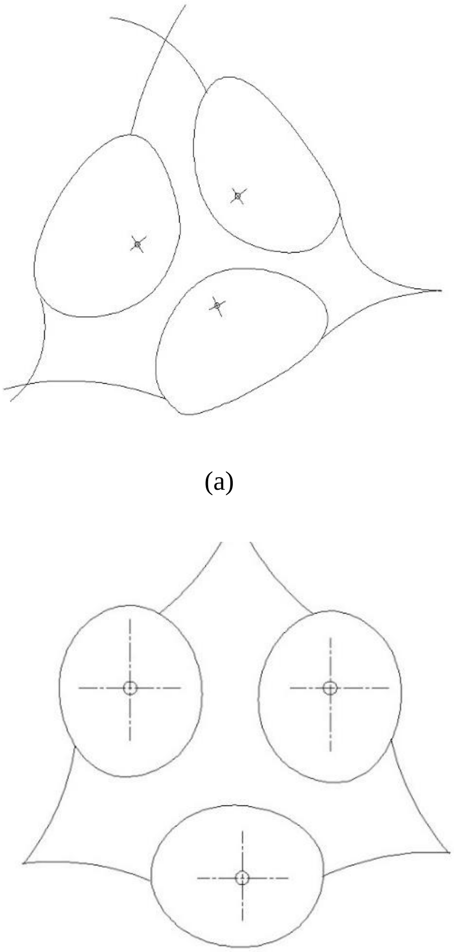


Figure 7 Hydraulic jump interactions captured and traced on a graph paper in the laboratory experiments



(a)

(b)

Figure 8(a) and (b) Sketches of jump interactions due to three equal and normal impinging

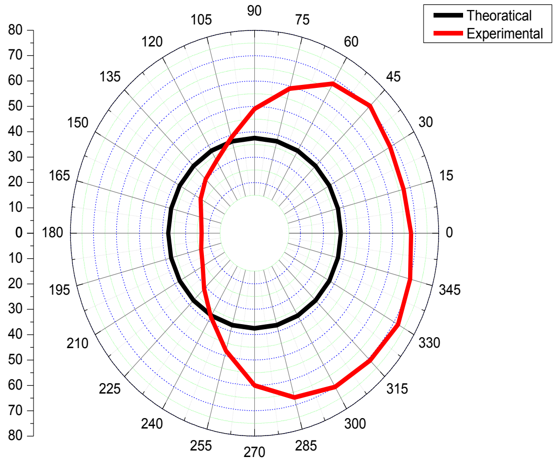


Figure 9. Deformed hydraulic jump jump due to three impinging jet (*Q* = 4 lpm, S = 75 mm, *d* = 6 mm)

As can be seen from these figures, the hydraulic jump interactions seems to be similar to that the hydraulic jump interactions in twin impinging jets. However, there is one distinct additional feature is observed in the flow field of hydraulic jump interaction due to more than two impinging jets.

The flow due to twin impinging jets, in general, is characterized by the following six distinct regions namely free jet flow, jet impingement region, inner wall jet region, outer wall jet region, jump interaction region, and entrainment region [10]. The jump interaction region in case of adjacent impinging jets can further grouped into two subgroups as jump interaction region, and upwash region.

In case of twin impinging jets, upon the collision of the wall jets, wall jet interaction zone, accompanied by a stagnation spot between the two jets, appears. In this stagnation spot, there is a stagnation line along the collision zone. The location where the inner wall jets due to the adjacent nozzles meet or collide is termed as the ‘stagnation line’. The characteristics of a stagnation line depend on the relative strength (momentum) of the individual jets. If the two vertical jets impinge on a flat horizontal surface with equal momentum, the stagnation line will be a straight line everywhere, equidistant from the two-jet impingement centres[9].

However, in case of flow due to more than two impinging jets in addition to six regions mentioned above, an additional and very distinct flow region is observed. Each hydraulic jump forms a stagnation line with other jump. Accordingly, in case of three impinging jets, three stagnation lines are formed where the jump interaction takes place. These three stagnation line intersect with each other at a point, around which a dome shaped region is formed. This additional very complex flow region is termed as ‘stagnation zone region’.

HYDRAULIC JUMP INTERACTIONS DUE TO FOUR NORMAL IMPINGING JETS

Hydraulic jump interactions due to four normal impinging equal jets are shown in Figures 10 (a). The contour of the jumps and their interactions traced on a graph paper in the laboratory experiments is depicted in Figure 10(b). A typical deformed hydraulic jump due to four normal impinging jets is depicted in Figure 12.

In case of four normal impinging jets, upon the collision of the wall jets, wall jet interaction zone, complemented by a stagnation line between the two jets, appears. Hence, four distinct stagnation lines are formed, as each jump interacts with a neighboring jump. These stagnation lines interact at a point giving rise to a dome like region termed as ‘stagnation zone’ similar to that of three normal impinging jets. As can be seen in figure 10, the liquid film thickness is maximum at the intersection of stagnation lines, as the wall jets segments of all the four hydraulic jumps collide at a point. The flow pattern in this stagnation zone is very complex and needs further detailed investigation.

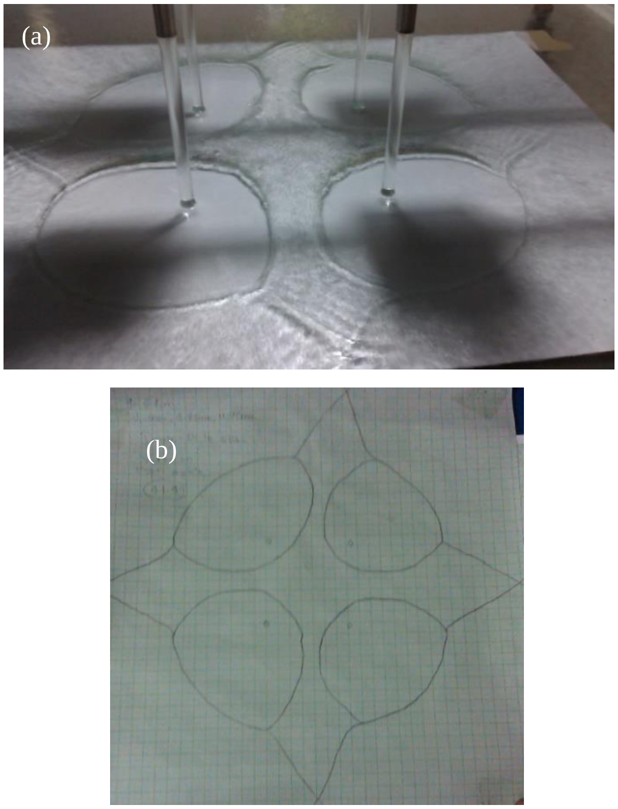


Figure 10 (a) Hydraulic jump interactions due to four normal impinging circular liquid jets, (b) Hydraulic jump interactions due to four normal impinging circular liquid jets traced in a laboratory experiments

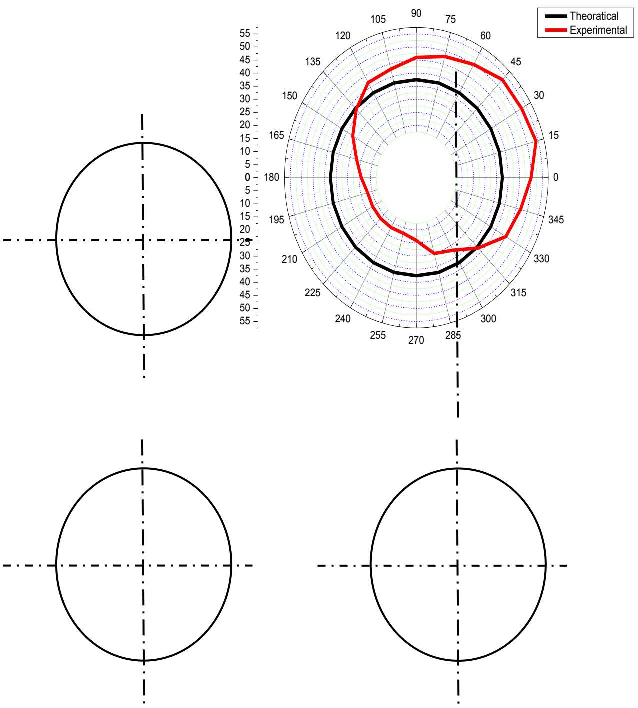


Figure 12 Deformed hydraulic jump jump due to fourimpinging jet (Q = 3 lpm, S = 75 mm, d = 6mm)

ANALOGY WITH SHOCK WAVE INTERACTIONS

As can be seen in the Figures 4, 6 and 10 very sharp corners and secondary waves are are formed along the stagnation lines. Such non-intuitive hydraulic jump profiles can be explained by appealing to the similarity between a hydraulic jump and a compression shock[9]. When two oblique waves meet each other, the axis of symmetry passing through the meeting point conceptually acts as an impervious wall. One of the shocks may be considered to be incident on that wall, while the other is reflected[10].

Waves and structures of a secondary nature similar to those encountered in compressible gas dynamics beyond the shock wave interactions, have also been observed during the present experiments.

CONCLUDING REMARKS

Flow pattern due to two normal impinging jets is characterized by the hydraulic jump interactions at the stagnation line. Depending on the types of the two jets various hydraulic jump interactions are possible. However, in case of more than two impinging jets, more than one stagnation lines are formed depending on the number of impinging jets. Flow pattern due to more than two normal impinging jets is characterized not only by the jump interactions along the stagnation line, but also by the stagnation line interactions giving rise to an additional dome like flow region termed as stagnation zone. This stagnation zone is formed when more than two normal impinging jets are used. This complex flow region is characterized by the maximum film thickness at the point of intersection of the stagnation lines. The film thickness gradually decreases along the stagnation lines in the radial direction.

The hydraulic jump interactions due to multiple impinging liquid jets are analogous to the shock wave interactions in the compressible fluid dynamics.

REFERENCES

[1] Klapp J., Medina A., Cros A., and Vergas C.A., Fluid dynamics in physics, engineering and environmental applications, *Springer Science & Business Media*, 2012.

[2] Bohr P., Dimon P., and Putkaradze V., Shallow water approach to the circular hydraulic jump, *Journal of Fluid Mechanics*, Vol. 254, 1993, pp. 635-648.

[3] Arakeri J.H., and Rao A., On radial flow on a horizontal surface and the circular hydraulic jump, *Journal of Indian Institute of Science*, Vol. 76, 1996, pp. 73-91.

[4] Higuera F.J., Hydraulic jump in a viscous laminar flow, *Journal of Fluid Mechanics*, Vol. 274, 1994, pp. 69-42.

[5] Higuera F.J., The circular hydraulic jump, *Physics of Fluids*, Vol. 9, 1997, pp. 1476-14-78.

[6] Godwin R., The hydraulic jump ('shocks' and viscous flow in the kitchen sink), *American Journal of Physics*, Vol. 61, 1993, pp. 829-832.

[7] Rao A., and Arakeri J.H., Integral analysis applied to radial film flows, *International Journal of Heat and Mass Transfer*, Vol. 41, 1998, pp. 2557-2767.

[8] Kate R.P., Das P.K., and Chakraborty S., Hydraulic jumps due to oblique impingement of circular liquid jet on a flat horizontal surface, *Journal of Fluid Mechanics*, vol. 573, 2007, pp. 247-273.

[9] Kate, R.P., Das P.K., and Chakraborty S., An Experimental Investigation on the interaction of hydraulic jumps formed by two normal impinging circular liquid jets, *Journal of Fluid Mechanics*, Vol. 590, 2007, pp. 355-380.

[10] Preiswerk E., Applications of the methods of gas dynamics to water flows with free surfaces, *NACA TM* , Vol. 934 and 935, 1940.