INVESTIGATION OF HYDRAULIC JUMP DUE TO TWO PHASE AIR –WATER FLOW IN A RECTANGULAR DUCT

Shahid Ali I.A [1]

[1]Assistant professor, SVKM's, NMIMS, MPSTME, Shirpur , Dhule,Maharashtra,India
Shahid.ansari1507@gmail.com

Abstract

The This paper presents an experimental investigation of the occurrence of hydraulic jumps due to two phase air-water flow in a rectangular duct in a horizontal position as well as inclined position .Hydraulic jump is a phenomenon frequently observed in an open channel flow. It occurs when liquid at high velocity discharges into a zone of lower velocity leading to a rather abrupt rise (a step or standing wave) in the liquid surface. In this present experimental investigation, various parameters like strength of the hydraulic jump, location of hydraulic jump, length of hydraulic jump is found out and the effect of flow rate of water and the effect of air flow on hydraulic jump is studied .Hydraulic jump results in the reduction of total energy of a moving fluid, which in turn prevents the fluid from scouring the channel banks. Also hydraulic jump enables a portion of the fluid's kinetic energy to reduce which stabilizes downstream flow conditions. Some of the other application areas of this phenomenon are efficient operation of flow measurement flumes, mixing of chemicals, intense mixing and gas transfer in chemical processes, desalination of sea water and aeration of streams which are polluted by bio-degradable wastes.

Keywords: Hydraulic jump, open channel flow. Scouring

I INTRODUCTION

Hydraulic jumps are among the most puzzling phenomena that occur in the nature under a variety of conditions, and have elected attention for centuries. This intriguing phenomenon of fluid dynamics was first sketched and described by Leonardo Da Vinci (1942-1519) in the 15^{th} century and complexity of the flow and the first experimental investigations on hydraulic jump were published by the Italian, Giorgio Bidone (1781-1839) in 1820[5]. Since then, plenteous of papers have been devoted to the topic, coming from diverse branches of engineering and science. The hydraulic jumps encountered in different natural and engineered environments are characterized by intense mixing, turbulence and aeration.

A common phenomenon that occurs in hydraulic behavior is an abrupt rise in water surface elevation, caused by deeper, slower-moving water downstream. This is known as a hydraulic jump, and has been the focus of interest for hydraulics engineers for almost two centuries, mostly because of its potential for energy dissipation (Chow 1959)[3]. Hydraulic jumps can also be highly erosive to the channels that contain them. In order to determine the required channel protection, practicing engineers must be able to predict the height, length, and location of a potential jump, which may be a difficult task depending on the channel shape. The length of a hydraulic jump is typically obtained from empirical functions of the jump height, based solely upon experimentation (Sturm 2001), and the location depends on both the length and height of the jump, as well as the upstream and downstream water surface profiles (Chow 1959). The jump height, however, may be predicted quite accurately using momentum theory alone (Hotchkiss et al. 2003). Typically, the discharge and upstream depth are already known, and what remains to be determined is the downstream "sequent depth" (Chadwick et al. 2004). This holds true for hydraulic jumps in closed conduits, although in this case a jump in water surface can potentially fill the conduit completely, producing pressure flow conditions downstream and preventing the surface from reaching the expected sequent depth (Hager 1999). Hydraulic jumps can easily observe in the kitchen and bathroom sinks when a vertical stream of water impinges on a horizontal surface. For examples hydraulic jumps can also be seen downstream of hydraulic structures such as spillways, sluice gates, venturi flumes and downstream of bridge piers during flooding, drinking fountains, and even in aspects of shock waves in the atmosphere of pulsating stars. Hydraulic jump can also occur incompressible fluid flows as demonstrated by cloud formation downwind of mountain ranges. 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 dissipates but also because of its fascinating complexity.

Types of Hydraulic Jumps

Hydraulic jump can be broadly grouped into two categories as stationary hydraulic jump, and moving hydraulic jumps. Stationary hydraulic jumps have fixed position with respect to time, while moving hydraulic jumps commonly referred as hydraulic bores, propagates into quiescent waters of uniform depth. A bore is defined as a broken wave of an infinite wavelength propagating into a quiescent water of a uniform depth, while a hydraulic jump is a stationary transition from a supercritical to subcritical flow [4]. It may form a “bore”, which is travelling form of hydraulic jump. The bore is a propagating discontinuity and the hydraulic jump is the stationary wave seen in a frame moving with the bore.

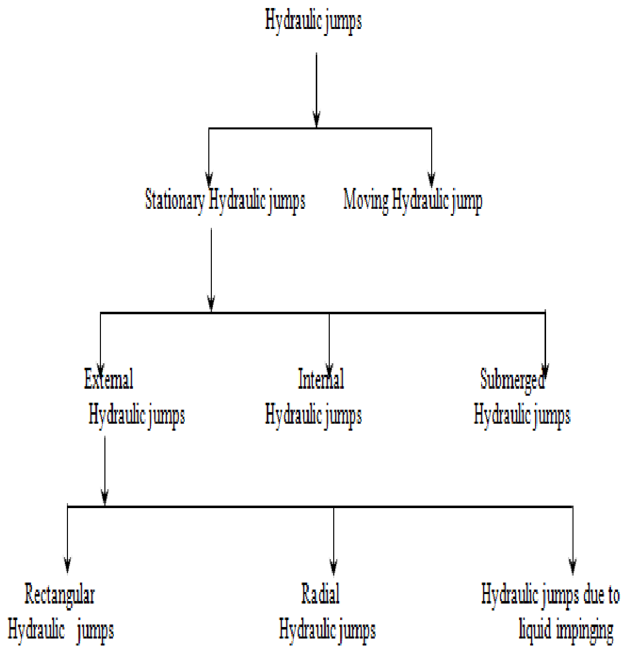

Fig.1. Types of Hydraulic Jump

External hydraulic jump again grouped as rectangular hydraulic jumps, radial hydraulic jumps, and the hydraulic jumps due to impinging liquid jets on target plates on the basis of type of flow. Rectangular and radial hydraulic jumps are the hydraulic jumps due to flow in rectangular and radial shaped channels respectively, and the wall jet type of flow.

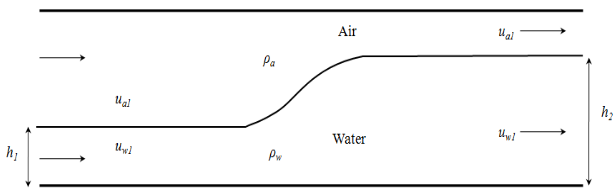

Fig.2. Definitions and Sketch of Internal Hydraulic Jump

Hydraulic jumps in multilayer or multiphase flows are often termed as internal hydraulic jumps, normally with reference to hydraulic jumps in oceanic flows. Internal hydraulic jump have been schematically described in figure 2. The definition of internal hydraulic jump is not clear. “There is often much confusion in the literature regarding the definition of internal hydraulic jump” (Wright et al. 1991), this confusion continues to the present day.

II LITERATURE REVIEW

Experimental and theoretical studies of hydraulic jumps in one and two layer system has been presented in the literature (MCcorquodale,1986), the numbers of work for two layer case is considerably less than that of single layer[14]. Benton (1954) first treated internal hydraulics jumps for two moving layers .He recognize that the principles of momentum conservation and decrease of energy are together insufficient to specify downstream condition, given a complete description of upstream flow. For jumps with negligible mixing of the layers , there are the three main approach as which have been reported .The application of the momentum principle to individual layer was first suggested by Yih and Guha (1955) and used in the study of internal jumps in moving layers by Rajaratnam et al .(1991) Stahl & Hanger (1990) investigated experimentally the main features of such jumps and obtained limits for conduit choking[6]. The sequent depth ratio is determined in terms of approach Froude number based on the conventional momentum approach. Stratified two-phase flows often involve a hydraulic jump, as is reported for the counter current steam-water flow in a hot leg of a nuclear power reactor (Krishnan, 1987)[7]. The ability of the model presented to simulate the hydraulic jump in the stratified flow is verified by simulations of flow conditions presented and numerically computed by Rahman et al[8]. (1991).

Mehrohtra and Kelly (1973) extended this approach to bounded two – layer flows, and suggested that the two resulting legitimate solutions, the physical solution would approach an infinitesimally weak jump in the limit when the condition upstream of the jump tends to the critical state .A conclusion was that the conjugate state that is closer to the upstream state was physically realizable for both open and closed channels. For horizontal as well as in upward and downward inclined flow, the flow patterns observed are stratified, intermittent, annular and dispersed bubble .stratified flows are further designated as stratified smooth, stratified wavy, laminar stratified .in many of the above mentioned flow situation, formation of hydraulic jump is possible, e.g. stratified flows (Hayakawa 1770)[2], countercurrent flow (Krishnan 1987), Roberts et al. [1] presented a nice theoretical explanation of the hydraulic jumps occurring in stratified flows in T-junctions as depicted in figure 3.

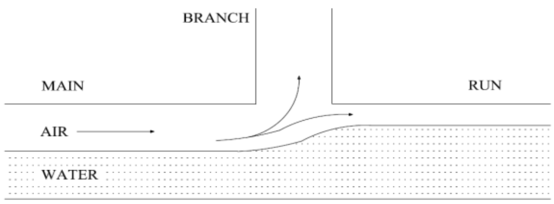

Fig.3. Hydraulic jump at T-junction

III EXPERIMENTAL DETAILS AND METHODOLOGY

Experimental set-up was developed for the characterization of flow pattern, with the main focus on hydraulic jumps, using a suddenly expanded rectangular section. A typical section consists of a rectangular duct section was made without expansion made up of transparent Perspex acrylic sheet having dimensions 1500 mm × 30 mm × 34 mm. The entire unit was supported on two leveling screws and a hinge at the extreme left of the smaller section. Hinge is provided so that the entire unit can be inclined to horizontal. One centrifugal pump is used for circulation of filtered water. The water flow rate is measured by a rotameter .A rotameter bank containing two rotameter (calibrated in the range of 1-20 LPM for water) is used for this purpose. Flow rate of both air and water are controlled using control valves and bypass arrangement as shown in figure 4 and the schematic diagram of experimental set-up is shown in figure 4.

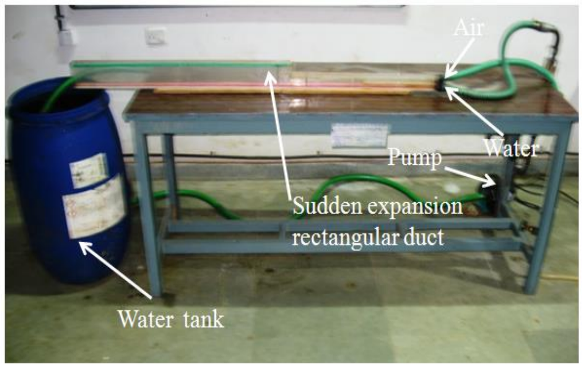

Fig.4. Schematic Diagram of Experimental Set-Up

Flow patterns involving hydraulic jump are investigated corresponding to both horizontal and inclined (upward as well as downward) orientation of the duct, as well as for different volume flow rates of air and water. The air and water were supplied at controlled flow rate to the inlet section by two different ducts. The air was supplied at the top of the water as shown in figure 4.The set up has a provision to change the test section from a constant one to a suddenly expanding one. The flow rates were controlled by control valve provided before the respective rotameter. Figure 4 shows the sample still shots of the experiments of the hydraulic jump without air flow rate in expanded as well as unexpanded horizontal test-section conducted in the Refrigeration and Air Conditioning Laboratory at Dr. BATU, Lonere.

Description of the Phenomenon

The density of water and air are ρ_{w1} and ρ_{a1} respectively. The height of the water layer (h_{w1}) remains more or less uniform (neglecting small gradual increase in the thickness due to boundary layer effect) throughout the length of the smaller section having length (L_1). However, as the water enter into the expanded section of depth D_2, the water film height suddenly increases to (h_{w2}), with corresponding decrease in its velocity to V_{w2} signifying formation of hydraulic jump. Figure 5 shows schematic diagram of hydraulic Jump in a two- phase air water flow due to sudden expansion .A two- layers flow, consisting of a bottom water layer and air at the top of water level. V_{w1} and $V_{a1}$are the velocities of water and air flow through smaller section (section before expansion) having depth (D_1) respectively

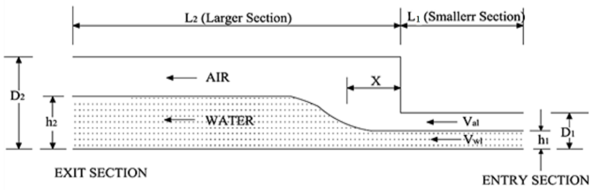

Fig.5. Hydraulic jump in a two- phase air water flow due to sudden expansion

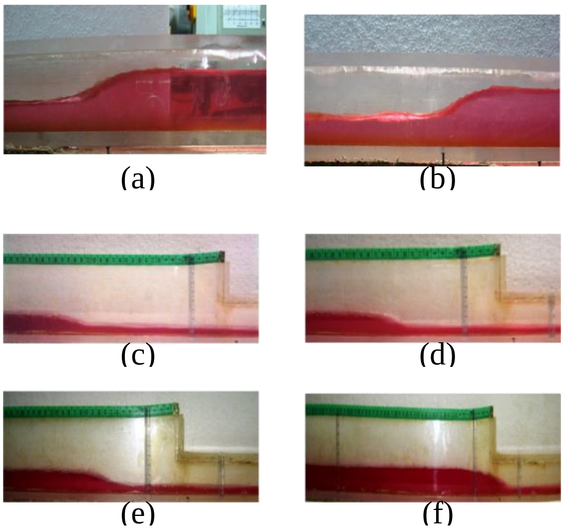

Fig. 6 . Still shots of the experiments of the hydraulic jump without air flow rate in rectangular test-section (a),(b) : (Q_w = 1.83 × 10^{-4} m^3/s) and in expanded horizontal test-section (c), (d),(e) and (f): (Q_w = 1.66 × 10^{-4} m^3/s)

IV RESULT AND DISCUSSION

Hydraulic jumps due to single phase flow in unexpanded horizontal duct

The hydraulic jump observed during a laboratory experiment in unexpanded horizontal test-section without air flow is depicted in figure 7.

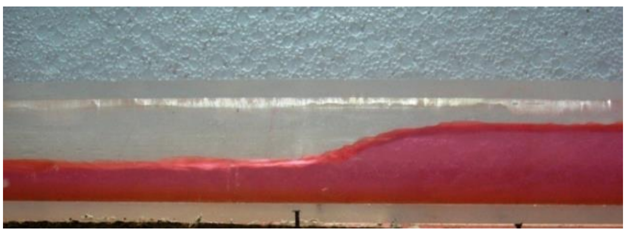

Fig.7. Hydraulic jump in a horizontal test-section without air flow (Q_w=2.0 × 10^{-4} m^3/s, Q_a=0.0), (h_1=10 mm, h_2=30 mm)

For checking the effect of water flow rate on the downstream height of the jump same experimentation procedure has been carried out as that of previous one .The multiple readings were taken at different water flow rates. The graph of the reading was plotted for the downstream height of the jump (h_2) in mm against the water flow rate in m^3/s as shown in figure 8.

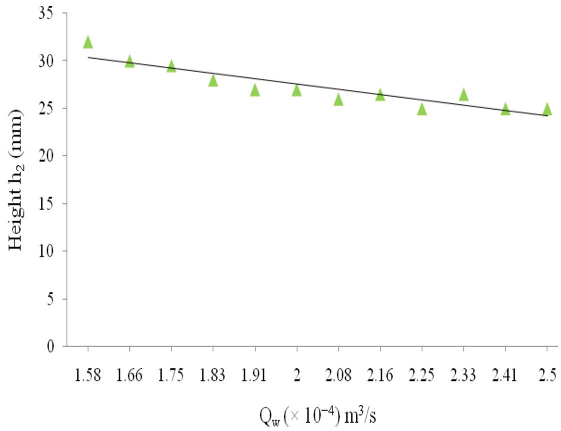

Fig.8. Downstream height of the jump (h_2) formed in unexpanded horizontal section with no induction of air

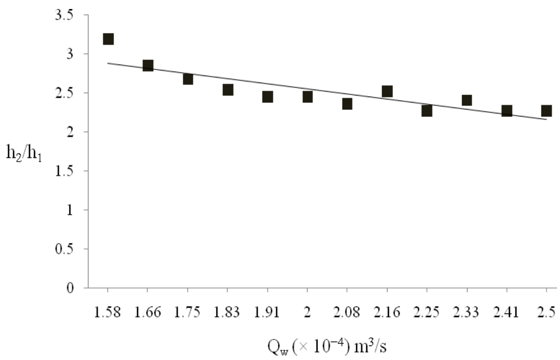

Fig.9.Strength of the jump formed in unexpanded horizontal section with no induction of air

As the volume flow rate of water increases the height of the jump initially increases and it decreases to the exit of the test-section due to volume flow rate of water. For checking the effect of volume flow rate of water on the strength of the jump experimentation have been carried out by changing the volume flow rate of water. The readings were taken for each volume flow rate throughout the test-section. The graph of strength of the jump is plotted against the water flow rate as depicted in figure 9.

Hydraulic jumps due to two-phase air-water flow

Another kind of experimentation had carried out for visualization of hydraulic jump due to two-phase air-water flow in unexpanded as well as expanded horizontal duct. The water flow rate during the experimentation was kept constant while the air flow rate increases small increment. The images are showing the experimentation and the effect of air flow rate on the hydraulic jump at different flow rates of air. In single phase flow as water flow rate increases downstream height decreases, but in case of two phases due to the introduction of air at same flow rate of water initially jump height is increased. If we increase the air flow rates then the top surface get disturbed as shown in figure 10.

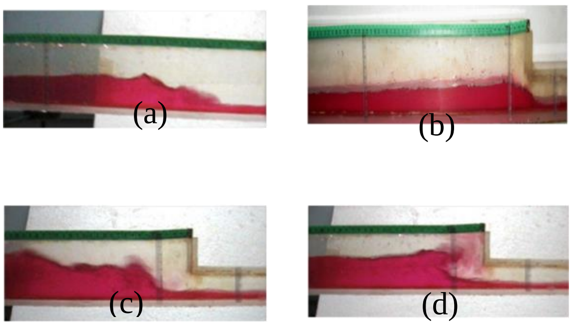

Fig.10. Hydraulic jump in horizontal test-section with induction of air (a), (b), (c), (d) top surface of jump get disturbed due to air., (Q_w = 1.91 × 10^{-4} m^3/s, Q_a=3.19 × 10^{-3} m^3/s)

Experimentation has been carried out for checking the effect of air flow rate on the location of hydraulic jump as well as downstream height of jump. Same experimentation procedure has been carried out as that of previous one only difference is that the volume flow rate of water was kept constant and volume flow rate of air was supplied at small incremental value. The graph of the downstream height of jump is plotted against the water flow rate as depicted in figure 11.

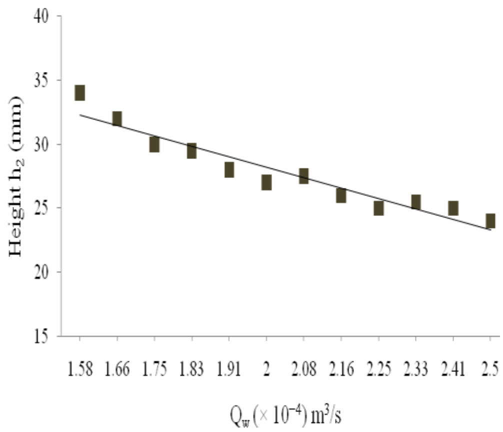

Fig.11. Downstream height of the jump (h_2) formed in expanded rectangular duct with induction of air Q_a =7.08 × 10^{-4} m^3/s

The graph of reading is plotted for the effect of air on the downstream height of the jump (h_2) in mm against the water flow rate m^3/s is depicted in figure 11.As seen from the graph it is concluded that as water-air flow rate increases the location of hydraulic jump shifts downstream in an expanded test section. The comparison between a strength of jump due to single and two phase water- air flow in expanded duct is shown in figure 12.

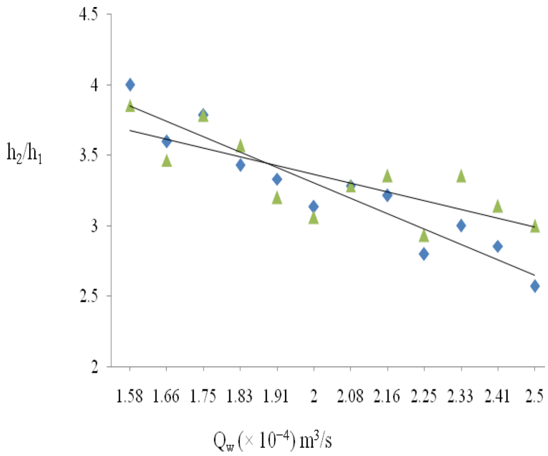

Fig.12. Comparison between strength of jump due to induction of air in single and two phase flow (Air flow rate, Q_a =7.08 × 10^{-4} m^3/s)

Experimental Observations

Flow Regimes

Only three kinds of basic flows are observed - stratified smooth, stratified wavy and intermittent or slug flow. Their different parameters varied without changing the flow regime. Stratified flow had different liquid content in the duct as the liquid flow rate is changed. It increased with the flow rate. Similarly, the slug size, speed and geometry changed with the flow rate. Bubble entrained in the liquid layer also varied with flow rates.

Stratified Smooth (SS)

In horizontal and slightly inclined flows, the stratified smooth flow was observed when the flow rates of both of fluids are low. The two phases flow separately with the relatively smooth interface.

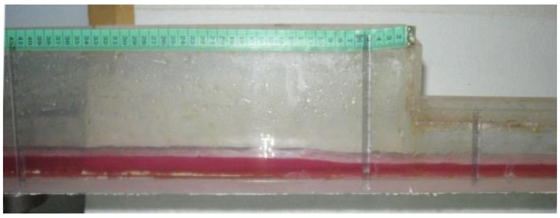

Fig.13. Stratified smooth flow in suddenly expanding rectangular channel

As the water flow rate is increased, keeping the air rate constant, firstly the water content of the section was observed to increase and finally the flow went into an intermittent flow regime.

Stratified Wavy (SW)

At lesser gas flow rates, if the water rate is increased beyond a limit, it results in a stratified wavy flow. This should transit into dispersed flow if liquid rate would have been increased further, but because of experimental limitation this pattern was not observed. Keeping the water flow rate constant and increasing the air rate results into intermittent flow.

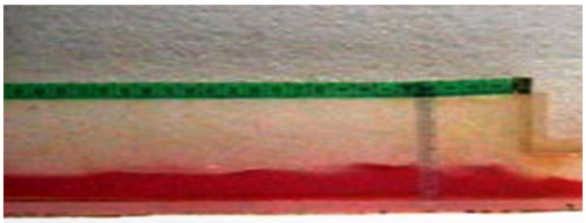

Fig.14. Stratified wavy flow in suddenly expanding channel

Intermittent Slug Flow (I or SF)

Intermittent and slug flow were observed when either of the flow rates is increased while keeping the other to a lower value. If the liquid flow rate is increased then the gas slug flow formed and if gas flow rate is increased it results into liquid slug flow that is referred as intermittent flow.

Fig.15. Slug flow in suddenly expanding channel

Slug flow is characterized by the movement of the gas slug and their size. As the gas flow rate is increased, the slug speed as well as the size increases finally results into stratified wavy flow or intermittent flow, depending on the inclination of the channel.Intermittent flow has a liquid slug moving impetuously from upstream to downstream. It generally happens with the liquid slug touching the upper wall of the channel. In suddenly expanding section, however, it posses some vortices and bubble entrapment too.

CONCLUSIONS

Internal hydraulic jumps in an expanded as well as unexpanded rectangular duct are observed to be characteristics to the orientation of the test–section (i.e. Horizontal or inclined). With a fixed orientation, these jumps are characteristics to both the volume flow rates of the air and the water. From the experiments it is observed that after some amount of air flow rate the flow becomes highly pulsating and static jump formation becomes difficult to determine. Hydraulic jumps are observed without flow of air, for certain flow rates of water, both for the horizontal and inclined duct-section. Types of a jump, their strength and location are observed to be function of inclination angle of test section, and volume flow rates of water and the air

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