Abstract

Hydraulic jumps are among the most puzzling flow phenomena that occur in nature under a variety of conditions, and have elicited attention for centuries. Hydraulic jumps, in general, are the regions of rapidly varied flow, connecting supercritical to subcritical free-surface or interfacial flows. Hydraulic jump is typical to natural flows in rivers, channels, oceans and spreading of impinging jets. Hydraulic jumps can also easily observed in a kitchen sink, when vertical stream of water impinges on a horizontal surface. Plenteous of papers have been devoted to the topic, coming from diverse branches of engineering and science. The hydraulic jump has attracted wide attention for many years not only because of its importance in the design of engineering structures in rivers as energy dissipaters but also because of its fascinating complexity.

Extensive studies, (experimental, theoretical and numerical) on normal impinging liquid jet and the circular hydraulic jump have been carried out so far. Many of these studies are focused on characterization of the radius of the jump. However, oblique impinging jet, specifically liquid jets, have received very less attention in the literature. And even elementary theories for quantitative characterization of the hydraulic jumps formed as a consequence of oblique impingement of the liquid jets with the target plates, supported by requisite validation experiments, are yet to be reported in the literature. Similarly, only a few studies have incorporated the effects of plate motion on hydraulic jumps profiles with these studies being restricted to the cases of normal impinging jets only.

Though with a single jet, very high heat transfer rates can be achieved in the vicinity of the stagnation point (or impingement point region), the heat transfer rate decreases significantly as the distance from the stagnation point increases. As a

result, the net heat flux distribution is highly non-uniform. To overcome this limitation, in many industrial applications, multiple impinging jets are used. Multiple impinging jets, again specifically liquid jets, have received almost negligible attention in comparison with single impinging jets. Whatsoever studies deals with compressible fluid (air or gas) as a working fluid. In addition nearly all the studies deals with adjacent impinging jets. However, flow field due to adjacent and distant impinging jets are likely to differs a lot. Hydraulic jumps and their interactions due to multiple impinging jets are yet to be reported in the literature.

Hydraulic jumps in multilayered fluids are well studied, however, the majority of the studies deals with either free surface flows, or oceanic flows as compared to closed channel (or internal) multilayer flows.

Accordingly, this study deals with three different problems, namely, hydraulic jumps formed due to single impinging circular liquid jet on stationary and moving plates, hydraulic jumps formed due to two normal impinging jets and hydraulic jumps in two phase air-water flow in a suddenly expanded duct.

First part of this study deals with hydraulic jumps formed due to single impinging circular liquid jet on stationary and moving plates. It is discovered that an obliquely inclined circular water jet, impinging on a flat horizontal surface, confers a series of interesting hydraulic jump profiles, pertaining to different jet inclinations and jet velocities. These jump profiles are non-circular, and can be broadly grouped under two categories, based on the angle of jet inclination, ϕ, made with horizontal. Jumps corrosponding to the range ($25^0 < \phi \leq 90^0$) are observed to be bounded by a smooth curves, whereas those corresponding to $\phi \leq 25^0$ are characterized with distinct corners. The present work attempts for a geometric and hydrodynamic characterization of the spatial patterns formed as a consequence of such non-circular hydraulic jump profiles, in general.

Flow visualization experiments are conducted to depict the shape of demarcating boundaries between super-critical and sub-critical flows, and the corresponding radial jump locations are obtained. Theoretical calculations are also executed to obtain radial locations of the jumps with geometricaly smooth profiles. Comparisons are subsequently made between the theoretical predictions and the experimental observations, and a good agreement between these two can be observed. Jumps with corners, however, turn out to be comprising of strikingly contrasting profiles, which can be attributed to the "jump-jet" interaction and the "jump-jump" interaction mechanisms. A phenomenological explanation is also provided, by drawing analogy from the theory of shock-wave interactions.

Measurements of stagnation pressure and film thickness for different jet inclination angles and volume flow rates of liquid are reported. Film thickness measurements are made using an innovative cylindrical conductive probe, at the upstream ($\theta = \pi$) and downstream ($\theta = 0$) radial locations, for regions both before and after the jump. Theoretical calculations are executed to obtain the locations of the jump, for different jet and plate velocities and jet inclination angles. Comparisons are subsequently made between the theoretical predictions and experimental observations reported in the literature, and a good agreement between these two can be observed. Special cases of a circular hydraulic jump when the target plate is stationary and the impinging jet is vertical, and elliptic hydraulic jumps when the target plate is stationary and the impinging jet is obliquely inclined, are also discussed. It is conjectured that flow due to impinging jets on a horizontal moving plate can be modeled as an equivalent flow due to an inclined impinging jet on stationary horizontal flat plates, with appropriate alterations in the jet velocity and the jet inclination angles.

In the second part of this study hydraulic jumps formed by two normal impinging circular liquid jets have been discussed. Systems of two impinging jets have been classified into three groups, namely, far-distant impinging jets, distant impinging jets and adjacent impinging jets. Non-circular hydraulic jump profiles due to wall jet interactions have been observed for these groups, both for identical and non-identical impinging jets. Film thicknesses have been measured at the center of the stganation line. Effects of film thickness on corresponding jump locations have been reported. Twin adjacent impinging jets present a striking pattern of upwash fountain flow. A vertical fan of fluid with a very small thickness emerges on a line perpendicular to the line joining the centerline of the two jets. The outer periphery of the fan is described by a circular arc and a thick rim is observed at the outer periphery. Exploiting the symmetry of the situation, identical flow has been created by a single jet and fence vertically erected over the target plate. Flow visualization by dye injection shows liquid flow radially upwards through the upwash fan but falls back on the target plate through the peripheral rim.

In the third and final part of this sudy hydraulic jumps in two phase air-water flow in a suddenly expanded duct have been investigated. Experiments were performed for characterization of flow patterns in a two phase air-water flow, with the main focus on hydraulic jumps formed due to sudden expansion of the duct, corresponding to both horizontal and inclined (upward as well downward) orientation of the duct, as well as for different volume flow rates of air and water. Internal hydraulic jumps in a suddenly expanded duct are observed to be characteristic to the the orientation of the test-section (i.e., horizontal or inclined). With a fixed orientation, these jumps are characteristic to both the volume flow rates of the air and the water. Variety of hydraulic jump patterns, such as undular jumps, oscillating jumps, steady jumps, traveling jumps, pertinent to the orientation of the duct and the relative volume flow rates of air and water, have been observed. Phase diagrams indicative of regions of flow involving hydraulic jumps have been constructed for both the horizontal and inclined sections.