A project report on

An experimental study of hydraulic jump due to moving jet impingement

By

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Certificate

This is to certify that the thesis titled "**An Experimental Study of Hydraulic Jump due to Moving Jet Impingement**" by Mr. Mithilesh Kumar Janghel, submitted to the National Institute of Technology Rourkela for the award of degree of Master of Technology with specialization in Thermal Engineering is a record of bonafide research work carried out by him in the Department of Mechanical Engineering, under my supervision. I believe that this thesis fulfils part of the requirements for the award of degree of Master of Technology.

The results embodied in this thesis have not been submitted in parts or full to any other University or Institute for the award of any other degree elsewhere to the best of my knowledge.

Date: 01 / June / 2015

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Self-Declaration

I, Mithilesh Kumar Janghel, Roll No. 213ME3433, student of M. Tech (2013-2015) Thermal Engineering at Department of Mechanical Engineering, National Institute of Technology Rourkela, do hereby declare that I have not adopted any kind of unfair means and carried out the research work reported in this thesis work ethically to methe best of my knowledge. If adoption of any kind of unfair means is found in this thesis work at a later stage, then appropriate action can be taken against me includingwithdrawal of this thesis work.

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Mithilesh Kumar Janghel

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Abstract

The objective of this project work is to study experimentally the hydraulic jump with a moving jet impingement on a glass plate surface. The jet strikes the horizontally placed glass plate and the jump occur which is investigated with different flow rate and discussed here in detail. Hydraulic jump of two different variety has been observed in this study when jet is stationary with respect to horizontal glass plate and moving. When jet is stationary with higher angle of jet inclination, smooth curve is appeared at the jump location, and for lower angle of jet inclination, curve with sharp change in profile is observed. Radius of hydraulic jump and the profile formed due to variation in flow rate are studied experimentally. When jet is in still condition we found that the radius of hydraulic jump increases with the flow rate and elliptical shape is formed due to jet inclination and when it moves normally with respect to horizontal glass plate a semicircular shape occur in the direction of jet movement. The result are found out for hydraulic jump with variation of flow rate through graph and validate with existing results of literature. The jet is moved by the means of slider crank mechanism.

Keywords: Hydraulic jump, Jet impingement.

Contents

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Nomenclature:

C_r	Crank radius, mm
d	Jet diameter, mm
g	Acceleration due to gravity, m/s^2
H	Film thickness of hydraulic jump, mm
h	Vertical distance from nozzle to glass plate, mm
q	Flow rate of water, ml/min
R	Radius of hydraulic jump, mm
U_r	Velocity of jet, m/s

Greek symbols:

θ	Azimuthal angle of fluid flow after jet impingement.
ϕ	Jet inclination angle

Chapter 1

Introduction

When a liquid jet impinges on a surface then the liquid spread out radially along the surface. A certain distance from the jet impingement one notice a sudden thickening of flow called circular hydraulic jump. The hydraulic jump formed is termed as “Circular hydraulic jump” due to radially symmetric flow from the point of jet impingement

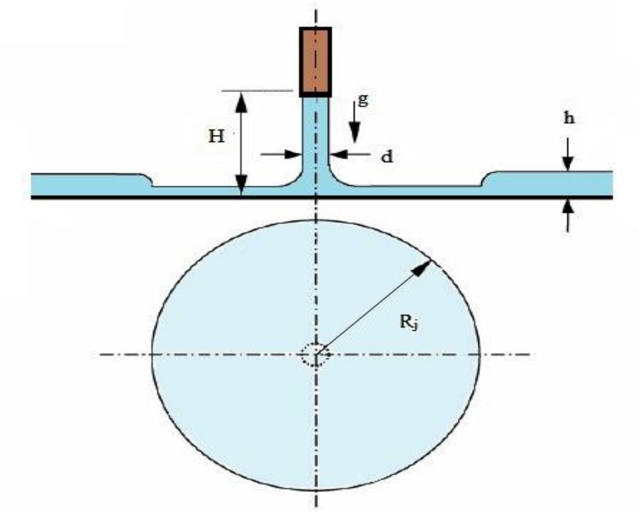


Fig. 1.1 Schematic diagram of circular hydraulic jump.

Liquid jet can me made very easily by using a straight hallow tube or nozzle. When this liquid jet impinges the target surface forms a boundary layer of very thin stagnation zone which helps to provide least resistance to heat flow. This creates the high value of convective heat transfer coefficient and suits the working environment where a high load of heat needs to remove for maintaining a low temperature or temperature difference in the system e.g. in some semiconductor system, the junction temperature is required to maintain a temperature of less than 150°c whereas the load of heat can reach up to 10 MW/m^2. So a high attention should be given to fluid jet to maintain the temperature.

This liquid jet can carry a huge amount of heat flux from the target source if the velocity of fluid reach to provide a high stagnation zone pressure. A jet having small diameter with velocity of 130m/sec can remove a heat load up to 400 MW/m^2. So, liquid jets are suitable for cooling and for creating high heat flux source.

This the best technique to provide local heat and mass transfer between liquid and surface where jump strikes. Now a days this method of heat transfer is used in many industries including gas turbine for cooling of blade, paper industry, electronic packaging, glass manufacturing, rolling mill etc.

This method of heat transfer is widely used in rolling mill to fulfil customer requirement of coiling temperature. So the temperature of strip and run out that is used to hold the strip is controlled by hydraulic jump phenomenon by varying the parameter such as the spacing between the nozzle and surface, flow rate of water, nozzle shape, and turbulence of fluid, jet inclination angle.

In many industry, the jet impingement is used in obliquely inclined position with respect to the target surface for cooling purpose. When jet inclination angle is differ than normal angle, jump profile becomes non circular and oblate shape formed. However when the jet inclination angle is higher than critical angle smooth curves formed and one can assume that an axis of symmetry that passes through the point where the liquid jet impinges.

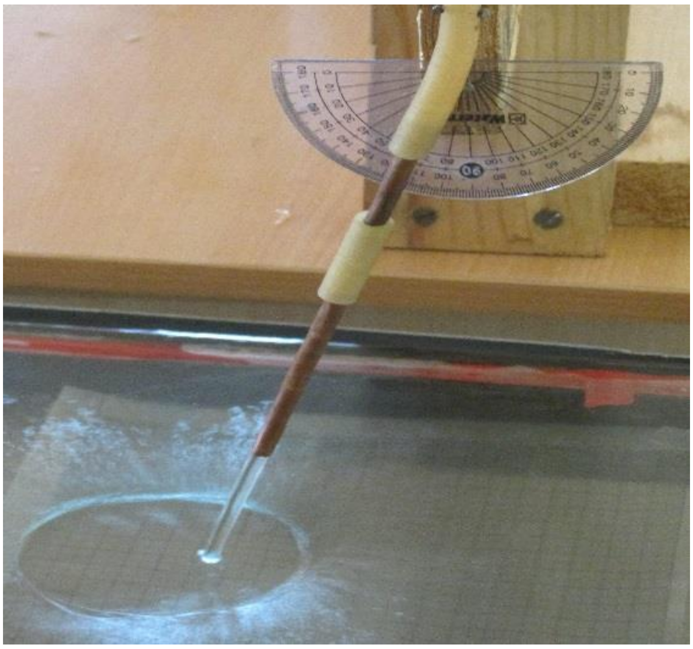


Fig. 1.2 Non-circular hydraulic jump due to oblique jet impingement (actual photograph)

It is clear in Fig. 1.2 that the smooth curve is formed which is more or less elliptical in shape and is independent of the inclination of angle of jet or the velocity of jet. The hydraulic Jump profile become enlarges in shape or the smooth curve elongates with respect to the increase in jet velocity or increase with flow rate. However, the hydraulic jump structure remains smooth with elliptical in shape.

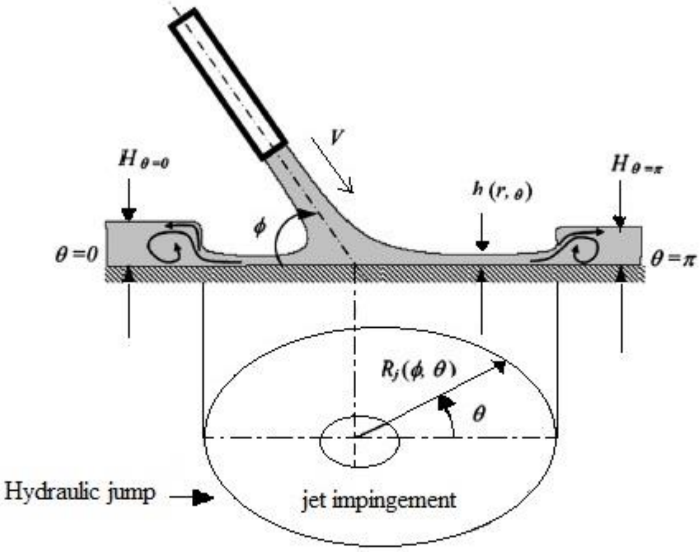


Fig. 1.3. Schematic diagram of non-circular hydraulic jump profile due to oblique angle jet impingement. [1]

The radial location of the jump is found out by using the relation when the inclination of jet impingement angle with respect to horizontal plate surface is greater than 25° is

$$R_j(\Phi,\theta) = c\left(\frac{U_r^2 \times sin^3\Phi}{2(ccos\Phi cos\theta)^2}\right)^{\frac{5}{8}} \times v^{\frac{-3}{8}} g^{\frac{-1}{8}} \qquad (1)$$

Characteristic of hydraulic jump profile:

Profile of hydraulic jump because of obliquely inclined jet impingement may be classified into two categories which are as given below:

a. Hydraulic jump formed of smooth curve only when the angle of jet inclination is greater than a critical value i.e. 25°.
b. In practical the value the critical value depends on the flow rate of water and diameter of jet. Hydraulic jump form with corner when the angle is set with more or equal to critical vale of jet inclination angle [1].

Chapter 2

Physics of jet impingement

When a jet of water strikes a flat surface a quick rise in pressure take place which enforce the liquid to accelerate from the jet impingement point called as stagnation point and the thin liquid film form in order small height (millimetre) which spread along the radial direction and covers the whole region. The friction effect which is present on plate causing a kinematic boundary layer and difference in temperature between the fluid and target plate or surface cause a thermal boundary layer .the radius of hydraulic jump can be found by theoretical and experimental data. In theoretical analysis the thickness can be found by the Reynolds number this liquid film thickness changes rapidly by varying the flow from laminar to turbulent flow. The velocity of fluid along the surface goes on decreasing with increase in distance from stagnation point which cause the liquid film thickness and boundary layer thicker.

The jet impingement is configured into three regions. The first one is free surface jet in which the fluid used in jet impingement is less dense like an air. Secondly submerged jet that permits the liquid to impinge into identical liquid. Third confined submerged jet in which the flow area is restricted with the help of wall. The free surface shape is very much critical to design as it is effected by gravitation force, surface tension and pressure and this pressure depends upon shape size and velocity of jet. Here in my project work we study the circular hydraulic jump on the free surface experimentally.

The heat transfer through a jet impingement is very complex method because it involves number of parameter such as Reynolds number, jet diameter, flow rate, spacing distance i.e. distance between jet and target surface, jet velocity, and jet inclination etc.

Figure 2.1 shows a schematic diagram in which the stagnation zone exist perpendicular to liquid jet and then the stagnation region lies along the radial direction where the fluid flow after jet impingement. The length of the stagnation zone depends upon the vertical distance between nozzle and target surface, diameter of jet and Reynolds number. The most important process in impingement of jet is the feature of hydraulic jump which exists because of deceleration of fluid flow. The position of hydraulic jump was found out and compare with existence literature which will be discussed later on in this paper.

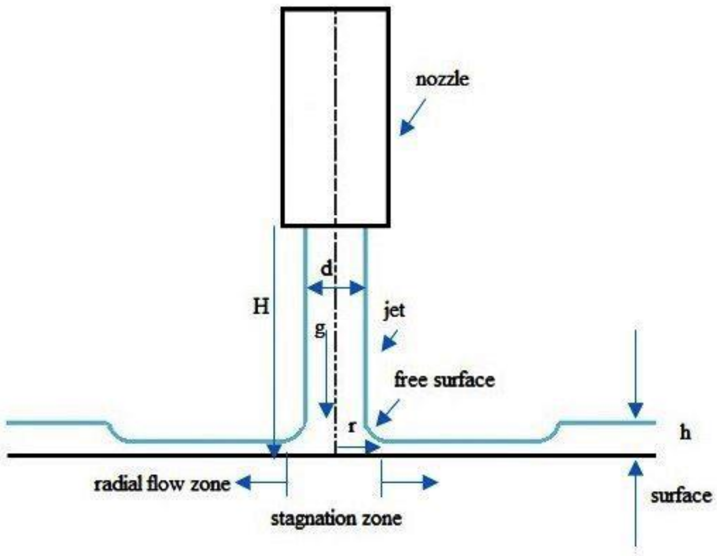


Fig. 2.1 Schematic diagram of an axisymmetric circular hydraulic jump.

The three characteristic region are as follows:

1. Free jet region: it is the initial region of jet impingement.it is defined as the jet entering the large container that contains fluid in rest condition the fluid flow in radial direction the axial velocity of jet decreases continuously in the direction of stream wise.
    a. Potential core: In jet flow region where the flow field unaffected by the developing annular shear-layer is termed as the Potential core region. There is irritation type of fluid flow in this region.
    b. Shear layer: the region where we observed a velocity gradient when fluid flow over the surface.
2. Stagnation zone: the region around the point of impact the fluid flow after jet impingement and the heat transfer feature is described in general term known as stagnation zone. Parabolic velocity profile jet: it is created by laminar flow coming from a cylindrical tube with Reynolds number below 2000-4000. This parabolic profile spread with a uniform velocity as the liquid jet travels toward the surface. If the length of liquid jet is large enough for viscosity then the parabolic velocity distribution continue.
3. Wall jet region.
4. Both boundary layer i.e. thermal boundary layer and hydrodynamic boundary layer within the stagnation zone help for large amount of transfer of heat between the fluid and the target surface.

When a water jet strikes vertically on a horizontally placed glass plate surface then the fluid moves towards the radial direction from stagnation point. If the fluid flow rate is more than the critical value then flow will be supercritical near the point of impingement. The film thickness form which is a fraction of millimetre and the circular hydraulic jump is developed after some distance. The important parameter in phenomenon of circular hydraulic jump are fluid flow rate, radius from the point of impingement, kinematic viscosity, surface tension acceleration due to gravity and jet velocity is given by [2]

$$U_j = Q/\pi r^2 \qquad (2)$$

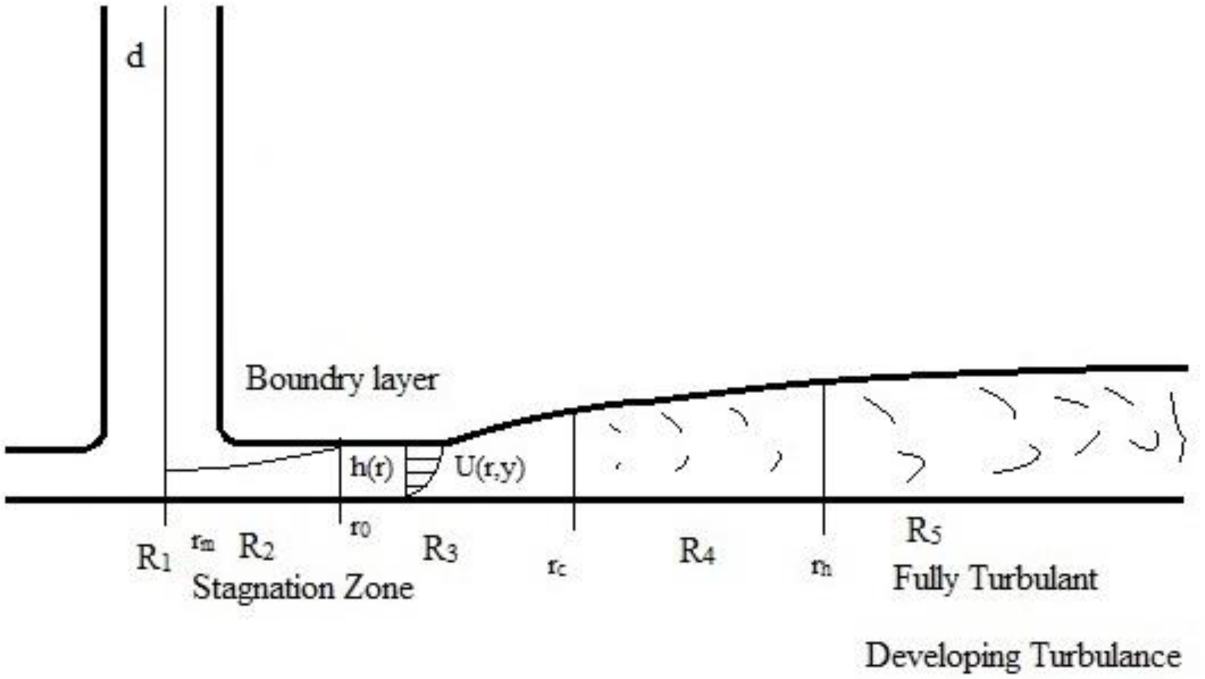


Fig. 2.2 Different zones of an axisymmetric impinging jet [2].

Fig. 2.2 shows the axisymmetric zone with different zone.

R_1: Stagnation zone where the velocity of jet first becomes zero.

R_2: Here the film thickness is larger than the momentum boundary layer.

R_3: The film surface reaches by the momentum boundary layer.

R_4: In this region the flow become transition to turbulent and the thermal and momentum boundary layer both reaches the free surface of liquid.

R_5: The flow of liquid in this region become fully turbulent.

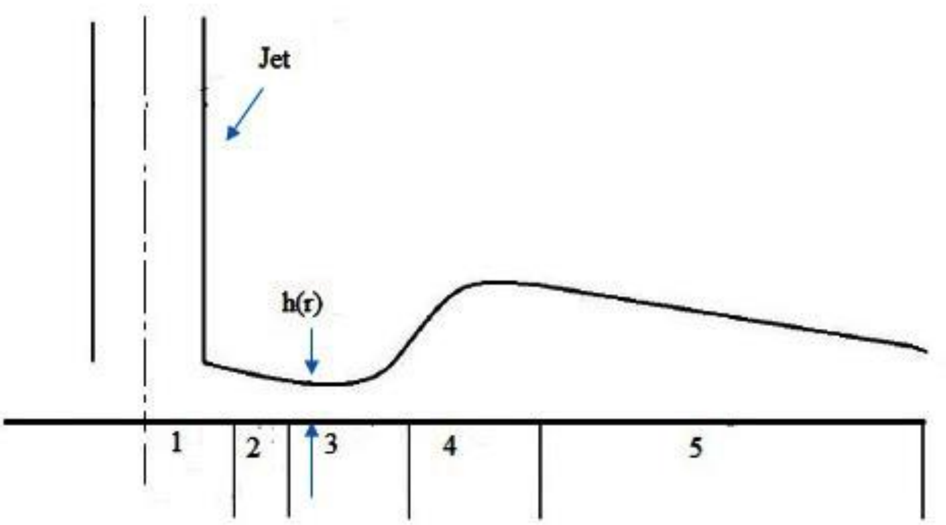


Fig. 2.3 The various region of fluid when it flows in radial direction after impingement [3].

1. Stagnation region;
2. Developing region in which the boundary layer lies under the free surface and the velocity over the boundary layer is more or less equal to the velocity of jet.
3. Developed region in which the viscous effects exist up to the free surface and gravity is not so crucial.
4. Effect of gravity is important and there is adverse pressure gradient is exist.
5. The jump region with addition to the separation eddy.
6. The fluid flow towards the downstream of the hydraulic jump up to the edge of the surface.

Chapter 3

Literature Review

We found the number of theoretical and experimental work of research has been done on circular hydraulic jump with stationary jet impingement on flat surface but all the works has been carried out with stationary jet only but moving jet are too less. Hence for this we are required to study the theoretical and experimental work.

Kate et al. [1] investigate the hydraulic jump experimentally, observed two category of this phenomenon with higher angle of jet inclination angle a smooth curve profile is formed and lower inclination angle profile with corner was observed. They measure the film thickness for different flow rates and with different jet angles. The film thickness was measure by using conductive probe for both forward and backward in radial direction and for before and after hydraulic jump. They also analysed the striking difference between profile of non-circular and circular profile hydraulic jump. And comes to conclusion that the circular hydraulic jump form when the jet inclination angle is normal to surface and when these angle other than it than more or less elliptical shape obtain. There is an increase in the area of hydraulic jump profile with increase in the angle of jet and its maximum when is it normal. The stagnation pressure also maximum when jet inclination angle is normal. In case of inclined jet there is variation in liquid film thickness along the azimuthal direction.

Vishwanath et al. [4] they studies the hydraulic jump phenomenon experimentally and did numerical simulation to validate their result. They shows that the momentum flux is a major component of controlling and finding the hydraulic jump position beyond this the variation of hydraulic jump thickness with flow rate of fluid is found from their experimental work and numerical simulation. They perform two sets of their experimental work for measurement of radius of hydraulic jump and film thickness. In both the case momentum flux was varied into two method by changing the nozzle diameter and spacing height impingement.

Coomber et al. [5] did the experimental work to find the relation between the flow rate and hydraulic jump. In previous literature based on hydraulic jump there was an assumption is made that the relation between the flow rate and radius of hydraulic jump is linear but the found that the curve is non-linear and is logarithmic. In their experimental setup the bucket is kept on the top on the table and the measure the time for every 500 ml with the help of stop watch to calculate the flow rate. A siphon tube is attached to the nozzle. The jet impinges on target plate (glass plate). Graph paper was attach under the glass with distance indicated on it helps to find the radius of circular hydraulic jump. This profile was photograph each time to ensure the reading accurately.

Brechet et al. [6] did both theoretical and experimental work and the problem associated with the radial hydraulic jump by using elementary hydrodynamics and studied the law which governs the location of circular hydraulic jump and to correlate the prediction with experimental data. They plot with different flow rate and to find radius and either different spacing distance and deriver the relation for radius for viscous fluid. They find solution for the problem which can be adequately used for study and applicable for both theoretical and experimental work for application of fluid mechanics.

An experimental study have been carried out by Teamah et al. [7]. They investigate the circular hydraulic jump with jet inclination on a horizontal target smooth plate. The profile formed was unique and non-circular shape due to oblique jet inclination angle. The nozzle was inclined from (30° to 90°) and water flow rate from 2 lpm to 5 lpm with constant spacing between target plate to nozzle of 30 mm. The nozzle was used in this experiment of cylindrical in shape which has 5 mm diameter. When the nozzle or jet impingement is normal then circular shape was formed whereas when this angle was other than normal then elliptical shape profile is formed. This experimental study shows that the film thickness in radial direction decreases slowly up to minimum value then increases up to hydraulic jump.

Katti et al. [8] study the phenomenon of hydraulic jump experimentally on the basis of Reynolds number and nozzle to plate spacing and its effect on distribution of local heat transfer due to liquid jet which is submerged with air on target plate which is flat and smooth by using a jet which is obtained from cylindrical shaped nozzle having length to diameter ratio of 83. They vary the Re from 12,000 to 28,000 and target spacing to nozzle of 0.5 to 8 nozzle diameter. They uses infrared imaging method to obtain images for determining the feature of heat transfer. The feature of local heat transfer are investigated on the basis of experimental result and theoretical prediction of flow characteristic in various region of jet impingement.

Bohr's et al. [9] investigate experimentally the process of hydraulic jump by using viscous fluid i.e. ethylene-glycol with water. Setup is made to control the spacing between the target plate and jet. When the depth of is increased they find separation occur at the bottom with respect to transition state with broken wave. The system can be controlled as the flow is laminar before and after the hydraulic jump. They present the data for height of profile of fluid and further they have given the numerical simulation of Navier-Strokes equation to correlate the results of their experiments.

Kavcic et al. [10] worked on two layer of fluid and investigated experimentally to present their result by keeping focus on flow rate, density difference in two fluid i.e. between fresh water and salty water. When the flow rates are stable circular pattern formed which consist of 3-4 well defined waves. This entire wave pattern deformed when the flow rates are higher. They maintain constant flow rate about three to four minute for stable circular profile after that instability appear when the flow rate increases which brakes this wave structure in turbulent motion. The radius of hydraulic jump were recorded fir inner and outer region of hydraulic jump to find the critical value, depth of fluid , Froud number this values are depends upon the flow rate, density difference of fluid but does not depends upon Froud number outside the jump profile. Further these results was correlated with Watson model which indicate the density difference can be make smooth by diffusion.

Ndao et al. [11] studied experimentally heat transfer from micro pin fin structure by using R134a and water. They investigate the jet impingement of single phase stagnation point over a wide range of Reynolds number. The experimental setup has a single jet having diameter of 2 mm. The micro structure were fabricated and consisted of series of 64 circular micro pin fin has a diameter of 125 µm and height of 230 µm with a total area to base area ratio of 2.11. They found that the Nusselt number increases by increasing Reynolds number. There was a significant increase in heat transfer coefficient observed in existence of micro pin fins. By this experiment, they increases the heat transfer coefficient about 200%.

Mikielewicz et al. [12] studied that the hydraulic jump phenomenon formed due to circular jet impingement on flat surface. This effect is cause because of inertia force. The hydraulic jump came into existence due to supercritical flow condition. They derived the expression for radius of hydraulic jump by applying the principal of Bernoulli's equation, they did the preliminary analysis of the formation of 1st and 2nd type of hydraulic jump and correlate their results with the experimental data.

Gradeck et al. [13] study experimentally and numerically the formation of hydraulic jump due to stationary jet on moving surface. And apply this phenomenon of hydraulic jump for heat transfer. They derived the power relation of determining the radius of circular hydraulic jump. They compare their experiential result with numerical simulation by using star CD software to validate their result. First they validate their result with numerical date then apply it on rolling process in steel manufacturing industry. Their set up consist of two nozzle having diameter of 17mm and 20 mm. Their numerical simulation was based on turbulence modelling and on K-ε model and near-wall treatment. It helps in many industrial purpose e.g. well predict heat and mass transfer.

Lienhard et al. [14] studied experimentally and theoretically on circular jet impingement on his laboratory. He discussed the effect of turbulence including stagnation zone and Nusselt number, heat transfer in jet impingement which is laminar in nature are also discussed by him in his paper. He uses the jet for high heat flux cooling.

Liu et al. [15] suggested that the surface tension plays a vital part in the development of circular hydraulic jump for jet impingement. Surface tension effect the shape of hydraulic jump. A series of instabilities occur in the structure of hydraulic jump if the effect of surface tension decrease than the film thickness also decreases. This conclusion are verify by experiment on planar film which cause unusual jump structure.

Rice et al. [16] studied experimentally and numerically the hydraulic jump phenomenon on rotating disk. The analysis was done by using volume of fluid method. The disk was made up of aluminium the investigation was held with the flow rate in the range of 3 lpm to 5 lpm and the rotation of disk between 50 rpm to 200 rpm. They study the effect of inlet temperature on the thickness of film and heat transfer from rotating disc. They studied heat transfer process for fluid from increasing and then decreasing rate. The water become evaporated so they captured when the jet impinges on the rotating disc in saturated condition. Flow rate was maintain very slow for evaporation to develop the thermal field.

Rolley et al. [17] have studied experimentally and compare their results with mathematical modelling. The use liquid helium as working fluid for hydraulic jump formation. They suggested that the radius of hydraulic jump do not change for superfluid transition and they compare jump radius with various model, jump was treated as disturbance called wave and capillary action were also crucial. When the fluid is below super fluid condition they observed a capillary wave between effect of jet and hydraulic jump.by assuming the superfluid with a viscosity they calculate the wave vector and film thickness which was agreed with the various models.

Bush et al. [18] present their result in theoretical and experimental form. They study the effect of surface tension on circular jump of laminar flow and derive the expression for radius of curvature, force per unit length of hydraulic that act along the circular jump. They also extend the theoretical model of Watson including curvature force which give rise to new prediction for jump radius. Their experimental study shows that the surface tension was very small in laboratory for small height and radius of circular hydraulic jump.

Zaki et al. [19] studies numerically the circular hydraulic jump phenomenon. They apply its numerical solution on manufacturing process i.e. abrasive jet machining as top optimize the use of high pressure water jet. It's very difficult to carry an experimental investigation of abrasive jet cutting so numerical study is the best way to study for it. By the help of numerical solution they optimize the use of high pressure water jet by controlling impingement, flow rate and partial.

Lawson et al. [20] work experimental and present with the mathematical model of radial hydraulic jump. They assumed a linear profile for hydraulic jump. By applying the momentum conservation equation they derived the equation for depth ratio for hydraulic jump. Keeping the length of hydraulic jump constant the model was used to find the relation between liquid jet thickness from source flow rate and the position of jump. Their experimental analysis shows that the energy loss in sequent height of circular hydraulic jump and energy loss in formation of hydraulic jump are less or and more respectively. Further the experimental results shown the model correctly relates with the numerical simulation of hydraulic jump.

Chapter 4

Experimental setup

The setup consist of submerged water pump having capacity of 1.85 m head and 2 lpm and is used to supply water in the form of jet in desired rate of flow to the target surface plate having dimensions of 60 cm × 60 cm. The cylindrical tube of copper having diameter of 4 mm and length 8 cm is used as nozzle for jet formation. These tube is having a length to diameter ratio of 16-20 to ensure that the flow should be fully develop at the exit of nozzle. The water jet coming from the nozzle is made to impinge on glass plate surface which is mounted on stand made up of mild steel. A chamfered is made with radius 2 mm on surface so water will fall on the drainage system. The drainage system consist of cup shaped PVC pipe, connected along the periphery of the target plate and funnel attached to the corner which supply water back to the bucket for reuse. Nozzle is supported by the slider crank -mechanism which is used to give linear motion to it so that the hydraulic jump phenomenon is made by moving jet.

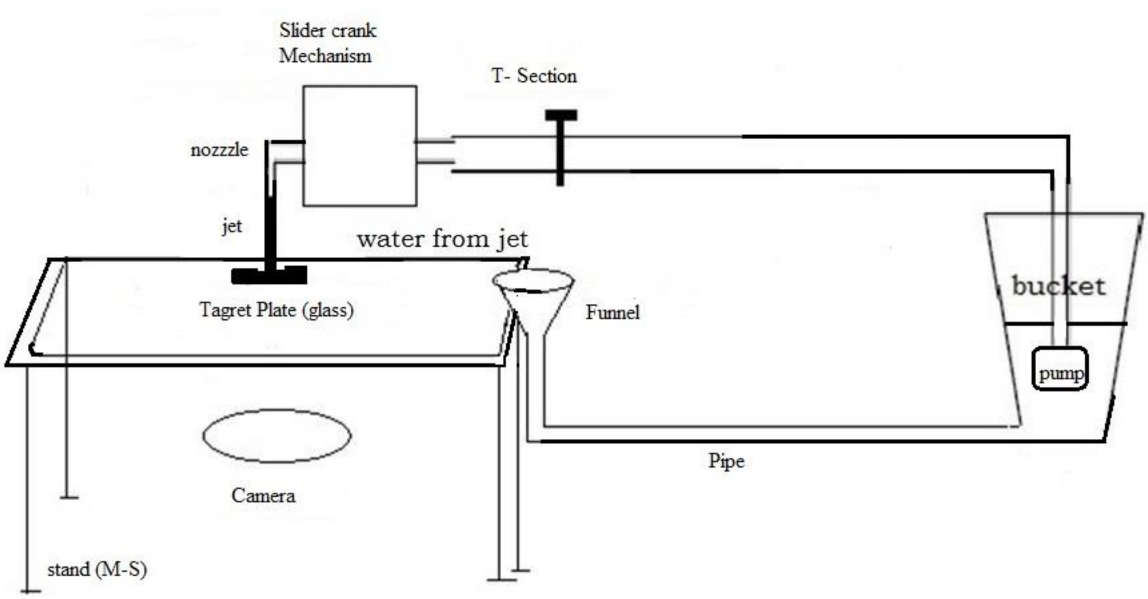


Fig. 4.1 Schematic diagram of experimental setup.

Fig. 4.2 Shows the slider crank mechanism which is made of wood in carpentry shop and is used to give a smooth reciprocating motion to jet.

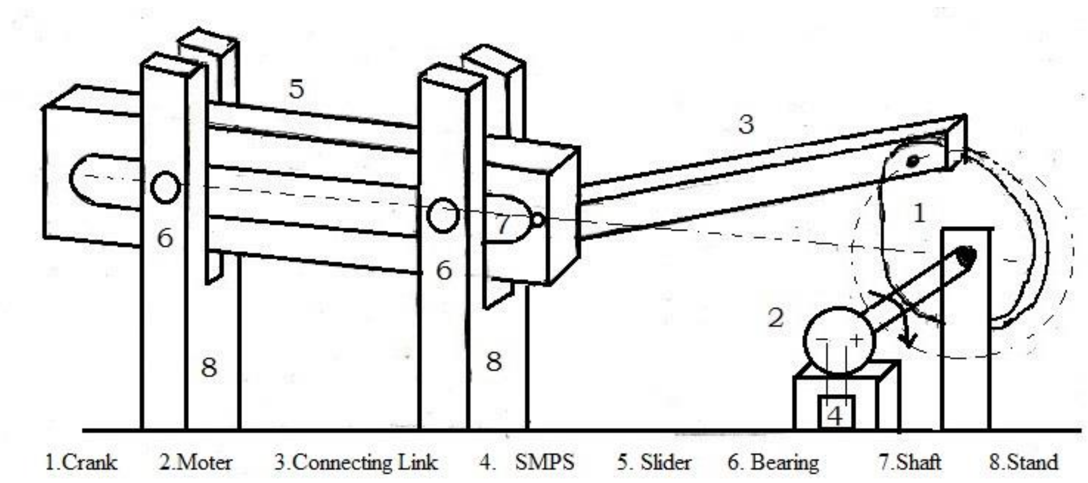


Fig. 4.2 Slider-crank mechanism.

Fig. 4.3 Crank

1 Crank: It is a mechanical link or member which rotates completely and where input power is given in order to give translation motion to the slider. In this project work it is made up of pine wood having crank radius Cr = 25 cm.

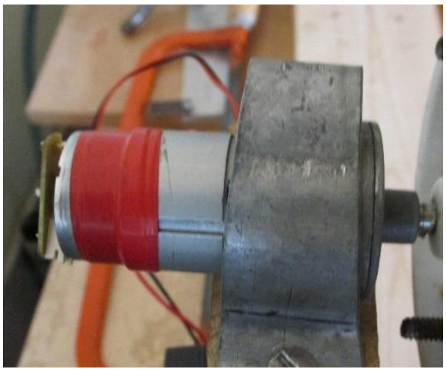


Fig. 4.4 DC motor

2. DC motor: DC motor of 12 volt, 5 ampere is used here with 10 rpm and in used to give input power to the crank to rotate.

3. Connecting link: Connecting link is a mechanical link which is used to connect crank to slider by using connecting pin. The connecting rod is made up of pine wood of 30 length.

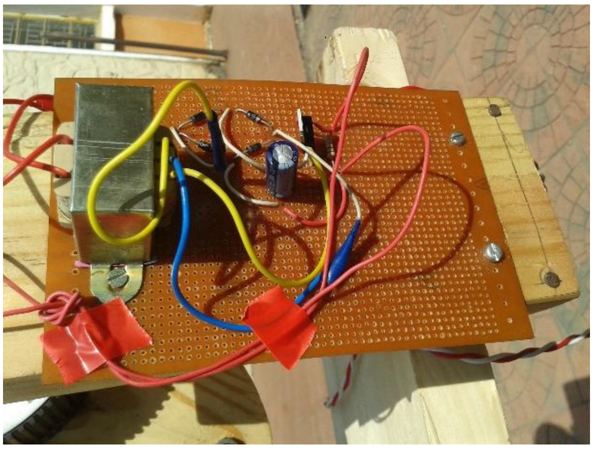


Fig. 4.5 SMPS

4. Switched mode power supply (SMPS): It is use to supply a DC power to motor from an Ac input. Here the input supply to SMPS is 220 volt and output is 12 volt DC, 5 ampere require for motor to operate.

Fig. 4.6 Slider

5. Slider: It is used to hold the nozzle and to in order to give reciprocating motion to jet a protector is attached to slider in the front to indicate the jet inclination angle.

Fig. 4.7 Bearing

6. Bearing: It is used to reduce friction between slider and stand and is supported by stand. The size of bearing is 9 mm ID and 24 mm OD.

Fig. 4.8 M-S shaft

7. M-S shaft: It is use to hold bearing and is of mild steel having a length and diameter of 70 mm 8.87 mm respectively.

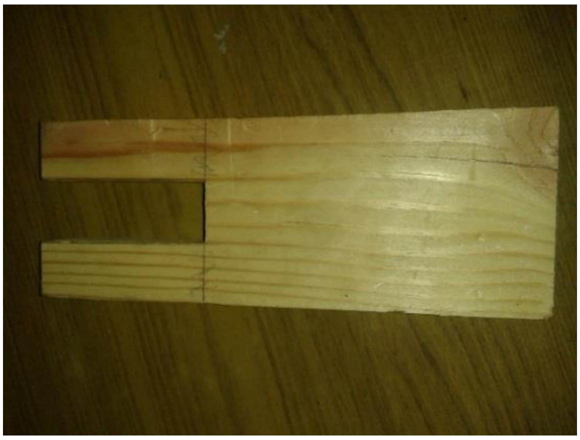


Fig. 4.9 Wooden stand

8. Wooden stand: It supports the shaft, slider and is made up of wood. The length of the shaft is 30cm.

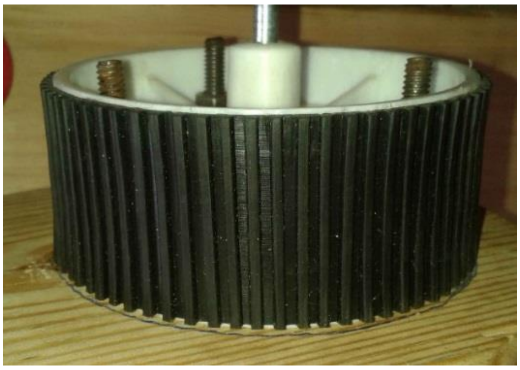


Fig. 4.10 Robotic wheel.

9. Robotic wheel**:** Wheel is used to connect motor to crank as motor is used to give a high torque to the mechanism of radius of 6 cm.

The speed of the slide- crank mechanism depends upon the motor speed so in order to maintain the speed, speed of motor should be taken into account. The whole assembly is supported by the wooden table which is shown in Fig. 4.11

Fig. 4.11 Experimental setup

A high resolution camera is used for taking photograph and a transparent graph is attach to bottom of the surface plate in order to measure the radius of hydraulic jump and jump profile when jet impinges obliquely .

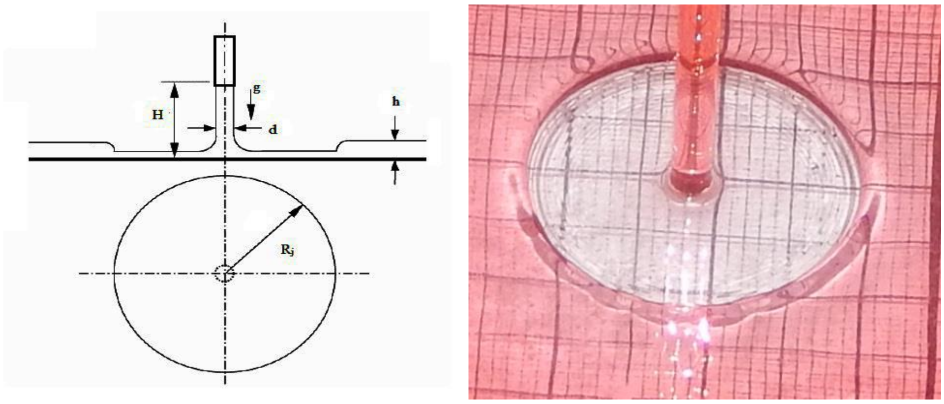
The experiment was repeated number of times to reduce the uncertainty and for reliability of measurement. The readings were recorded and the profile of hydraulic jump was photograph from the top and bottom of the target glass plate. The photograph was taken from the different angle to ensure the accuracy of the measurement.

20 liter of water which has about 20^{o} C to 25^{o} C ($q = 1000$ kg/m^3 and dynamic viscosity $=10^3$ Pa s) is taken into bucket a submerged water pump which supply water to nozzle the flow rate of water was controlled by butter fly valve connected between nozzle and pump through pipe. The flow rate of water was measured by graduated cylinder and stopwatch. The hydraulic jump profile can be seen on the target plate.

Chapter 5

Result and Discussion

When fluid jet impinges on a horizontal flat plate surface a free definite region is clearly seen as shown in Fig. 5.1 and after impingement the velocity decreases as the fluid flow in outer radial direction. Which causes a thickening of boundary layer and slowly decreases in heat transfer coefficient with the radial direction. The objective of this project work is to study experimentally the effect of moving jet impingement and flow rate on hydrodynamic flow profile or structure of jet impingement zone as it has a direct effect on heat and transfer coefficient.



(a) (b)

Fig. 5.1 Hydraulic jump Profile when jet impingement is normal to horizontal glass surface. (a) Schematic diagram (b) Actual photograph.

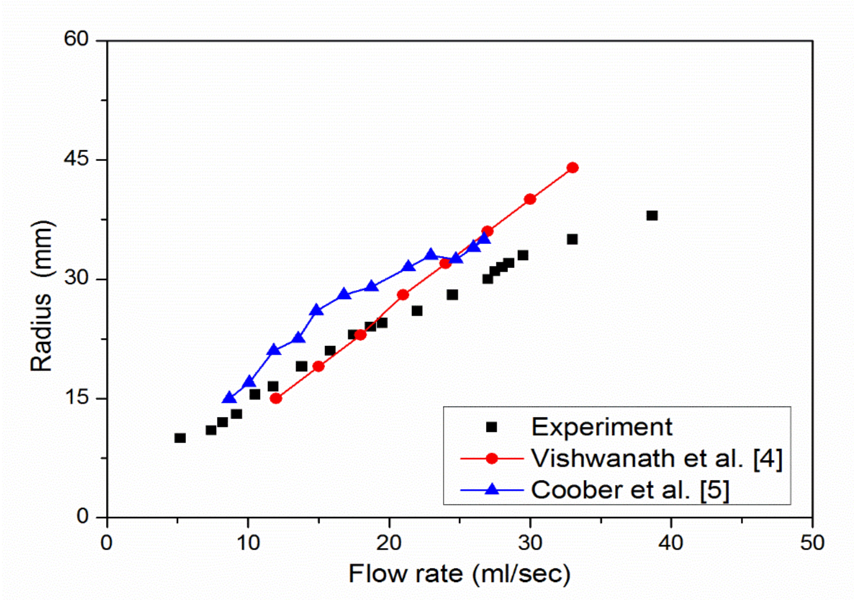


Fig. 5.2 Variation of radius with flow rate and comparison with other author.

Fig. 5.2 shows the Variation of radius with flow rate, the present experimental work data i.e. flow rate and radius of hydraulic jump with other experimental work data of Vishwanath et al. [4] and Coober et al. [5] the radius found form our experiment is similar to previous work so this validate our experimental result.

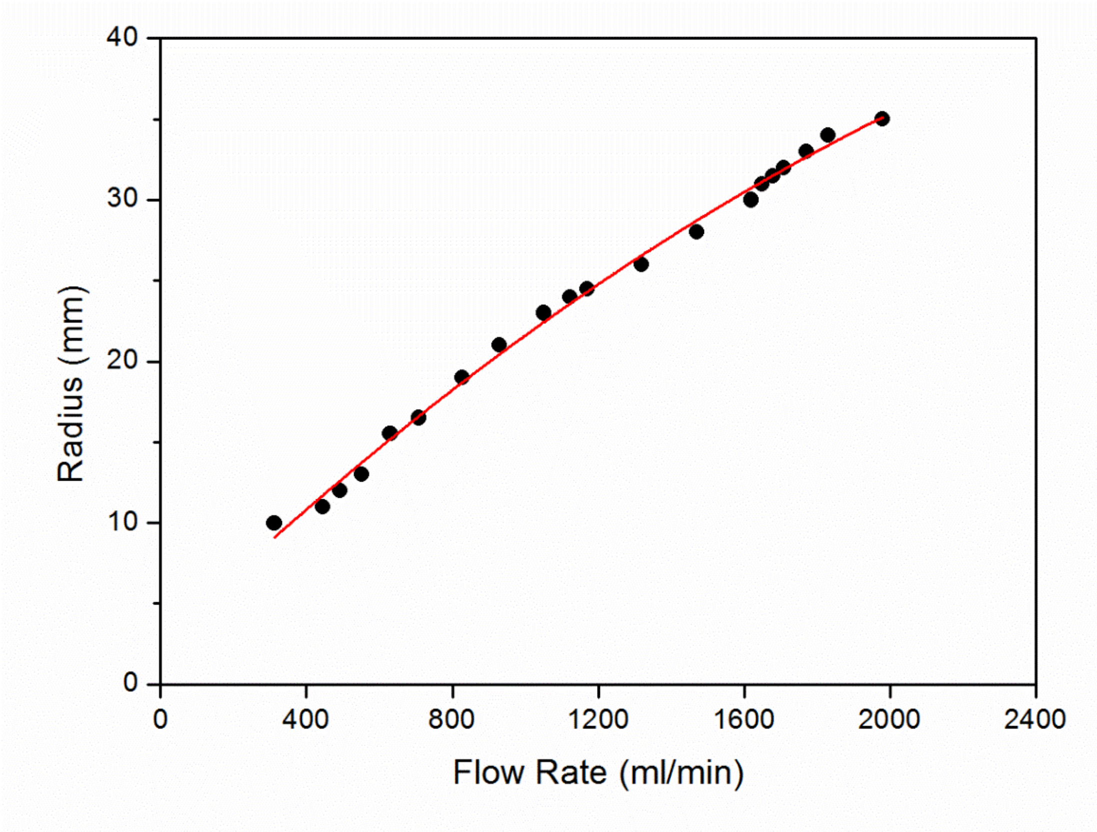


Fig. 5.3 Variation of flow rate with radius of hydraulic jump.

Fig. 5.3 shows that the relation between the flow rate and radius of hydraulic jump which is nonlinear. The best fit that our experimental data fitted smoothly is quadratic polynomial with equation of:

$$R_j = -2.635706 \times 10^{-6} q^2 + 0.0216q + 2.589$$

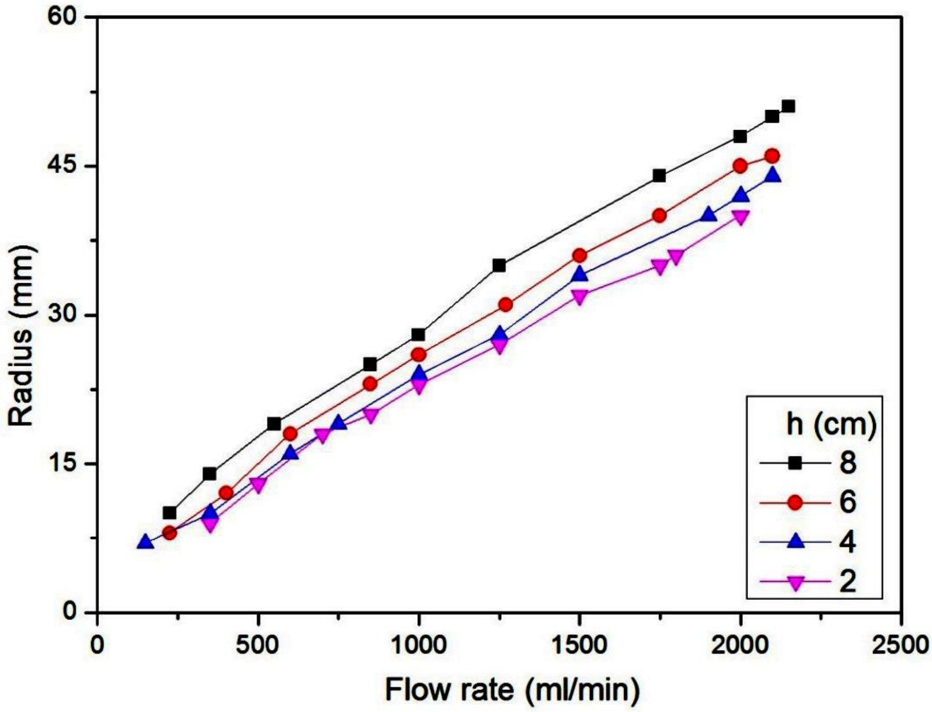


Fig. 5.4 Variation of flow rate with radius of hydraulic jump at constant drop height (h).

In Fig. 5.4 the spacing distance i.e. distance between the glass plate and the nozzle is kept constant for one set of experiment after this it was changed from 2 cm to 8 cm with an interval of 2 cm. The flow rate of liquid jet varied and correspond value of radius were noted down.

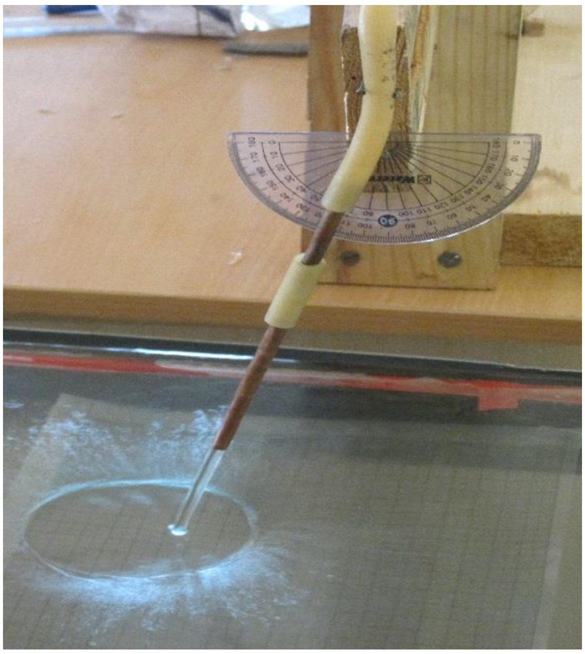


Fig.5.5 Non- Circular Hydraulic jump due to oblique jet impingement.

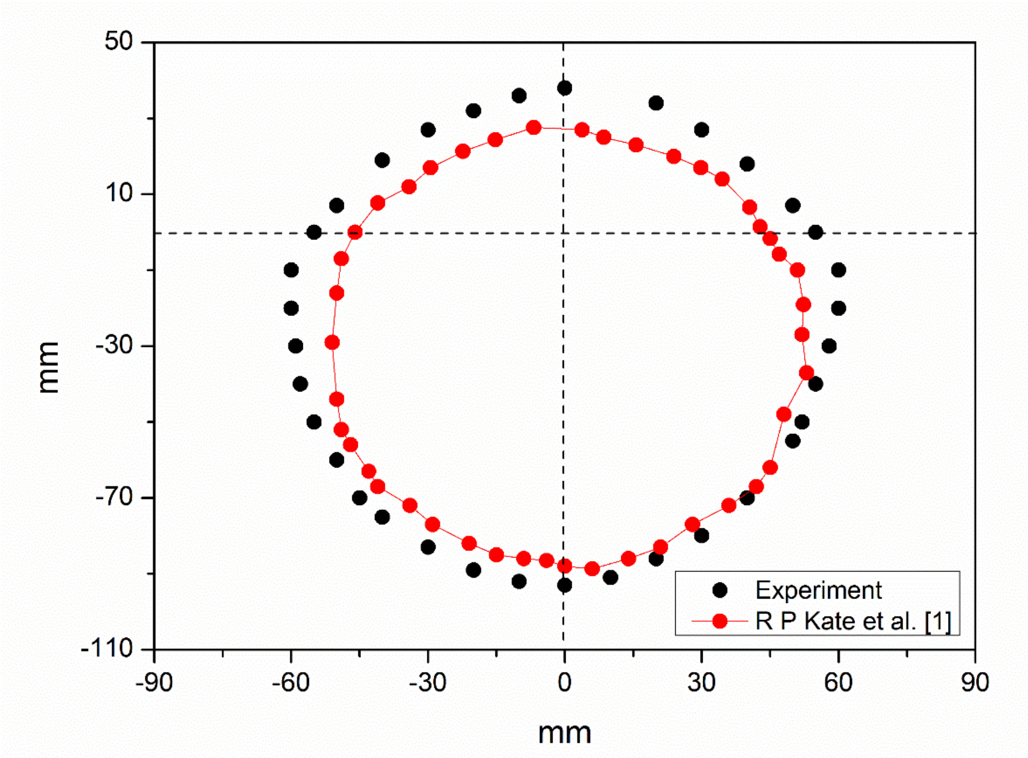
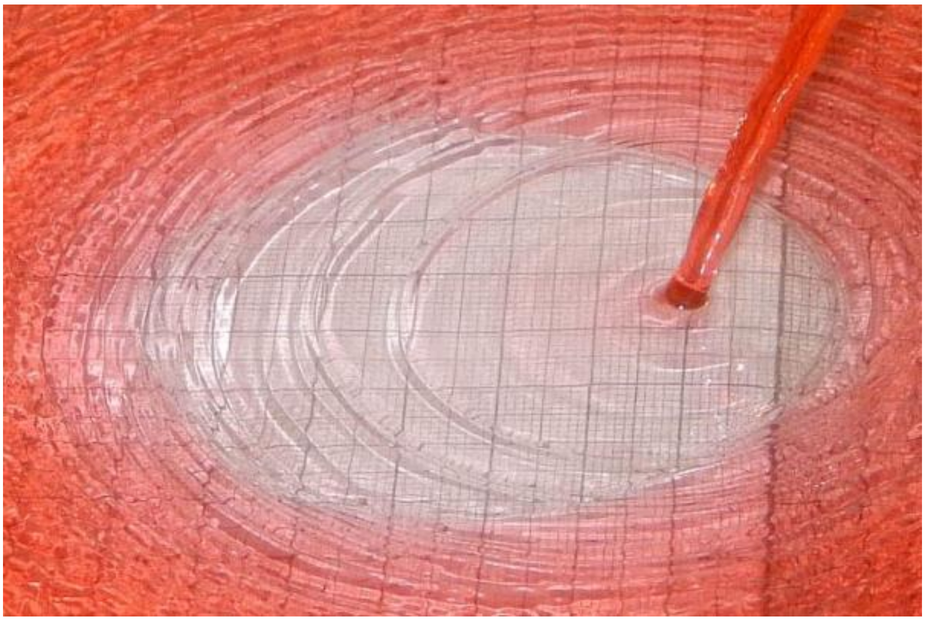


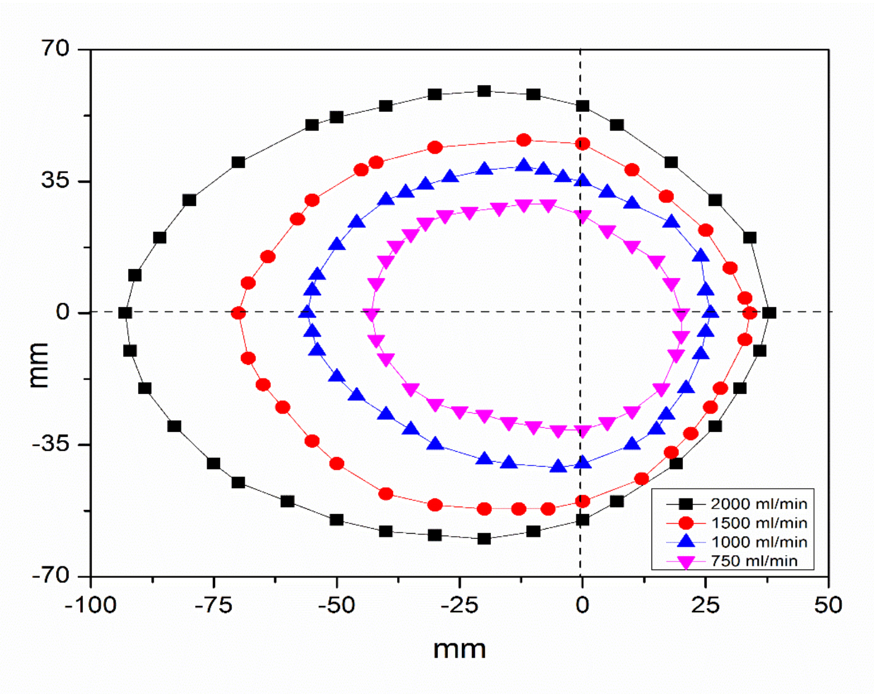
Fig 5.6 Comparison of jump profile by oblique jet impingement (ϕ = 55˚) with Kate et al. [1]

Fig. 5.5 shows that the profile formed when the jet impingement angle other than normal with horizontal surface is more or less elliptical in shape and does not depend upon the flow rate and jet inclination angle but it should not be 90˚. The profile elongates with increase in the jet velocity but the profile always seems to be elliptical in shape.

Fig. 5.6 shows the comparison graph between our experimental data when jet impinges obliquely on the horizontal glass surface the angle of jet impingement is 55˚with Kate et al. [1] The drop height is 10 cm and the flow rate is 2000 ml/min.



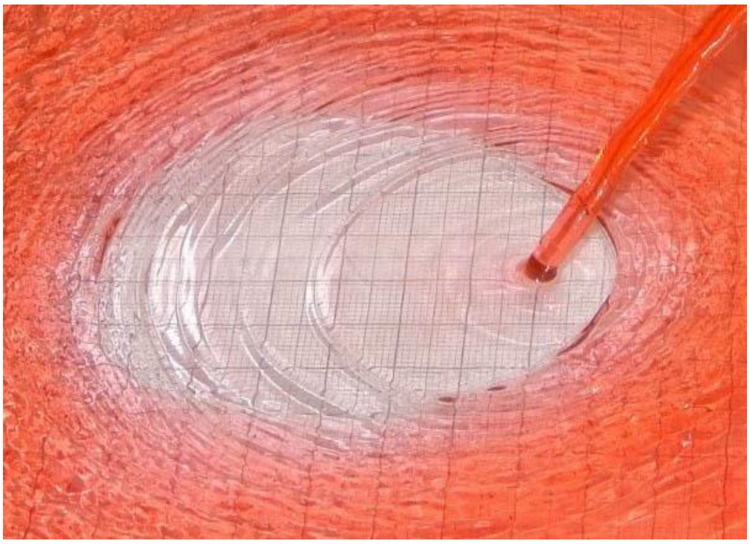
(a)



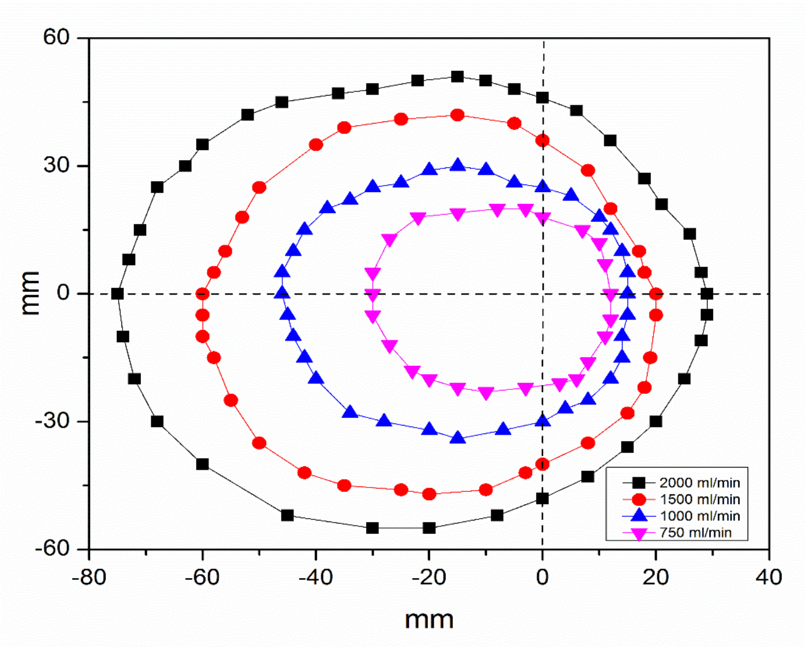
(b)

Fig. 5.7 Hydraulic jump profile when ϕ = 55˚ (a) Actual photograph (b) Experimental contour for flow rate from 750 ml/min to 2000 ml/min.

Fig 5.7 (a) & (b) shows the hydraulic jump profile due to oblique angle. Here the jet inclination angle is 55˚. The spacing distance between the nozzle and surface plate is maintain throughout the reading is 8 cm. flow rate of water is varied from 750 ml/min to 2000 ml/min and correspond hydraulic jump is obtained and the dimension shown in graph is in millimetre.

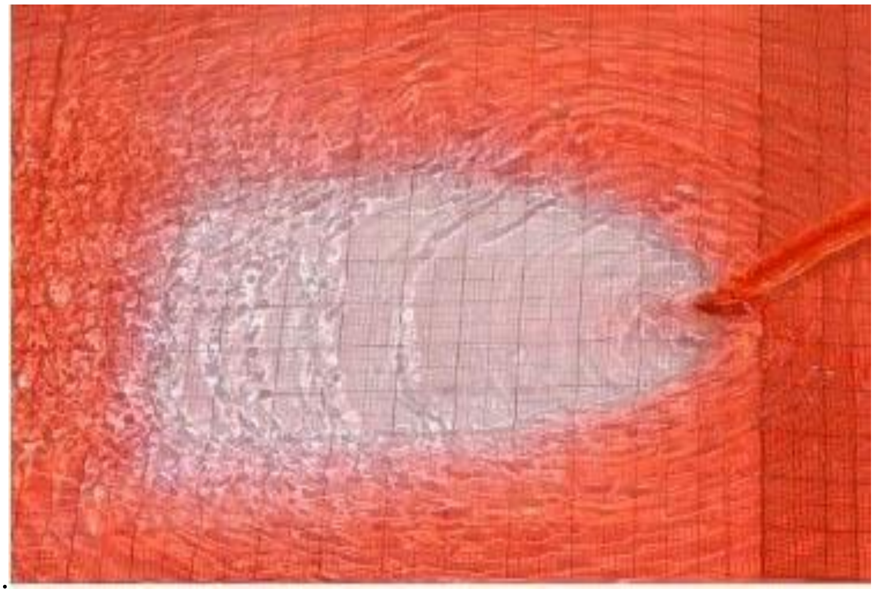


(a)

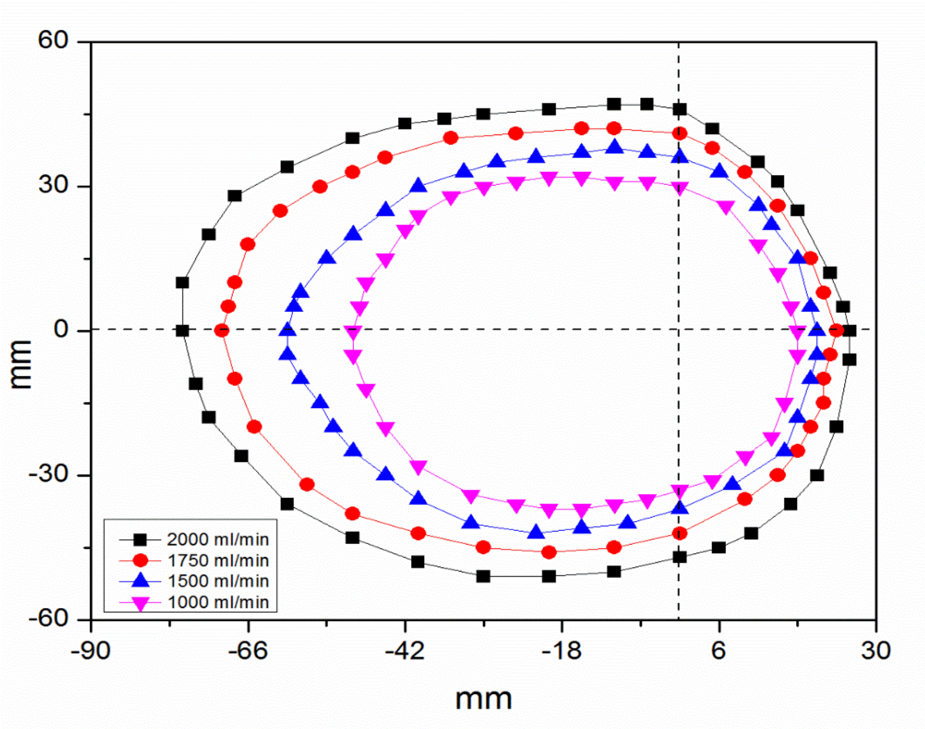


(b)

Fig. 5.8 Hydraulic jump profile when ϕ = 45° (a) actual photograph (b) experimental contour for flow rate from 750ml/min to 2000 ml/min.



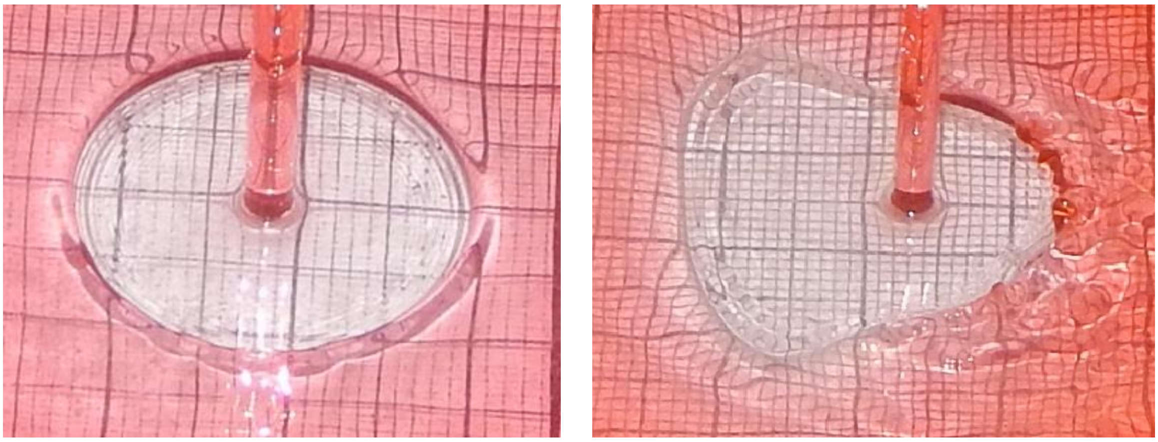
(a)



(b)

Fig. 5.9 Hydraulic jump profile when ϕ = 35˚. (a) Actual photograph (b) Experimental contour for flow rate from 1000 ml/min to 2000 ml/min.

The hydraulic jump phenomenon when both jet and surface plate is stationary then there will be no need to use a high speed pictures or video but when any of these two is moving then we require a high speed picture in order to study the phenomenon of hydraulic jump but capturing high speed picture the profile can be easily seen and investigated by the help of grid so that the detail structure of hydraulic jump patter can be measured when jet moves.



(a) (b)

Fig. 5.10 Jump profile when jet (a) stationary (b) moving with 400 ml/min flow rate.

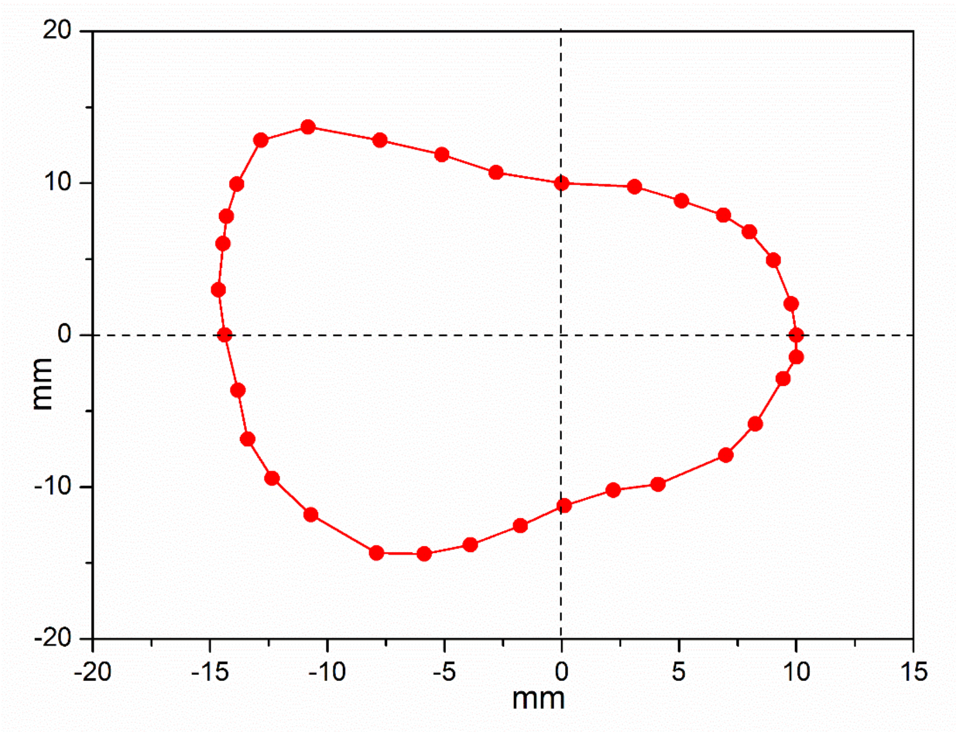
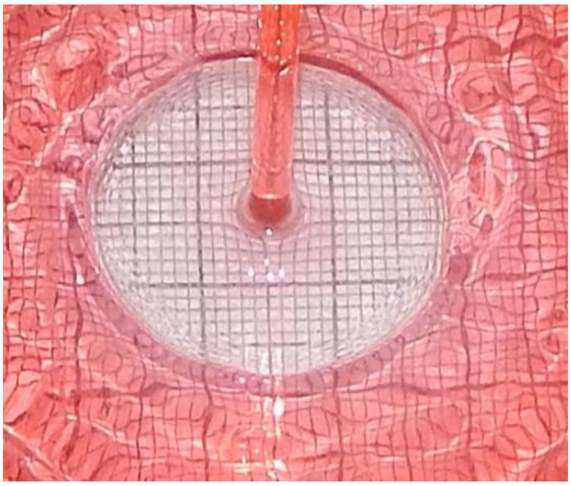
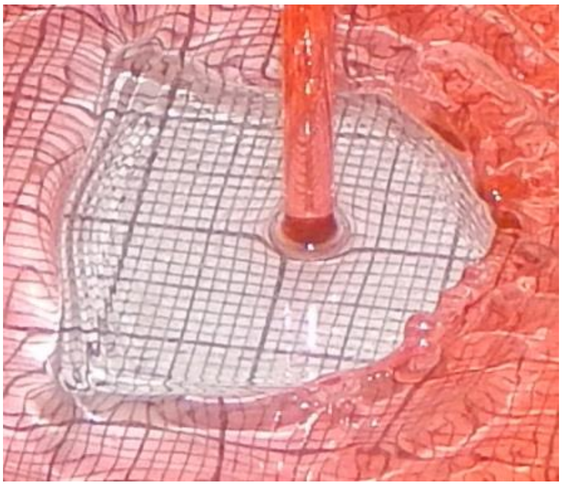


Fig. 5.10 Jump profile for flow rate of 400 ml/min when jet is (a) stationary (actual photograph), moving (b) actual photograph (c) experimental contour.

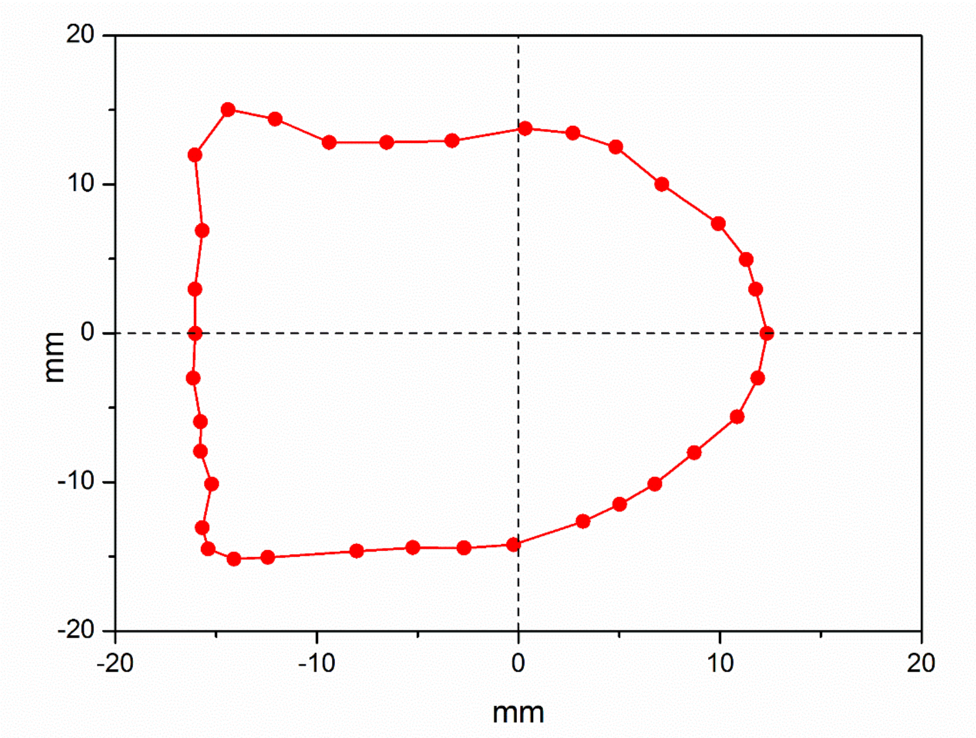
Fig 5.10 (a) shows the hydraulic jump formed when the jet is stationary. (b) & (c) represents the hydraulic jump profile when jet moves. The flow rate and spacing distance are 400 ml/min and 10 cm respectively. The radius of hydraulic jump when the jet is stationary was 11 mm and a semi-circular shape is obtained when jet moves with 5 cm/min velocity having radius of 10 mm.



(a)



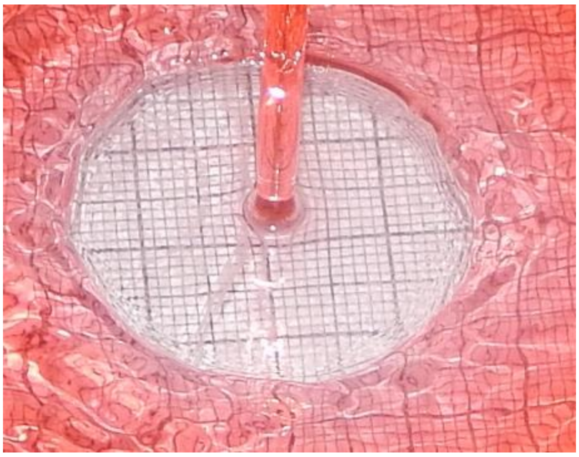
(b)



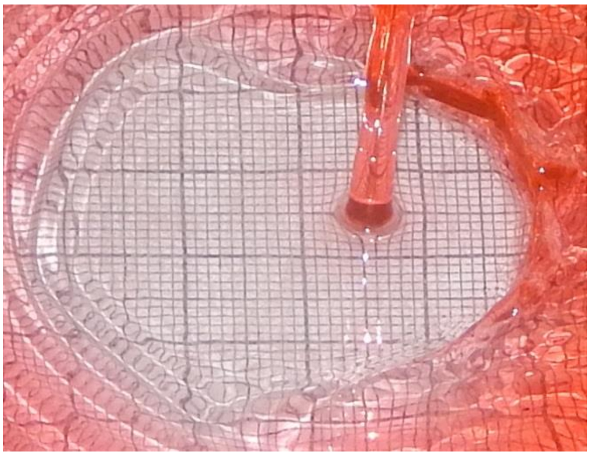
(c)

Fig. 5.11 Jump profile for flow rate of 550 ml/min when jet is (a) stationary (actual photograph), moving (b) actual photograph (c) experimental contour.

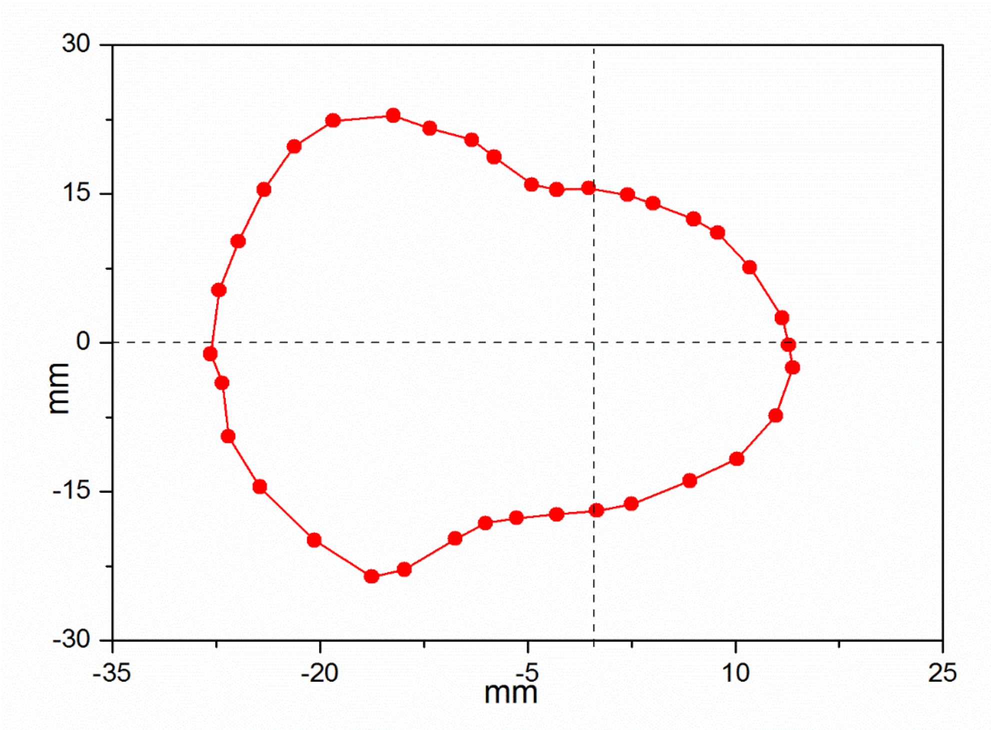
Fig 5.11 (a) represents the hydraulic jump developed when the jet is stationary (b) & (c) shows the hydraulic jump profile when jet moves linearly. The water flow rate and distance between nozzle and target plate are 550 ml/min and 10 cm respectively. The radius of hydraulic jump when the jet is stationary was 14 mm and a semi-circular shape is obtained when jet moves with 5cm/min velocity having radius of 12 mm.



(a)



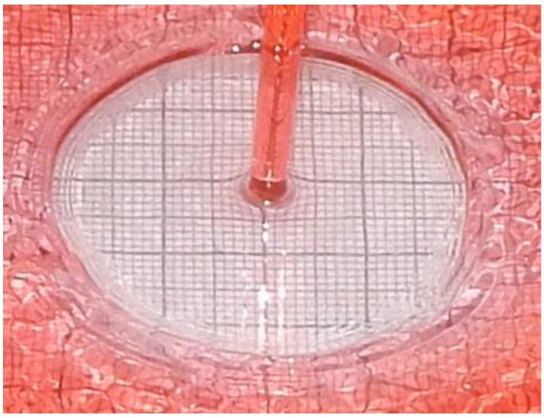
(b)



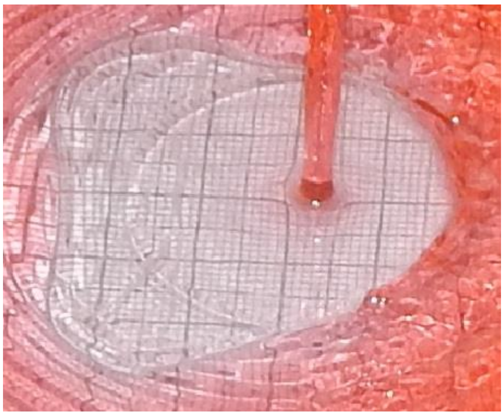
(c)

Fig. 5.12 Jump profile for flow rate of 700 ml/min when jet is (a) stationary (actual photograph), moving (b) actual photograph (c) experimental contour.

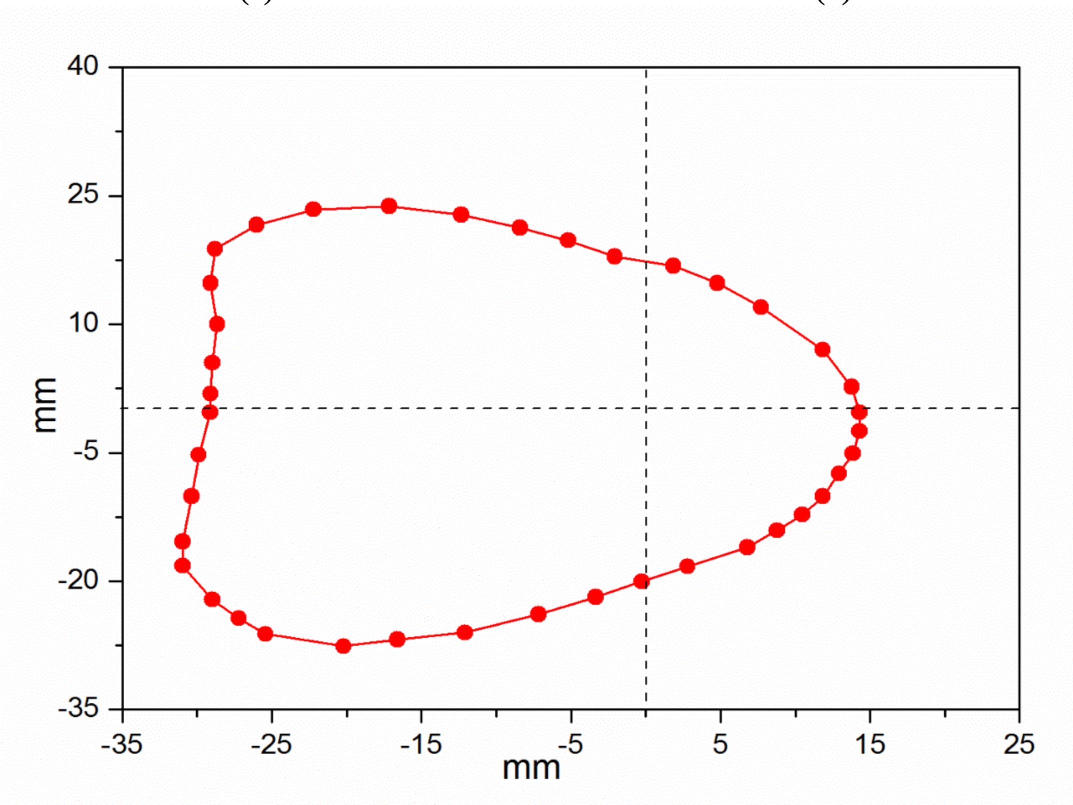
Fig 5.12 (a) represents the hydraulic jump obtained when the jet is in stationary position with respect to surface plate. (b) & (c) shows the hydraulic jump structure when jet moves linearly. The water flow rate and distance between nozzle and target surface plate are 700 ml/min and 10 cm respectively. The radius of hydraulic jump when the jet is stationary was 15 mm and a semi-circular shape is obtained when jet moves with 5cm/min velocity having radius of 13 mm.



(a)



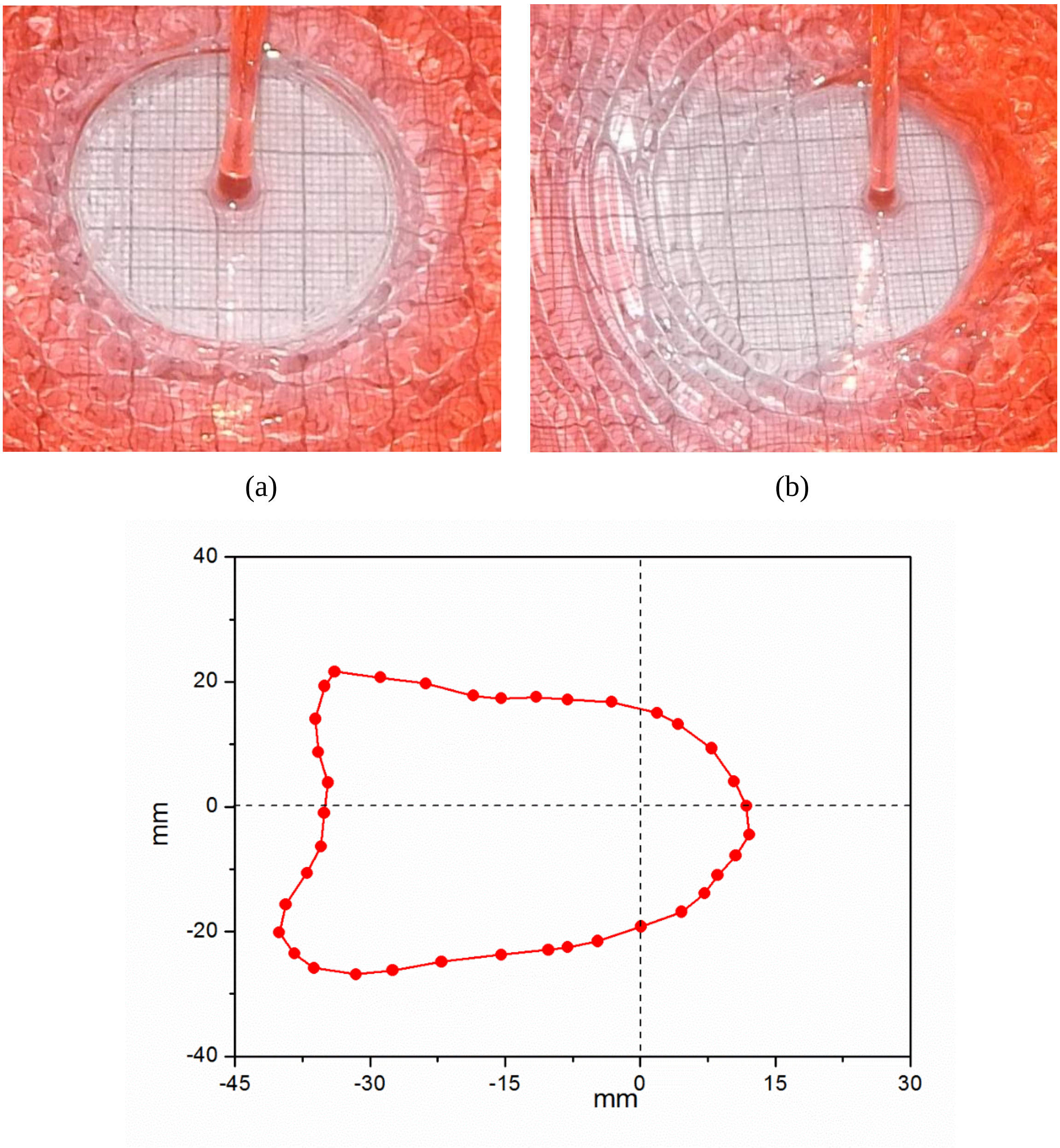
(b)



(c)

Fig. 5.13 Jump profile for flow rate of 800 ml/min when jet is (a) stationary (actual photograph), moving (b) actual photograph (c) experimental contour.

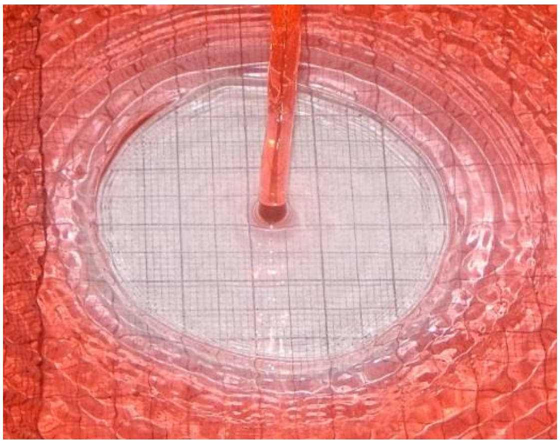
Here Fig 5.13 (a) represents the hydraulic jump obtained when the jet is in still position with respect to glass plate surface. (b) & (c) shows the hydraulic jump structure when jet moves linearly. The water flow rate and distance between nozzle and target surface plate are 800 ml/min and 10 cm respectively. The radius of hydraulic jump when the jet is stationary was 18 mm and a semi-circular shape is formed when jet moves with 5 cm/min velocity which decrease the radius and of 16 mm.



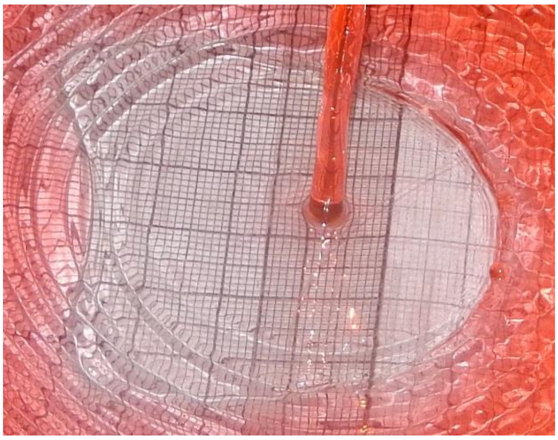
(c)

Fig. 5.14 Jump profile for flow rate of 900 ml/min when jet is (a) stationary (actual photograph), moving (b) actual photograph (c) experimental contour.

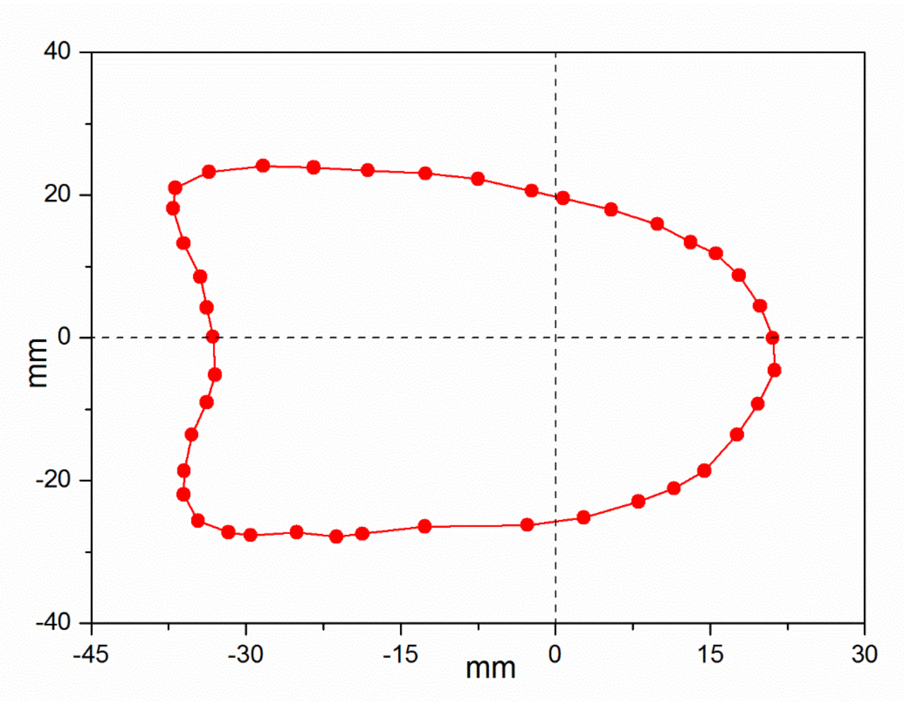
Above Fig 5.14 (a) shows that the hydraulic jump developed when the jet is stationary with respect to horizontal glass plate surface. (b) & (c) shows the hydraulic jump structure when jet moves linearly. The water flow rate and distance between nozzle and target surface plate are 900 ml/min and 10 cm respectively. The radius of circular hydraulic jump when the jet is stationary was 19 mm and a semi-circular structure is formed when jet moves with 5 cm/min velocity which decrease the radius and of 14 mm.



(a)



(b)



(c)

Fig. 5.15 Jump profile for flow rate of 1000 ml/min when jet is (a) stationary (actual photograph), moving (b) actual photograph (c) experimental contour.

Fig. 5.15 (a) shows that the hydraulic jump developed when the jet is stationary with respect to horizontal glass plate surface (b) & (c) shows the hydraulic jump structure when jet moves linearly. The water flow rate and distance between nozzle and target surface plate are 1000 ml/min and 10 cm respectively. The radius of hydraulic jump when the jet is stationary was 25 mm and a semi-circular structure is formed when jet moves with 5 cm/min velocity which decrease the radius and of 20 mm.

Chapter 6

Conclusion

This present experimental work has been carried out in the range of flow rate from 500 ml/min to 2000 ml/min to calculate the radius of circular hydraulic jump and to find the behaviour of jump profile when jet is a. stationary (jet inclination is normal and oblique) b. moving (jet inclination is normal) and following conclusion has been made:

(a) When the jet inclination angle is normal to horizontal glass surface then hydraulic jump is formed which is circular in shape and when this jet inclination angle changes from normal to any other angle than it affect the circular shape and become non-circular.

(b) Hydraulic jump of an elliptical shape is obtained due to oblique angle jet impingement on horizontal glass plate. The position of hydraulic jump increases with increase in the direction of downstream flow i.e. ($\theta = 0°$) where as there is decrease in the location of hydraulic jump along the upstream flow i.e. ($\theta = 180°$).

(c) In case of fixed jet inclination angle flow rate of water is important. The film thickness increases with decrease in the flow rate whereas decreases with increase in flow rate and jet inclination also has direct effect on the hydraulic jump location. With increasing jet inclination angle (ϕ) the profile increases and become minimum for normal jet impingement angle then again increases with it.

(d) When jet moves linearly on horizontal glass surface with normal angle then semi-circular shape of hydraulic jump formed and radius of semi-circular hydraulic jump decreases compare to hydraulic jump when jet is in stationary condition.

(e) The semi-circular shape formed towards the direction of moving jet and fish tail like structure forms against the direction moving jet.

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