AN EXPERIMENTAL STUDY ON FLOW BEHAVIOUR FOR SELECTED FISH SPECIES IN A VERTICAL SLOT FISH PASS

by

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AN EXPERIMENTAL STUDY ON FLOW BEHAVIOUR FOR SELECTED FISH SPECIES IN A VERTICAL SLOT FISH PASS

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CERTIFICATION OF APPROVAL

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It is hereby declared that this thesis or any part of it has not been submitted elsewhere for the award of any degree or diploma.

Signature of the Candidate

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LIST OF NOTATIONS

Symbol	**Meaning**
b_o	Characteristics width (e.g. fish pass opening, slot width, orifice width, culvert diameter)
g	Acceleration of gravity
Q	Fish pass discharge
Q_*	Dimensionless discharge
Q_{3d}	Three day delay discharge
S_0	Slope of the Fish pass bed
T_v	Swimming performance
U_*	Dimensionless velocity scale
u	Local velocity at a depth y
u_m	Velocity scale representing the maximum values of u
u_m'	The velocity at 75% of the depth
u/u_m	Dimensionless local velocity
V_{thr}	Threshold current velocity
V_{er}	Critical velocity
y_o	Total depth
y_o/b_o	Dimensionless depth
y/y_o and y/z_o	Dimensionless local depth
z_o	Height of baffle or weir in culvert fish passes

LIST OF ABBREVIATIONS

ADV	Acoustic Doppler velocimeter
BFRSS	Bangladesh Fisheries Survey Statistics
BRE	Brahmaputra Right Embankment
BWDB	Bangladesh Water Development Board
BUET	Bangladesh University of Engineering and Technology
CEGIS	Centre for Environmental and Geographic Information Services
CFD	Computational Fluid Dynamics
CPP	Compartment Pilot Project
DoF	Department of Fisheries
DWRE	Department of Water Resources Engineering
FAP	Flood Action Plan
FCD	Flood Control and Drainage
FCDI	Flood Control Drainage and Irrigation
FFS	Fish Friendly Structures
Fps	Fish Passes
FPP	Fish Pass Pilot Project
GBM	Ganges-Brahmaputra-Megna
IUCN	International Union for Conservation of Nature
MRP	Manu River Flood Control and Irrigation Project
NWMP	National Water Management Plan

PIV	Particle Image Velocimetry
PIT	Passive Integrated Transponder
POD	Proper Orthogonal Decomposition
SD	Standard Deviation
VSF	Vertical Slot Fish pass

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ABSTRACT

Food chain and life cycle of natural fish and other aquatic species have become vulnerable due to interruption in the natural sequence of flooding and floodplain in Bangladesh. As a technical solution to this problem, fish friendly structures and fish passes have been built in different locations of Bangladesh mainly on the important fish migrations routes. Some field investigations and research works have been performed several agencies and researchers to analyze the performance of the existing fish friendly structures and fish passes. But no laboratory study with a physical model structures have been done with some selected fish species in Bangladesh.

In this research work an experimental study has been performed with a distorted physical model in the laboratory flume of DWRE, BUET by down scaling the existing prototype at Sarikandi, Bogra. The experimental arrangement consists of an adverse slope of 6% followed by a 3.4% mild slope. The model structure consists of four pools. Each of the pool was approximately 1 m long, 0.762 m wide and 0.60 m high. The width of the opening of each pool was 0.127 m. The experiments were conducted by maintaining upstream water level of 40 cm, 50 cm and 60 cm for different ranges of velocities. Velocities were in the range of 0.3 m/s to 0.8 m/s and discharges were in the range of 37 m^3/hr to 145 m^3/hr. Total 18 sets of experiments have been conducted for this study. For each set of experiments, three dimensional velocity data were collected at 0.4, 0.6 and 0.8 hydraulic depth by using an ADV (Acoustic Doppler Velocimeter).

The X and Y components of velocity data have been analyzed to plot the velocity vector fields and velocity contour maps to understand the flow pattern. The response of the selected fish species (Rui, Katla and Mrigel) of different sizes with respect to different hydrodynamic conditions provided has been analyzed. It has been found that though the developed hydrodynamic conditions were favourable for the juvenile size of the selected species but were quite unfavourable for the fry and fingerling size of the selected species in most of the cases. The results that have been found from this study will be very much helpful to carry out further field and laboratory studies in future.

CHAPTER 1
INTRODUCTION

1.1 Background of the Study

Bangladesh is situated in the delta of the Ganges-Brahmaputra-Meghna (GBM) Rivers which are three of the largest rivers in the world. The river systems have shaped the history, economy, literature and rich culture of people of this country. They provide an arterial transportation network for people, goods and fish migration. Major concerns related to natural environment and water-related impacts on fisheries have been emerged.

Migratory fishes travel from upstream to downstream to reach larger body of water where food is available (Bajestan et al., 2002). The occurrence and succession of flood is a controlling factor in the lifecycle of most fish species in the floodplains of Bangladesh. During the monsoon period, the floodplains become the primary source of reproduction and increase of fish biomass in open water fisheries system. Fishes move out into the floodplains for feeding, grazing, growth and reproduction during floods. Inundation of the floodplains provides the spawning grounds, nursery areas and major feeding opportunities for a wide range of fish and prawn species (Minkin, 1989, Ali, 1991). More than 256 species of indigenous fish (IUCN, 2002) and more than 20 species of indigenous prawn have been recorded in open water system of Bangladesh (Rahman, 1989). Many of these species travel considerable distance under the stimulus of rising of waters to reach their spawning grounds and also move over the floodplains when the water extends laterally (Tsai et al., 1985, Ali, 1990). The nature of fisheries ecosystem and the movement of the fishes are dictated by seasonal changes in water levels and discharge rates in extensive floodplain systems (Welcomme, 1985). As the floodplains become inundated by rainfall and over bank flooding, some species of fishes, such as major carp begins a longitudinal migration to spawn. Once river begins to flood most fishes make lateral migration into the many distributary channels of the rivers. From these channels fishes start to move to floodplains to exploit the food resources of the flooded area. Fish species migrate from floodplain to river as the floodwater recedes (Aguero, 1989).

Fisheries sector requires urgent attention to tackle the challenges occurred from unplanned flood control structures. Capture fishing on the floodplains and the haor basins, a traditional activity of the poor, is declining rapidly and will disappear altogether unless proper measures are taken. Due to interruption in the natural sequence of flooding in floodplain of Bangladesh, food chain and life cycle of natural fish and other aquatic species have become vulnerable (NWMP, 2001). The impact on fish migration for flood control embankment and regulator appears to be of major concern to the perpetual survival of the natural fish stocks utilizing rivers and floodplain in many parts of Bangladesh (FAP-6, 1993; 1994; and 1998; FAP-17, 1994).

The water regulatory structures like dams and weirs causing river fragmentation play a major role in declining the freshwater fisheries (Lucas and Frear, 1997; Cowx and Welcomme, 1998; Lucas and Baras, 2001). The fishes that complete their migrations within the river system are mostly affected by such arrangements (Nicola et al., 1996; Poulet, 2007). If no arrangement is made in the weir or the dam, to enable the fish to pass upstream, then such migratory fish have been found to be striking against the water current in their efforts to move up, till death. Non-provision of an arrangement for fish to pass upstream, may thus, lead to large scale destruction of fish life. If simply an open gap is left in the weir for this migration, the velocity of flow through such an opening will be very high. Therefore, even the strongest fish will not be able to travel upstream; resulting in large scale destruction of fish near the downstream end of fish gap (Garg, 2008).

A fish pass is a hydraulic structure that enables fishes to overcome obstructions in the passage to the spawning grounds and other upstream migrations and is built when it is required for ecological, economical or legal considerations. Fish passes are so designed to attract fishes readily and allow them to enter, pass through and exit safely with no undue stress, injury and especially without any undue delay for adult spawners. Most commonly used fish passes are divided into four groups: pool and weir, denil, vertical slot and culvert fish passes (Bell, 1973; Clay, 1995; Katopodis, 1990).

The concept of fish pass was introduced in Bangladesh in the 1990s and since then 4 fish friendly structures and fish passes have been built. Among them Sariakandi fish pass was constructed at Sariakandi in Bogra. Jamuna and Bengali Rivers had plenty of freshwater fishes before implementation of the Brahmaputra Right Embankment (BRE) project. After the construction of BRE, fish production in Bengali river was reduced drastically due to the disruption of the natural fish migration routes between these two rivers. As Jamuna and Bengali Rivers are the closest to each other near Sariakandi, BWDB took an initiative to construct a fish pass at Sariakandi as an integral component of BRE system which was designed as a vertical slot fish pass (Biswas, 2007). Vertical slot type fish pass provides more area and time for resting of different aquatic species during their migration from upstream to downstream (Kamula, 2001; Rajaratnam et al., 1999; 1992; 1989; and 1986). It allows for variations in discharge and permits fish to ascend the fish pass at any depth they choose (Liu et al., 2006). In addition, the path of a fish ascending the fish pass is not tortuous and the fish pass provides resting locations for fish (Clay, 1995).

1.2 Scope of the Study

A number of studies have addressed the flow circulation patterns, the jet characteristics and the turbulence generated by the energy dissipation in pools for different configurations, and their relevance for the development of suitable hydraulic criteria for passage of salmonid species (Rajaratnam and Katopodis, 1986; Wu et al., 1999; Ead et al., 2004; Puertas et al., 2004; Barton et al. 2008). These findings have been developed with experimental flume results tested with different physical models of different designs and model scales.

Although the hydraulics of vertical slot fish pass has been studied by several investigators around the world (Rajaratnam et al., 1992; Liu et al., 2006), the understanding of the characteristics of the overall flow hydraulics and fish behaviour appears to be incomplete for common Bangladeshi fish species like Rui, Katla and

Mrigel etc. Based on this, an experimental research approach combining both the flow and fish behaviour has been carried out inside a distorted physical model of Sariakandi fish pass which has been developed in the laboratory flume of the Hydraulics and River Engineering Laboratory, DWRE, BUET. The behavior of different fish species (Rui, Catla and Mrigel) of different sizes such as fry, fingerling and juvenile has been observed in different hydrodynamic conditions in this study.

1.3 Objectives of the Study

This research work mainly focuses on the flow hydraulics inside a vertical slot fish pass. For this purpose a laboratory set up has been established to investigate the following specific objectives:

1. To investigate the flow circulation pattern inside the pool of the vertical slot fish pass with different combination of water depth and velocity.
2. To observe the velocity field developed inside the pool for different hydrodynamic conditions.
3. To observe the behavior of different species of fishes for different velocity fields.

Possible Outcome of the Research Work

The expected outcomes of this research work are as follows:

1. Understanding of the behavior of the velocity and the flow circulation pattern inside a pool of the vertical slot fish pass.
2. To observe the cruising velocity of different fish species.
3. Performance of the model structure in creating circulating region of lower velocities which is very much effective as resting places for fishes.

1.4 Organization of the Thesis

This research work has been done step by step through six chapters as given below.

Chapter 1 deals with the background, scope and objectives of the study.

Chapter 2 mainly focuses on the reviews of literature related to the theme of this study. Scenarios of fish friendly structures (FFS) of Bangladesh and important biological characteristics of fish species have been discussed in this chapter. Here some findings of the previous research works have also been discussed briefly.

Chapter 3 deals with the theoretical background behind the hydraulics of vertical slot type fish pass e.g. design flow, depth-discharge relationship, velocity inside the fish pass etc. The ichthyomechanics of fish species has also been discussed here.

Chapter 4 represents the detail experimental set up, data collection processes in the laboratory and overall description of the working procedure.

Chapter 5 illustrates the data analysis, results and discussions related to the plane velocity fields, velocity contours, vertical velocity profiles and relationship of fish behavior with these.

Chapter 6 discusses the major findings of the study. In this chapter the recommendations for further study have also been discussed.

CHAPTER 2

LITERATURE REVIEW

2.1 General

In this chapter, the present condition of the existing fish friendly structures in Bangladesh has been discussed very briefly. The need for fish friendly structures through weirs, dams or culverts have been highlighted. Biological requirements such as fish behaviour, motivation, preferences, migration timing and swimming ability drive design and construction criteria for fish passes. Some features about biological characteristics of fishes which are needed to understand the fish behavior and response inside the fish pass have been studied in detail in this chapter. In addition to these, some laboratory and field research works performed by the experts around the world as well as in Bangladesh have been illustrated here.

2.2 Fish Pass in Bangladesh Context

FCD (Flood Control and Drainage) and FCDI (Flood Control, Drainage an Irrigation) schemes in Bangladesh have certainly entailed the greater use of embankments to control or partially control the encroachment of floodwater since their implementation over a few decades ago. But these flood control structures have certainly uncertain impacts on fisheries production by creating obstruction of the riverine fish to the flood plain. Feeding and breeding grounds of fishes will be compacted to some extent due to reduced flood extension. Consequently it will result in a fall in production of fish. Fish movement will be inevitably disrupted to some extent due to construction of embankments although provisions for controlled water inflow can be made to minimize the damage to fisheries resources and maintain some elements of the natural system (FAP 17, 1993).

2.2.1 Needs of Fish Friendly Structures

It is become alarming that the fish production in the river and floodplain constantly declining (BFRSS Statistics), condition (water quality, inundation, connectivity) for fish habitat become a concern and also seriously hamper the migration route by siltation and flood control measures. It is possible to partially mitigate the negative impacts due to restriction of the river bank overspill, through structural addition and / or modification of flood control engineering (FAP 17, 1993). Fish passes and fish friendly structures have been employed in different parts of the world including Bangladesh to facilitate migration and reduce mortality rate of hatchling movement through the hydraulic gates. The hydraulic conditions at any obstruction are determined by the topography and the velocity and nature of the flows entering and passing through the reach. The high velocity of the water and turbulence at the hydraulic structure are the prime factors preventing fish to migrate (Clay, 1995).

The fish way or fish pass structure or modification of existing structure must be cost effective is to improve following conditions (Hassan, 2002):

- Support and maintain the natural longitudinal and lateral migration;
- Reduce the hatchling mortality rate;
- Maintain connectivity between the river and beels for flushing and to maintain the condition for fish habitat;
- Reduce the turbulence;
- Enough flow and depth to attract fish (especially young fish) to use the structure; and
- Exit and entrance velocity must within swimming speed of species (which species expected to be used the structure).

In general, the fish way or fish pass may ensure the safe movement of all kind of aquatic lives through it throughout the year from outside river system to the water bodies and vice versa. It also required ensuring safe movement and migration of the fish spawn, fish fry and fingerling to and from the flood control area. Inundation of the fisheries habitat in the beel area (for spawning, grazing, feeding etc.) during pre-monsoon period in a planned way so that addition inundation does not damage standing crops. Regulating maximum water level inside the flood control project to achieve management objectives (protect environment, maintain economic growth, balance animal protein intake, food security and maintain habitat/ecosystem) is needed (Hassan, 2002).

2.2.2 Fish Migration

The species in Bangladesh that reside on the flood plain and beels at the height of dry season tend to be those with adaptations to withstand limiting conditions. Most of the fish species in Bangladesh are migratory. Among these species some reside on limited area and subjected to migration of only 20-30 km. But some species make migration of several thousand kilometers between widely different habitats. Table 2.1 represents peak migration timing of different species of fishes. The peak migration time for Hilsa is August to October while for Carp and Catfish is May to July. Active river flow is needed for small fishes to move from one floodplain to other as they are not migratory. Winter breeders are also not migratory and they breed during the months of January and February (Hassan, 2002).

Table 2.1: Fish migration timing

Category of Fish	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Hilsha			▨	░	░			■	■	■		
Carp				▨	■	■	■	░	░			
Catfish				▨	■	■	■	░	░			
Small fish		▨	■	■	■	■	■	■	■			
Winter breeder	■	■										▨
Hatchlings					■	■	■	░	■	■		

Legend

░ Lean time ▨ Preparation time

▦ Wintering ■ Peak time

(Source: Hassan, 2002)

2.2.3 Mechanism of Migration

Hydrology has influence on both lateral and longitudinal migration of fish and its seasonality. Table 2.2 summarized the influence of hydrology on fish activity. River water level started to rising at the onset of monsoon resulting in accumulation of water in low pockets and beels and the floodplains are inundated. Foods are stored in the beels due to the effect of flow of river water to the floodplains and rainfall run off. Then the storage of food for aquatic ecosystem in floodplain makes it very much suitable for spawning and feeding ground for fish. The major carps make longitudinal movement from the beels and duars against the river current in the river to the spawning ground during the earlier period of the pre monsoon. And at the recession period of monsoon passive migration i.e. from beels to river of fish species is initiated. This passive migration starts from mid-September and continues up to November (Hassan, 2002).

Table 2.2: Hydrology control on fish activity

Hydrological controls	Time	Fish activity
Early rain	February – April	Small fish prepare for breeding in the beel.
Thunder	February - March	Small fishes breed. Big fishes like carps and catfish prepare for breeding and spawning migration.
Water level rise	March – May	Breeding continues for small fish and spawning migratory fish. Dispersion of hatchlings of small fish.
Water current (pre-monsoon)	March – May	Spawning migration continues. Hatchling movement between river and floodplain.
Flood	June - September	Grazing and feeding in the floodplain. Mixing and dispersion of species, migration and movements occur.
Water recession	September - November	Taking shelter to perennial water bodies. Move from floodplain to river for shelter.
Drought	December-February	Shelter in the deeper water area either in the river (dors) or in the beels.

(Source: Hassan, 2002)

2.2.4 Water Current and Velocity

The locomotive activity of fish in a water flow may be characterized by a number of functional indices. **Threshold current velocity** (V_{thr}) is the minimum current velocity which leads to an orientation reaction against the current (values range from 1-30 cm/sec). **Critical velocity (**V_{er}) is the minimum current velocity at which fish begin to be carried away by the water flow. Bottom dwellers typically have critical velocities 2-3 times lower than species inhabiting the water column or surface layer. **Swimming performance** (T_v), is the duration of active swimming as a function of a fish's speed. The greater the speed, the lower the duration of movement, with characteristic burst, maximum and cruising speeds (Bell, 1984).

Rheoreaction is influenced by temperature, level of illumination, degree of turbulence, flow velocity and the physiological condition of the fish. Velocity gradients are usually very different in natural environments, i.e. in non-uniform flows, and fish consequently react differently to them. Two main types of reaction current can be discerned. The first involves precise orientation and movement against the current where current velocities exceed 0.3 V_{er}. The second, where current velocities are below 0.3 V_{er}, involves disorientation relative to the direction of the main flow. Here V_{er} is the critical velocity (maximum) of the fish which enable fish to move against the water current. This is the limiting velocity. Fishes are carried away by flowing water when velocities of flowing water exceed this limit (Arnold, 1974).

Migrating fish proceeds at cruising speed, only rarely at maximum speed. If current velocities in the main river channel exceed the swimming performance of the fish they move closer to the banks seeking zones of less vigorous water flow. The presence of whirlpools or circular currents leads to the disorientation of migrants and they delay and accumulate in such places (Biswas, 2007).

2.2.5 Water Temperature and Light

Water temperature is one of the important parameters for orientation and cue directing migration. The common understanding is that the downstream fish movement in the river is caused with the combination of augmented river discharge and increased temperature. Pelagic fish and some benthic species which rely on visual orientation, move upstream near the surface of the water column or through shallow waters along the riverbanks. On the whole their migrations occur at the daytime or during twilight hours. Rather than time of the day, illumination is the principal criterion for migration (Biswas, 2007).

2.2.6 Depth Preferences of Fish Species

There is a long correlation among floodplain water depth with species concentration, biomass, biodiversity and other physical and biological factors (CEGIS, 1997). Floodpalin fish habitat study was defined five depth class group. Table 2.3 gives information on depth classes and its depth of water.

Table 2.3: Depth classes and its depths of water

Depth Class	Water Depth, cm
Depth 1	1-15
Depth 2	16-30
Depth 3	31-90
Depth 4	91-180
Depth 5	>180

(Source: CEGIS, 1997)

Fish exhibit a preference for a certain depth class (habitat) by concentrating within that depth range. The prawn, puffer, eel, perch, and gurami, barb, cyprinid, small catfish and snakehead prefer shallow water. Their concentration is the highest in between depth class 1 to depth class 3. Glassfish and Goby do not show any strong preference, occupy all depth classes. The carp guilds have strong preference for deeper water (depth class 3-5). This is due to their body shape and size.

The prawn, cyprinid and snakehead species are small (< 30 mm in length) and tend to prefer shallower depths. Carp are generally larger (>50 mm) and concentrate in deeper water. Eel are generally large (>50 mm) and can be found between depth class 1 to depth class, glassfish and gobies are small (<30 mm) and can be found throughout the depth classes.

2.2.7 Velocity Related to Swimming Speed

The most important factors to be kept in mind while designing a fish pass is the water velocity related to swimming speed. Detailed analysis of the swimming performance of the targeted species must be performed to set up the allowable velocity limit of the fish pass.

Bell (1984) defines three level of speeds that are critical in designing fish way as follows:

- Cruising – a speed that can be maintained for long period of times (hours), for benthic fish 0.5 to 1 times the body length per sec and 3-4 times body length per sec for pelagic species;
- Sustained – a speed that can be maintained for minutes; and
- Darting (or burst) – a single effort, not sustainable.

The cruising and maximum swimming speed were estimated in two categories such as boromach (rui, catla, Ilish, catfish – boal, air,) and chotomach (puti, mala, etc.) are shown in Table 2.4.

Table 2.4: Swimming speed for boromach and chotomach

Type	**Group**	**Species**	**Type**	**Crusing Velocity (cm/s)**
Boromach	Carp	Rui, Catla,Mrigel	Pelagic	3.5 * BL
	Catfish	Boal, air, Rita, etc.	Benthic	0.7 * BL
	Knife fish	Chital	Pelagic	3.5 * BL
	Herring	Ilish	Pelagic	3.6 * BL
	Spiny Eel	Baim	Benthic	0.8 * BL
Chotomach	Small barbs	Puti, Mola, Chela	Pelagic	2.85 to 3.6 * BL
	Small catfish	Pabda, Bacha, Batachi	Pelagic	3.6 * BL
		Tengra, Gulsha	Benthic	.6 to 1 * BL

*Note : BL = body length of the fish, maximum velocity = 2 * Crusing velocity.*
(Source: Hassan, 2002)

2.3 Existing Fish Friendly Structures in Bangladesh

Since 1990s there are have been four FFS (Fish Friendly Structures) and FPs (Fish Passes) in Bangladesh. These are: 1) Jugini Regulator: Tangail Compartmentalization Project 2) Kashimpur Regulator of Manu River FCDI project, Moulavibazar 3) Jamalpur Fish pass and 4) Sariakandi Fish Pass, Bogra.

2.3.1 Sariakandi Fish Pass, Bogra

The Sariakandi fish pass in Bogra district is the largest and newest fish pass of the country. Sariakandi is located between 24°44′ and 25°03′ N latitudes and between 89°30′ and 89°45′ E longitudes. Main rivers adjoining to this area are Jamuna, Bangali and Sukhdaha; Ruhia Beel is notable.

The fish pass is located at village Debganga of Kutubpur Union of Sariakandi Upazila. Jamuna River is on the east and Bangali River is on the west of the fish pass. The fish pass is at the nearest corridor between Jamuna and Bangali Rivers. The fish pass is situated between the Sariakandi and Mathurapara Hard Points. This is an integeral part of Brahmaputra Right Embankment that allows fish movement between Brahmaputra and Bangali Rivers.

Figure 2.1: Sariakandi fish pass (view towards Jamuna River)

Figure 2.2: Sariakandi fish pass (view towards Bangali River)

The fish pass is a vertical slot type structure (Figure 2.1 and Figure 2.2). It has three separate vents composed of 16 pools in each vent. Each pool has 0.7m opening with width and length of 3.5m and 4.5m (Biswas, 2007). Flow pattern inside the pool and at the pool opening of Sariakandi fish pass is shown in Figure 2.3 and 2.4.

Figure 2.3: Flow pattern inside a pool of Sariakandi fish pass

Figure 2.4: Flow pattern at the opening of a pool of Sariakandi fish pass

Tengra (*Mystas tengra*), mola (*Amblypharyngodon mola*), dhela (*Raspbora dani*) , rui (*Labeo rohita*), katla (*Catla catla*), mrigel (*Cirrhinus mrigala*), carpio (*Cyprinus carpio*), boal (*Wallago attu*), bagha ayr (*Mystus ayr*), chingri (*Penaeus monodon*), chela (*Chela labuka*), puti (*Puntius sophore*), sarputi (*Puntius sarana*) etc. fish species of different sizes are found passing through the fish pass during monsoon season.

2.3.2 Jugini Regulator: Tangail Compartmentalization Project

The Lohajang river enters into the Tangail Compartment at the Northern boundary of the project. The Main Inlet regulator is situated on the Lohajang river, 4.3 km downstream of the Dhaleswari offtake and just downstream of the confluence of Gala khal & Lohajang river. The main purpose of this gated regulator is to ensure controlled flooding and drainage by maintaining appropriate water levels in the Lohajang river inside the compartment. Consequently the river could act as the main drainage system for the outlets along the river. The outlets are responsible for the draining the water entering through the peripheral inlets and the local rainfall to the CPP area.

Jugini regulator was constructed on the Lohajang to regulate the water level inside the Compartment Pilot Project (CPP) at Tangail in 1994/95. The hydraulic structure consists of 5 vents of which 3 vents are main regulator. Additionally two vents were constructed on the two sides of the main regulator with an objective to maintain the fish migration between Dhaleshwari to the Lohajang River to its floodplain. The total design discharge of the Jugini regulator is 40 m^3/s. Without the intervention, the flow in the Lohajang river was over 100 m^3/s. Hence it reduced flow in the Lohajang river at least 60 percent.

Hatchling densities (no./m3) are highest at the top layer near the river embankment and the lowest near the bottom in the middle of the river. Based on this observation, the location of fish entry point of the Jugini regulator was constructed near the river bank in order to facilitate hatchling migration during closure of the middle regulators.

It is also evident that the sill level of fish gate is too high to allow first flood water, which may reduce fish hatchling in the Lohajang river. *The hatchling friendliness of the structure is yet to be proved* (FAP 20, 1998). The study on hatchling friendliness in 1996 is inconclusive due to insignificant number of hatchling caught after and before the regulator for the survival study.

The fish production in the CPP area from beels, floodplain, khals and the Lohajang river with project is about 41 tons lower than the without-project condition. The possible consequences of the water control in CPP on fish production and fish ecology. With the fish friendly structure, the project mange to reduce fisheries losses and facilitate the hatchling movement from river to the floodplain in the early monsoon (Hassan, 2002).

2.3.3 Kashampur Regulator of Manu River FCDI project

The Fish pass Pilot project (F.P.P) was designed to re-store the fish migration between the Kushiyara river and Kawadighi Haor which was disrupted by the flood embankments constructed under the Manu river flood control and Irrigation project (MRP).

The results of the first 5 months of operation of the fish pass are extremely encouraging. The most general results are as follows.

i. All 104 samples taken during the first 5 months trapped fish. The 100% success rate suggests that there is a continuous traffic of fish through the fish pass whenever there is sufficient water flow inside the structure. In contrast, conventional fish pass applications elsewhere usually cater for seasonally migrating species, and water flow in the structure typically carries fish traffic for only part of the operational year.
ii. Fish traffic moved simultaneously bio-directionally in the fish pass. Conventional fish pass applications usually cater for fish traffic moving unidirectional.
iii. Fish traffic moves both countercurrent and concurrent conventional fish pass applications are usually designed only for counter current fish traffic.
iv. Fish traffic responded positively to flow reversal inside the structure, Conventional fish passes usually operate under conditions of unidirectional water flow.

The presence of fish in the concurrent sample could be interpreted wholly or in part as passive drift into the structure especially small fish. However, the consistent presence of fish of all sizes classes in the counter current samples indicates unquestionably that active entry and migration through the structure is also taking place. There is probably some contamination of samples by fish which reverse swimming direction or are non-migrating litterers inside the structure, but the consistency in the sampling results suggest that a large portion of the fish sampled are intentional migrants (Hassan, 2002).

2.3.4 Jamalpur Fish Pass

In mid-May to mid-July, fish fry begin to arrive in the floodplain. In the first week in July, water levels in both the floodplain and rivers are generally low. There are little opportunities for fish pass due to invert levels. Only standard under shot gates are provided in these circumstances. During mid-July the level of the flood rises and full flow conditions through the northern inlet structures (Chatal, Jhenai, Islampur) are applied with until the gates are closed. If the standard under shot gates was used, the resulting flow condition would not be fish friendly due to abrupt changes in flow velocities and pressures, during the early flood all minor structures would mostly dry or only covered with a shallow depth or water during this time. Free flow conditions would thus prevail.

The small percentage of fish fry immediately downstream of the inlet structures which evade capture by fishermen grow in the flooded area. Most of these fish are caught between May and July. At the end of July, a very small proportion of fish of 2-10 cm length then leave the project area to the southwards with the general flow of the rivers through the outlet structures (Jhenai/Chatal, Bangi Bridge). These structures therefore are fish friendly (Hassan, 2002).

2.4 Reviews on Previous Laboratory Studies for Fish Pass

Silva et al. (2010) conducted an experimental study to understand the effects of water velocity and turbulence on the behavior of a cyprinid species- the Iberian barbel *Luciobarbus bocagei* particularly their upstream movements upon different discharges (38.5 to 77.0 L / s), through an indoor full scale pool-type fish pass prototype. Larger adults had a higher passage success (mean=79%) and took less time (mean±SD (min): 5.7±1.3) to negotiate the entire six pool fish pass, when compared to small adults. Correlation analysis between hydraulic variables and fish transit time yielded different results. Correlations were found to be the highest between the horizontal component of Reynolds shear stress and fish transit time, particularly for smaller size-individuals, highlighting this variable as a key-parameter which strongly determines the movements of Iberian barbel. That study identified some key factors on Iberian barbel movements that may have direct application to fish pass designs for this species and for other 'weak' swimmers.

Silva et al. (2012) investigated the swimming behaviour of 140 adult Iberian barbel (Luciobarbus bocagei) of two size-classes (small fish: $15 \leq TL < 25$ cm, large fish: $25 < TL \leq 35$ cm) under turbulent flow conditions created by three submerged orifice arrangements in an experimental pool-type fishway: (i) offset orifices, (ii) straight orifices and (iii) straight orifices with a deflector bar of $0.5b_o$ located at 0.2L from the inlet orifices, where b_o is the width of the square orifices ranging from 0.18 to 0.23 m and L is the pool length (1.90 m). Water velocity and turbulence (turbulent kinetic energy, Reynolds shear stress, turbulence intensity and eddy size) were characterized using a 3D Acoustic Doppler Velocimeter (ADV) and were related with fish swimming behaviour. The influence of turbulent flow on the swimming behaviour of barbel was assessed through the number of successful fish passage attempts and associated passage times. The amount of time fish spent in a certain cell of the pool (transit time) was measured and related to hydraulic conditions. The highest rates of passage and the corresponding lowest times were found in experiments conducted with offset orifices. Although size-related behavioural responses to turbulence were observed, Reynolds shear stress appeared as one of the most important turbulence descriptors explaining fish transit time for both size-classes in experiments conducted with offset and straight orifices; furthermore, swimming behaviour of larger fish was found to be strongly affected by the eddies created, in particular by those of similar size to fish total length, which were mainly found in straight orifices with a deflector bar arrangement. The results provide valuable insights on barbel swimming behavioural responses to turbulence, which may help engineers and biologists to develop effective systems for the passage of this species and others with similar biomechanical capacities.

Rajaratnam et al. (1986) conducted an experimental study on the hydraulics of vertical slot fish pass. They undertook that project to understand the hydraulics of the conventional-type vertical slot fish pass and to develop simpler designs of the baffles that mold the jet at the slot. Seven designs, including some conventional designs, were tested. A conceptual uniform flow state had been defined for which a linear relation had been found between the dimensionless flow rate and relative flow depth. A rating curve had been developed for each design in terms of the dimensionless flow rate Q* and the relative depth of flow. Non-uniform flow of the Ml and M2 types had been analyzed using the Bakhmeteff-Chow method. Some observations had also been made on the velocity profiles at the slot and circulation patterns in the pools. Based on those results, a conceptual idea of uniform and non-uniform flow states had been developed. Submergence of the fish pass entrance by the tailwater had been studied, and the jet at the slots had been observed. Some observations of circulation in the pools where the fish would rest had been made. Some results had also been obtained on the discharge coefficient of the slots.

Liu et al. (2006) conducted an experimental study on the mean and turbulence structures of flow in a vertical slot fishway with slopes of 5.06 and 10.52%. Two flow patterns existed in the fishway and for each one, two flow regions were formed in the pools: a jet flow region and a recirculating flow region. The mean kinetic energy was decayed rapidly in the jet region and the dissipation rate in most of the areas in the pool was less than 200 W/m3. For the jet flow, the non-dimensional mean velocity profile across the jet agreed very well with that of a plane turbulent jet in the central part of the jet with some scatter near its boundaries. Its maximum velocity was decayed faster compared to a plane turbulent jet in a large stagnant ambient. The jet presented different turbulence structure for the two flow patterns and for each pattern, the turbulence characteristics appear different between the left and right halves of the jet. However, the turbulence characteristics showed some similarity for each case. The normalized energy dissipation rate showed some similarity and has a maximum value on the center of the jet. The results were believed to provide useful insight on the turbulence characteristics of flow in vertical slot fishways and can be used to verify numerical models and also for guidance in the design of fishways in the future.

Rajaratnam et al. (1992) examined 18 designs of vertical slot fish passes in order to develop effective yet simple designs. They tested the sensitivity of the performance of vertical slot fish passes to the length and width of pools. It was found that a length of $10b0$ and a width of $8b0$ could be considered as the proper length and width of pools based on effective energy dissipation and the existence of a large circulating region of lower velocity for fish to rest. These dimensions have generally been used in the United States. The authors also recommended Designs 6, 16, and 18 for practical use, based on overall performance and simplicity in design and construction.

Wu et al. (1999) studied the structure of the mean flow in a vertical slot fish pass of Design 18 with a model scale of 1:2.67 for three slopes of 5, 10, and 20% with several discharges. They found that two typical flow patterns existed in the pools, referred to as Patterns 1 and 2. In Pattern 1, the main flow traveled from one slot to the next through the center of the pool with two recirculation regions located on either side of the jet. In Pattern 2, the main flow traveled toward the sidewall in between the long baffles with a recirculation region created between the short baffles along with a horizontal eddy near the long baffle on the downstream end of the pool. The jet flow was studied along some arbitrary vertical planes in the general direction of the jet instead of along the jet trajectory. It was found that the jet had no potential core and its longitudinal maximum velocity decayed more rapidly than that of a plane turbulent jet. An estimate was made of the relative volume of the recirculation regions.

Puertas et al. (2004) measured the mean flow structure of vertical slot fishways of Designs 6 and 16 as of Rajaratnam et al. (1992) for two different slopes of 5.7 and 10%. A microacoustic Doppler velocimeter (MicroADV) was used to measure the three dimensional (3D) velocity fields. They also confirmed the linear relation between the dimensionless discharge and the relative flow depth for each design. Regarding turbulence, only the turbulent kinetic energy information was provided.

Guiny et al. (2005) conducted an experimental study through a series of novel experiments testing the relative efficiencies in passing juvenile salmon (parr) through a range of model fish passes incorporating devices such as vertical slots, orifices, weirs, and combinations of all three. The hydraulic parameters—head loss, velocity patterns, and turbulence structure—were measured under each set of test conditions. A significantly higher proportion of fish moved through submerged orifices and vertical slots than through overflow weirs for any given flow rate, velocity, and head loss. The orifice and vertical slot efficiencies were directly correlated to the velocities at their entrances. To reach the tested devices, salmon parr tended to remain near the bottom of the flume and followed paths providing them with low velocities and cover along the sides of the test arena. The movements of salmon approaching entrances were consistent with energy-conserving strategies. The mean efficiency of salmon parr passing a weir, orifice, and slot in a physical scale model were: 2.5, 68, and 44% respectively. These data were based on a 40 min trial period for each fish tested in the model flume. The efficiency declined almost linearly with increased velocities in the vicinity of the fish pass device for both orifices and slots. The overall efficiency of an orifice over a range of discharges might be improved by introducing a weir in parallel, with the weir operating mainly at high flows. The results of this study presented a tentative approach for computing energy expenditure for a range of fish pass devices and provided clear guidance for fish pass design for Atlantic salmon parr.

Yagsi (2010) experimentally explored three dimensional mean flow and turbulence structure of pool-weir fishways. During the experiments, three different notch sizes were applied while the size of the orifice was kept constant. Two acoustic Doppler velocimeters were employed throughout the velocity measurements. Three-dimensional mean velocity and normalized turbulent kinetic energy patterns in the pool were experimentally analyzed considering the swimming ability of different fish species to check whether the given design conditions provide suitable flow patterns. Based on the data, a linear relationship between the parameters “the discharge” and “the average depth in a pool” was generated. An equation was derived which gives the “energy dissipation rate per unit pool volume” in terms of the parameters “geometrical characteristics of the fishway”, “head difference between pools”, “slope”, and “acceleration due to gravity”. The discharge ratios between “flow through orifice” and “flow over notch” were expressed based on the data.

Tarrade et al. (2011) studied the kinematics of hydrodynamic turbulent flows developed in vertical slot fishways in detail in flow pattern. A transparent device based on the typical prototype dimensions of VSF in France was constructed for the experiment. The velocity measurements were carried out by Particle Image Velocimetry (PIV). These measurements were used to determine the various kinematics parameters characterizing the flow. From the dimensions and slope of the fishway, two flow topologies highlighting the swirling pattern were proposed. The method of Proper Orthogonal Decomposition (POD) was used to undertake unsteady and energetic analyses to characterize the main phases of flow evolution that fish passing through the passage may encounter.

Rodriguez et al. (2006) represented a methodology for evaluating fishway designs in terms of the swimming capabilities of the target species through an experimental study. Specifically, they had evaluated two vertical-slot designs whose hydraulic properties were empirically characterized in a previous study. In view of these empirical data, for each design they had estimated (a) minimum discharges giving minimum fish-acceptable depths; (b) maximum pool sizes ensuring flow velocities low enough to be overcome by the fish; (c) maximum pool sizes ensuring turbulence low enough to be acceptable to the fish. These design constraints were calculated for different slopes (∼6 or ∼10%), different water temperatures (10, 15 or 20 ◦C), and different fish lengths. This methodology constituted an effective means of taking fish swimming capabilities into account at the fishway design stage.

Scale effects arise due to force ratios which are not identical between a model and its full-scale prototype and result in deviations between the scaled model and prototype observations. CALLUAUD et al. (2012) conducted study on scales effects in vertical slot fishway flow by comparisons of turbulence behaviours measured in 1:4 scale laboratory model and full-scale fishway. Full-scale measurements were exposed. Flow topology, mean flow and unsteady velocity components features, turbulence kinetic energy profiles are evaluated and compared to measurements model. The results emphasized significant differences on fluctuating velocity and turbulence kinetic energy values between full scale and model flow behaviours. Consequently, extrapolate optimization design based on flow average to fishes ascent efficiency could be performed if scale effects are corrected as regard of fluctuating velocities and if fish swimming limits against turbulent flows are known.

2.5 Reviews on Previous Field Studies for Fish Pass

Thiem et al. (2011) examined fine-scale movements of adult lake sturgeon *Acipenser fulvescens* during passage through a vertical slot fish pass located on the Richelieu River in Quebec, Canada, to determine passage success, passage duration and inter-individual differences in fish pass use. Migratory lake sturgeon (n = 107, range 939 to 1625 mm total length [TL]) were captured immediately downstream of the fish pass, tagged with passive integrated transponder (PIT) tags and released into the fish pass entrance basin over a period of 2 wk (water temperature 11–20°C). An array of 16 PIT antennas acted as gates to enable quantification of movements within the fish pass. Volitional entry into the fish pass occurred for most individuals (82.2%), 32 individuals successfully ascended the entire fish pass, and overall passage efficiency was 36.4%. Sturgeon exhibited an ability to traverse the fish pass quickly (minimum duration of 1.2 h upon entry into the fish pass); however, the duration of successful passage events was variable (6.2–75.4 h following release). Neither passage duration nor maximum distance of ascent was correlated with TL or water temperature. Passage behaviour was variable, in some cases resulting in cumulative upstream movements 3 times in excess of fish pass length. Passage durations through the 2 turning basins were disproportionately longer compared with other basins; however, the activity of individuals within these and other locations remains unknown and represents an important knowledge gap. Collectively, data from that study contributes to understanding how fish passes can be used to facilitate the upstream passage of imperiled sturgeon at dams.

Thiem et al. (2012) used a passive integrated transponder antenna array to quantify passage success and passage duration of fish using a vertical slot fish pass (85m in length, 2.65m elevation rise, 12 regular pools and 2 turning basins) at a low head dam on the Richelieu River in Quebec, Canada. Fourteen of the 18 tagged species re-ascended the fish pass, and passage efficiency was highly variable among species (range 25%–100%); however, it was >50% for five of the species well represented in this study (n>10) (Atlantic salmon, channel catfish, smallmouth bass, walleye and white sucker). Passage duration was likewise highly variable both among and within species (e.g. 1.0–452.9 h for smallmouth bass, 2.4–237.5 h for shorthead redhorse). Although this fish pass design was not uniformly successful in passing fish of all species, this study does reveal the species that have problems with ascent and provides an estimate on the time spent in the fish pass that is an important component of passage delay. Such information could be used to inform future design refinements to facilitate passage of the entire assemblage with minimal delay.

Christopher et al. (2000) conducted a study in a denil fish pass in Dunneville, Ontario and observed Few walleyes. Coded radiotelemetry was used to track 24 adult walleyes (12 male, 12 female) downstream from the fishway to explore reasons for limited use. Activity was monitored by a fixed array of three antennas within the fishway that continuously scanned for signals from all radio-tagged fish, and by mobile tracking. In April and May 1997, 17 attempts to use the fishway by 3 male and 2 female radiotagged walleyes were recorded. During this period, the attraction efficiency of the Dunnville Fishway was approximately 21%. All attempts took place between 1600 and 0600 hours, with most activity near midnight. Walleyes occupied the first resting pool of the fishway for up to 17 h. Subsurface water velocity during the study was approximately 2 m/s. No radio-tagged walleyes passed through the Dunnville Fishway. Behavior modifying hydraulic conditions including turbulence, entrained air, backcurrents and whirlpools in fishway resting areas may delay or prevent successful upstream passage of walleyes. There was also evidence of large-scale movements by walleyes that may have spawned in the Grand River downstream from Dunnville.

Marriner et al. (2013) conducted a study on the hydraulics of turning pools in vertical slot fishways focusing on the Vianney-Legendre vertical slot fishway in Quebec, Canada, which is one of few fishways worldwide to successfully pass sturgeon (i.e., lake sturgeon, Acipenser fulvescens). Field velocity measurements were taken in two pools and a computational fluid dynamics (CFD) model study was used to assess the turning pool hydraulics of seven design geometries. Parallel biological studies of sturgeon in the fishway revealed that turning pools were the location with the highest rate of failed passage, apparently associated with large vortices in the centre of the turning pools which serve to delay or inhibit passage. Interestingly, the velocity, and turbulence levels were comparable to results from regular pools in vertical slot fishways. The volumetric energy dissipation rate in turning pools was suitable for fish passage. Based on in silico modelling they revealed that the addition of a baffle wall extending from the inside centre wall of the pool reduced the size of the vortex and provided a resting area for ascending fish. Adding a baffle wall should be considered in turning pools with semi-circular or straight back walls. There is a need for research to evaluate exactly how fish respond to different turning pool designs but in the interim, the approach used here demonstrates the potential for using hydraulic studies to design turning pools in fishways that meet biological criteria and presumably increase passage efficiency.

White et al. (2011) developed models of general movement patterns of three potamodromous non-salmonid fishes in the Murray River, Australia from empirical data in a low-gradient vertical-slot fishway. The models integrate data on times of entry and exit, ascent rates, and whether fish continued to ascend during the night. These fish species did not favour resting pools. Ascent rates of fish 120mm were more closely related to fish behaviour than to length; for a given fishway height, reducing bed slope by increasing the number of pools may slow the ascent of such fish, whereas enlarging pool volumes increases costs.

Biswas (2007) performed a field study at Sariakandi fish pass in Bogra and found that velocity in the pool decreased linearly over the length. The velocity was sub- critical at the approach section and prevailed over the length and no hydraulic jump developed. The magnitude of velocity jet near water surface was highest and its direction was not perpendicular to slot. The velocity inside the transverse direction reduced faster than the longitudinal direction. The flow traveled through the center of the pool with two recirculation zones on either sides of the jet. The velocity components struck the sidewalls and caused damages to fish-eggs and fingerlings. It indicted that the pool size that was provided was not adequate. Opening dimension should be designed based on the biological characteristics (e.g. darting speed, fish length etc.) of fish in addition to other hydraulic parameters. In this structure velocity at the opening was found higher than the darting speed of the most local fish juveniles.

2.6 Summary

The review of findings of previous study is very much needed before undertaking any research work. Therefore the literature review of the previous studies around the world as well as in Bangladesh has been done in this chapter in a very extensive scale. It is necessary to gain a clear concept about the research work and also to identify the lacking and shortcomings of previous studies. Based on these literature review works, this laboratory study has been performed by developing a physical model of the vertical slot fish pass in the laboratory flume. Furthermore three dimensional velocity data has been collected and analyzed to develop plane velocity field models.

Chapter 3

THEORY AND METHODOLOGY

3.1 General

A fish pass is a waterway designed to allow the passage of a species or a number of different species of fish past a particular obstruction. While in most cases fish passes are built for adult spawners in some cases migrating juveniles are the target species. For adult fish spawning migrations are usually involved and delays are critical to reproductive success. For juveniles feeding migrations are usually involved and delays are not as critical. Fish also move from one area to another to feed. These movements may be upstream or downstream and occur over an extended period of time. Fry and juvenile fish also show movement in seeking rearing habitat. As they grow older, they require access up and down the stream and into side channels and tributaries to find food and escape predators.

Fish passage over dams and weirs or through culverts is an important consideration in fish bearing streams. Adequate design, construction and provision for fish passage are required to maintain healthy fish populations. Well designed and constructed fish passes provide a path that allows fish to continue migrating past dams, weirs or through culverts without unacceptable delays. In this chapter relevant theory regarding the hydraulic criterions for the design of fish pass, important biological characteristics of fish and methodology of the research work have been discussed in an elaborative manner.

3.2 Types of Fish Pass

Fish passes usually consist of a sloping channel partitioned by weirs, baffles, or vanes with openings for fish to swim through. The in-channel devices act hydraulically together to produce flow conditions that fish can navigate. Several types of fishways have been developed and are usually distinguished by the arrangement of in-channel devices. Although several variations of each fish pass type exist, fish passes are classified into vertical slot, Denil, weir and culvert fish passes. Excavated channels utilizing rocks, sills or weirs are also used as fish pass. The different physical and hydraulic characteristics of each fish pass type may make them suitable for some fish species and not suitable for others. Several types of fish passes have been developed and the most common are described in sections 3.1-3.4. An effective fish pass attracts fish readily and allows them to enter, pass through, and exit safely with minimum cost to the fish in time and energy (Katopodis, 1992).

3.2.1 Vertical Slot Fish Pass

In the vertical slot fish pass, baffles are installed at regular intervals along the length to create a series of pools (Fig.3.1) Fish easily maintain their position within each pool. Travel between pools, however, requires a burst effort through each slot. Water velocities at the slots remain almost the same from top to bottom. The main advantage of the vertical slot fish pass is in its ability to handle large variations in water levels. Usually the difference between water levels in successive pools is 300 mm for adult salmon and 200 mm for adult freshwater fish. Vertical slot fish passes usually have a slope of 10% (Andrew, 1990).

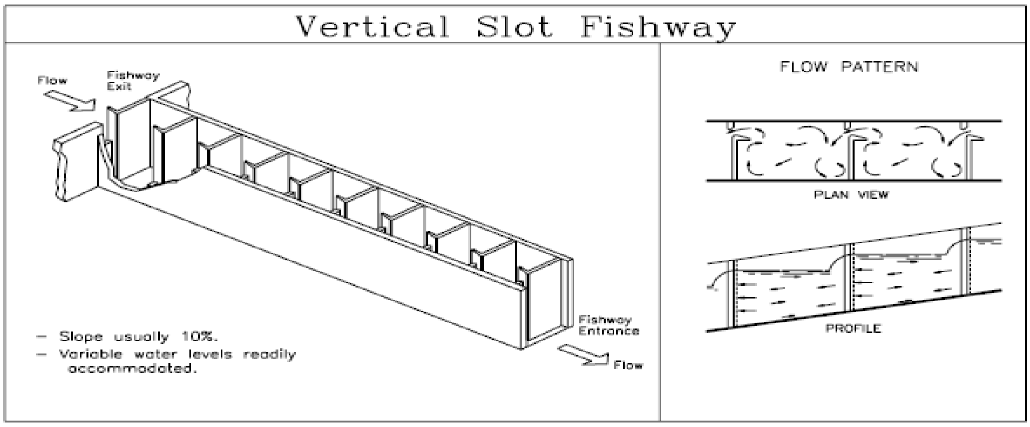


Figure 3.1: Vertical slot fish pass (Source: Katopodis, 1992)

3.2.2 Denil Fish Pass

Named after its inventor, the Denil fish pass consists of a rectangular chute with closely spaced baffles or vanes located along the sides and bottom. Over the years various versions of the Denil fish pass have been developed and used for fish passage. Two of the more common Denil fish pass types used today are shown in Figure 3.2. The plain Denil contains a series of planar baffles pointing upstream, at an angle of 45 degrees with the fish pass floor. Baffles in the steeppass Denil also point in the upstream direction but are angled away from the walls of the chute (Katopodis, 1983).

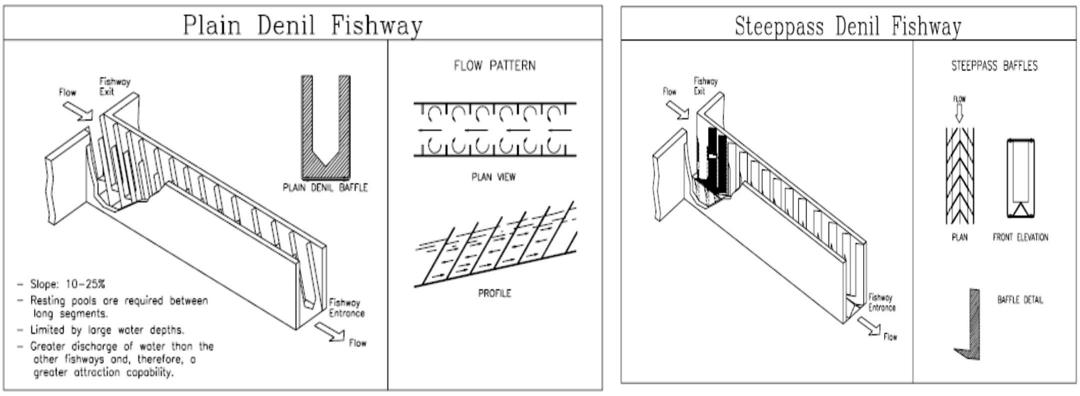


Figure 3.2: Denil fish pass (Source: Katopodis, 1992)

Flow through Denil fish passes is highly turbulent, with large momentum exchange and high energy dissipation. For the plain Denil the water in the chute flows at a relatively low velocity near the bottom with a faster velocity near the top. For the steeppass, at low depths velocities tend to be higher near the bottom of the fish pass and decrease towards the water surface. At high depths, flow divides into an upper and a lower layer, and velocity profiles become roughly symmetrical with maximum velocities at mid-depth. The large flow associated with the Denil designs, reduces the deposition of sediment within the fishway and also provides good attraction capability, assisting the fish in finding the fishway. Since fish need to constantly swim while in the chute, resting pools are placed along the fishway every 10 to 15 m for adult salmon and 5 to 10 m for adult freshwater species. Slopes for Denil fish passes usually range from 10% to 15% for adult freshwater fish and 15% to 25% for adult salmon (Katopodis et al., 1984).

3.2.3 Weir Fish Pass

The weir fish pass consists of a number of pools arranged in a stepped pattern separated by weirs, each of which is slightly higher than the one immediately downstream (Fig. 3.3). The fish, attracted by the flowing water, move from pool to pool by jumping or swimming (depending on the water depth) until they have cleared the obstruction. Movement between pools usually involves burst speeds. Fish can rest in the pools, if necessary as they move through the fish pass. An orifice may also be added to the submerged portion of the weir allowing the fish to pass through the orifice rather than over the weir. While simple to construct, the pool and weir is sensitive to fluctuating water levels and requires adjustments. The water level drop between pools is usually set at 300 mm for adult salmon and 200 mm for adult freshwater fish. Weir fishways usually have a slope of 10% (Rajaratnam et al., 1992).

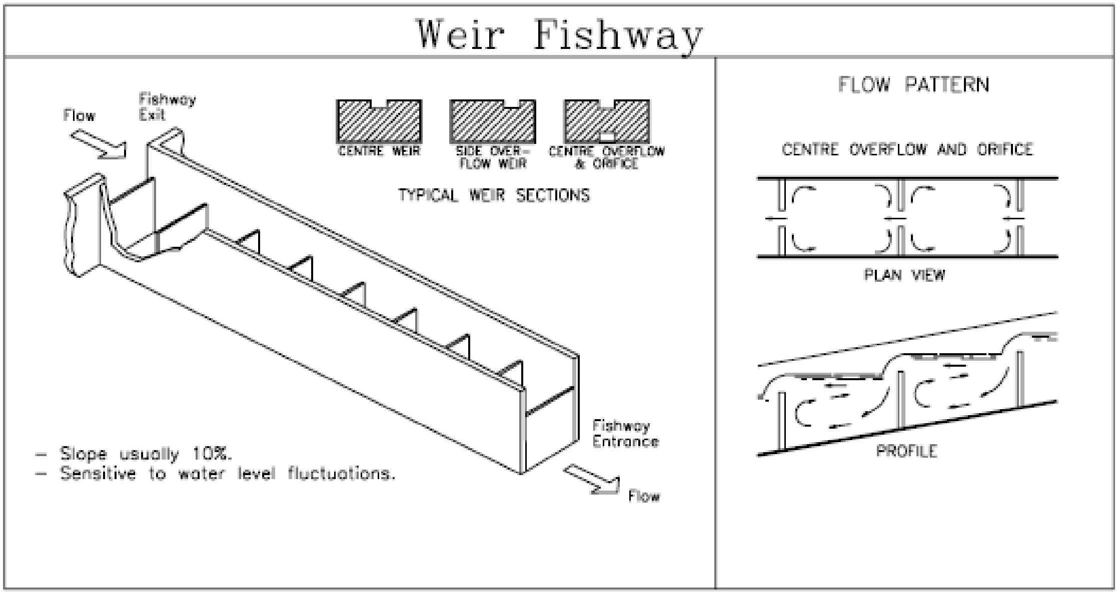
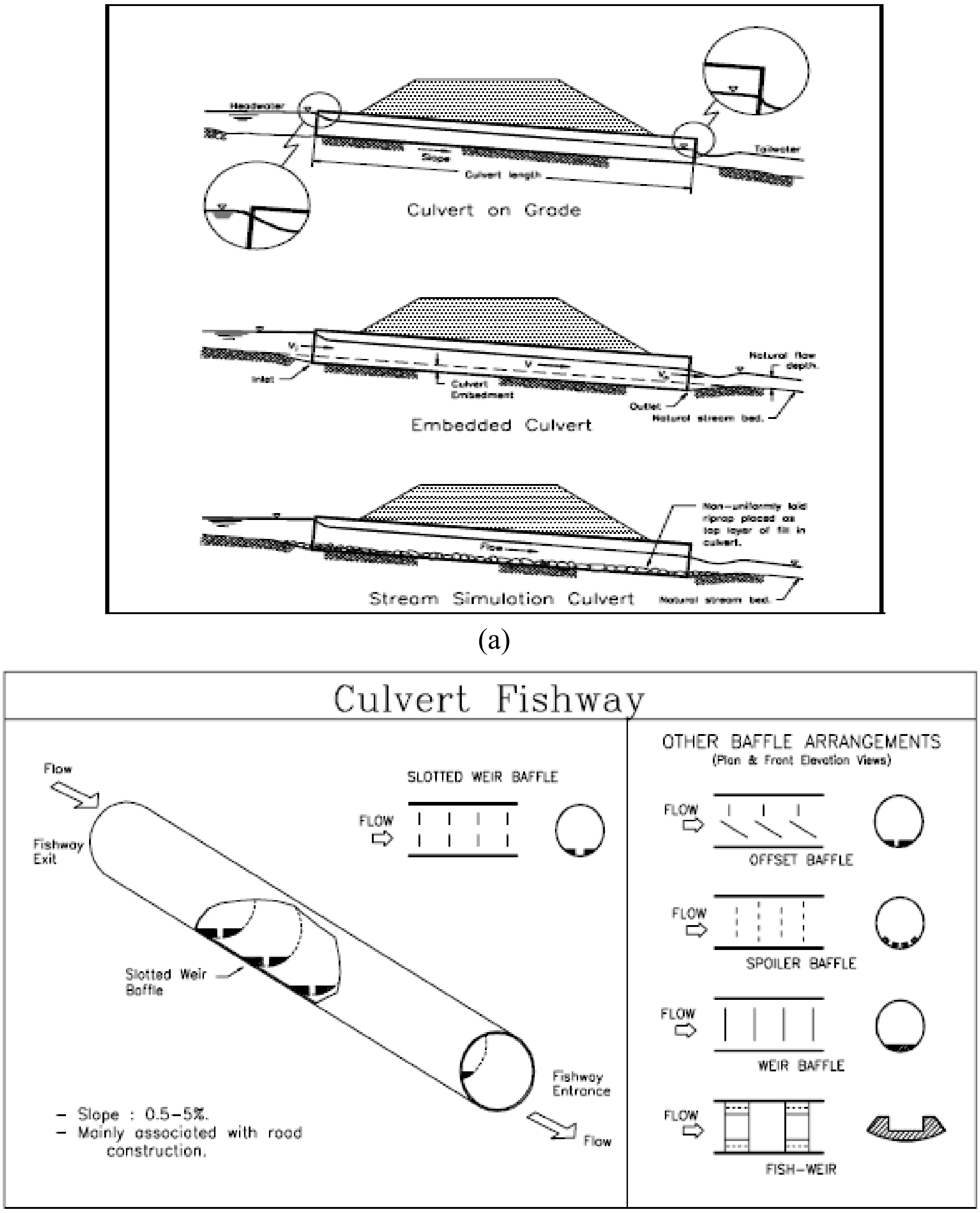


Figure 3.3: Weir fish pass figure (Source: Katopodis, 1992)

3.2.4 Culvert Fish Pass

Culverts are used to convey water from one side of a roadway embankment to the other. Culverts are built with circular, elliptic, pipe-arch, rectangular or square crosssections. If a culvert is required to pass fish, special considerations are needed to ensure that fish can enter, pass through and exit the culvert without undue or harmful delay. In many cases culverts are placed below the stream bed and special devices such as riprap, baffles, weirs, blocks or plates are used to form a culvert fish pass (Figs. 3.4a&3.4b). Mainly associated with roadway construction, culvert fish passes



(a)

(b)

Figure 3.4: (a) Culvert placement and (b) Culvert fishpass (Katopodis, 1992)

usually have slopes of between 0.5 and 5% (Rajaratnam et al 1991, Rajaratnam et al., 1990).

3.3 Design Considerations

In the design of a fish pass, important factors to be considered include the hydraulic characteristics of the fish pass type, as well as the swimming performance and behaviour of the species of fish to be passed. Biological and hydraulic criteria for designing fish passes vary with species and sizes of fish. Fish pass efficiency depends on attraction, as well as safe and speedy transport of fish. Attracting fish to the fish pass entrance is critical and depends on species behavior and motivation. Commonly, flows and appropriate water velocities at the entrance are used for fish attraction. Experience with the target species is usually the best guide for designing fish pass entrances. In Denils, fast velocities near the water surface provide good attraction conditions at the fish entrance. Backwater conditions reduce fish pass velocities, although considerable tailwater levels are usually needed to drown out Denil fish pass flows. In vertical slot fish passes, slot velocities and fish attraction conditions are affected by backwater when tailwater level exceeds some critical value (generally half of the critical depth in the slot). With slot flows drowned, the entrance pool provides little attraction for fish. Weir fish passes are very sensitive to changes in water levels (Andrew, 1990; Bell, 1973; Clay, 1961; Collins et al., 1985).

The most important factor in selecting the type of fish pass to be used is the record of experience with the species of fish it is desired to pass. The Denil and vertical slot fish passes have been successfully used by a wide variety of anadromous and freshwater fish. Culvert fish passes have also been successful in passing various species. The weir, orifice and orifice-weir fish passes have been used successfully by anadromous salmonids, but not readily by alewife, shad and probably other fish that rarely leap over obstacles or swim through submerged orifices. Both the vertical slot and the Denil allow fish to swim at their preferred depth. The Denil provides the most direct route of ascent while in the vertical slot fish use a "burst-rest" pattern to move between pools. Fish move through Denil fishways faster than through vertical slot or weir fishways (Fleming, 1991; Jordan 1987; Katopodis, 1990; Behlke et al., 1991; Boiten, 1990; Dane, 1978).

In fish pass channels, fish transport relies on water velocities not exceeding the swimming abilities of the migrating species. Swimming ability varies with species, size, as well as water, temperature, oxygen, pH, and salinity. Water velocities depend on fish pass type, channel slope and water depth. Velocities and depths are functions of fish pass discharge and slope. Scale models of various types of fish passes have provided velocities and depths for a range of discharges and slopes, as well as the functional relationship between these variables. Field studies with various fish species have tested fish pass designs and demonstrated successful applications of fish passage technology (Katopodis, 1985; Katopodis 1981 a.; Katopodis 1981 b).

Weir fish passes are frequently the least expensive, while Denil fish passes are usually less costly than vertical slot fish passes. In Denil fish passes effectiveness in water velocity control decreases as water depth increases. Since water velocities in Denils increase with depth, a limit is reached when water velocities start to exceed fish swimming speeds. If larger depths are required a second Denil fish pass is needed. Vertical slot fish passes maintain water velocities at the slots for very large water depths. This means that vertical slots can be built as deep as required to cover the entire range of water levels. Water level range and economics play a decisive role on which type of fish pass is used (Katopodis, 1990).

The main problem with improperly designed and installed culverts is that they form velocity barriers to fish migrants at the outlet, inlet or within the culvert barrel. If water depths are too low or water velocities at any of these three culvert locations exceed fish swimming ability, fish may be prevented from reaching their spawning grounds. Since hydraulic efficiency and optimum fish passage requirements are mutually exclusive objectives, compromises must be effected that permit adequate fish protection with maximum economy. Such compromises involve the matching of water velocities with fish swimming performance at design discharges that allow limited, if any, delay in fish migrations (Kotopodis, 1977).

Water velocities in plain culverts are usually much higher than those in natural channels. In addition, culverts provide fairly uniform velocities throughout their length, while streams provide a diverse pattern of slow to fast velocities both longitudinally and laterally. Sustained speeds are generally exceeded by culvert velocities, while fish cannot maintain burst speeds long enough to navigate the entire length of most culverts. Prolonged speeds are used for continuous passage through culverts when no resting areas are available. However, fish use a burst and rest pattern to take advantage of low water velocities that are created by the placement of rip-rap, baffles, weirs or other forms of culvert fishways. Consequently, considerable emphasismust be placedon retaining as many qualities of the original stream channel as possible at each crossing (Behlke et al., 1991).

Migrating fish must negotiate the culvert outlet, the culvert barrel and the culvert inlet before successfully passing upstream. Hydraulic conditions, such as water velocities and depths, at each one of these three locations must be suitable for passage at the highest and lowest stream flows expected during fish migration. Fish need to swim continuously for the entire culvert length when no resting opportunities are available. Culvert length and velocities, as well as maximum distance that fish are able to swim, determine whether fish can pass through a culvert once they enter it (Dane, 1978).

For culverts, the following three approaches need to be assessed in arriving at a culvert design that satisfies engineering, economic, and fish passage requirements (Katopodis, 1977).

- Plain culvert that meets fish passage velocity (usually 1.2 m/s or less) and minimum water depth criteria (usually 0.2 m at inlet, barrel, and outlet).
- Stream simulation approach where the status quo in the stream is preserved, i.e. average stream width and slope are maintained up to the fish passage design flow, and stream substrate is kept from washing out either by supports fixed at the culvert bottom or by large stable riprap.
- Culvert with fish passage devices.

Culverts are the most popular stream crossing structure over other alternatives for economic reasons. The final stream crossing alternative is based on a need for a crossing structure, hydrological conditions, economic factors related to installation and maintenance of the structure, and the natural resource value of the stream. Designing a culvert that is both economical and allows for the successful movement of fish is not always successful. From an environmental point of view the preferred stream crossing structure is a bridge, especially if there is a known fisheries resource. However, if a culvert is properly designed and installed, it is an acceptable stream crossing structure from both an environmental and economic point of view. Field studies with various fish species have tested culvert fish pass designs and demonstrated successful applications of fish passage technology (Jordan, 1987).

3.4 Design Process

The information required and the design steps needed to design a fish pass for dams, weirs or culverts are outlined below (Katopodis, 1985; Katopodis 1981 a.; Katopodis 1981 b.):

- To obtain a) maps of the project location and drainage basin, b) plan views and profiles of the proposed or existing dam, weir or culvert, c) aerial photos, if available.
- To list fish species which require access to habitat upstream of the project site and the main purpose for such access (e.g. spawning); provide population estimates if available, minimum and maximum length of the species considered for passage.
- To describe the migration period for each species by giving, where possible, the dates for the start, peak, and end of migration, associated water temperatures, and estimates of peak migrant numbers.
- To show, whenever possible, locations of spawning, rearing and feeding areas upstream, downstream and at the project site.
- To perform a flow frequency analysis for the existing or proposed dam, weir or culvert, the followings are to be estimated:
  a) low, average, and high flows (e.g. flows at 98-95% probability of being equalled or exceeded, mean annual flood, bankfull discharge, flows at 10% and 2% probability),

b) dam, weir or culvert design flow (e.g. 1:50 year flood) and fish pass design flow (e.g. 3-day delay for 1:10 year flood).

- To prepare stage-discharge relationships for the headwater and tailwater of the existing or proposed dam, weir or culvert.
- To examine various design alternatives and prepare a short list of feasible options by considering site conditions and dam, weir or culvert characteristics, fish species and sizes, water levels and flows, fish behaviour and stamina, debris and ice, bank protection and stream scour or sedimentation.
- To prepare a discharge rating curve and characteristic velocity profiles for low, average and high flows for each feasible option.
- To prepare preliminary engineering report, drawings, and estimate costs. To show fish pass dimensions, inverts and elevations, provide plan, side and cross-sectional views, stream bed and bank protection measures and fish passage devices.
- To ensure review of the preliminary report and drawings. Prepare final report and drawings.
- To develop a monitoring and evaluation program where desirable; includes both biological and hydraulic parameters.
- To provide a regular maintenance program, particularly to alleviate ice and debris problems.

3.5 Design Flow for Fish Pass

One of the important tasks in designing a hydraulic structure is the estimation of the design flow through flood frequency analysis. Design flows through fish passes are estimated in similar ways except that stream flows during the fish migration period are of primary interest. Another factor that affects the choice of stream flows for analysis is the biological effect of migration delay. Some spawning fish may be able to tolerate short delays in migration. Depending on the species involved excess delay may lead to spawning in marginal areas, reabsorption of spawn, depletion of energy reserves or even mortality. In many cases, particularly with Pacific salmon no delay is required by regulatory agencies. A delay period of less than three days in annual spawning migrations is usually accepted for several freshwater species. Delays longer than three days may be acceptable with 1:10 year frequency. These two criteria are used whenever sufficient data exist to estimate the maximum flow that is likely to prevail at the time of fish migration. This flow, may be used as fish pass design flow, and can be estimated directly from existing or reconstructed daily flow records for each species and migration period. Design flows for other delay periods may be estimated in a similar manner (Katopodis ,1985).

To create a three day delay discharge frequency curve, first the three day delay discharge value, Q_{3d} to be found for each year. Q_{3d} is the largest discharge value which is equalled or exceeded three times in three consecutive days over the fish migration period during a particular year. The initial Q_{3d} value to be set equal to the lowest discharge value from the first three daily discharge values for the migration period. Next, the lowest discharge for the next three day period, i.e. the lowest discharge from the second, third and fourth days to be determined. This discharge to be compared with the initial Q_{3d} value, the larger of the two becomes the new Q_{3d} value. This process to be repeated for next three day period. This process of comparing values for 3 consecutive days is repeated for the entire migration period (Katopodis, 1990).

The Q_{3d} values for each year are then arranged in order of descending magnitude, the largest ranked as number one and the smallest ranked as number "n". The return period, T, for each Q_{3d} value is calculated by dividing the total number of Q_{3d} values plus one (n+1) by the rank number. For example, the return period for the fourth largest Q_{3d} value based on a 32 year record would be equal to 8.25 years, (32+1)/4. Return period, T, is then plotted against the corresponding value Q_{3d} on a log-log plot. The points usually plot in a straight line. This line is the frequency curve and is used to estimate other Q_{3d} values. The 1:10 year (T = 10), 3 day delay discharge may then be estimated from this frequency curve. Other more sophisticated methods of estimating return period or probability may also be used in constructing the frequency curve (Katopodis, 1990).

3.6 Hydraulics of Fish Pass

The hydraulic characteristics of various types of fish passes were studied using geometrically similar scale models. Hydraulic modelling was performed on several variations of vertical slot (18 designs), Denil (6 designs), weir (2 kinds) and culvert (6 kinds) fish passes. Discharge rating curves and characteristic velocity profiles for these fish passes are available for a wide range of slopes and water depths. Froudian similitude laws were found to reproduce flow phenomena well, and were used for all models to transfer values between model and prototype. In Froudian models gravitational forces predominate, the velocity and time scales are represented by the square root of the geometric scale and the discharge scale is provided by the geometric scale raised to the 5/2 power. Fluid turbulent shear stresses between water jets and recirculating water seem to dominate in fish pass flows providing large momentum exchange and high energy dissipation. Neglecting wall shear stresses provides a good approximation for flow analysis. Discharge rating curves were derived using a simple force balance on the predominant flow stream in each fish pass type. Applicable to different fish pass sizes or scales, dimensionless variables were used to summarize experimental results. For fish pass discharge, the corresponding dimensionless variable is usually expressed by:

$$\boldsymbol{Q_* = \frac{Q}{\sqrt{gS_\circ b_\circ{}^5}}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (\mathbf{3.1})$$

where Q is fish pass discharge, S_o is slope of the fish pass bed, b_o is a characteristic width (e.g. fish passage opening, slot width, orifice width, culvert diameter) and g is gravitational acceleration (constant). Dimensionless discharge Q_* is a linear or a power function of dimensionless depth, y_o/b_o. For most fish pass designs tested, velocity profiles along a vertical line exhibit similar geometrical shapes. Velocity profile similarity is a property manifested by a large number of turbulent jet flows. Similarity allows the analysis of velocity profiles using dimensionless variables applicable to various fish pass sizes or scales. In a typical velocity profile, dimensionless local velocity, u/u_m, is commonly a linear or power function of dimensionless local depth,

y/y_o or y/z_o. Here u is the local velocity at a depth y, u_m is the velocity scale representing the maximum values of u, y_o is the total depth and z_o is the height of baffle or weir in culvert fish passes. In plain Denil fish passes, u_m is not well defined in the profile and it is substituted by u_m', the velocity at 75% of the depth. In vertical slot fish passes u and u_m are approximately the same throughout the profile except near the fish pass bed. Analogous to the dimensionless discharge Q_* defined above, a dimensionless velocity scale was expressed as:

$$\boldsymbol{U_*} = \frac{\boldsymbol{u_m\ or\ u'_m}}{\sqrt{\boldsymbol{gS_{\circ}b_{\circ}}}} \dots\dots\dots\dots\dots\dots\dots\dots (\boldsymbol{3.2})$$

The dimensionless velocity scale U_* is a linear or power function of y_o/b_o or Q_* and provides an estimate of the maximum velocities in a fish pass. Velocity profiles in a fish pass may be derived from the similarity analysis and the dimensionless velocity scale (Katopodis et al., 1983; Katopodis et al., 1978; Rajaratnam et al., 1990; Katopodis et al., 1992).

3.6.1 Vertical Slot Fish Pass

A vertical slot fish pass consists of a sloping (or stepped) rectangular channel which is partitioned into pools. Water flows down the channel from pool to pool through slots oriented vertically. A water jet is formed at each slot and energy dissipation by jet mixing occurs in each pool. The hydraulic characteristics of several variations of the vertical slot fish pass (Fig. 3.5) were studied by scale models. Both "uniform flow", where depth of flow in each pool (y_o) is approximately the same, and "gradually varied" flow, where M1 or M2 - type backwater curves may occur, were studied. Shear stress between the jet and the recirculating mass predominates, while bed or wall shear stress on the jet is negligible in comparison. Dimensionless discharge (Q_*) varies linearly with relative depth of flow (y_o/b_o) for the 18 designs (Figure 3.5) tested:

$$Q_* = \frac{Q}{\sqrt{\boldsymbol{gS_{\circ}b_{\circ}}^5}} \dots\dots\dots\dots\dots\dots\dots. (3.3)$$

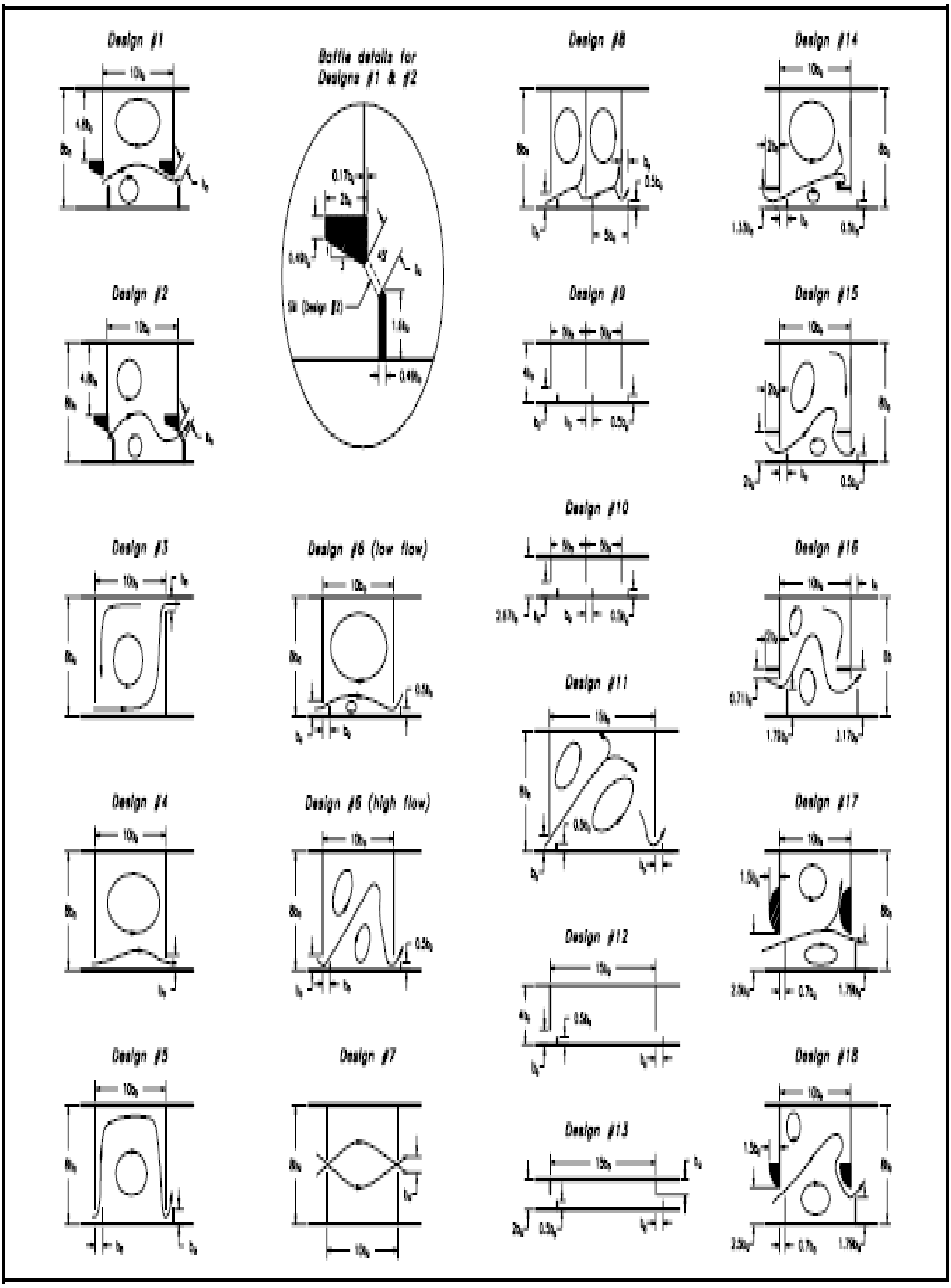


Figure 3.5: Vertical slot fish pass design layouts including circulation patterns in pools (Source: Katopodis, 1992)

Table 3.1: Vertical Slot dimensionless discharge equations

Design	**y_0/b_0 range**	$\boldsymbol{Q^* = \dfrac{Q}{\sqrt{(gS_\circ b_\circ^5)}}}$
Design # 1	1.90 - 9.02	$Q_* = 3.77(y_o/b_o) - 1.11$
Design # 2	2.46 - 9.51	$Q_* = 3.75(y_o/b_o) - 3.52$
Design # 3	2.30 - 25.79	$Q_* = 2.84(y_o/b_o) - 1.62$
Design # 4	1.77 - 10.79	$Q_* = 5.85(y_o/b_o) + 0.67$
Design # 5	2.17 - 13.29	$Q_* = 2.67(y_o/b_o) - 0.52$
Design # 6	2.17 - 13.55	$Q_* = 2.71(y_o/b_o)$
Design # 7	4.53 - 24.28	$Q_* = 2.91(y_o/b_o) - 3.22$
Design # 8	1.93 - 12.62	$Q_* = 1.66(y_o/b_o)$
Design # 9	1.97 - 11.61	$Q_* = 1.65(y_o/b_o)$
Design # 10	2 - 12.37	$Q_* = 1.4(y_o/b_o)$
Design # 11	1.71 - 12.1	$Q_* = 2.98(y_o/b_o)$
Design # 12	2.26 - 12.63	$Q_* = 3.11(y_o/b_o)$
Design # 13	3.85 - 12.22	$Q_* = 4.13(y_o/b_o)$
Design # 14	3.07 - 13.04	$Q_* = 3.21(y_o/b_o)$
Design # 15	3.3 - 12.83	$Q_* = 2.89(y_o/b_o)$
Design # 16	3.19 - 12.87	$Q_* = 3.59(y_o/b_o)$
Design # 17	3.69 - 9.38	$Q_* = 3.27(y_o/b_o)$
Design # 18	3.64 - 7.48	$Q_* = 3.71(y_o/b_o)$

The maximum velocity in each slot, u_m, is a function of the head drop between pools, h, and is approximated by $\sqrt{2gh}$, if the velocity in the upstream pool is neglected:

$$u_m = \sqrt{2gh} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..(3.4)$$

Analysis of "gradually varied" flow conditions is important, particularly at the fish pass entrance, where fish attraction velocities are reduced by backwater.

Many of the vertical slot designs tested were selected in order to evaluate how hydraulic characteristics change with pool dimensions and baffle geometry. For example, designs 8-13 were tested primarily to find out how sensitive the standard pool length and width are for satisfactory performance. Designs 14-18 are modified versions of Design 1. From the results summarized in Table 3.1, it appears that a pool width of $8b_o$ and a pool length of $10b_o$ are generally satisfactory. Minor variations in these pool dimensions would not seriously affect fish pass hydraulic performance. In addition to the widely used designs 1 and 2, designs 6, 16 and 18 are recommended for practical use (Rajaratnam et al., 1992; Rajaratnam et al., 1986; Katopodis, 1992).

3.7 Ichthyomechanics

Fish locomotion and the mechanics of fish swimming, fish behaviour and motivation, fish responses to natural and artificial stimuli, are all critical to the development of fish protection technology in general and to fish pass design in particular. Despite a growing data base, significant gains in knowledge and better understanding of fish biomechanics, specific information on how long (endurance time) or how far (swimming distance) a particular fish can swim against a given water velocity, is limited or simply not available for many fish species (Katopodis, 1990).

Analyses with dimensionless variables indicate similarity in the swimming performance of several fish species. Most fish swim with undulatory motions by passing alternating waves of contraction backward along the body muscles. Most of the data gathered involve fish swimming in the subcarangiform and anguilliform modes. Subcarangiform is an undulatory mode of swimming characterized by small side-to-side amplitude at the anterior and large amplitude only in the posterior half or one-third of the body. The characteristic body shape is fusiform, the caudal peduncle is fairly deep and the caudal fin has a rather low aspect ratio. In the anguilliform mode most or all of the length of the body participates in propulsion. The body is long and thin, the anterior cylindrical, the posterior compressed and caudal fin is usually small. Similar hydrodynamic analysis may be applicable to fish swimming in the same mode, regardless of phyletic origin.

3.8 Methodology

3.8.1 Stepwise Procedure for the Experiment

Working procedure for each experimental run has been maintained in a very consecutive way. These include flume cleaning, ADV positioning at a particular point and at a specific depth, water depth maintaining, pump discharge adjusting, data collection during experimental run and preparation for the next run. Stepwise working procedure has been discussed briefly here:

Step 1

Long tilting flume was cleared to make free from all kinds of floating debris, wastes and dirt before starting each experimental run. Water to be used for experimental run from reservoir was also changed frequently to get clear water during experimental run which is very much necessary to observe the fish behavior. Slope bed of the structure was also cleaned by allowing clear water flow from the pump and brushing the bed surface.

Step 2

Before conducting each experimental run with a certain hydrodynamic condition by maintaining a specific water depth necessary hand calculations were done to fix the pump discharge which was in m^3/hr. After switching on the flume pump discharge was fixed by magnetic flow meter reading.

Step 3

After adjusting the pump discharge water level was maintained by tailgate operation.

Step 4

After adjusting certain hydrodynamic conditions ADV was placed at a certain depth to measure the velocity 10 cm down from the ADV probe. After placing at a certain depth it was moved both in a longitudinal and transverse direction for data collection.

Step 5

After maintaining the right position of ADV, it was connected to a laptop with a cable. Necessary software was installed in the laptop and by using that software three dimensional velocity data were collected and stored in the laptop.

Step 6

After ensuring the certain hydrodynamic condition and data collection set up, selected fish species of particular size were discharged into the flume and their behavior were observed for a certain period of time.

Step 7

After completing the above mentioned steps for an experimental run, the flume and the experimental set ups were to be prepared for next run.

3.8.2 Simplified Flow Chart of the Overall Research Work

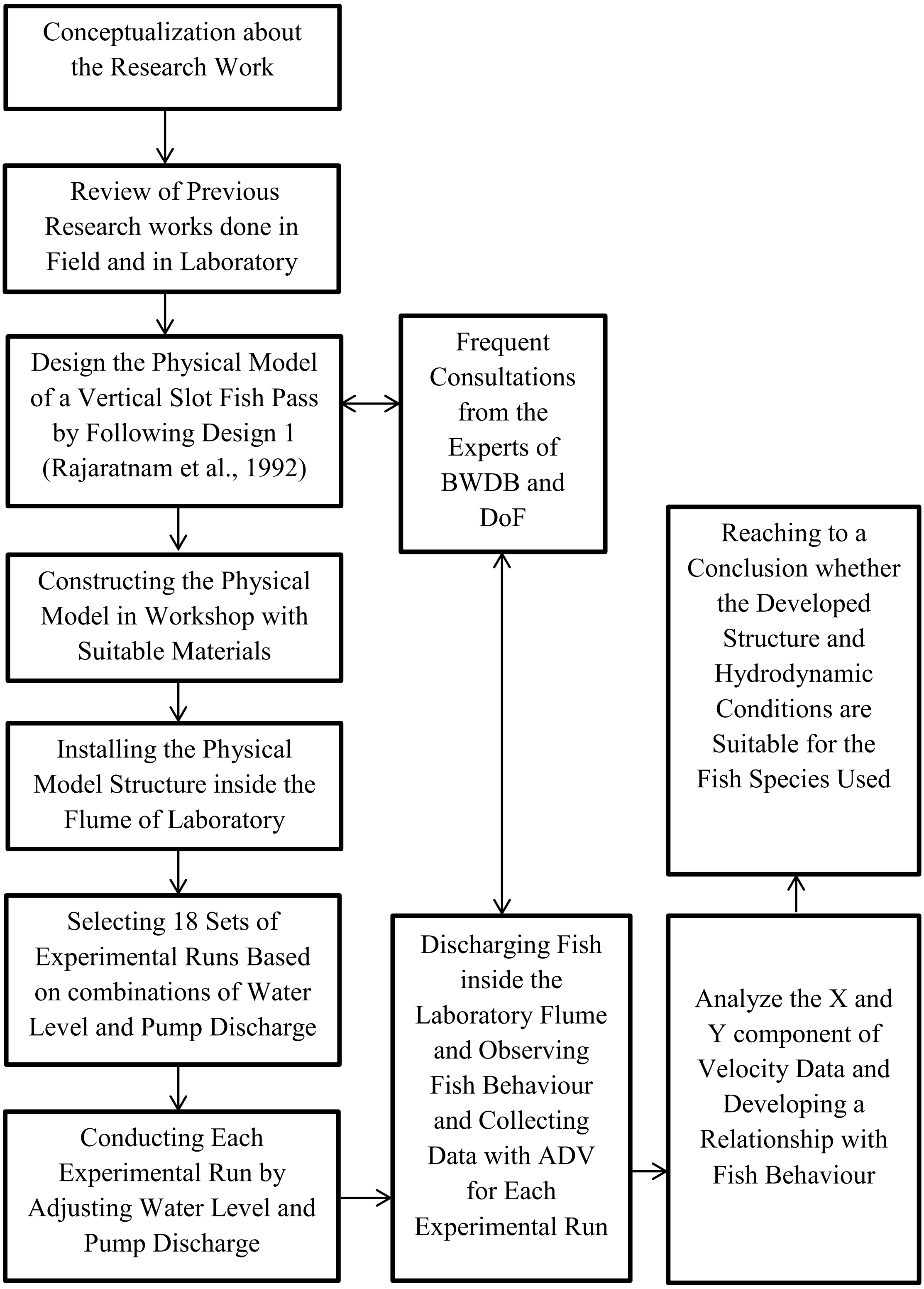


Figure 3.6: Simplified flow chart for overall research work

3.9 Summary

The understandings of theoretical background of fish pass design and hydraulics and fish ichthyomechanics in a detail and comprehensive manner is very important before conducting any research work. The factors that contribute to the design of fish pass and fish behavior inside it have been studied in this chapter. The information and theory that have been discussed are the research outcome of the scientists and engineers around the world. And lastly stepwise procedure for experimental set up is discussed and a simplified flowchart of the overall research work is presented to give a clear view about this study.

CHAPTER 4

EXPERIMENTAL SET UP AND DATA COLLECTION

4.1 General

It has been observed from the studies conducted by experts around the world that velocity fields inside the pools of the fish pass have significant effect on the biological characteristics of fish species. To understand the fish behavior with the different hydrodynamic conditions a relevant experimental setup was arranged in the laboratory flume. The experimental arrangement consists of an adverse slope of 6% followed by a 3.4% mild slope built in a rectangular laboratory flume. The fish pass is constructed on the mild slope portion which contains four pools. Total 18 sets of experiments were conducted by maintaining upstream water level of 40 cm, 50 cm and 60 cm for different ranges of velocities.

This experiment was carried out in the Hydraulics and River Engineering Laboratory of the Department of Water Resources Engineering of Bangladesh University of Engineering and Technology. Different experimental runs have been conducted in the laboratory flume by varying water depth and pump discharge.

4.2 Laboratory Set up

The laboratory set ups and equipment that have been used for carrying out the experiments and collecting necessary data are as follows:

- Laboratory Flume
- Water Reservoir
- Developed Model of a Vertical Slot Fish Pass
- Developed Adverse Slope and Mild Slope of the Physical Model
- Acoustic Doppler Velocity meter (ADV)

Other necessary accessories that were used to conduct the experiments are laboratory pumps, discharge reading meter, wire screens to stop the fish to go inside the pumps and reservoir of the flume.

4.2.1 Laboratory Flume

The experiment has been conducted in a 70 feet (21.34 m) long, 2.5 feet (0.762 m) wide and 2.5 feet (0.762 m) deep rectangular tilting flume in the Hydraulics and River Engineering Laboratory (Figure 4.1).

Figure 4.1: Laboratory flume in the hydraulics and river engineering laboratory, DWRE, BUET

The side walls of the flume are made of clear glass and they are vertical. The water resistant color has been used to pain the flume bed to avoid the development of any unnecessary bed friction. In the upstream and downstream end of the flume two wire mesh screens were placed to stop the fish to go inside the pumps and reservoir of the flume. An adverse slope of 1:16.67 was placed at the upstream portion and a mild slope of 1: 29.17 was placed at the downstream portion of the physical model. The entire model structure including the sloping portion was painted with protective coating to prevent the decomposing of wood from the effect of hydraulic flow.

Flume bed has been maintained as horizontal and it is supported on an elevated steel truss system. Two pumps were used to supply the head tank from the laboratory sump and the discharges were measured by means of magnetic flow meters located in the supply lines. Necessary steps were taken to prevent any unnecessary damage in the flume structure while conducting the experiment.

4.2.2 Water Reservoir

The water reservoir used in the flume was made of steel. Water required to supply during the experiment was stored in the reservoir. The water supply can be controlled by existing facilities in the reservoir.

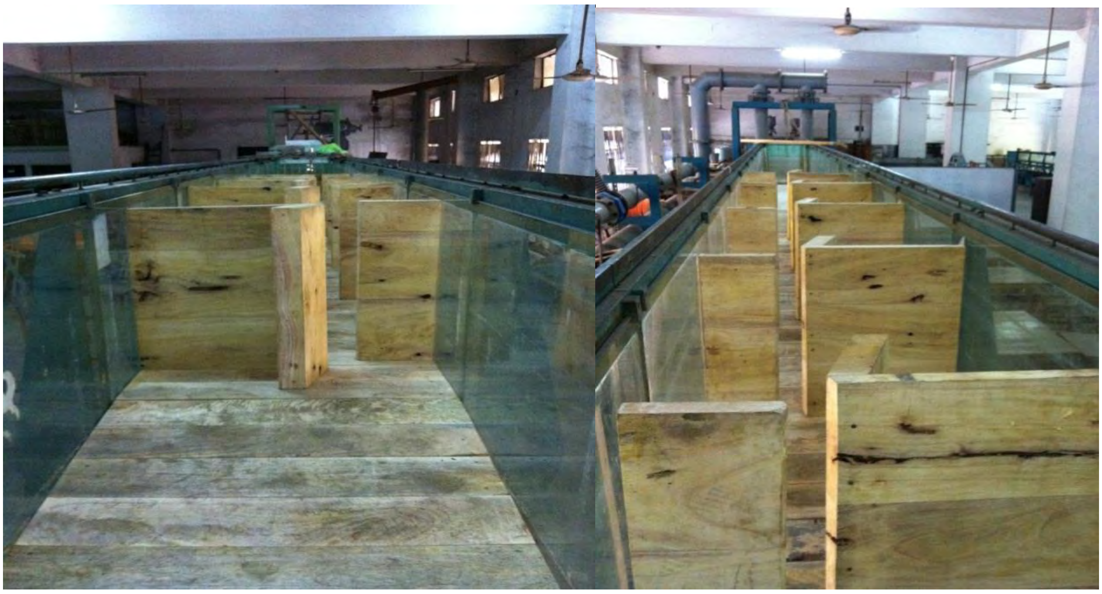
4.2.3 Construction and Placement of the Structure

The sloping portion of the structure was made of mango wood and the vertical portion was made of the gamari wood. The adverse portion of the slope was connected to the mild portion with screws. The vertical portion of the structure was placed on the mild slope portion and it was kept fixed inside the flume by using pudding on the side glass and screw connection with the sloping portion (Figure 4.2).

Figure 4.2: Construction and placement stage of the structure

4.2.4 Developed Physical Model

The physical model of the structure was developed as a vertical slot fish pass. The structural design that has been applied in this study is the design 1 (Rajaratnam et al., 1992) which is widely used for designing vertical slot fish pass all over the world. The structural set up consists of an adverse slope of 6% followed by a mild slope of 3.4%. The adverse slope is 2.54 m in length and the mild slope is 4.45 m in length. The fish pass is constructed on the mild slope which contains four pools. Each of the pool is approximately 1 m long, 0.762 m wide and 0.60 m high. The width of the opening of each pool was 0.127 m. Each component of the overall structure was built with wooden sheets (Figure 4.3). Schematic diagram of the physical model set up is shown in Figure 4.4 and 4.5.



(a)Upstream Portion (b) Downstream Portion

Figure 4.3 : Upstream and downstream portion of the model inside the flume

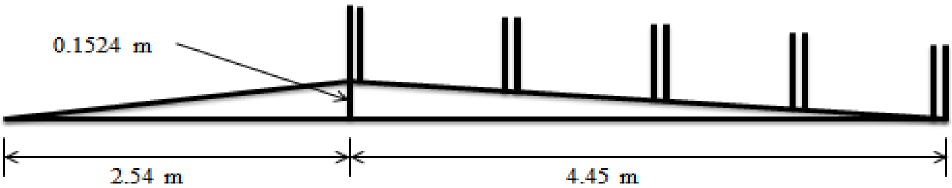


Figure 4.4 : Side view of the schematic diagram of the physical model

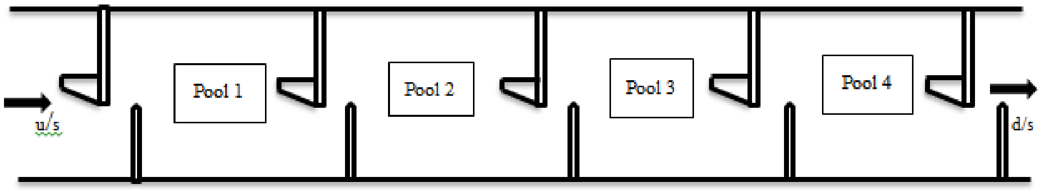


Figure 4.5: Plan view of the schematic diagram of the physical Model

A comparison of geometric dimensional parameters between the prototype in Sariakandi and developed physical model in laboratory flume is given in Table 4.1. Detailed drawings of the physical model developed in the laboratory flume are given in Figure A.1 and A.2 in Appendix A.

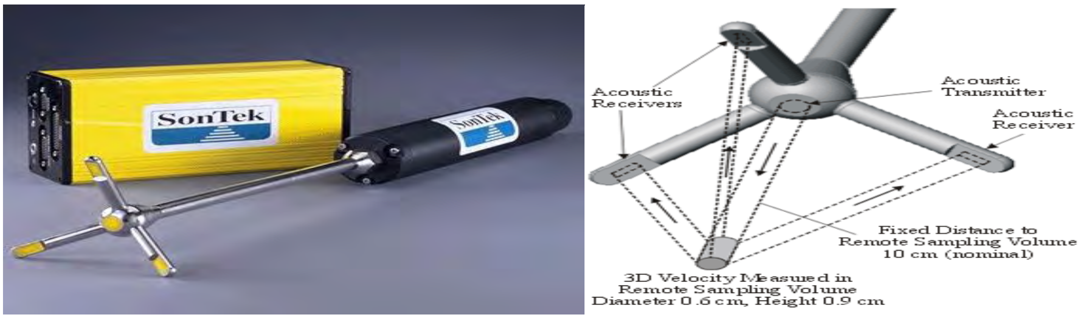
Table 4.1: Comparison of Geometric Dimensional Parameters of Prototype and Model

Parameters	Sariakandi Prototype	Physical Model in Flume	Scale Ratio
Length	4.5 m	≅1 m	4.5
Width	3.5 m	0.762 m	4.6
Height	5.9 m	0.6 m	9.8
Pool Opening	0.7 m	0.127 m	5.5

4.2.5 Acoustic Doppler Velocimeter (ADV)

Measurements were carried out using an ADV as shown in Figure 4.6. ADV has become a useful instrument in point wise measurement of 3D velocity fields in laboratory and field environments by recording the Doppler shift produced by acoustic targets in the flow (Kraus et al., 1994; Lohrmann et al., 1994; SonTek, 1997). Velocities are measured in a sampling volume located 10 cm away from the probe head. The probe head is made up of a single transmitter located in the center of the probe head and either two or three receivers mounted on arms. The transmitter generates a narrow beam of sound that is projected through the water. Reflections from particles or "scatterers" (such as suspended sediment, biological matter, or bubbles) in the water are reflected and sampled by the highly sensitivity receivers. The intersection of the receiver axes designates the location of the sampling volume.

SonTek ADV specifications state that the shape of the sampling volume is a cylinder of diameter of 0.6 cm and height of 0.9 cm. Data has been acquired at a sampling rate of 1 Hz. It can measure flow velocities from about 1 mm/ s to 2.5 m/ s with an accuracy of ±1% of the measurement range (Sontek Horizon ADV User Guide, July 2007).



(a) (b)

Figure 4.6: Acoustic doppler velocimeter (a) Picture of ADV (b) Working principle of ADV

4.3 Data Collection

Total 18 sets of experiments have been conducted. Specifications of the experiment sets are shown in Table 4.2. For each set of experiments, data points were distributed on a 10 cm (in the longitudinal direction) ×10 cm (in the transverse direction) grid at 0.6 hydraulic depth and 10 cm (in the longitudinal direction) ×20 cm (in the transverse direction) grid at 0.4 and 0.8 hydraulic depth. Since ADV measures velocity in a sampling volume located 10 cm away from the probe head, measurement at 0.2 hydraulic depth is very difficult. It has been found that the flow pattern and the head drop per pool remain almost same in most of the pools (Wu et al., 1999). For that reason most of the measurements were made in the fourth pool. Again measurements have been carried out in all the four pools for the critical and good conditions to obtain the velocity fields, contours and vertical velocity profiles.

Figure 4.7: Placement of ADV for data collection at different depths

Table 4.2: Specifications of the Experiment Runs

Experiment Run No.	U/s Water Level (cm)	Discharge, Q (m3/hr)	Total Head Loss, ∆h (cm)
1	50	81	6
2	50	94	8.6
3	50	104	12.1
4	50	118	19.5
5	50	55	1.75
6	50	68	3.35
7	40	65	6
8	40	75	10.75
9	40	87	16.67
10	40	96	29.17
11	40	37	1
12	40	52	3.5
13	60	100	5.75
14	60	110	7.4
15	60	125	10.75
16	60	145	15.75
17	60	70	2
18	60	84	3.33

4.4 Summary

In this chapter, the details of the laboratory equipments that were used during conducting the experiment have been discussed thoroughly with experimental setting.

The data collection techniques and procedure have also been discussed here for convenience.

CHAPTER 5
RESULTS AND DISCUSSIONS

5.1 General

It is necessary to collect and analyze the flow velocity data to understand the flow pattern inside a fish pass and the response of fish species to the flow characteristics. The flow characteristics inside the pools of a fish pass can be understood by collecting velocity data and analyzing it. Plotting plane velocity field and velocity contour map would give a clear idea to understand the flow characteristics inside the pools of a fish pass. The hydraulics of fish pass is very much important to meet the biological criteria of fish species so that fish can pass the obstructions like dams, barrages or flood control structures safely with no or minimum stress or injury. So study about the hydraulics of a fish pass is very important to cope up with the biological characteristics of fish species (Rajaratnam et al., 1991, Rajaratnam et al., 1990).

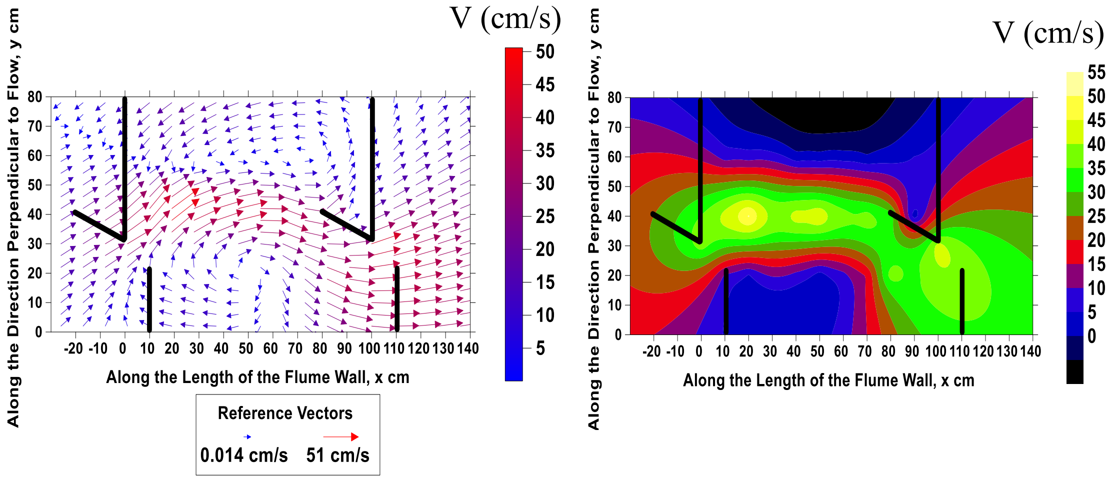
In Bangladesh a detailed field study has been performed by one investigator on the hydraulics of the Sariakandi fish pass in Bogra which is a vertical slot type fish pass (Biswas, 2007). But no laboratory study with a physical model has been carried out yet in Bangladeh. In this research work a detailed laboratory study has been performed with different types of fish species in a physical model of a vertical slot type fish pass which consists of four pools. Three dimensional velocity data has been collected by using an ADV (Acoustic Doppler Velocity Meter) for 18 sets of experimental runs and then these data has been analyzed to plot the velocity fields, velocity contours and vertical velocity profiles. The Reynolds number and Froud number have also been calculated at certain points to understand the type of flow. In addition to these, fish behaviour inside the pools has also been observed for each set of experimental run for hydrodynamic part of this research work. The biological characteristics of fish species are been analyzed in a separate study in University of Dhaka.

5.2 Velocity Fields and Velocity Contours in Pools

5.2.1 Features for Experiment Run 1 (U/S WL= 50 cm; Discharge = 81 m^3/hr)

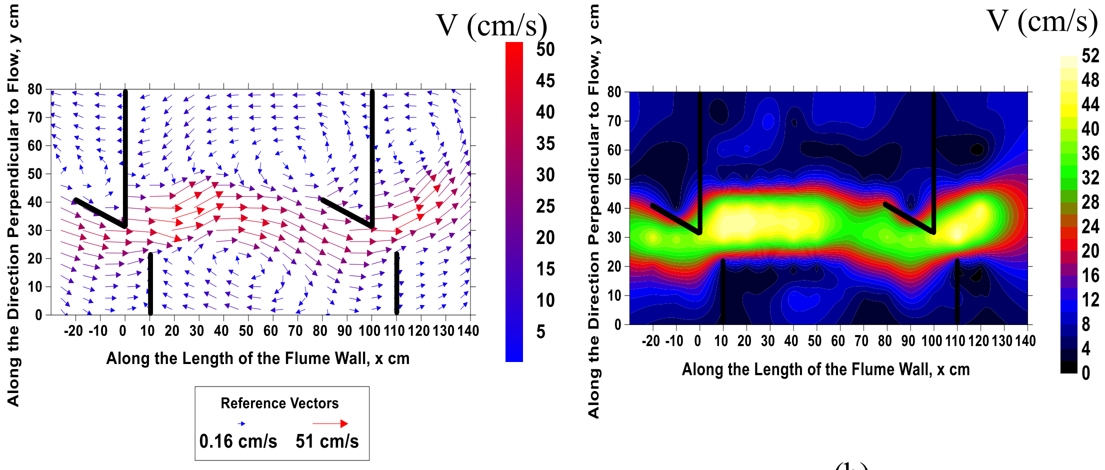
The plane velocity fields and velocity contour maps at 0.4, 0.6 and 0.8 hydraulic depths for experiment run 1 in pool 4 have been shown in figure 5.1, 5.2 and 5.3. From the velocity field analysis it is found that the flow circulation follows the pattern 1 of Design 1 (Rajaratnam et al., 1992) i.e. the flow from slot travels through the center of the pool to the next slot with two recirculation region on either side of the jet. At the pool opening the flow appear almost in the form of a shooting jet. The resultant vector components starting from the slot have made different angles with the X and Y axis at different positions. This indicates that the direction of the velocity components change randomly and the flow is non-uniform. From the velocity contour map analysis it is found that the maximum magnitude of flow occurs at the opening of slot and the mainstream continues through the center of the pool to the next slot while two recirculation regions of lower velocities are created on either side of the mainstream. And these recirculation regions with low velocities provide resting places for fish.

The velocity distribution in a channel section depends on some factors e.g. the unusual shape of the section, the roughness of the channel and the presence of bends. On a bend the velocity increases greatly at the convex side, owing to the centrifugal action of flow (Chow, 1973). The vertical velocity profile in pool 4 for experiment run 1 is shown at Figure 5.4. Vertical velocity profiles have been presented at three particular places inside a pool based on the collected velocity data at 0.4, 0.6 and 0.8 hydraulic depths. The magnitude of velocity at opening of upstream slot decreases with distance from the bottom. And the magnitude of velocity at opening of downstream slot is found higher at 0.6 hydraulic depths than depth at 0.4 and 0.8. The magnitude of higher velocity at a certain hydraulic depth also represents the attractive velocity of fish species at that hydraulic depth at a particular place inside a pool. The vertical velocity profile at the resting place of fish at recirculation region just before the partition wall represents the velocities of very small magnitude which matches with the theory of vertical slot fish pass. Here the magnitudes of velocities are almost same.



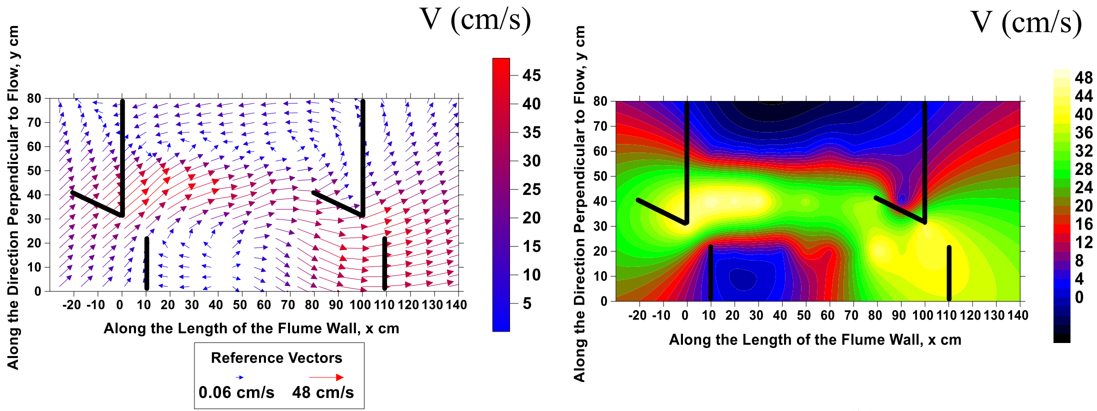
(a) (b)

Figure 5.1: (a) Plane velocity field and (b) Velocity contour map at 0.4 hydraulic depth for experiment run 1 in Pool 4



(a) (b)

Figure 5.2: (a) Plane velocity field and (b) Velocity contour map at 0.6 hydraulic depth for experiment run 1 in Pool



(a) (b)

Figure 5.3: (a) Plane velocity field and (b) Velocity contour map at 0.8 hydraulic depth for experiment run 1 in Pool 4

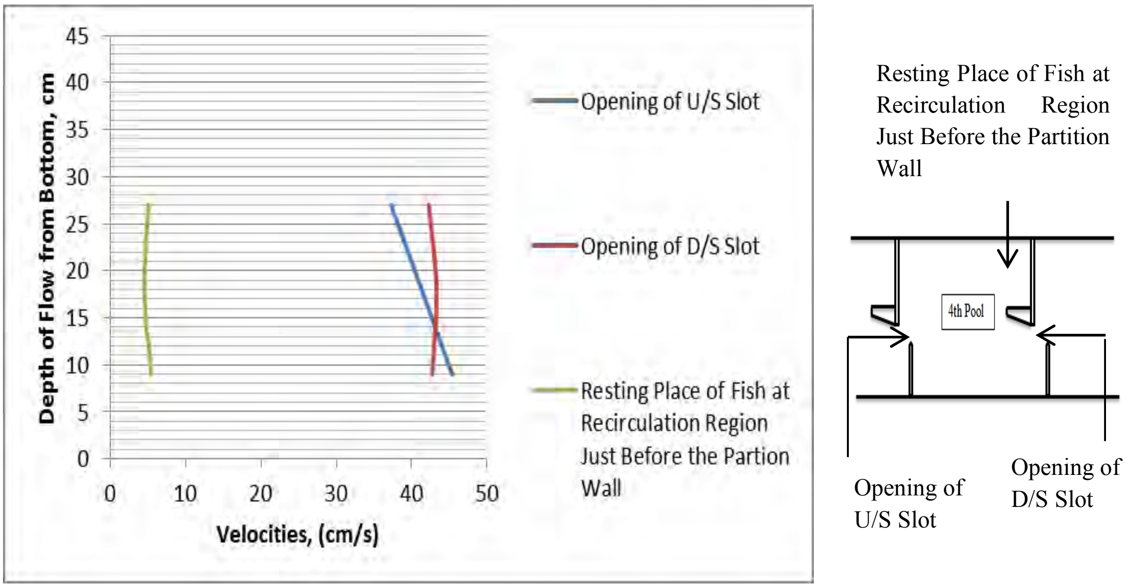


Figure 5.4: Vertical velocity profile in pool 4 for experiment run 1

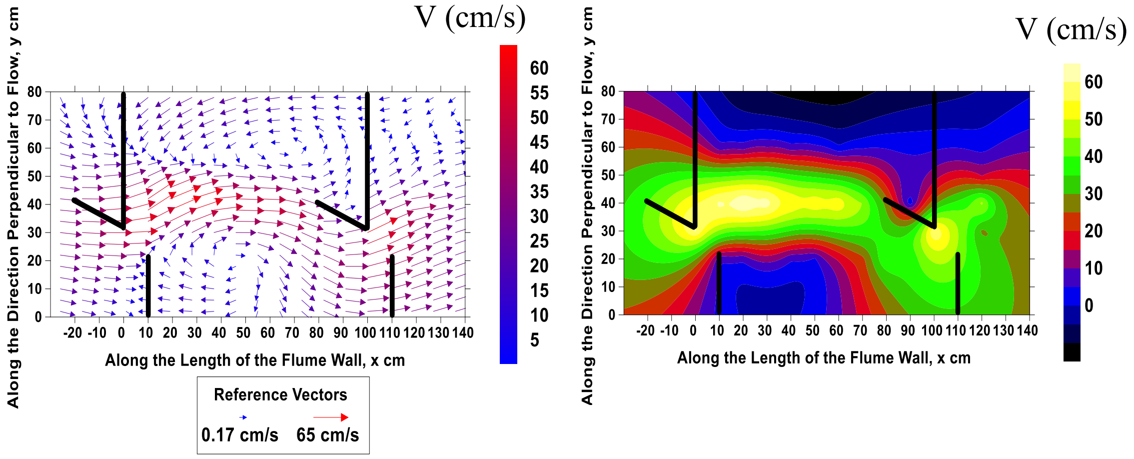
Table 5.1 shows Reynolds number and Froude number at different locations in pool 4 at 0.6 hydraulic depth for experiment run 1. By observing the values of Reynolds Number it is seen that the flow type is turbulent at selected locations which indicates that the viscous forces are very weak relative to the inertial forces and inertial forces dominate the flow. By observing the values of Froude Number it is found that the flow is subcritical at the selected locations i.e. the gravitational forces are dominant.

Table 5.1: Reynolds number and Froude number in pool 4 for experiment run 1

Position at the Pool	Hydraulic Depths	Reynolds Number	Froude Number
Opening of Upstream Slot	0.6	228605	0.216
Opening of Downstream Slot	0.6	215239	0.203
Resting Palace of Fish at Recirculation Region Just Before the Partition Wall	0.6	27564	0.026

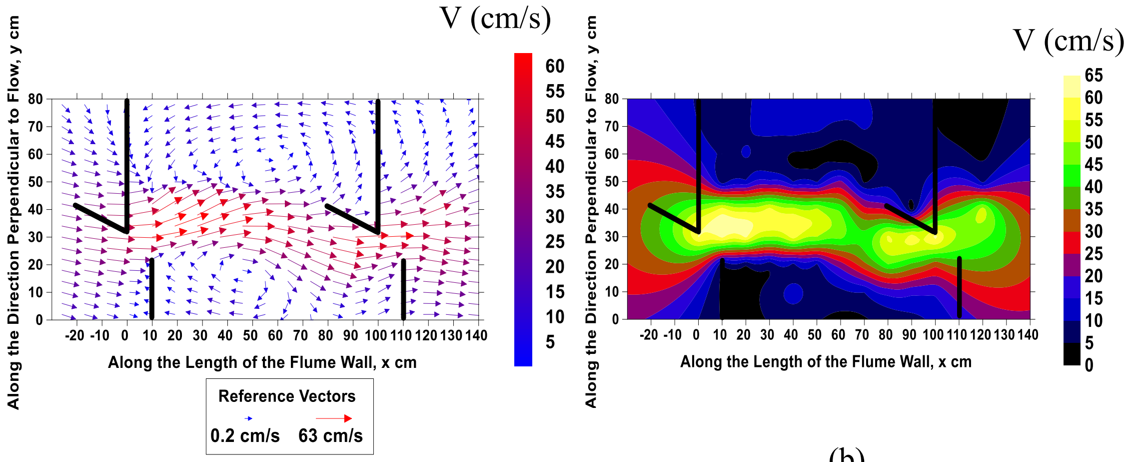
5.2.2 Features for Experiment Run 2 (U/S WL= 50 cm; Discharge = 94 m^3/hr)

The plane velocity fields and velocity contour maps at 0.4, 0.6 and 0.8 hydraulic depth for experiment run 2 in pool 4 have been shown in figure 5.5, 5.6 and 5.7.



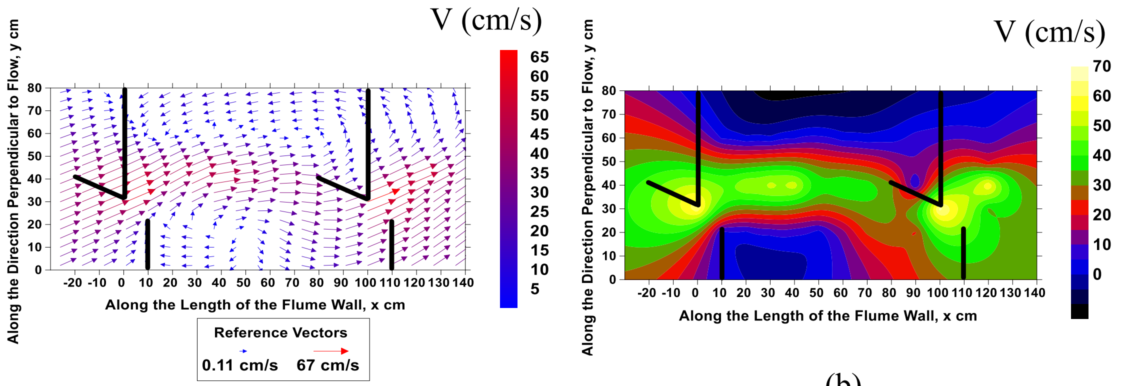
(a) (b)

Figure 5.5: (a) Plane velocity field and (b) Velocity contour map at 0.4 hydraulic depth for experiment run 2 in pool 4



(a) (b)

Figure 5.6: (a) Plane velocity field and (b) Velocity contour map at 0.6 hydraulic depth for experiment run 2 in pool 4



(a) (b)

Figure 5.7: (a) Plane velocity field and (b) Velocity contour map at 0.8 hydraulic depth for experiment run 2 in Pool 4

From the velocity field analysis it is found that the flow circulation follows the pattern 1 of Design 1 (Rajaratnam et al., 1992) i.e. the flow from slot travels through the center of the pool to the next slot with two recirculation region on either side of the jet. At the pool opening the flow appear almost in the form of a shooting jet. The resultant vector components starting from the slot have made different angles with the X and Y axis at different positions. This indicates that the direction of the velocity components change randomly and the flow is non-uniform. From the velocity contour map analysis it is found that the maximum magnitude of flow occurs at the opening of slot and the mainstream continues through the center of the pool to the next slot while two recirculation regions of lower velocities are created on either side of the mainstream. And these recirculation regions with low velocities provide resting places for fish.

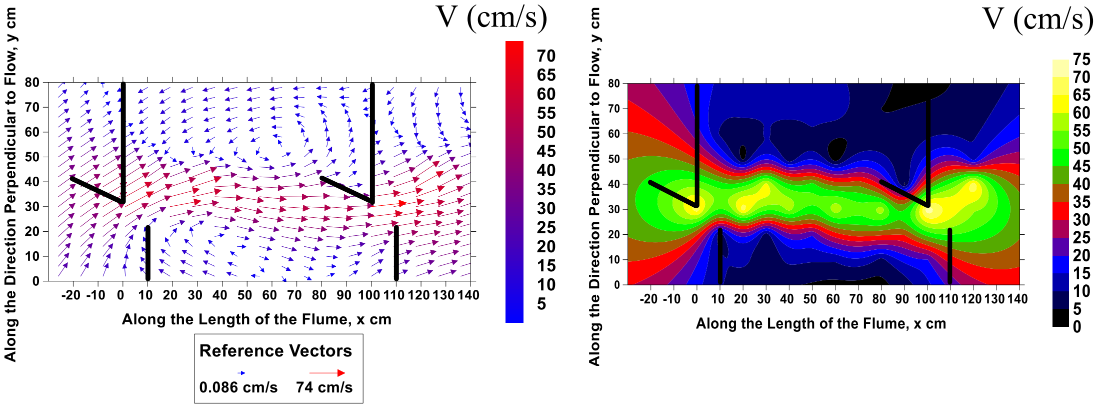
Table 5.2 shows Reynolds number and Froude number at different locations in pool 4 at 0.6 hydraulic depth for experiment run 2. By observing the values of Reynolds Number it is seen that the flow type is turbulent at selected locations which indicates that the viscous forces are very weak relative to the inertial forces and inertial forces dominate the flow. By observing the values of Froude Number it is found that the flow is subcritical at the selected locations i.e. the gravitational forces are dominant.

Table 5.2: Reynolds number and Froude number in pool 4 for experiment run 2

Position at the Pool	Hydraulic Depths	Reynolds Number	Froude Number
Opening of Upstream Slot	0.6	293880	0.292
Opening of Downstream Slot	0.6	301179	0.299
Resting Palace of Fish at Recirculation Region Just Before the Partition Wall	0.6	31365	0.031

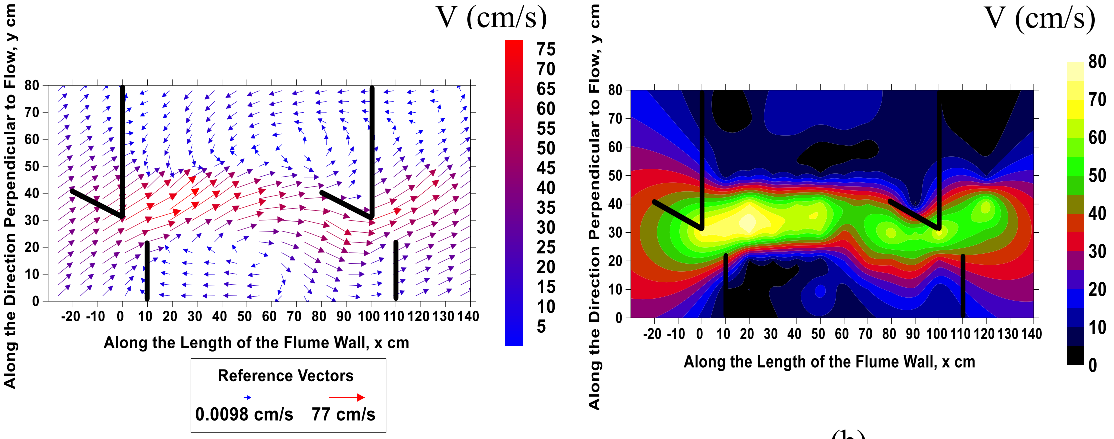
5.2.3 Features for Experiment Run 3 (U/S WL= 50 cm; Discharge = 104 m^3/hr)

The plane velocity fields and velocity contour maps at 0.4, 0.6 and 0.8 hydraulic depth for experiment run 3 in pool 4 have been shown in figure 5.8, 5.9 and 5.10.



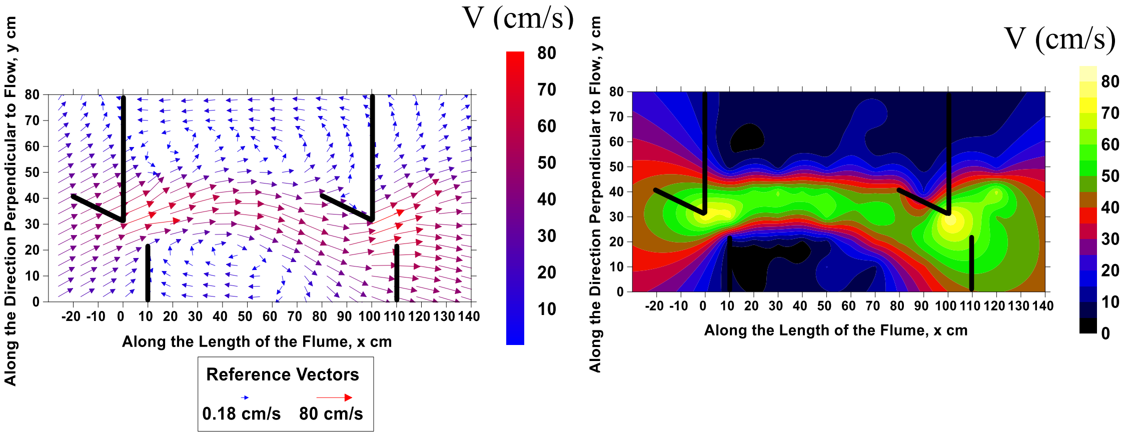
(a) (b)

Figure 5.8: (a) Plane velocity field and (b) Velocity contour map at 0.4 hydraulic depth for experiment run 3 in pool 4



(a) (b)

Figure 5.9: (a) Plane velocity field and (b) Velocity contour map at 0.6 hydraulic depth of 0.8 for experiment run 3 in pool 4



(a) (b)

Figure 5.10: (a) Plane velocity field and (b) Velocity contour map at 0.8 hydraulic depth for experiment run 3 in pool 4

From the velocity field analysis it is found that the flow circulation follows the pattern 1 of Design 1 (Rajaratnam et al., 1992) i.e. the flow from slot travels through the center of the pool to the next slot with two recirculation region on either side of the jet. At the pool opening the flow appear almost in the form of a shooting jet. The resultant vector components starting from the slot have made different angles with the X and Y axis at different positions. This indicates that the direction of the velocity components change randomly and the flow is non-uniform. From the velocity contour map analysis it is found that the maximum magnitude of flow occurs at the opening of slot and the mainstream continues through the center of the pool to the next slot while two recirculation regions of lower velocities are created on either side of the mainstream. And these recirculation regions with low velocities provide resting places for fish.

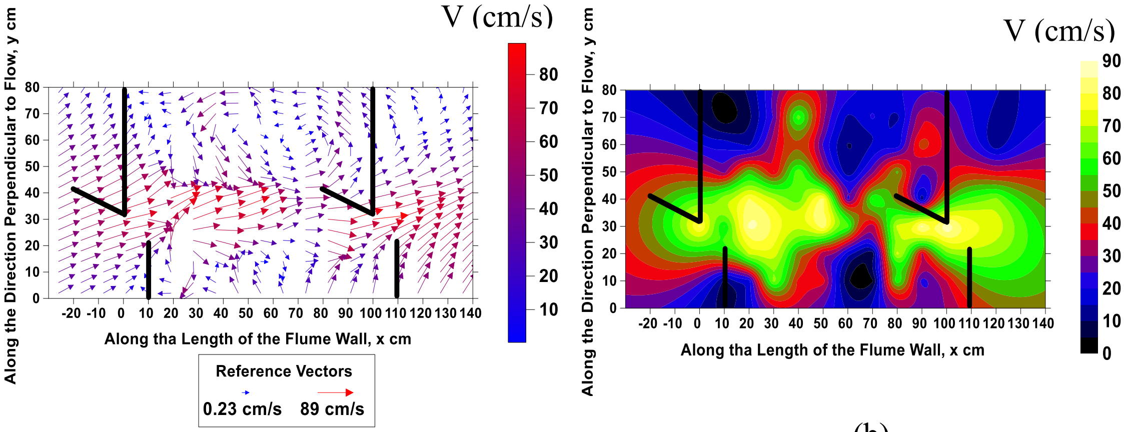
Table 5.3 shows Reynolds number and Froude number at different locations in pool 4 at 0.6 hydraulic depth for experiment run 3. By observing the values of Reynolds Number it is seen that the flow type is turbulent at selected locations which indicates that the viscous forces are very weak relative to the inertial forces and inertial forces dominate the flow. By observing the values of Froude Number it is found that the flow is subcritical at the selected locations i.e. the gravitational forces are dominant.

Table 5.3: Reynolds number and Froude number in pool 4 for experiment run 3

Position at the Pool	Hydraulic Depths	Reynolds Number	Froude Number
Opening of Upstream Slot	0.6	327453	0.362
Opening of Downstream Slot	0.6	311196	0.344
Resting Palace of Fish at Recirculation Region Just Before the Partition Wall	0.6	28135	0.031

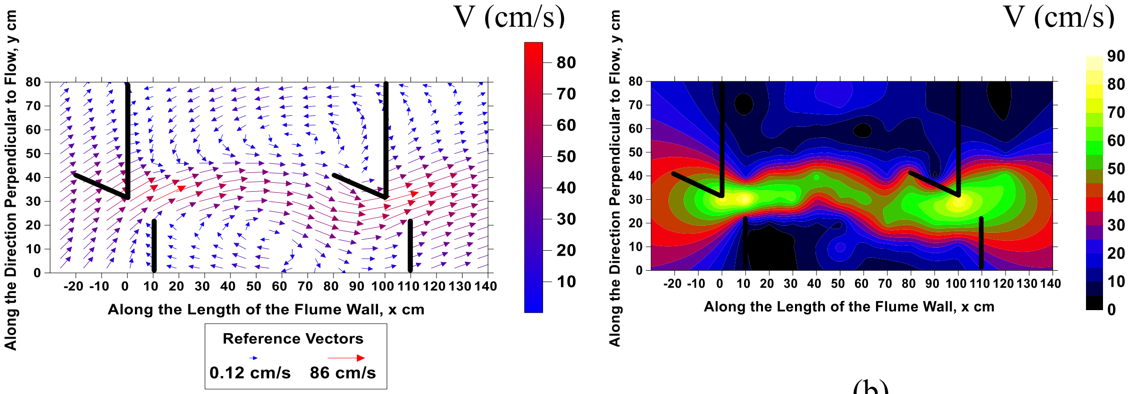
5.2.4 Features for Experiment Run 4 (U/S WL= 50 cm; Discharge = 118 m^3/hr)

The plane velocity fields and velocity contour maps at 0.4, 0.6 and 0.8 hydraulic depths for experiment run 4 in pool 4 have been shown in figure 5.11, 5.12 and 5.13.



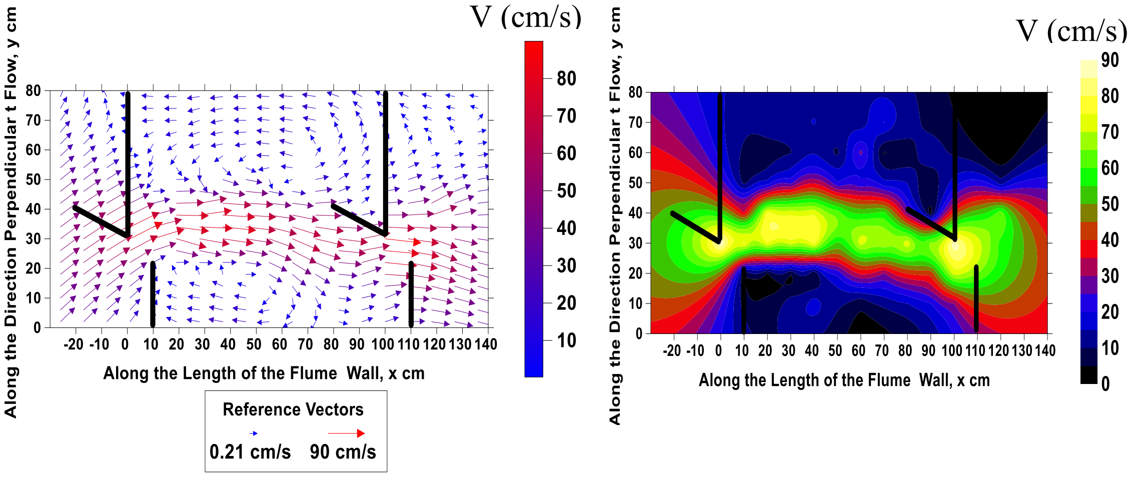
(a) (b)

Figure 5.11: (a) Plane velocity field and (b) Velocity contour map at 0.4 hydraulic depth experiment run 4 in pool 4



(a) (b)

Figure 5.12: (a) Plane velocity field and (b) Velocity contour map at 0.6 hydraulic depth for experiment run 4 in pool 4



(a) (b)

Figure 5.13: (a) Plane velocity field and (b) Velocity contour map at 0.8 hydraulic depth for experiment run 4 in pool 4

From the velocity field analysis it is found that the flow circulation follows the pattern 1 of Design 1 (Rajaratnam et al., 1992) i.e. the flow from slot travels through the center of the pool to the next slot with two recirculation region on either side of the jet. At the pool opening the flow appear almost in the form of a shooting jet. The resultant vector components starting from the slot have made different angles with the X and Y axis at different positions. This indicates that the direction of the velocity components change randomly and the flow is non-uniform. From the velocity contour map analysis it is found that the maximum magnitude of flow occurs at the opening of slot and the mainstream continues through the center of the pool to the next slot while two recirculation regions of lower velocities are created on either side of the mainstream. And these recirculation regions with lower velocities provide resting places for fish.

The velocity distribution in a channel section depends on some factors e.g. the unusual shape of the section, the roughness of the channel and the presence of bends. On a bend the velocity increases greatly at the convex side, owing to the centrifugal action of flow (Chow, 1973). The vertical velocity profile in pool 4 for experiment run 4 is shown at Figure 5.14. Vertical velocity profiles have been presented at three particular places inside a pool based on the collected velocity data at 0.4, 0.6 and 0.8 hydraulic depths. The magnitude of velocity at opening of both upstream and downstream slot is found lower at 0.6 hydraulic depths than depth at 0.4 and 0.8. The magnitude of higher velocity at a certain hydraulic depth also represents the attractive velocity of fish species at that hydraulic depth at a particular place inside a pool. The vertical velocity profile at the resting place of fish at recirculation region just before the partition wall represents the velocities of very small magnitude which matches with the theory of vertical slot fish pass. Here the magnitudes of velocities are almost same.

Table 5.4 shows Reynolds number and Froude number at different locations in pool 4 at 0.6 hydraulic depth for experiment run 4. By observing the values of Reynolds Number it is seen that the flow type is turbulent at selected locations which indicates that the viscous forces are very weak relative to the inertial forces and inertial forces dominate the flow. By observing the values of Froude Number it is found that the flow is subcritical at the selected locations i.e. the gravitational forces are dominant.

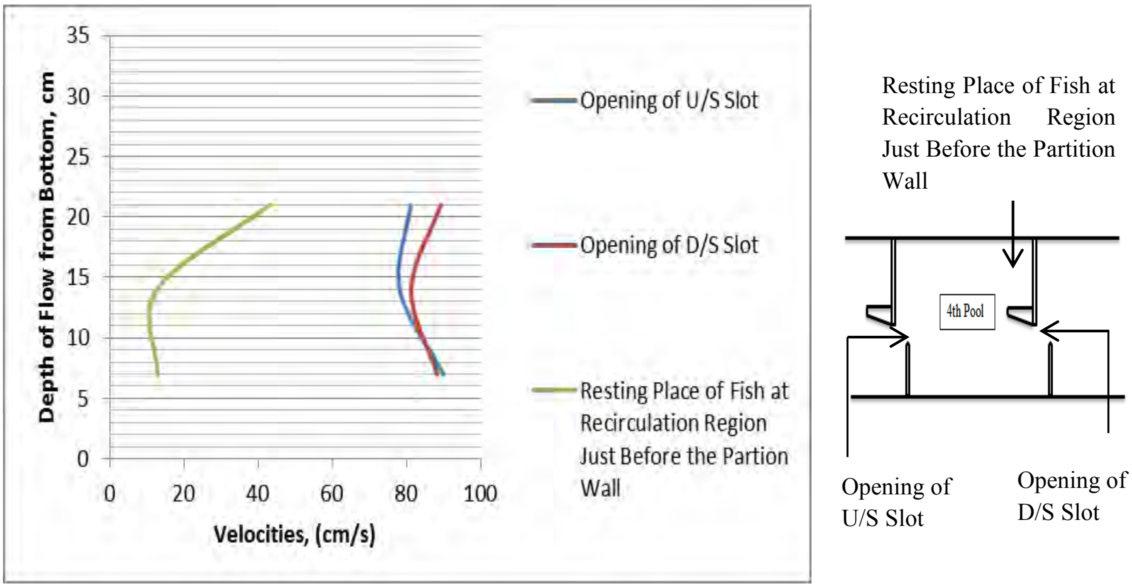


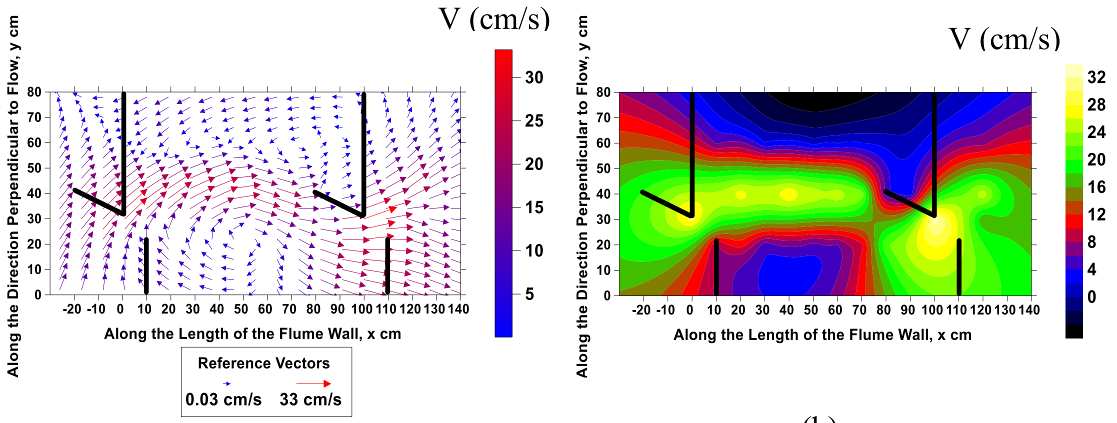
Figure 5.14: Vertical velocity profile in pool 4 for experiment run 4

Table 5.4: Reynolds number and froude number in pool 4 for experiment run 4

Position at the Pool	Hydraulic Depths	Reynolds Number	Froude Number
Opening of Upstream Slot	0.6	315202	0.416
Opening of Downstream Slot	0.6	327863	0.433
Resting Palace of Fish at Recirculation Region Just Before the Partition Wall	0.6	51328	0.068

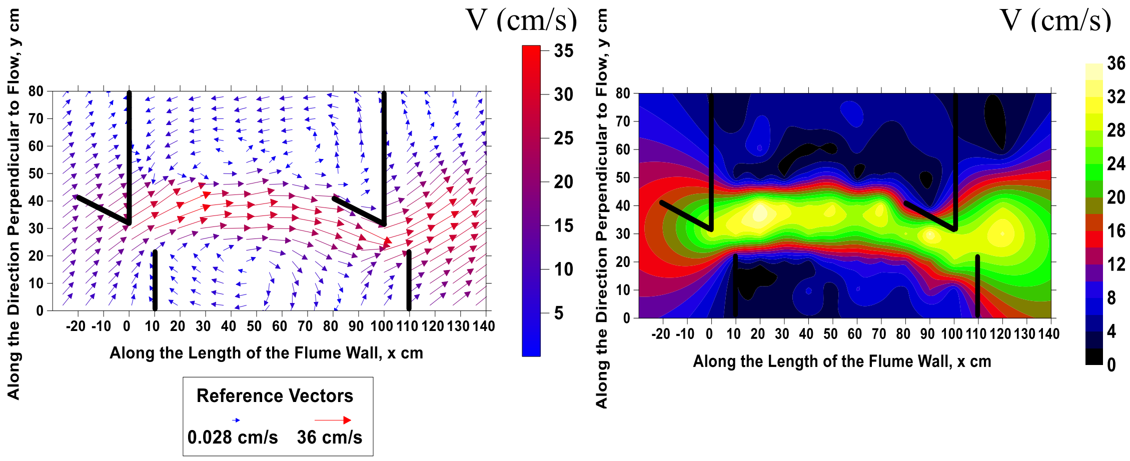
5.2.5 Features for Experiment Run 5 (U/S WL= 50 cm; Discharge = 55 m^3/hr)

The plane velocity fields and velocity contour maps at 0.4, 0.6 and 0.8 hydraulic depths for experiment run 5 in pool 4 have been shown in figure 5.15, 5.16 and 5 .17. From the velocity field analysis it is found that the flow circulation follows the pattern 1 of Design 1 (Rajaratnam et al., 1992) i.e. the flow from slot travels through the center of the pool to the next slot with two recirculation region on either side of the



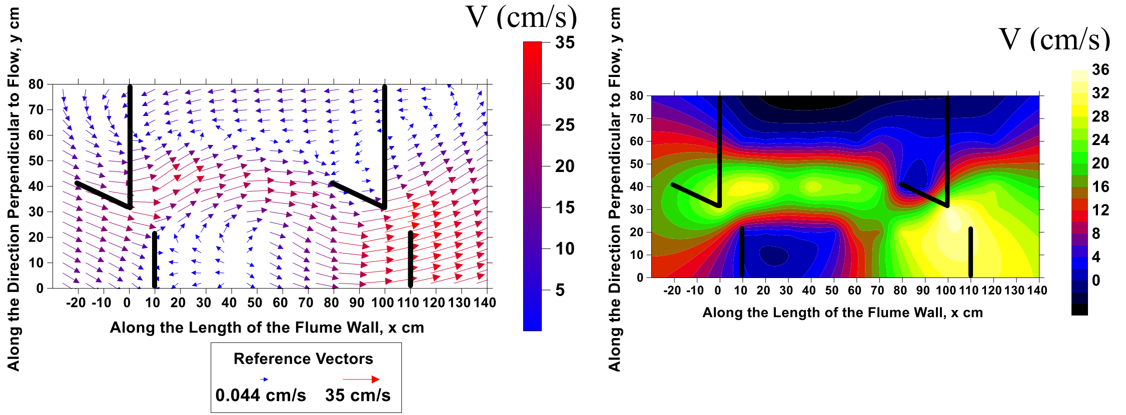
(a) (b)

Figure 5.15: (a) Plane velocity field and (b) Velocity contour map at 0.4 hydraulic depth for experiment run 5 in pool 4



(a) (b)

Figure 5.16: (a) Plane velocity field and (b) Velocity contour map at 0.6 hydraulic depth for experiment run 5 in pool 4



(b) (a)

Figure 5.17: (a) Plane velocity field and (b) Velocity contour map at 0.8 hydraulic depth for experiment run 5 in pool 4

jet. At the pool opening the flow appear almost in the form of a shooting jet. The resultant vector components starting from the slot have made different angles with the X and Y axis at different positions. This indicates that the direction of the velocity components change randomly and the flow is non-uniform. From the velocity contour map analysis it is found that the maximum magnitude of flow occurs at the opening of slot and the mainstream continues through the center of the pool to the next slot while two recirculation regions of lower velocities are created on either side of the mainstream. And these recirculation regions with lower velocities provide resting places for fish.

The velocity distribution in a channel section depends on some factors e.g. the unusual shape of the section, the roughness of the channel and the presence of bends. On a bend the velocity increases greatly at the convex side, owing to the centrifugal action of flow (Chow, 1973). The vertical velocity profile in pool 4 for experiment run 5 is shown at Figure 5.18. Vertical velocity profiles have been presented at three particular places inside a pool based on the collected velocity data at 0.4, 0.6 and 0.8 hydraulic depths. The magnitude of velocity at opening of upstream slot is found higher at 0.6 hydraulic depth than depth at 0.4 and 0.8. The magnitude of velocity at opening of downstream slot is found lower at 0.6 hydraulic depth than depth at 0.4 and 0.8. The magnitude of higher velocity at a certain hydraulic depth also represents the attractive velocity of fish species at that hydraulic depth at a particular place inside a pool. The vertical velocity profile at the resting place of fish at recirculation region just before the partition wall represents the velocities of very small magnitude which matches with the theory of vertical slot fish pass. Here the magnitudes of velocities are almost same.

Table 5.5 shows Reynolds number and Froude number at different locations in pool 4 at 0.6 hydraulic depth for experiment run 5. By observing the values of Reynolds Number it is seen that the flow type is turbulent at selected locations which indicates that the viscous forces are very weak relative to the inertial forces and inertial forces dominate the flow. By observing the values of Froude Number it is found that the flow is subcritical at the selected locations i.e. the gravitational forces are dominant.

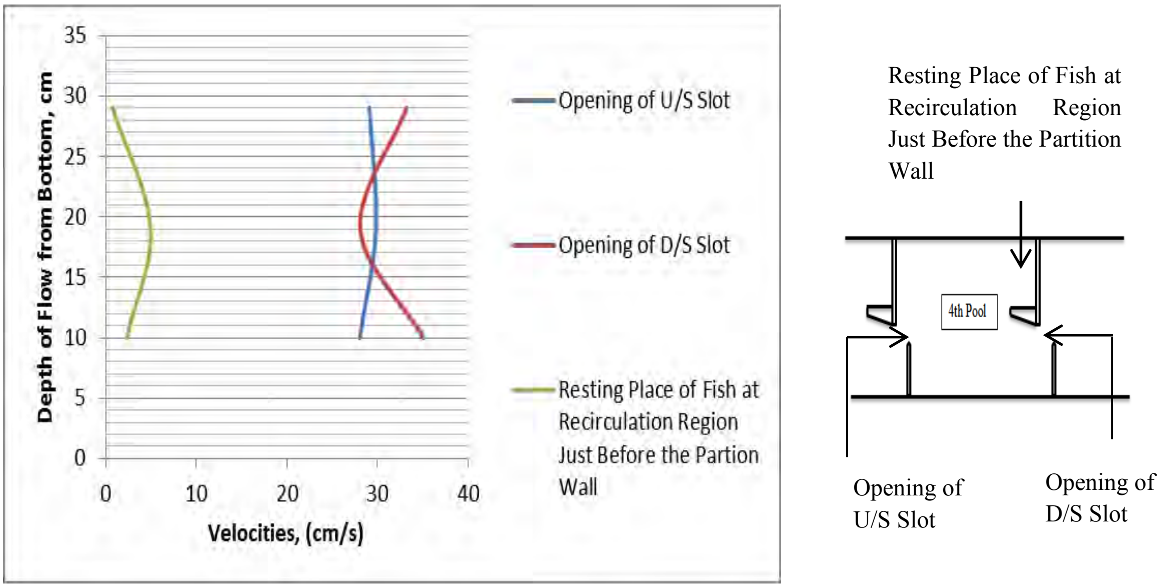


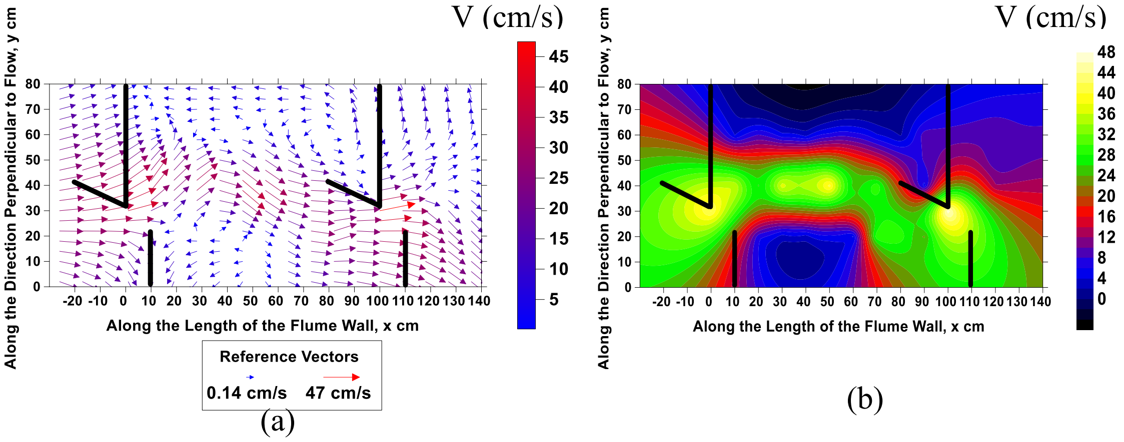
Figure 5.18: Vertical velocity profile in pool 4 for experiment run 5

Table 5. 5 : Reynolds number and Froude number in pool 4 for experiment run 5

Position at the Pool	Hydraulic Depths	Reynolds Number	Froude Number
Opening of Upstream Slot	0.6	160358	0.137
Opening of Downstream Slot	0.6	151028	0.129
Resting Palace of Fish at Recirculation Region Just Before the Partition Wall	0.6	26591	0.022

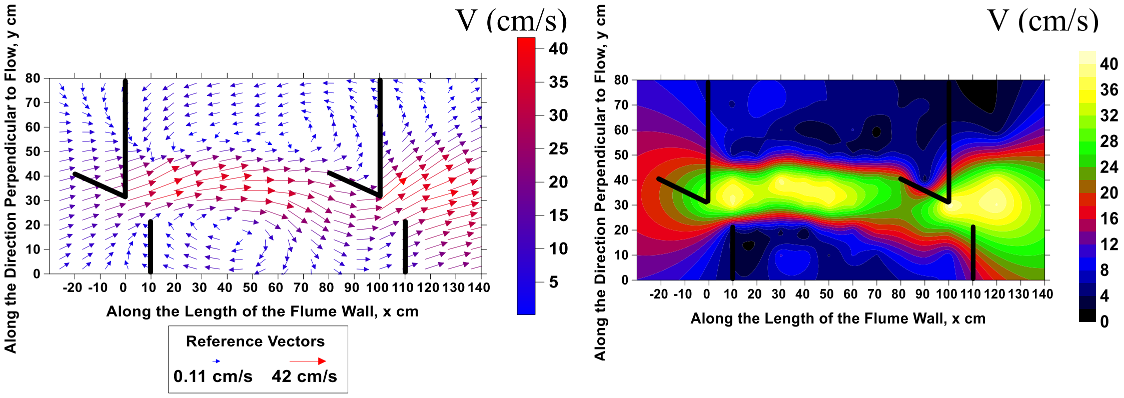
5.2.6 Features for Experiment Run 6 (U/S WL= 50 cm; Discharge = 68 m^3/hr)

The plane velocity fields and velocity contour maps at 0.4, 0.6 and 0.8 hydraulic depths for experiment run 6 in pool 4 have been shown in figure 5.19, 5.20 and 5.21. From the velocity field analysis it is found that the flow circulation follows the pattern 1 of Design 1 (Rajaratnam et al., 1992) i.e. the flow from slot travels through the center of the pool to the next slot with two recirculation region on either side of the jet. At the pool opening the flow appear almost in the form of a shooting jet. The resultant vector components starting from the slot have made different angles with the



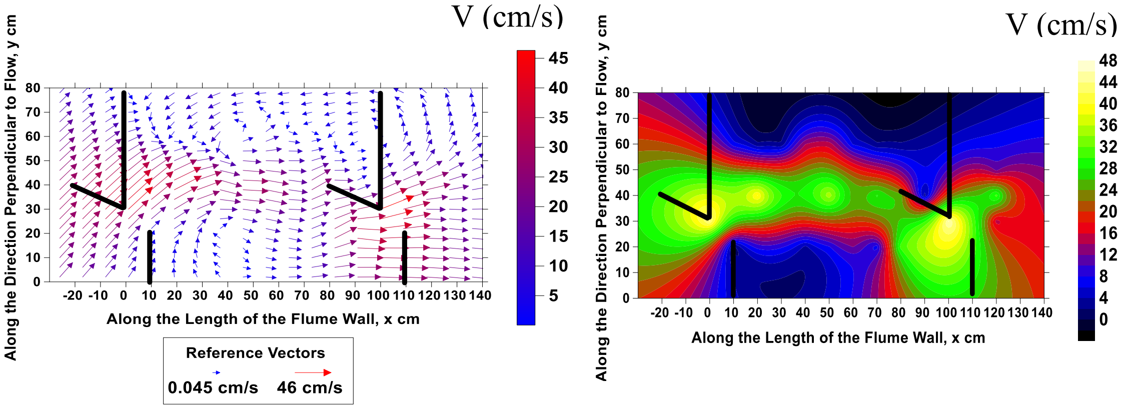
(a) (b)

Figure 5.19: (a) Plane velocity field and (b) Velocity contour map at 0.4 hydraulic depth for experiment run 6 in pool 4



(a) (b)

Figure 5.20: (a) Plane velocity field and (b) Velocity contour map at 0.6 hydraulic depth for experiment run 6 in pool 4



(a) (b)

Figure 5.21: (a) Plane velocity field and (b) Velocity contour map at 0.8 hydraulic depth for experiment run 6 in Pool 4

X and Y axis at different positions. This indicates that the direction of the velocity components change randomly and the flow is non-uniform. From the velocity contour map analysis it is found that the maximum magnitude of flow occurs at the opening of slot and the mainstream continues through the center of the pool to the next slot while two recirculation regions of lower velocities are created on either side of the mainstream. And these recirculation regions with lower velocities provide resting places for fish.

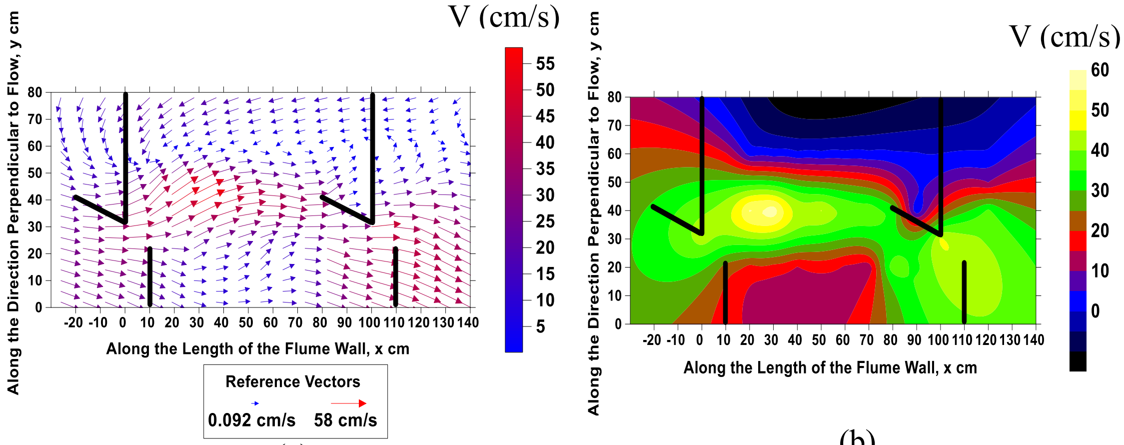
Table 5.6 shows Reynolds number and Froude number at different locations in pool 4 at 0.6 hydraulic depth for experiment run 6. By observing the values of Reynolds Number it is seen that the flow type is turbulent at selected locations which indicates that the viscous forces are very weak relative to the inertial forces and inertial forces dominate the flow. By observing the values of Froude Number it is found that the flow is subcritical at the selected locations i.e. the gravitational forces are dominant.

Table 5.6: Reynolds number and Froude number in pool 4 for experiment run 6

Position at the Pool	Hydraulic Depths	Reynolds Number	Froude Number
Opening of Upstream Slot	0.6	168615	0.147
Opening of Downstream Slot	0.6	221819	0.193
Resting Palace of Fish at Recirculation Region Just Before the Partition Wall	0.6	271288	0.236

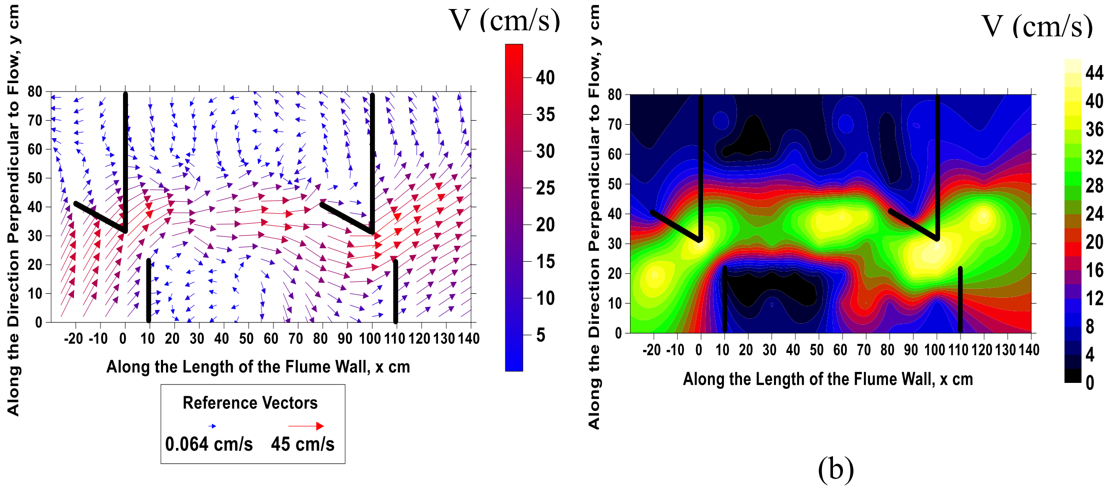
5.2.7 Features for Experiment Run 7 (U/S WL= 40 cm; Discharge = 65 m^3/hr)

The plane velocity fields and velocity contour maps at 0.4, 0.6 and 0.8 hydraulic depths for experiment run 7 in pool 4 have been shown in figure 5.22, 5.23 and 5.24. From the velocity field analysis it is found that the flow circulation follows the pattern 1 of Design 1 (Rajaratnam et al., 1992) i.e. the flow from slot travels through the center of the pool to the next slot with two recirculation region on either side of the jet. At the pool opening the flow appear almost in the form of a shooting jet. The resultant vector components starting from the slot have made different angles with the



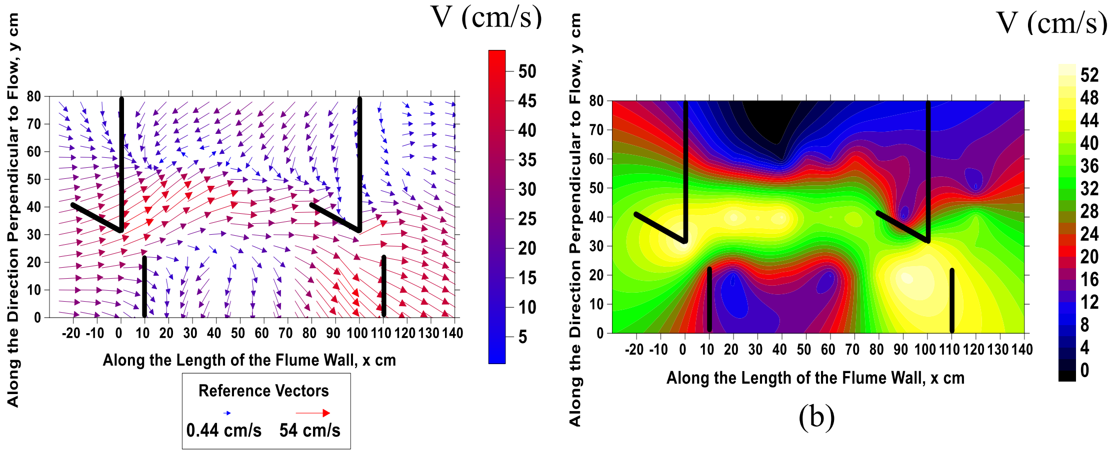
(a) (b)

Figure 5.22: (a) Plane velocity field and (b) Velocity contour map at 0.4 hydraulic depth for experiment run 7 in pool 4



(a) (b)

Figure 5.23: (a) Plane velocity field and (b) Velocity contour map at 0.6 hydraulic depth for experiment run 7 in pool 4



(a) (b)

Figure 5.24: (a) Plane velocity field and (b) Velocity contour map at 0.8 hydraulic depth for experiment run 7 in pool 4

X and Y axis at different positions. This indicates that the direction of the velocity components change randomly and the flow is non-uniform. From the velocity contour map analysis it is found that the maximum magnitude of flow occurs at the opening of slot and the mainstream continues through the center of the pool to the next slot while two recirculation regions of lower velocities are created on either side of the mainstream. And these recirculation regions with lower velocities provide resting places for fish.

The velocity distribution in a channel section depends on some factors e.g. the unusual shape of the section, the roughness of the channel and the presence of bends. On a bend the velocity increases greatly at the convex side, owing to the centrifugal action of flow (Chow, 1973). The vertical velocity profile in pool 4 for experiment run 7 is shown at Figure 5.25. Vertical velocity profiles have been presented at three particular places inside a pool based on the collected velocity data at 0.4, 0.6 and 0.8 hydraulic depths. The magnitude of velocity at opening of upstream slot decreases with distance from the bottom. The magnitude of velocity at opening of downstream slot is found lower at 0.6 hydraulic depth than depth at 0.4 and 0.8. The magnitude of higher velocity at a certain hydraulic depth also represents the attractive velocity of fish species at that hydraulic depth at a particular place inside a pool. The vertical velocity profile at the resting place of fish at recirculation region just before the partition wall represents the velocities of very small magnitude which matches with the theory of vertical slot fish pass. Here the magnitudes of velocities are almost same.

Table 5.7 shows Reynolds number and Froude number at different locations in pool 4 at 0.6 hydraulic depth for experiment run 7. By observing the values of Reynolds Number it is seen that the flow type is turbulent at selected locations which indicates that the viscous forces are very weak relative to the inertial forces and inertial forces dominate the flow. By observing the values of Froude Number it is found that the flow is subcritical at the selected locations i.e. the gravitational forces are dominant.

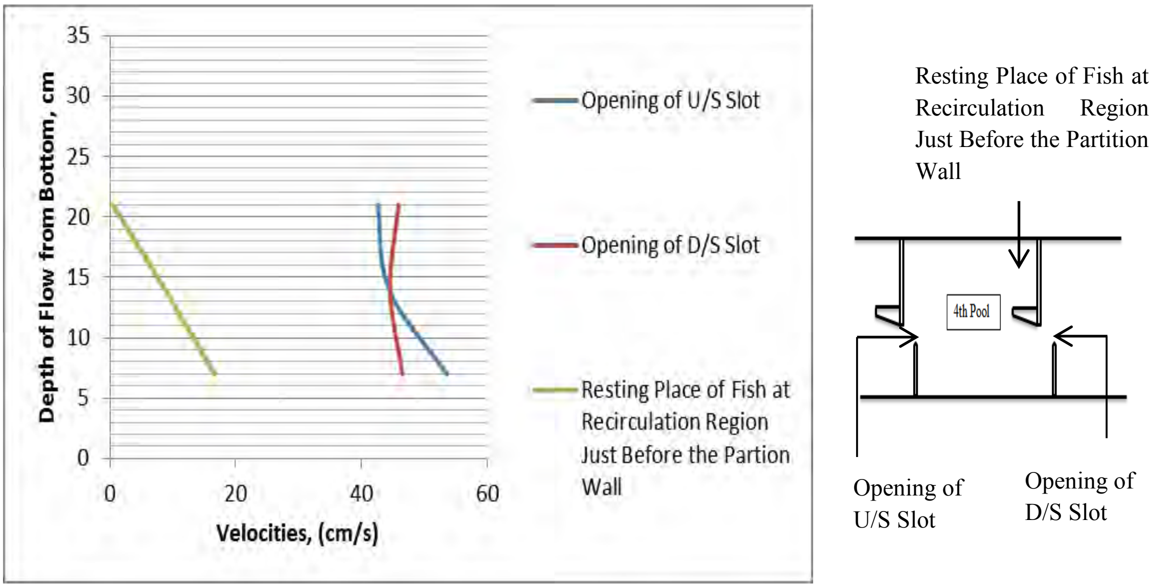


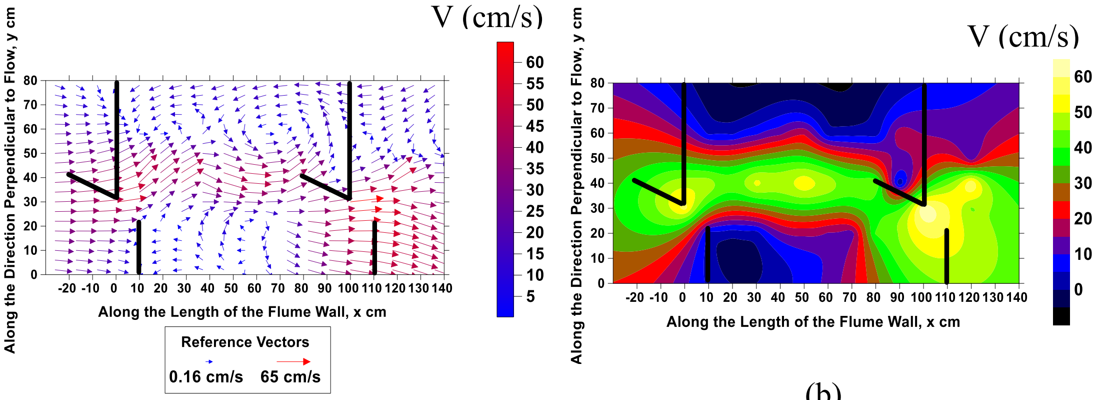
Figure 5.25: Vertical velocity profile in pool 4 for experiment run 7

Table 5.7: Reynolds number and Froude number in pool 4 for experiment run 7

Position at the Pool	Hydraulic Depths	Reynolds Number	Froude Number
Opening of Upstream Slot	0.6	173866	0.239
Opening of Downstream Slot	0.6	174622	0.240
Resting Palace of Fish at Recirculation Region Just Before the Partition Wall	0.6	34367	0.047

5.2.8 Features for Experiment Run 8 (U/S WL= 40 cm; Discharge = 75 m^3/hr)

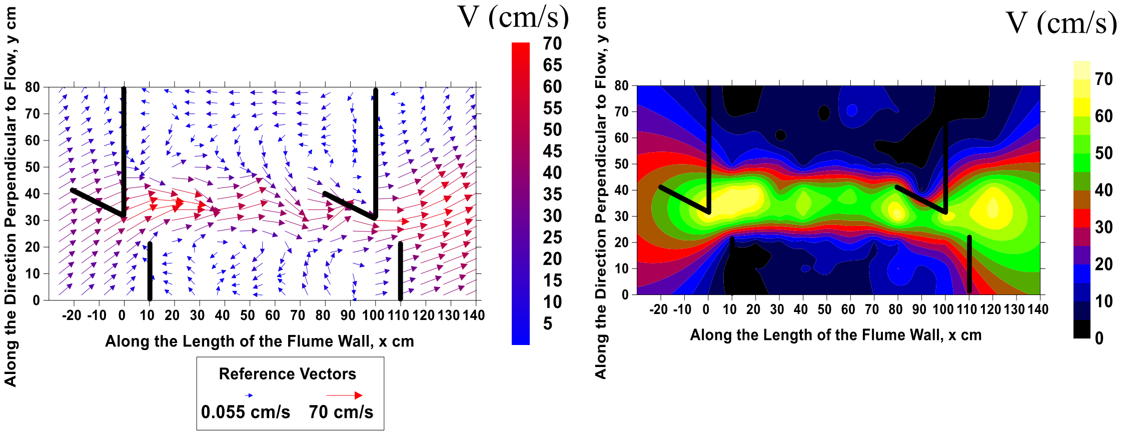
The plane velocity fields and velocity contour maps at 0.4, 0.6 and 0.8 hydraulic depths for experiment run 8 in pool 4 have been shown in figure 5.26, 5.27 and 5.28. From the velocity field analysis it is found that the flow circulation follows the pattern 1 of Design 1 (Rajaratnam et al., 1992) i.e. the flow from slot travels through the



(a)

(b)

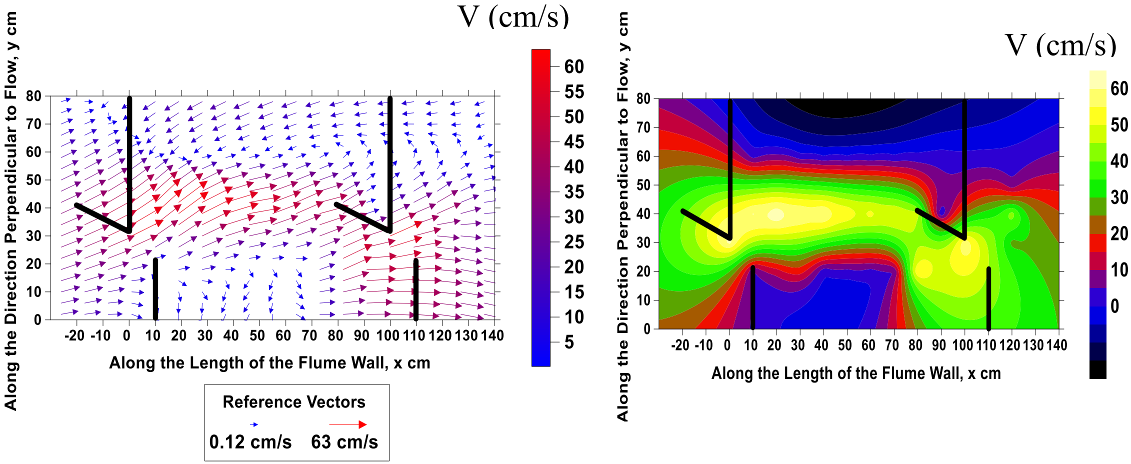
Figure 5.26: (a) Plane velocity field and (b) Velocity contour map at 0.4 hydraulic depth for experiment run 8 in Pool 4



(a)

(b)

Figure 5.27: (a) Plane velocity field and (b) Velocity contour map at 0.6 hydraulic depth for experiment run 8 in Pool 4



(b)

(a)

Figure 5.28: (a) Plane velocity field and (b) Velocity contour map at 0.8 hydraulic depth for experiment run 8 in Pool 4

center of the pool to the next slot with two recirculation region on either side of the jet. At the pool opening the flow appear almost in the form of a shooting jet. The resultant vector components starting from the slot have made different angles with the X and Y axis at different positions. This indicates that the direction of the velocity components change randomly and the flow is non-uniform. From the velocity contour map analysis it is found that the maximum magnitude of flow occurs at the opening of slot and the mainstream continues through the center of the pool to the next slot while two recirculation regions of lower velocities are created on either side of the mainstream. And these recirculation regions with lower velocities provide resting places for fish.

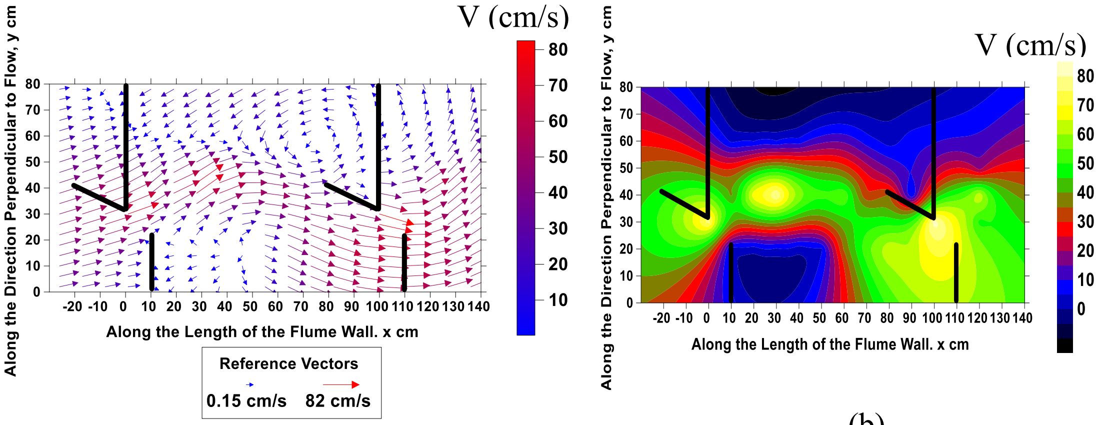
Table 5.8 shows Reynolds number and Froude number at different locations in pool 4 at 0.6 hydraulic depth for experiment run 8. By observing the values of Reynolds Number it is seen that the flow type is turbulent at selected locations which indicates that the viscous forces are very weak relative to the inertial forces and inertial forces dominate the flow. By observing the values of Froude Number it is found that the flow is subcritical at the selected locations i.e. the gravitational forces are dominant.

Table 5.8: Reynolds number and Froude number in pool 4 for experiment run 8

Position at the Pool	Hydraulic Depths	Reynolds Number	Froude Number
Opening of Upstream Slot	0.6	271931	0.408
Opening of Downstream Slot	0.6	240418	0.361
Resting Palace of Fish at Recirculation Region Just Before the Partition Wall	0.6	11542	0.017

5.2.9 Features for Experiment Run 9 (U/S WL= 40 cm; Discharge = 87 m^3/hr)

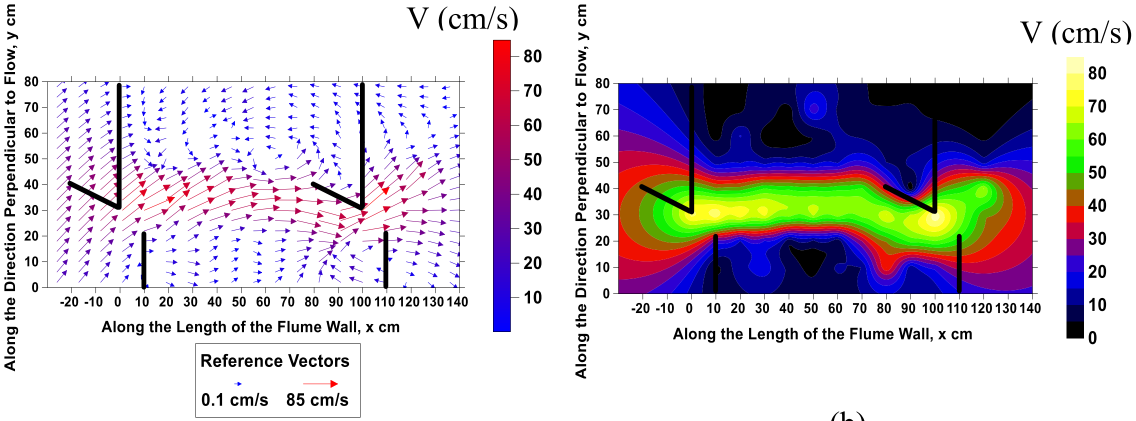
The plane velocity fields and velocity contour maps at 0.4, 0.6 and 0.8 hydraulic depths for experiment run 9 in pool 4 have been shown in figure 5.29, 5.30 and 5.31.



(a)

(b)

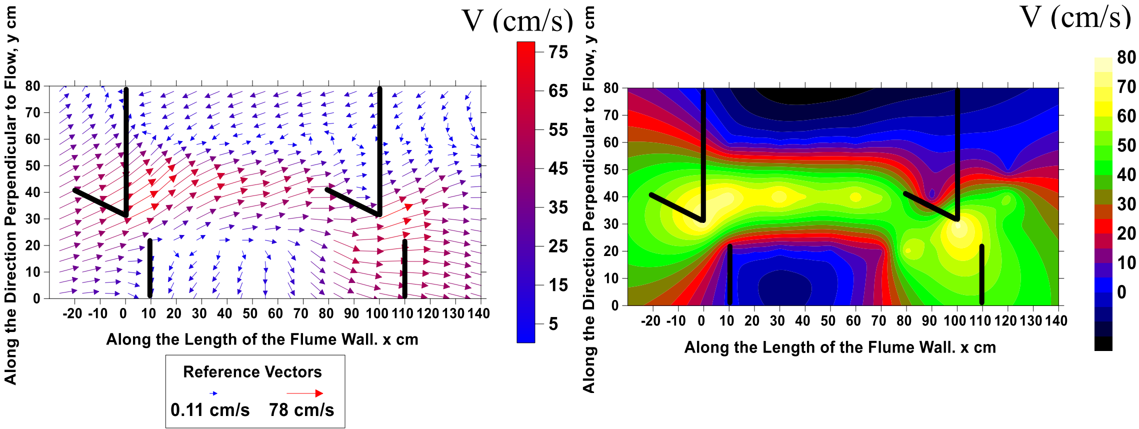
Figure 5.29: (a) Plane velocity field and (b) velocity contour map at 0.4 hydraulic depth for experiment run 9 in Pool 4



(a)

(b)

Figure 5.30: (a) Plane velocity field and (b) Velocity contour map at 0.6 hydraulic depth for experiment run 9 in Pool 4



(a)

(b)

Figure 5.31: (a) Plane velocity field and (b) Velocity contour map at 0.8 hydraulic depth for experiment run 9 in Pool 4

From the velocity field analysis it is found that the flow circulation follows the pattern 1 of Design 1 (Rajaratnam et al., 1992) i.e. the flow from slot travels through the center of the pool to the next slot with two recirculation region on either side of the jet. At the pool opening the flow appear almost in the form of a shooting jet. The resultant vector components starting from the slot have made different angles with the X and Y axis at different positions. This indicates that the direction of the velocity components change randomly and the flow is non-uniform. From the velocity contour map analysis it is found that the maximum magnitude of flow occurs at the opening of slot and the mainstream continues through the center of the pool to the next slot while two recirculation regions of lower velocities are created on either side of the mainstream. And these recirculation regions with lower velocities provide resting places for fish.

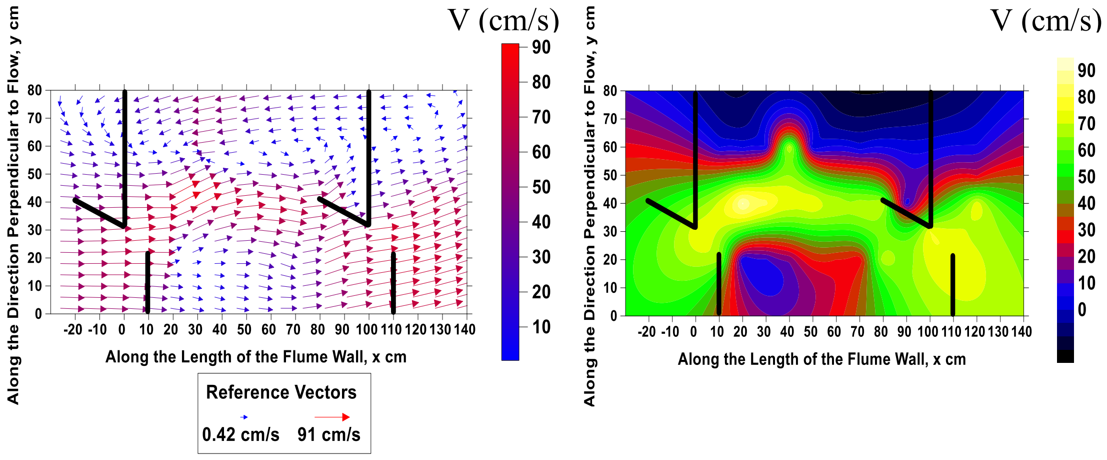
Table 5.9 shows Reynolds number and Froude number at different locations in pool 4 at 0.6 hydraulic depth for experiment run 9. By observing the values of Reynolds Number it is seen that the flow type is turbulent at selected locations which indicates that the viscous forces are very weak relative to the inertial forces and inertial forces dominate the flow. By observing the values of Froude Number it is found that the flow is subcritical at the selected locations i.e. the gravitational forces are dominant.

Table 5.9: Reynolds number and Froude number in pool 4 for experiment run 9

Position at the Pool	Hydraulic Depths	Reynolds Number	Froude Number
Opening of Upstream Slot	0.6	241461	0.464
Opening of Downstream Slot	0.6	265605	0.511
Resting Palace of Fish at Recirculation Region Just Before the Partition Wall	0.6	19177	0.037

5.2.10 Features for Experiment Run 10 (U/S WL = 40 cm; Discharge = 96 m^3/hr)

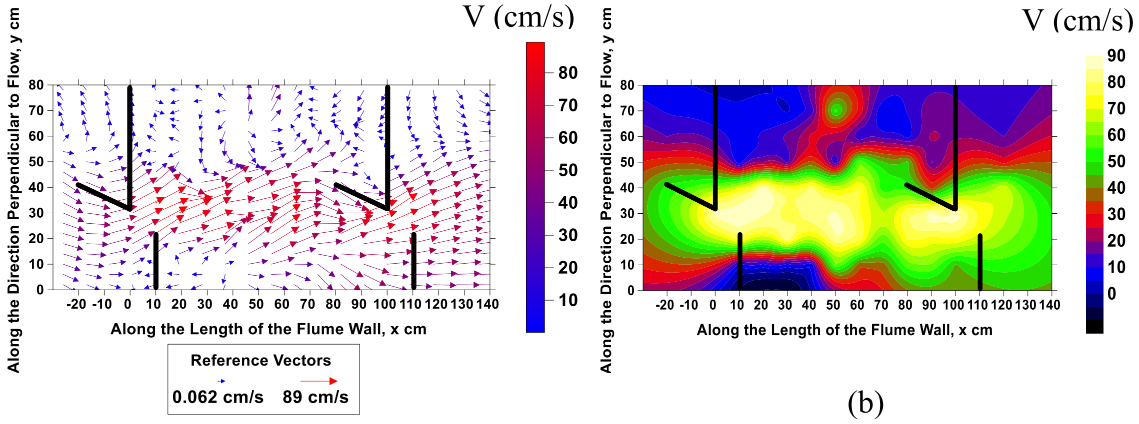
The plane velocity fields and velocity contour maps at 0.4, 0.6 and 0.8 hydraulic depths for experiment run 10 in pool 4 have been shown in figure 5.32, 5.33 and 5.34.



(a)

(b)

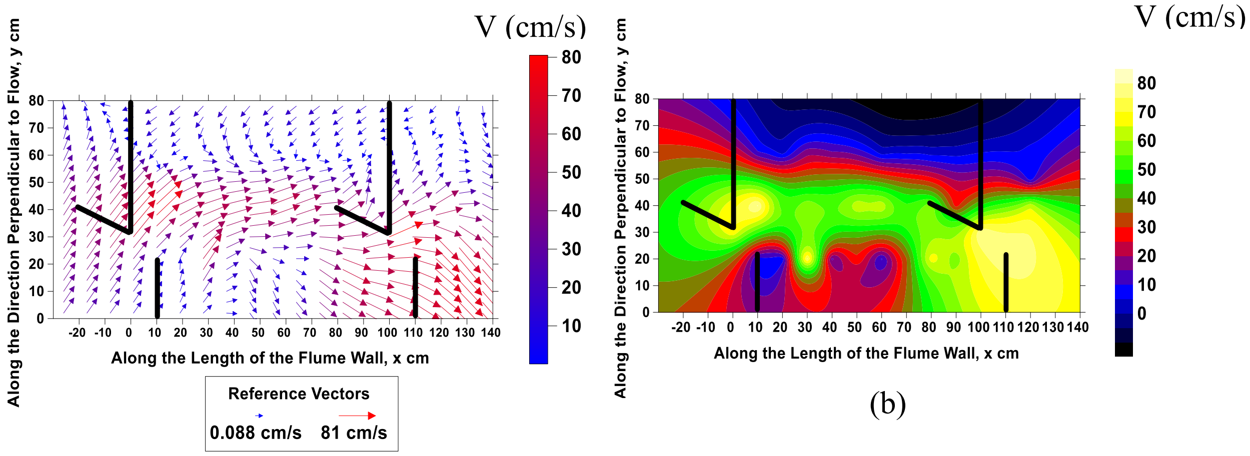
Figure 5.32: (a) Plane velocity field and (b) Velocity contour map at 0.4 hydraulic depth for experiment run 10 in pool 4



(a)

(b)

Figure 5.33: (a) Plane velocity field and (b) Velocity contour map at 0.6 hydraulic depth for experiment run 10 in pool 4



(a)

(b)

Figure 5.34: (a) Plane velocity field and (b) Velocity contour map at 0.8 hydraulic depth for experiment run 10 in pool 4

From the velocity field analysis it is found that the flow circulation follows the pattern 1 of Design 1 (Rajaratnam et al., 1992) i.e. the flow from slot travels through the center of the pool to the next slot with two recirculation region on either side of the jet. At the pool opening the flow appear almost in the form of a shooting jet. The resultant vector components starting from the slot have made different angles with the X and Y axis at different positions. This indicates that the direction of the velocity components change randomly and the flow is non-uniform. From the velocity contour map analysis it is found that the maximum magnitude of flow occurs at the opening of slot and the mainstream continues through the center of the pool to the next slot while two recirculation regions of lower velocities are created on either side of the mainstream. And these recirculation regions with lower velocities provide resting places for fish.

The velocity distribution in a channel section depends on some factors e.g. the unusual shape of the section, the roughness of the channel and the presence of bends. On a bend the velocity increases greatly at the convex side, owing to the centrifugal action of flow (Chow, 1973). The vertical velocity profile in pool 4 for experiment run 10 is shown at Figure 5.35. Vertical velocity profiles have been presented at three particular places inside a pool based on the collected velocity data at 0.4, 0.6 and 0.8 hydraulic depths. The magnitude of velocity at opening of both upstream and downstream slot is found higher at 0.6 hydraulic depth than depth at 0.4 and 0.8. The magnitude of higher velocity at a certain hydraulic depth also represents the attractive velocity of fish species at that hydraulic depth at a particular place inside a pool. The vertical velocity profile at the resting place of fish at recirculation region just before the partition wall represents the velocities of very small magnitude which matches with the theory of vertical slot fish pass. Here the magnitudes of velocities are almost same.

Table 5.10 shows Reynolds number and Froude number at different locations in Pool 4 at 0.6 hydraulic depth for experiment run 10. By observing the values of Reynolds Number it is seen that the flow type is turbulent at selected locations which indicates that the viscous forces are very weak relative to the inertial forces and inertial forces dominate the flow. By observing the values of Froude Number it is found that the flow is subcritical at the selected locations i.e. the gravitational forces are dominant.

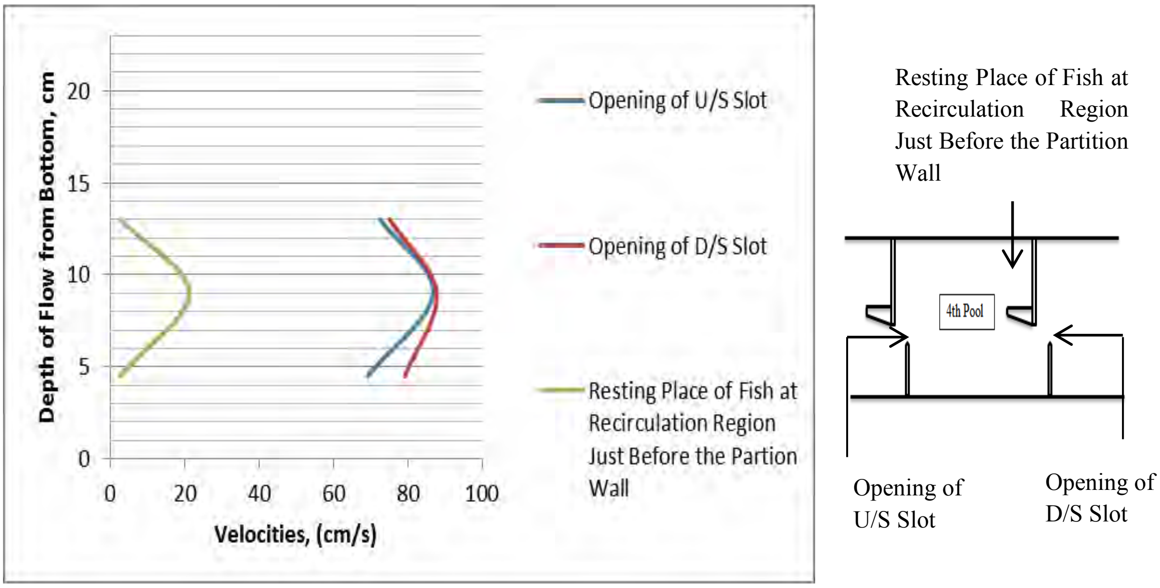


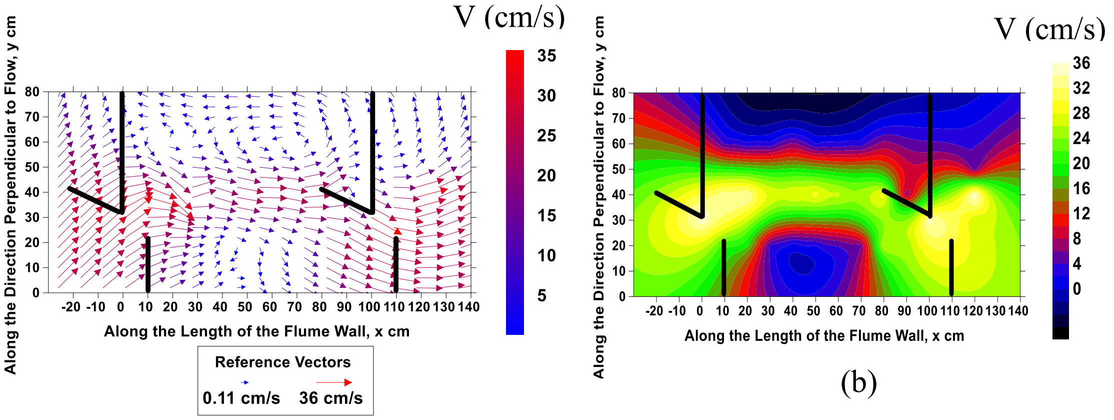
Figure 5.35: Vertical velocity profile in pool 4 for experiment run 10

Table 5.10: Reynolds number and Froude number in pool 4 for experiment run 10

Position at the Pool	Hydraulic Depths	Reynolds Number	Froude Number
Opening of Upstream Slot	0.6	223719	0.578
Opening of Downstream Slot	0.6	226129	0.584
Resting Palace of Fish at Recirculation Region Just Before the Partition Wall	0.6	54637	0.141

5.2.11 Features for Experiment Run 11 (U/S WL = 40 cm; Discharge = 37 m^3/hr)

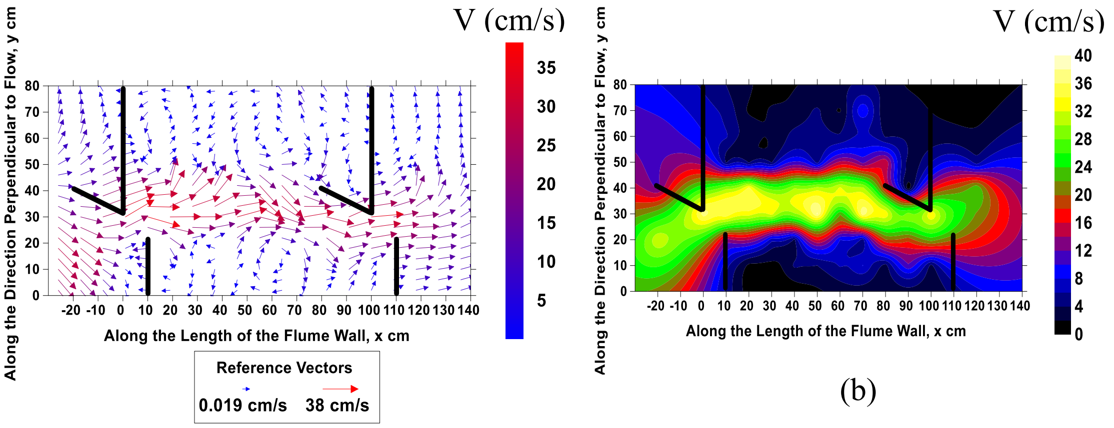
The plane velocity fields and velocity contour maps at 0.4, 0.6 and 0.8 hydraulic depths for experiment run 11 in pool 4 have been shown in figure 5.36, 5.37 and 5.38. From the velocity field analysis it is found that the flow circulation follows the pattern 1 of Design 1 (Rajaratnam et al., 1992) i.e. the flow from slot travels through the center of the pool to the next slot with two recirculation region on either side of the



(a)

(b)

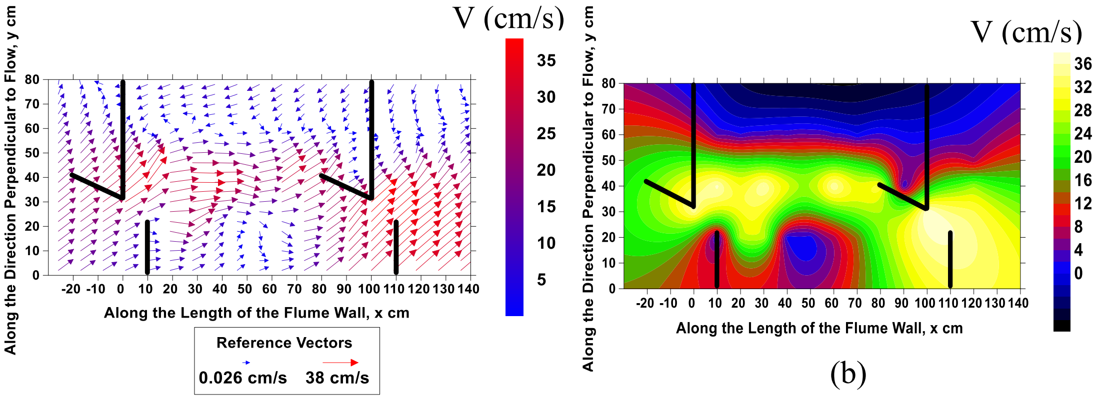
Figure 5.36: (a) Plane velocity field and (b) Velocity contour map at 0.4 hydraulic depth for experiment run 11 in pool 4



(a)

(b)

Figure 5.37: (a) Plane velocity field and (b) Velocity contour map at 0.6 hydraulic depth for experiment run 11 in pool 4



(a)

(b)

Figure 5.38: (a) Plane velocity field and (b) Velocity contour map at 0.8 hydraulic depth for experiment run 11 in pool 4

jet. At the pool opening the flow appear almost in the form of a shooting jet. The resultant vector components starting from the slot have made different angles with the X and Y axis at different positions. This indicates that the direction of the velocity components change randomly and the flow is non-uniform. From the velocity contour map analysis it is found that the maximum magnitude of flow occurs at the opening of slot and the mainstream continues through the center of the pool to the next slot while two recirculation regions of lower velocities are created on either side of the mainstream. And these recirculation regions with lower velocities provide resting places for fish.

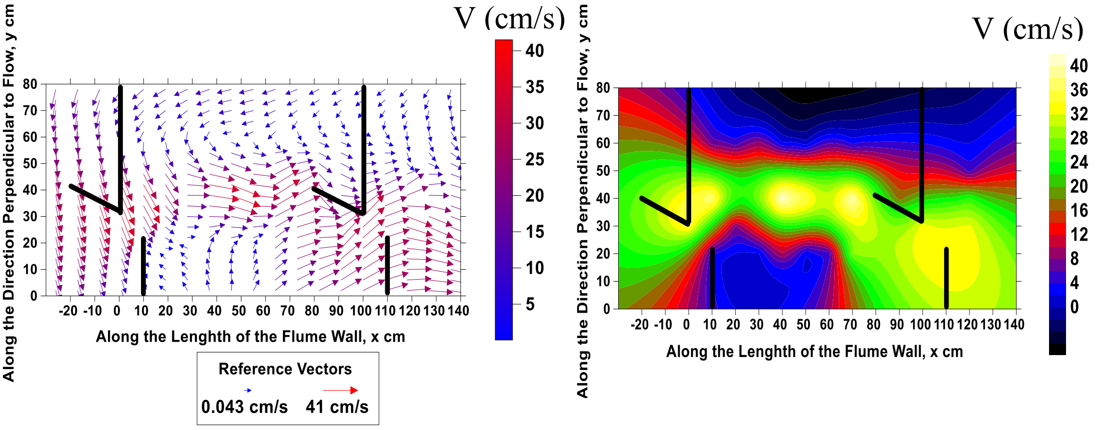
Table 5.11 shows Reynolds number and Froude number at different locations in pool 4 at 0.6 hydraulic depth for experiment run 11. By observing the values of Reynolds Number it is seen that the flow type is turbulent at selected locations which indicates that the viscous forces are very weak relative to the inertial forces and inertial forces dominate the flow. By observing the values of Froude Number it is found that the flow is subcritical at the selected locations i.e. the gravitational forces are dominant.

Table 5.11: Reynolds number and Froude number in pool 4 for experiment run 11

Position at the Pool	Hydraulic Depths	Reynolds Number	Froude Number
Opening of Upstream Slot	0.6	168384	0.186
Opening of Downstream Slot	0.6	154443	0.170
Resting Palace of Fish at Recirculation Region Just Before the Partition Wall	0.6	16708	0.018

5.2.12 Features for Experiment Run 12 (U/S WL = 40 cm; Discharge = 52 m^3/hr)

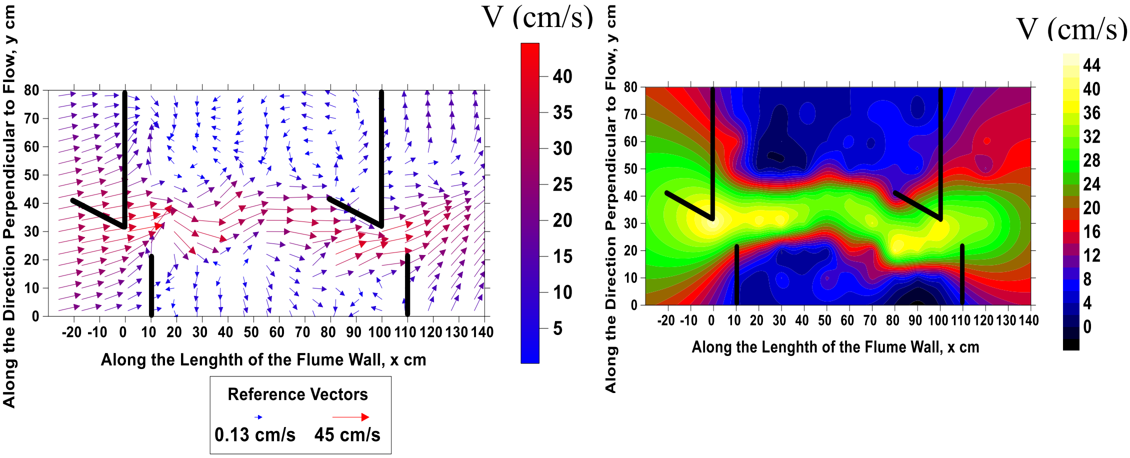
The plane velocity fields and velocity contour maps at 0.4, 0.6 and 0.8 hydraulic depths for experiment run 12 in pool 4 have been shown in figure 5.39, 5.40 and 5.41. From the velocity field analysis it is found that the flow circulation follows the pattern



(a)

(b)

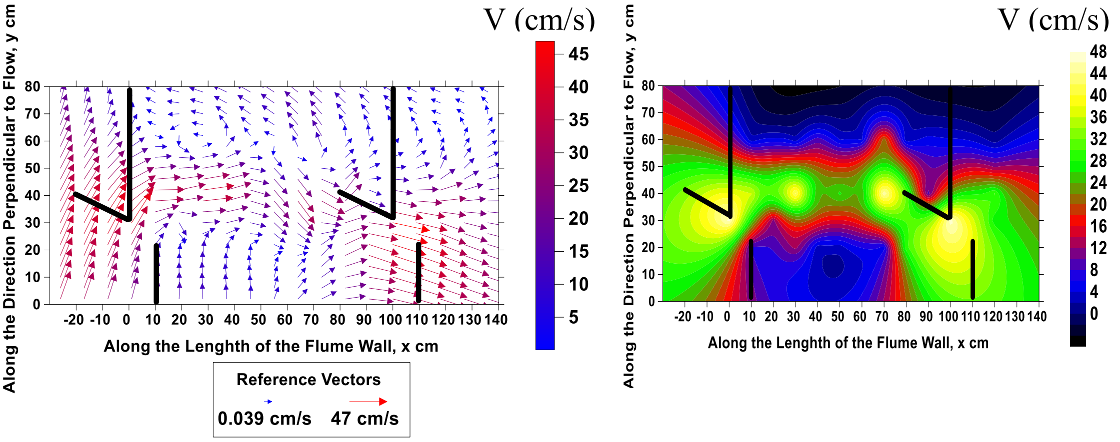
Figure 5.39: (a) Plane velocity field and (b) Velocity contour map at 0.4 hydraulic depth for experiment run 12 in Pool 4



(b)

(a)

Figure 5.40: (a) Plane velocity field and (b) Velocity contour map at 0.6 hydraulic depth for experiment run 12 in Pool 4



(a)

(b)

Figure 5.41: (a) Plane velocity field and (b) Velocity contour map at 0.8 hydraulic depth for experiment run 12 in Pool 4

1 of Design 1 (Rajaratnam et al., 1992) i.e. the flow from slot travels through the center of the pool to the next slot with two recirculation region on either side of the jet. At the pool opening the flow appear almost in the form of a shooting jet. The resultant vector components starting from the slot have made different angles with the X and Y axis at different positions. This indicates that the direction of the velocity components change randomly and the flow is non-uniform. From the velocity contour map analysis it is found that the maximum magnitude of flow occurs at the opening of slot and the mainstream continues through the center of the pool to the next slot while two recirculation regions of lower velocities are created on either side of the mainstream. And these recirculation regions with lower velocities provide resting places for fish.

The velocity distribution in a channel section depends on some factors e.g. the unusual shape of the section, the roughness of the channel and the presence of bends. On a bend the velocity increases greatly at the convex side, owing to the centrifugal action of flow (Chow, 1973). The vertical velocity profile in pool 4 for experiment run 12 is shown at Figure 5.42. Vertical velocity profiles have been presented at three particular places inside a pool based on the collected velocity data at 0.4, 0.6 and 0.8 hydraulic depths. The magnitude of velocity at opening of both upstream and downstream slot decreases with distance from the bottom. The magnitude of velocity at opening of both upstream and downstream slot is found higher at 0.8 hydraulic depth than depth at 0.6 and 0.4. The magnitude of higher velocity at a certain hydraulic depth also represents the attractive velocity of fish species at that hydraulic depth at a particular place inside a pool. The vertical velocity profile at the resting place of fish at recirculation region just before the partition wall represents the velocities of very small magnitude which matches with the theory of vertical slot fish pass. Here the magnitudes of velocities are almost same.

Table 5.12 shows Reynolds number and Froude number at different locations in pool 4 at 0.6 hydraulic depth for experiment run 12. By observing the values of Reynolds Number it is seen that the flow type is turbulent at selected locations which indicates that the viscous forces are very weak relative to the inertial forces and inertial forces

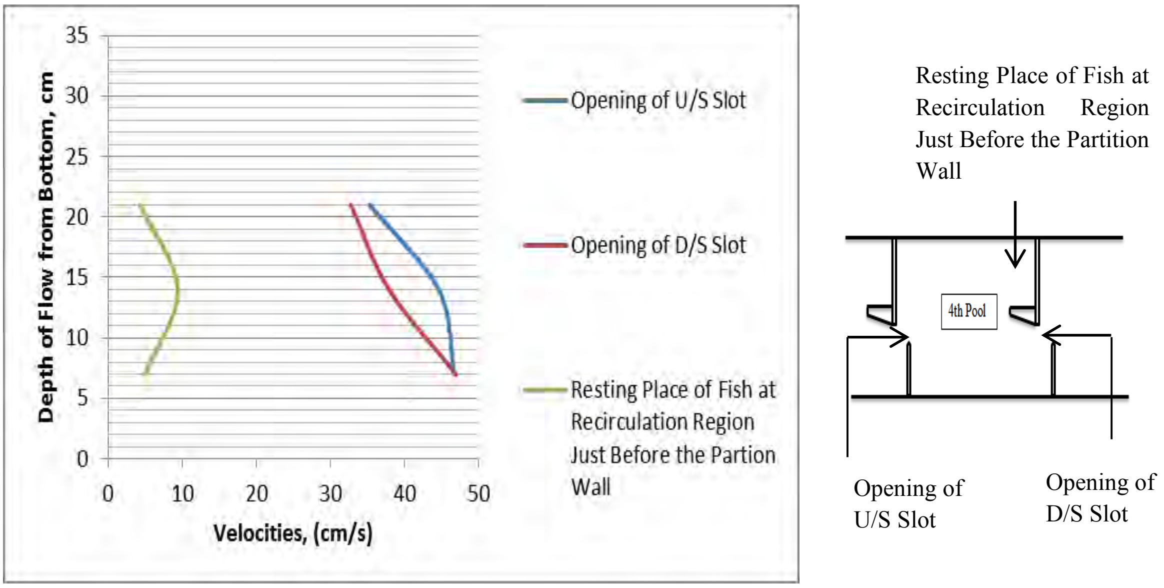


Figure 5.42: Vertical velocity profile in pool 4 for experiment run 12

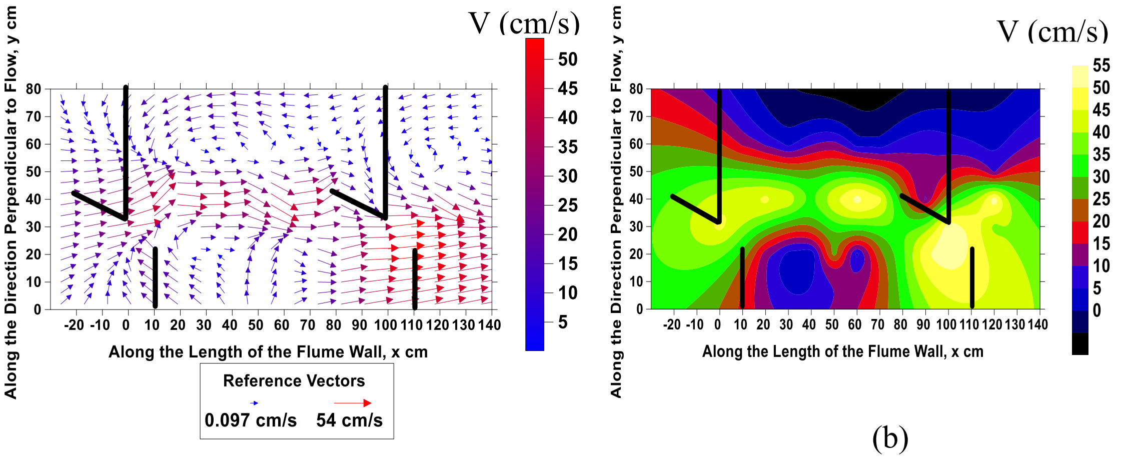
dominate the flow. By observing the values of Froude Number it is found that the flow is subcritical at the selected locations i.e. the gravitational forces are dominant.

Table 5. 12 : Reynolds number and Froude number in pool 4 for experiment run 12

Position at the Pool	Hydraulic Depths	Reynolds Number	Froude Number
Opening of Upstream Slot	0.6	189943	0.231
Opening of Downstream Slot	0.6	161425	0.196
Resting Palace of Fish at Recirculation Region Just Before the Partition Wall	0.6	40019	0.048

5.2.13 Features for Experiment Run 13 (U/S WL= 60 cm; Discharge =100 m^3/hr)

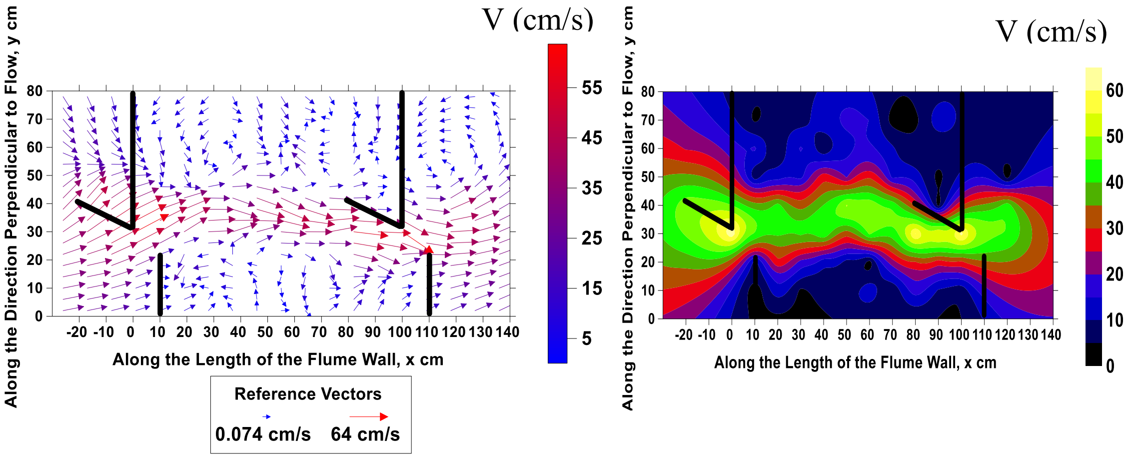
The plane velocity fields and velocity contour maps at 0.4, 0.6 and 0.8 hydraulic depths for experiment run 13 in pool 4 have been shown in figure 5.43, 5.44 and 5.45. From the velocity field analysis it is found that the flow circulation follows the pattern 1 of Design 1 (Rajaratnam et al., 1992) i.e. the flow from slot travels through the center of the pool to the next slot with two recirculation region on either side of the



(a)

(b)

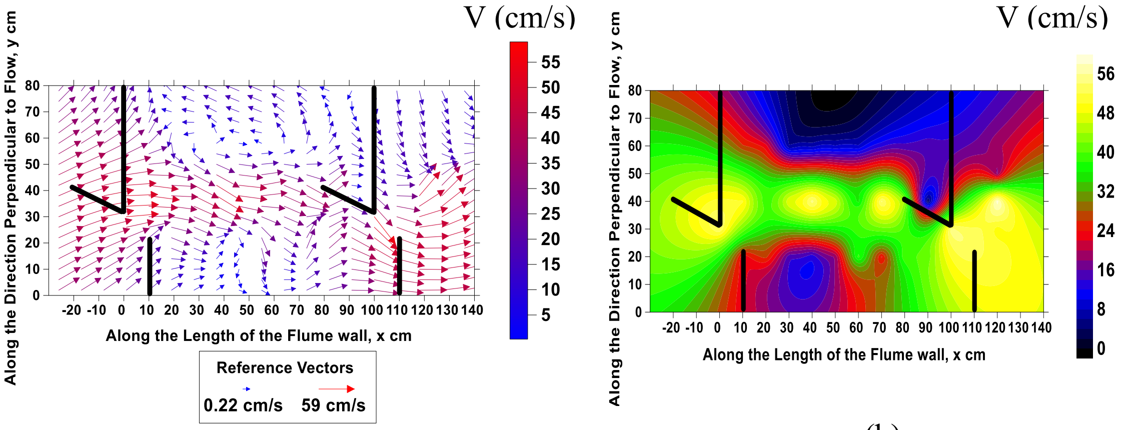
Figure 5.43: (a) Plane velocity field and (b) Velocity contour map at 0.4 hydraulic depth for experiment run 13 in pool 4



(a)

(b)

Figure 5.44: (a) Plane velocity field and (b) Velocity contour map at 0.6 hydraulic depth for experiment run 13 in pool 4



(a)

(b)

Figure 5.45: (a) Plane velocity field and (b) Velocity contour map at 0.8 hydraulic depth for experiment run 13 in Pool 4

jet. At the pool opening the flow appear almost in the form of a shooting jet. The resultant vector components starting from the slot have made different angles with the X and Y axis at different positions. This indicates that the direction of the velocity components change randomly and the flow is non-uniform. From the velocity contour map analysis it is found that the maximum magnitude of flow occurs at the opening of slot and the mainstream continues through the center of the pool to the next slot while two recirculation regions of lower velocities are created on either side of the mainstream. And these recirculation regions with lower velocities provide resting places for fish.

The velocity distribution in a channel section depends on some factors e.g. the unusual shape of the section, the roughness of the channel and the presence of bends. On a bend the velocity increases greatly at the convex side, owing to the centrifugal action of flow (Chow, 1973). The vertical velocity profile in pool 4 for experiment run 13 is shown at Figure 5.46. Vertical velocity profiles have been presented at three particular places inside a pool based on the collected velocity data at 0.4, 0.6 and 0.8 hydraulic depths. The magnitude of velocity at opening of both upstream and downstream slot is found higher at 0.6 hydraulic depth than depth at 0.8 and 0.4. The magnitude of higher velocity at a certain hydraulic depth also represents the attractive velocity of fish species at that hydraulic depth at a particular place inside a pool. The vertical velocity profile at the resting place of fish at recirculation region just before the partition wall represents the velocities of very small magnitude which matches with the theory of vertical slot fish pass. Here the magnitudes of velocities are almost same.

Table 5.13 shows Reynolds number and Froude number at different locations in pool 4 at 0.6 hydraulic depth for experiment run 13. By observing the values of Reynolds Number it is seen that the flow type is turbulent at selected locations which indicates that the viscous forces are very weak relative to the inertial forces and inertial forces dominate the flow. By observing the values of Froude Number it is found that the flow is subcritical at the selected locations i.e. the gravitational forces are dominant.

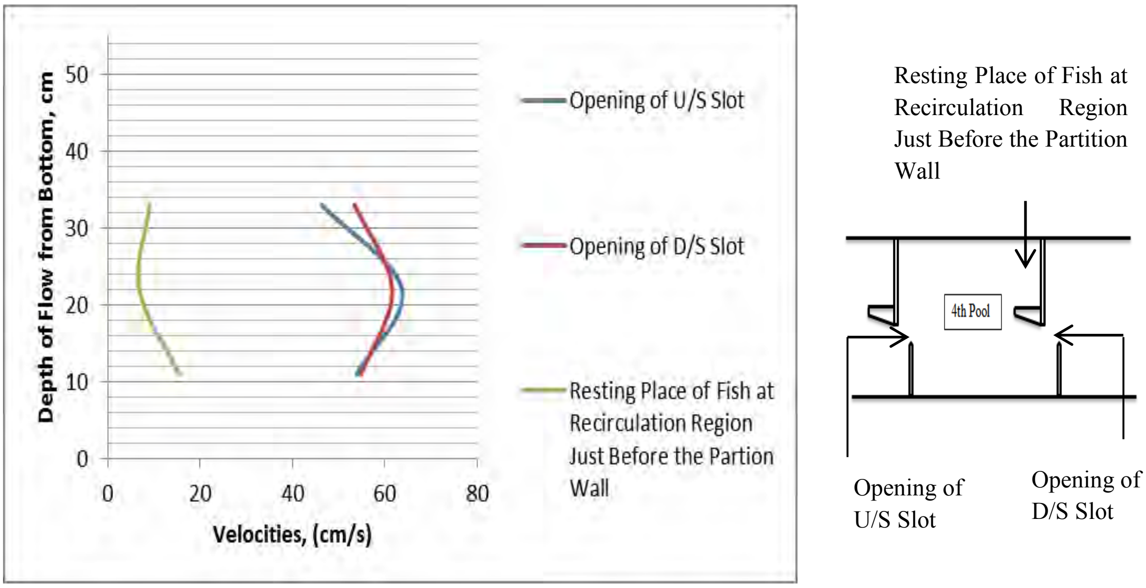


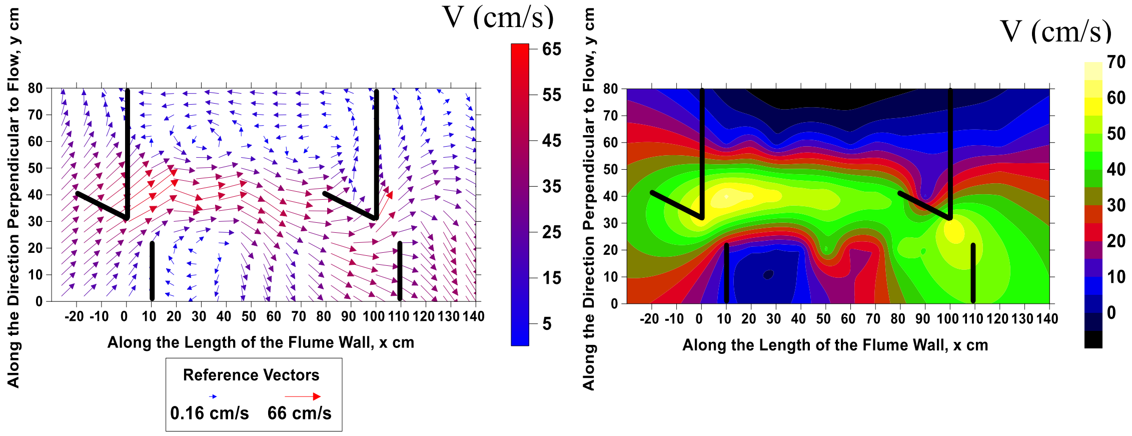
Figure 5.46 : Vertical velocity profile in pool 4 for experiment run 13

Table 5.13: Reynolds number and Froude number in pool 4 for experiment run 13

Position at the Pool	Hydraulic Depths	Reynolds Number	Froude Number
Opening of Upstream Slot	0.6	395910	0.273
Opening of Downstream Slot	0.6	382800	0.263
Resting Palace of Fish at Recirculation Region Just Before the Partition Wall	0.6	42420	0.029

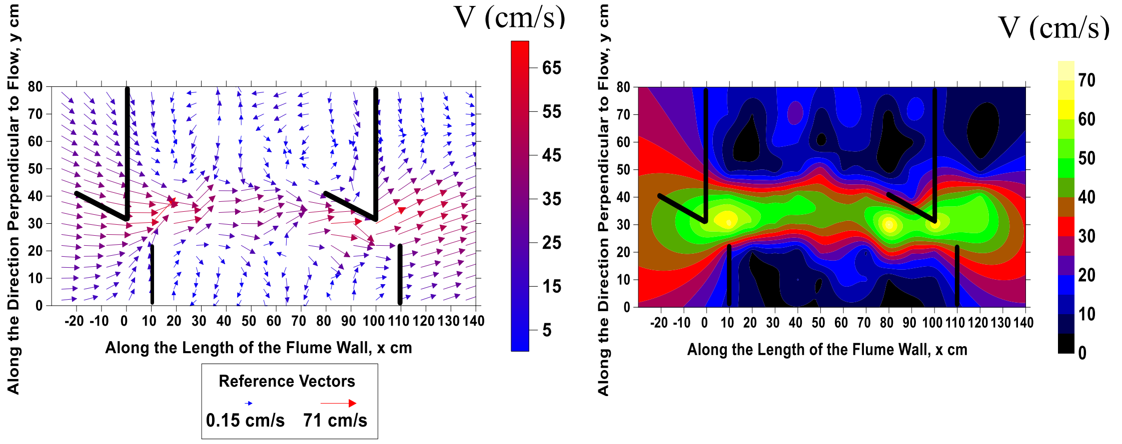
5.2.14 Features for Experiment Run 14 (U/S WL =60 cm; Discharge =110 m^3/hr)

The plane velocity fields and velocity contour maps at 0.4, 0.6 and 0.8 hydraulic depths for experiment run 14 in pool 4 have been shown in figure 5.47, 5.48 and 5.49. From the velocity field analysis it is found that the flow circulation follows the pattern 1 of Design 1 (Rajaratnam et al., 1992) i.e. the flow from slot travels through the center of the pool to the next slot with two recirculation region on either side of the jet. At the pool opening the flow appear almost in the form of a shooting jet. The resultant vector components starting from the slot have made different angles with the



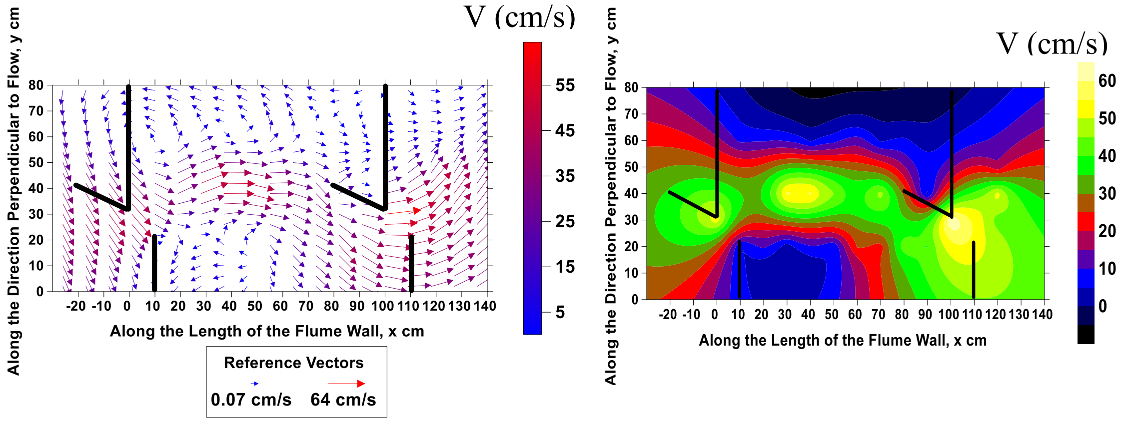
(a) (b)

Figure 5.47: (a) Plane velocity field and (b) Velocity contour map at 0.4 hydraulic depth for experiment run 14 in Pool 4



(a) (b)

Figure 5.48: (a) Plane velocity field and (b) Velocity contour map at 0.6 hydraulic depth for experiment run 14 in pool 4



(a) (b)

Figure 5.49: (a) Plane velocity field and (b) Velocity contour map at 0.8 hydraulic depth for experiment run 14 in Pool 4

X and Y axis at different positions. This indicates that the direction of the velocity components change randomly and the flow is non-uniform. From the velocity contour map analysis it is found that the maximum magnitude of flow occurs at the opening of slot and the mainstream continues through the center of the pool to the next slot while two recirculation regions of lower velocities are created on either side of the mainstream. And these recirculation regions with lower velocities provide resting places for fish.

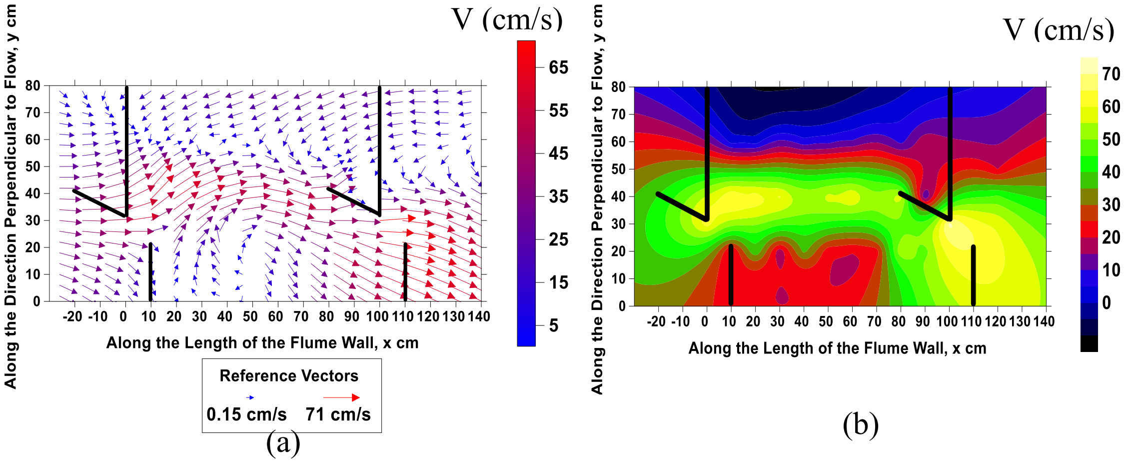
Table 5.14 shows Reynolds number and Froude number at different locations in pool 4 at 0.6 hydraulic depth for experiment run 14. By observing the values of Reynolds Number it is seen that the flow type is turbulent at selected locations which indicates that the viscous forces are very weak relative to the inertial forces and inertial forces dominate the flow. By observing the values of Froude Number it is found that the flow is subcritical at the selected locations i.e. the gravitational forces are dominant.

Table 5.14: Reynolds number and Froude number in Pool 4 for experiment run 14

Position at the Pool	Hydraulic Depths	Reynolds Number	Froude Number
Opening of Upstream Slot	0.6	436420	0.309
Opening of Downstream Slot	0.6	365224	0.259
Resting Palace of Fish at Recirculation Region Just Before the Partition Wall	0.6	23390	0.017

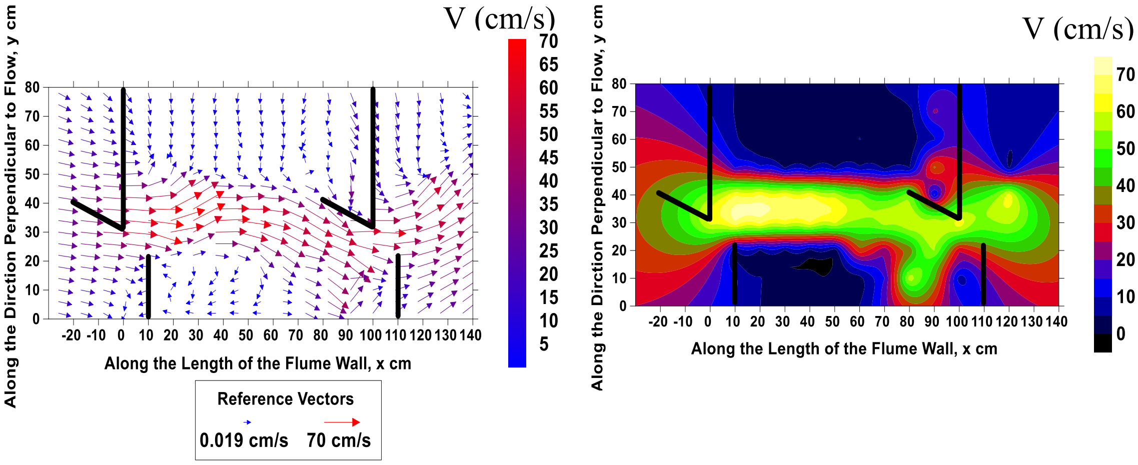
5.2.15 Features for Experiment Run 15 (U/S WL =60 cm; Discharge =125 m^3/hr)

The plane velocity fields and velocity contour maps at 0.4, 0.6 and 0.8 hydraulic depths for experiment run 15 in pool 4 have been shown in figure 5.50, 5.51 and 5.52. From the velocity field analysis it is found that the flow circulation follows the pattern 1 of Design 1 (Rajaratnam et al., 1992) i.e. the flow from slot travels through the center of the pool to the next slot with two recirculation region on either side of the



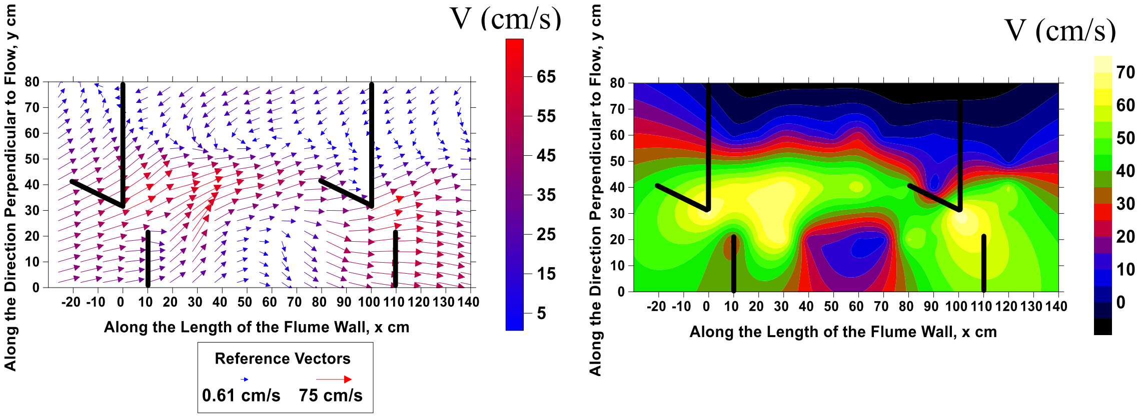
(a) (b)

Figure 5.50: (a) Plane velocity field and (b) Velocity contour map at 0.4 hydraulic depth for experiment run 15 in pool 4



(a) (b)

Figure 5.51: (a) Plane velocity field and (b) Velocity contour map at 0.6 hydraulic depth for experiment run 15 in Pool 4



(a) (b)

Figure 5.52: (a) Plane velocity field and (b) Velocity contour map at 0.8 hydraulic depth for experiment run 15 in pool 4

jet. At the pool opening the flow appear almost in the form of a shooting jet. The resultant vector components starting from the slot have made different angles with the X and Y axis at different positions. This indicates that the direction of the velocity components change randomly and the flow is non-uniform. From the velocity contour map analysis it is found that the maximum magnitude of flow occurs at the opening of slot and the mainstream continues through the center of the pool to the next slot while two recirculation regions of lower velocities are created on either side of the mainstream. And these recirculation regions with lower velocities provide resting places for fish.

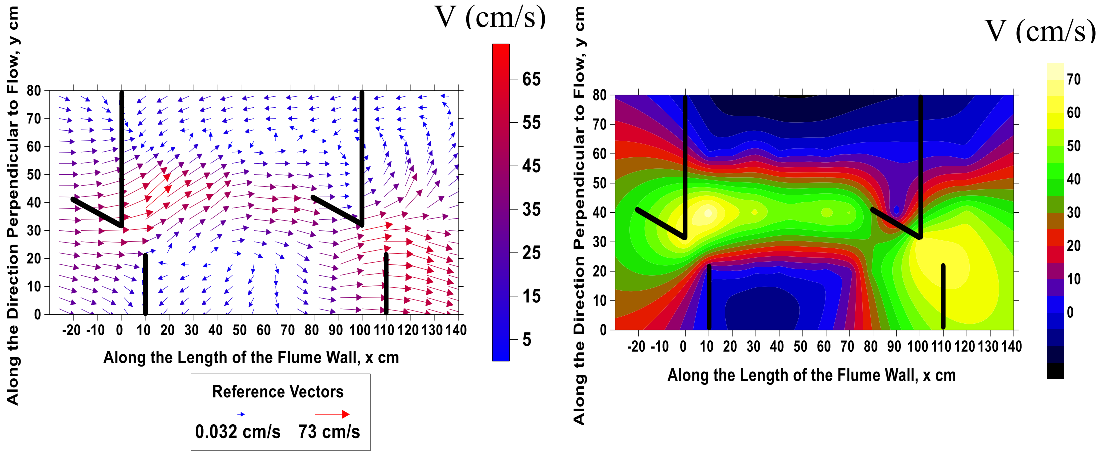
Table 5.15 shows Reynolds number and Froude number at different locations in pool 4 at 0.6 hydraulic depth for experiment run 15. By observing the values of Reynolds Number it is seen that the flow type is turbulent at selected locations which indicates that the viscous forces are very weak relative to the inertial forces and inertial forces dominate the flow. By observing the values of Froude Number it is found that the flow is subcritical at the selected locations i.e. the gravitational forces are dominant.

Table 5.15: Reynolds number and Froude number in pool 4 for experiment run 15

Position at the Pool	Hydraulic Depths	Reynolds Number	Froude Number
Opening of Upstream Slot	0.6	358359	0.272
Opening of Downstream Slot	0.6	373788	0.284
Resting Palace of Fish at Recirculation Region Just Before the Partition Wall	0.6	55364	0.042

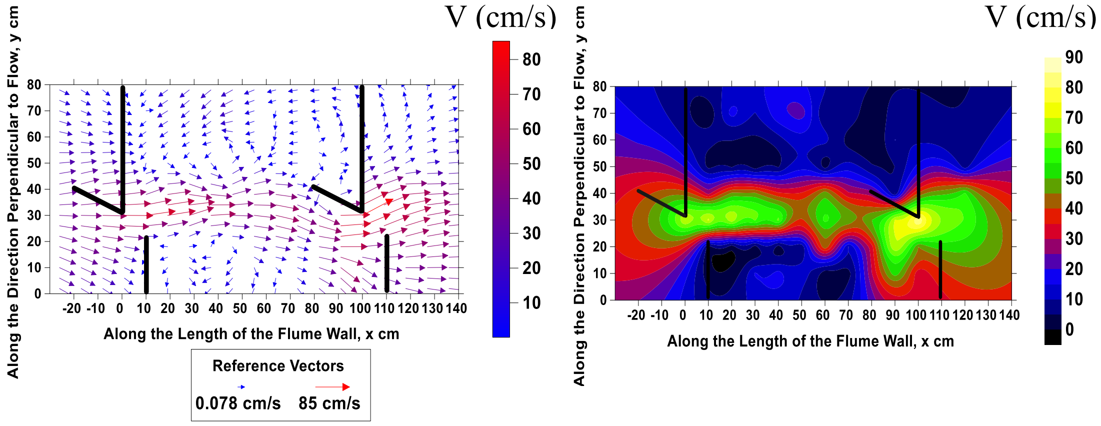
5.2.16 Features for Experiment Run 16 (U/S WL =60 cm; Discharge =145 m^3/hr)

The plane velocity fields and velocity contour maps at 0.4, 0.6 and 0.8 hydraulic depths for experiment run 16 in pool 4 have been shown in figure 5.53, 5.54 and 5.55. From the velocity field analysis it is found that the flow circulation follows the pattern



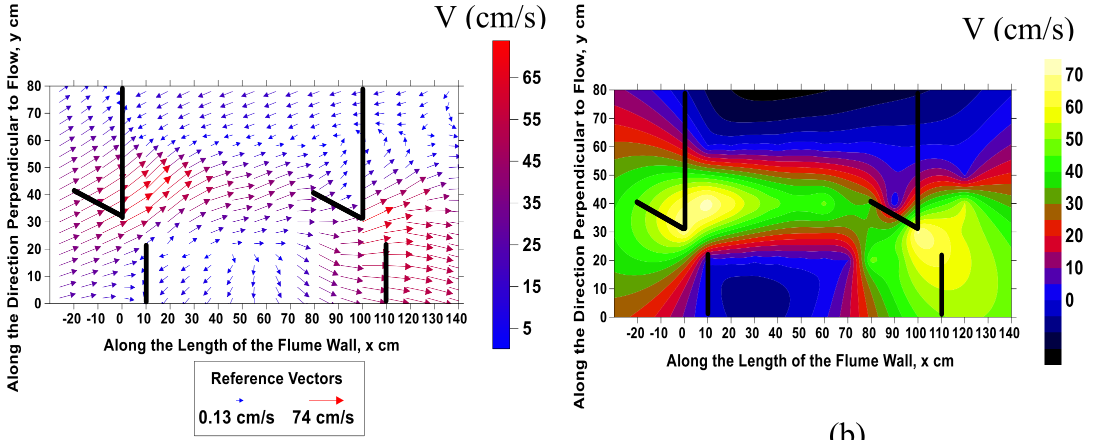
(a) (b)

Figure 5.53: (a) Plane velocity field and (b) Velocity contour map at 0.4 hydraulic depth for experiment run 16 in Pool 4



(a) (b)

Figure 5.54: (a) Plane velocity field and (b) Velocity contour map at 0.6 hydraulic depth for experiment run 16 in pool 4



(a) (b)

Figure 5.55: (a) Plane velocity field and (b) Velocity contour map at 0.8 hydraulic depth for experiment run 16 in pool 4

1 of Design 1 (Rajaratnam et al., 1992) i.e. the flow from slot travels through the center of the pool to the next slot with two recirculation region on either side of the jet. At the pool opening the flow appear almost in the form of a shooting jet. The resultant vector components starting from the slot have made different angles with the X and Y axis at different positions. This indicates that the direction of the velocity components change randomly and the flow is non-uniform. From the velocity contour map analysis it is found that the maximum magnitude of flow occurs at the opening of slot and the mainstream continues through the center of the pool to the next slot while two recirculation regions of lower velocities are created on either side of the mainstream. And these recirculation regions with lower velocities provide resting places for fish.

The velocity distribution in a channel section depends on some factors e.g. the unusual shape of the section, the roughness of the channel and the presence of bends. On a bend the velocity increases greatly at the convex side, owing to the centrifugal action of flow (Chow, 1973). The vertical velocity profile in pool 4 for experiment run 16 is shown at Figure 5.56. Vertical velocity profiles have been presented at three particular places inside a pool based on the collected velocity data at 0.4, 0.6 and 0.8 hydraulic depths. The magnitude of velocity at opening of both upstream and downstream slot is found higher at 0.6 hydraulic depth than depth at 0.8 and 0.4. The magnitude of higher velocity at a certain hydraulic depth also represents the attractive velocity of fish species at that hydraulic depth at a particular place inside a pool. The vertical velocity profile at the resting place of fish at recirculation region just before the partition wall represents the velocities of very small magnitude which matches with the theory of vertical slot fish pass. Here the magnitudes of velocities are almost same.

Table 5.16 shows Reynolds number and Froude number at different locations in pool 4 at 0.6 hydraulic depth for experiment run 16. By observing the values of Reynolds Number it is seen that the flow type is turbulent at selected locations which indicates that the viscous forces are very weak relative to the inertial forces and inertial forces dominate the flow. By observing the values of Froude Number it is found that the flow is subcritical at the selected locations i.e. the gravitational forces are dominant

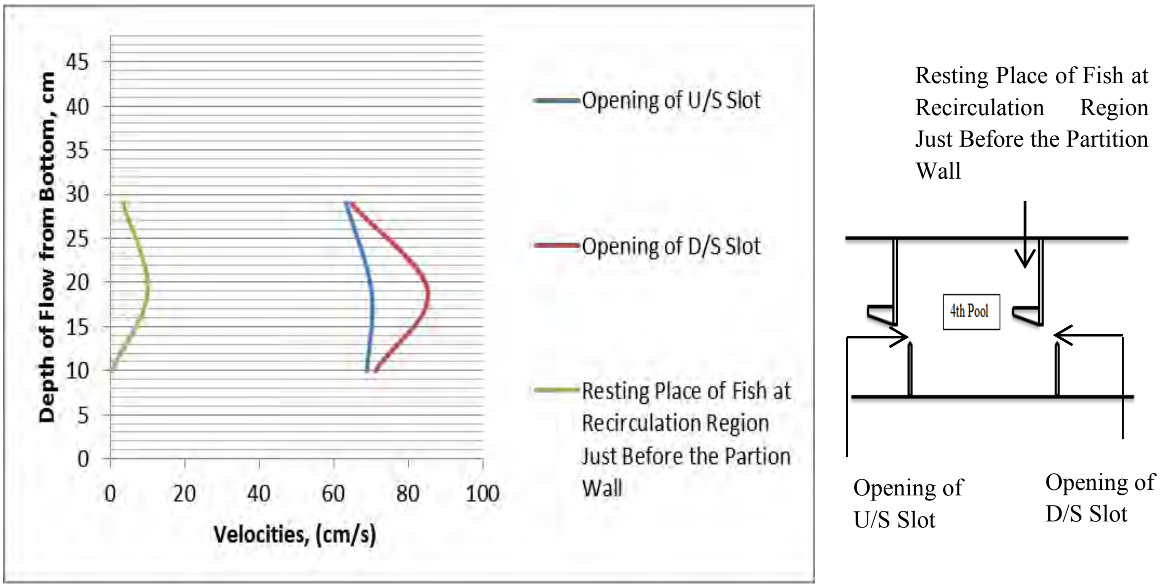


Figure 5.56: Vertical velocity profile in pool 4 for experiment run 16

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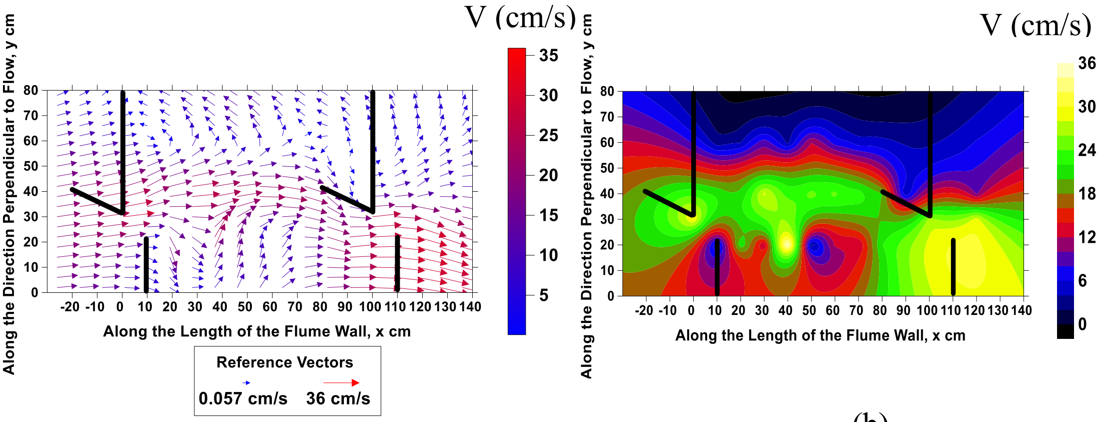
Table 5.16: Reynolds number and Froude number in pool 4 for experiment run 16

Position at the Pool	Hydraulic Depths	Reynolds Number	Froude Number
Opening of Upstream Slot	0.6	385033	0.320
Opening of Downstream Slot	0.6	467976	0.389
Resting Palace of Fish at Recirculation Region Just Before the Partition Wall	0.6	55442	0.046

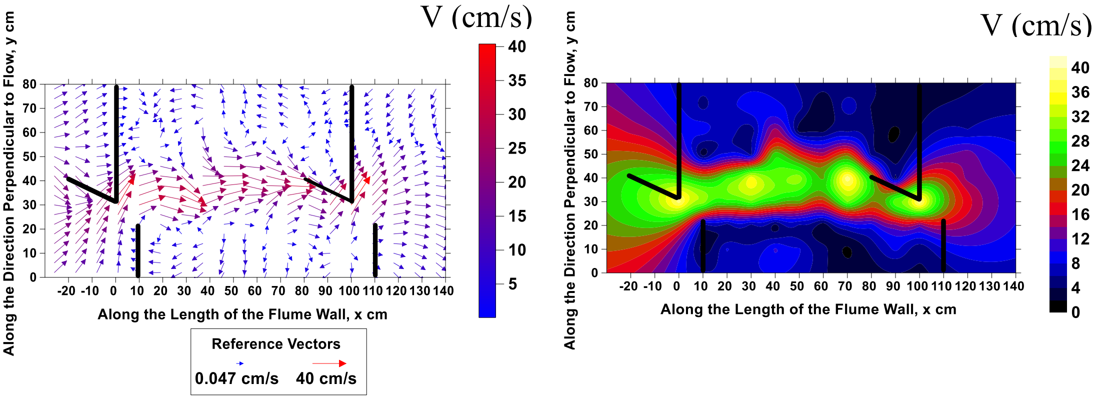
5.2.17 Features for Experiment Run 17 (U/S WL = 60 cm; Discharge = 70 m^3/hr)

The plane velocity fields and velocity contour maps at 0.4, 0.6 and 0.8 hydraulic depths for experiment run 17 in pool 4 have been shown in figure 5.57, 5.58 and 5.59. From the velocity field analysis it is found that the flow circulation follows the pattern 1 of Design 1 (Rajaratnam et al., 1992) i.e. the flow from slot travels through the center of the pool to the next slot with two recirculation region on either side of the jet. At the pool opening the flow appear almost in the form of a shooting jet. The



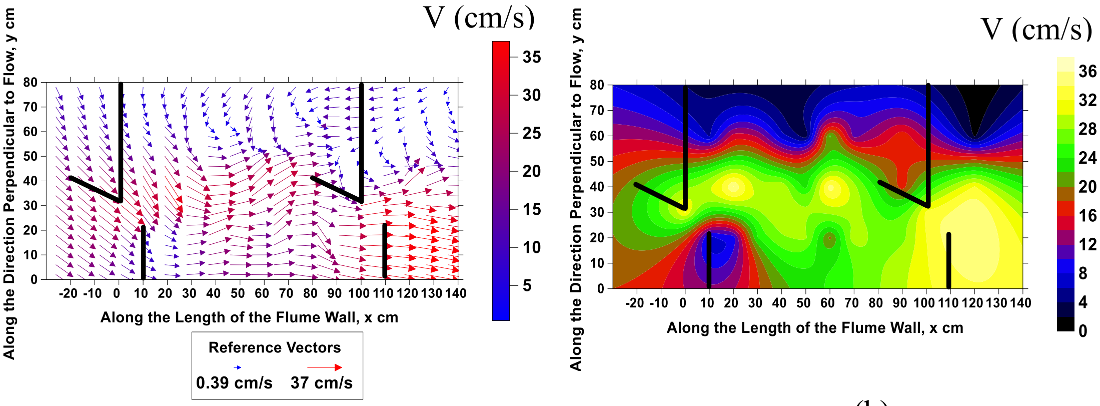
(a) (b)

Figure 5.57: (a) Plane velocity field and (b) Velocity contour map at 0.4 hydraulic depth for experiment run 17 in pool 4



(a) (b)

Figure 5.58: (a) Plane velocity field and (b) Velocity contour map at 0.6 hydraulic depth for experiment run 17 in pool 4



(a) (b)

Figure 5.59: (a) Plane velocity field and (b) Velocity contour map at 0.8 hydraulic depth for experiment run 17 in Pool 4

resultant vector components starting from the slot have made different angles with the X and Y axis at different positions. This indicates that the direction of the velocity components change randomly and the flow is non-uniform. From the velocity contour map analysis it is found that the maximum magnitude of flow occurs at the opening of slot and the mainstream continues through the center of the pool to the next slot while two recirculation regions of lower velocities are created on either side of the mainstream. And these recirculation regions with lower velocities provide resting places for fish.

The velocity distribution in a channel section depends on some factors e.g. the unusual shape of the section, the roughness of the channel and the presence of bends. On a bend the velocity increases greatly at the convex side, owing to the centrifugal action of flow (Chow, 1973). The vertical velocity profile in pool 4 for experiment run 17 is shown at Figure 5.60. Vertical velocity profiles have been presented at three particular places inside a pool based on the collected velocity data at 0.4, 0.6 and 0.8 hydraulic depths. The magnitude of velocity at opening of both upstream and downstream slot is found higher at 0.6 hydraulic depth than depth at 0.8 and 0.4. The magnitude of higher velocity at a certain hydraulic depth also represents the attractive velocity of fish species at that hydraulic depth at a particular place inside a pool. The vertical velocity profile at the resting place of fish at recirculation region just before the partition wall represents the velocities of very small magnitude which matches with the theory of vertical slot fish pass. Here the magnitudes of velocities are almost same.

Table 5.17 shows Reynolds number and Froude number at different locations in pool 4 at 0.6 hydraulic depth for experiment run 17. By observing the values of Reynolds Number it is seen that the flow type is turbulent at selected locations which indicates that the viscous forces are very weak relative to the inertial forces and inertial forces dominate the flow. By observing the values of Froude Number it is found that the flow is subcritical at the selected locations i.e. the gravitational forces are dominant.

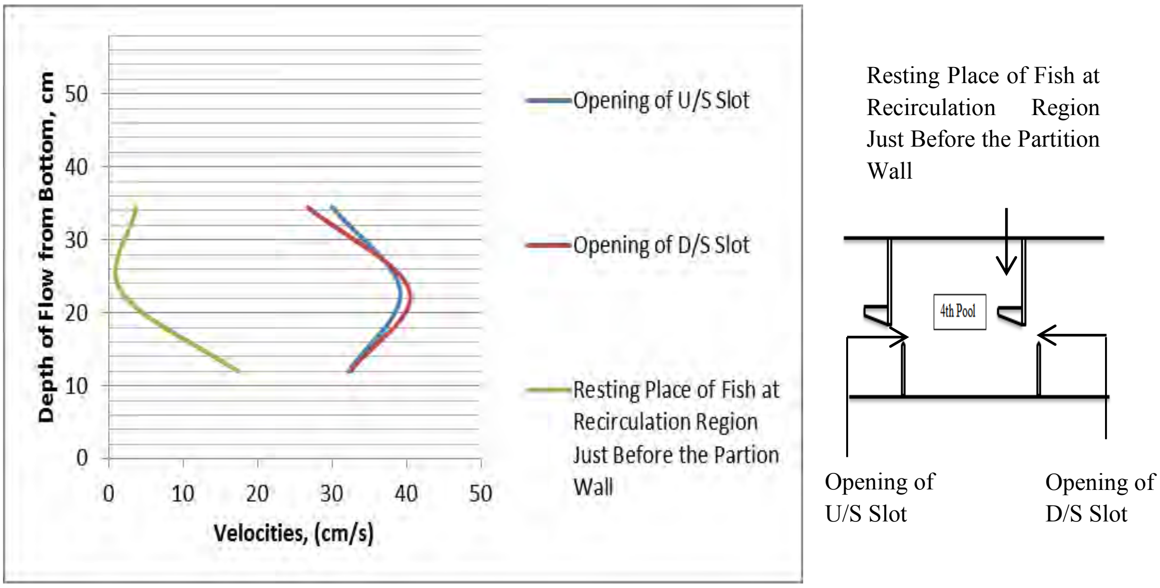


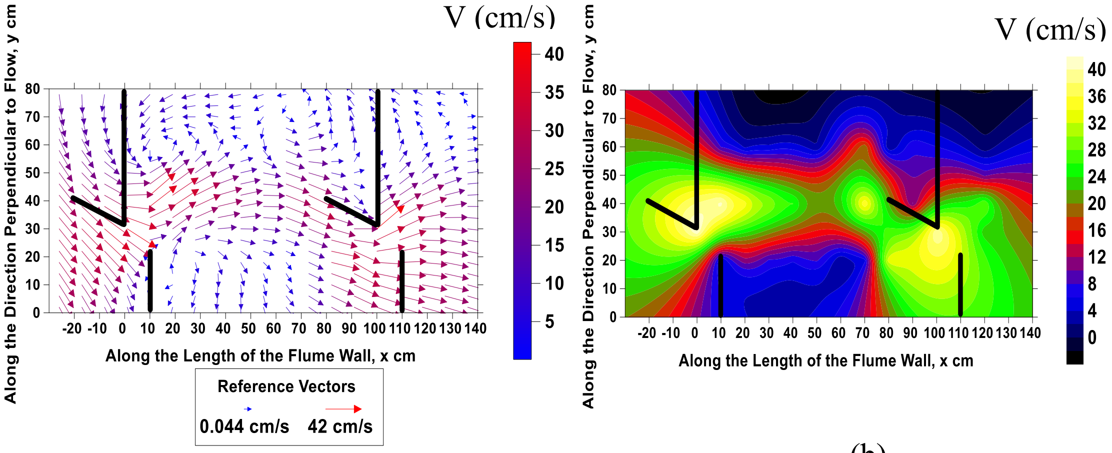
Figure 5.60: Vertical Velocity Profile in Pool 4 for Experiment Run 17

Table 5.17: Reynolds number and Froude number in pool 4 for experiment run 17

Position at the Pool	Hydraulic Depths	Reynolds Number	Froude Number
Opening of Upstream Slot	0.6	254206	0.1649
Opening of Downstream Slot	0.6	262322	0.169
Resting Palace of Fish at Recirculation Region Just Before the Partition Wall	0.6	10643	0.006

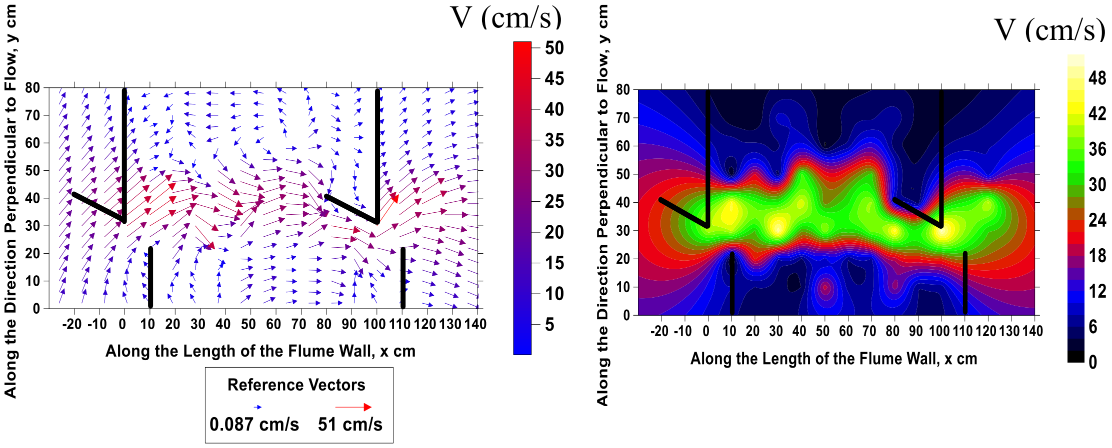
5.2.18 Features for Experiment Run 18 (U/S WL = 60 cm; Discharge = 84 m^3/hr)

The plane velocity fields and velocity contour maps at 0.4, 0.6 and 0.8 hydraulic depths for experiment run 18 in pool 4 have been shown in figure 5.61, 5.62 and 5.63. From the velocity field analysis it is found that the flow circulation follows the pattern 1 of Design 1 (Rajaratnam et al., 1992) i.e. the flow from slot travels through the center of the pool to the next slot with two recirculation region on either side of the jet. At the pool opening the flow appear almost in the form of a shooting jet. The



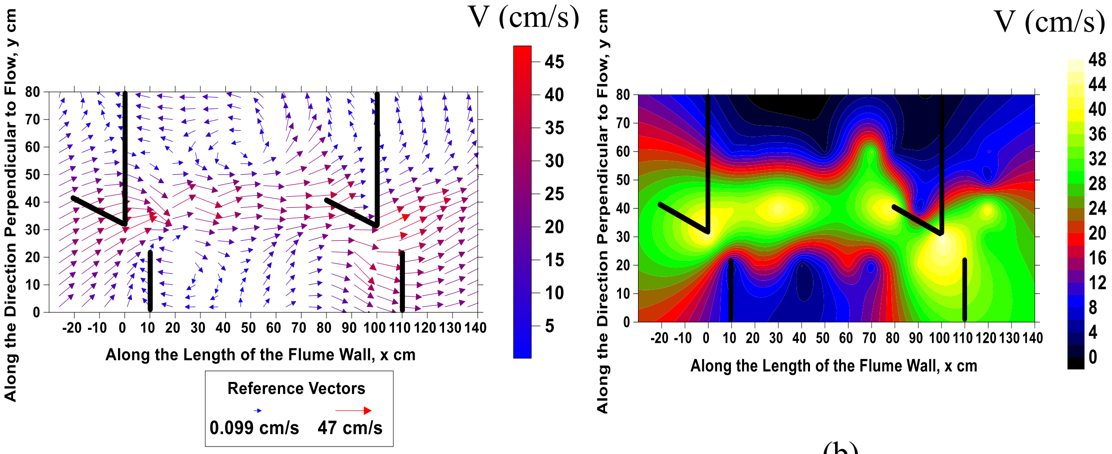
(a) (b)

Figure 5.61: (a) Plane velocity field and (b) Velocity contour map at hydraulic depth of 0.4 for experiment run 18 in pool 4



(a) (b)

Figure 5.62: (a) Plane velocity field and (b) Velocity contour map at hydraulic depth of 0.6 for experiment run 18 in pool



(a) (b)

Figure 5.63: (a) Plane velocity field and (b) Velocity contour map at hydraulic depth of 0.8 for experiment run 18 in pool 4

resultant vector components starting from the slot have made different angles with the X and Y axis at different positions. This indicates that the direction of the velocity components change randomly and the flow is non-uniform. From the velocity contour map analysis it is found that the maximum magnitude of flow occurs at the opening of slot in most of the cases and the mainstream continues through the center of the pool to the next slot while two recirculation regions of lower velocities are created on either side of the mainstream. And these recirculation regions with lower velocities provide resting places for fish.

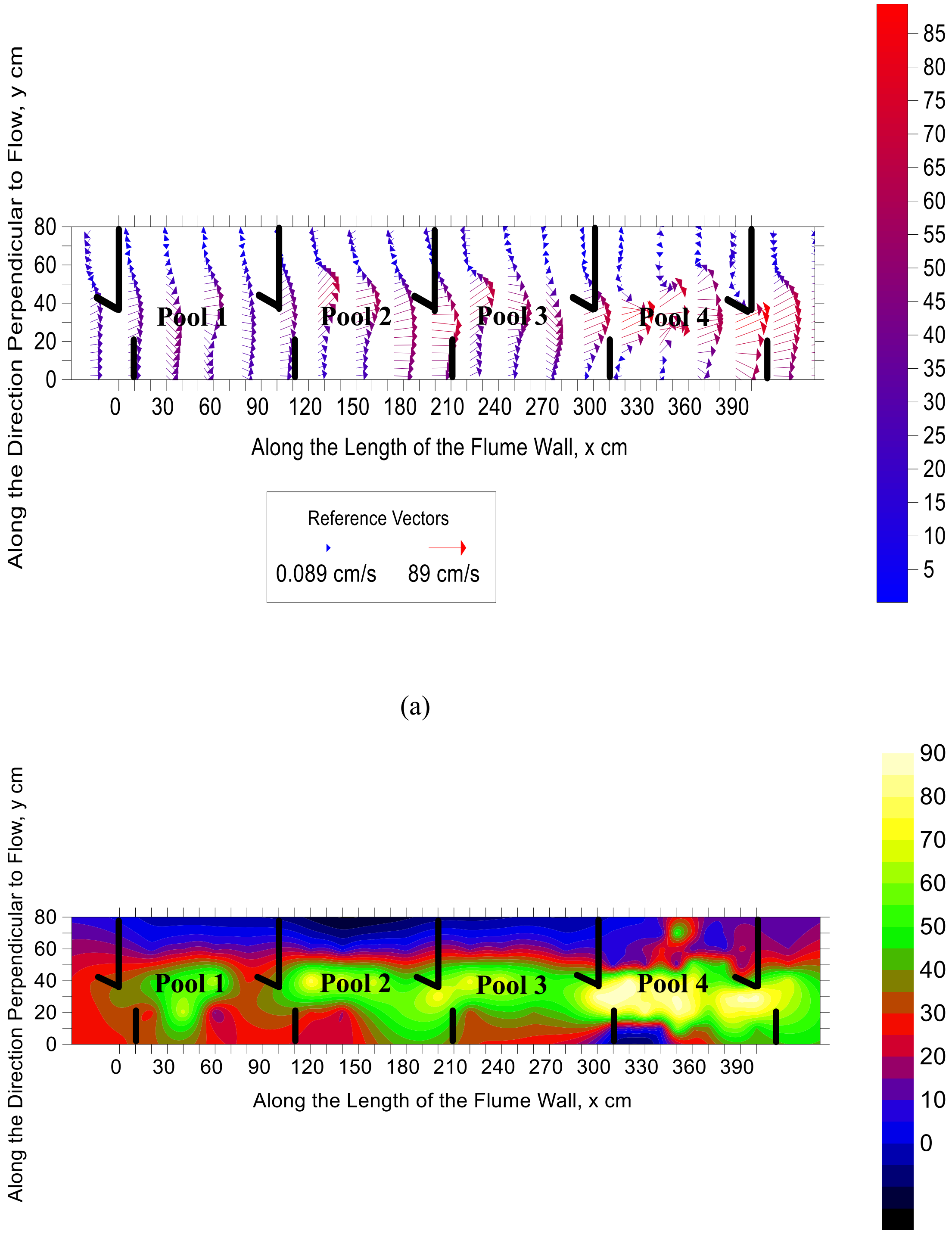
Table 5.18 shows Reynolds number and Froude number at different locations in pool 4 at 0.6 hydraulic depth for experiment run 18. By observing the values of Reynolds Number it is seen that the flow type is turbulent at selected locations which indicates that the viscous forces are very weak relative to the inertial forces and inertial forces dominate the flow. By observing the values of Froude Number it is found that the flow is subcritical at the selected locations i.e. the gravitational forces are dominant.

Table 5.18: Reynolds number and Froude number in pool 4 for experiment run 18

Position at the Pool	Hydraulic Depths	Reynolds Number	Froude Number
Opening of Upstream Slot	0.6	255999	0.165
Opening of Downstream Slot	0.6	331259	0.213
Resting Palace of Fish at Recirculation Region Just Before the Partition Wall	0.6	20298	0.013

5.3 Plane Velocity Field and Velocity Contour Map for the Fish Pass

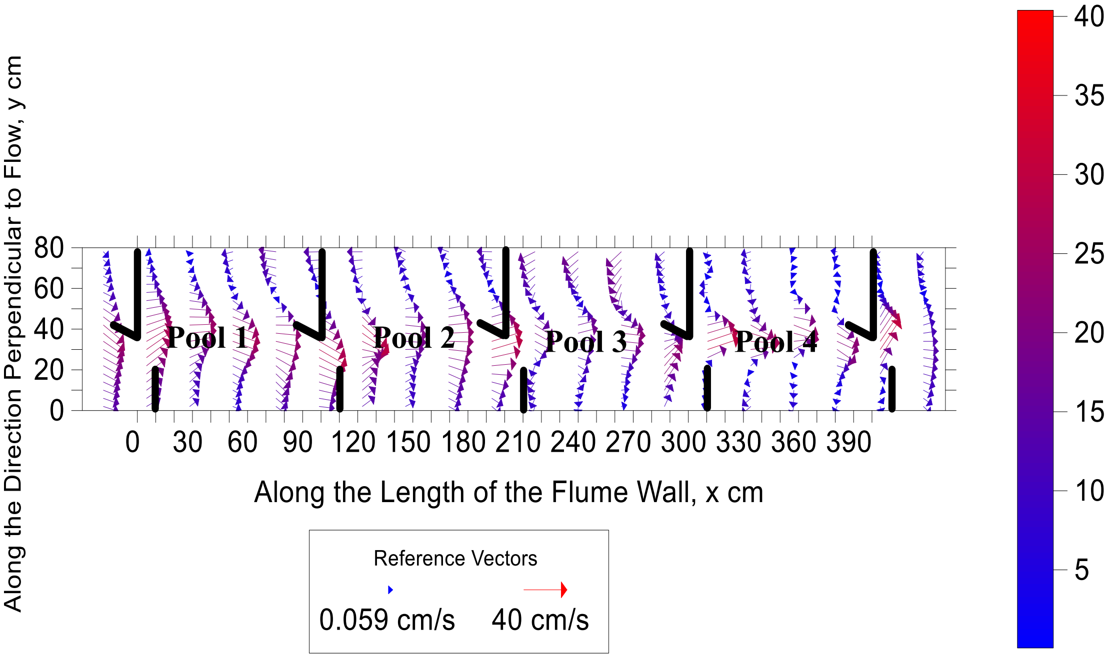
Velocity fields and velocity contour maps in pool 1 to pool 4 have been shown in Figure 5.64 and Figure 5.65 for experiment run 10 and experiment run 17 respectively. Experiment run 10 represents unfavourable condition for different sizes (fry, fingerling, juvenile) of fish species among the hydrodynamic conditions provided for 18 experimental runs while experiment run 17 represents favourable hydrodynamic condition. It is seen that the magnitude of velocities have been



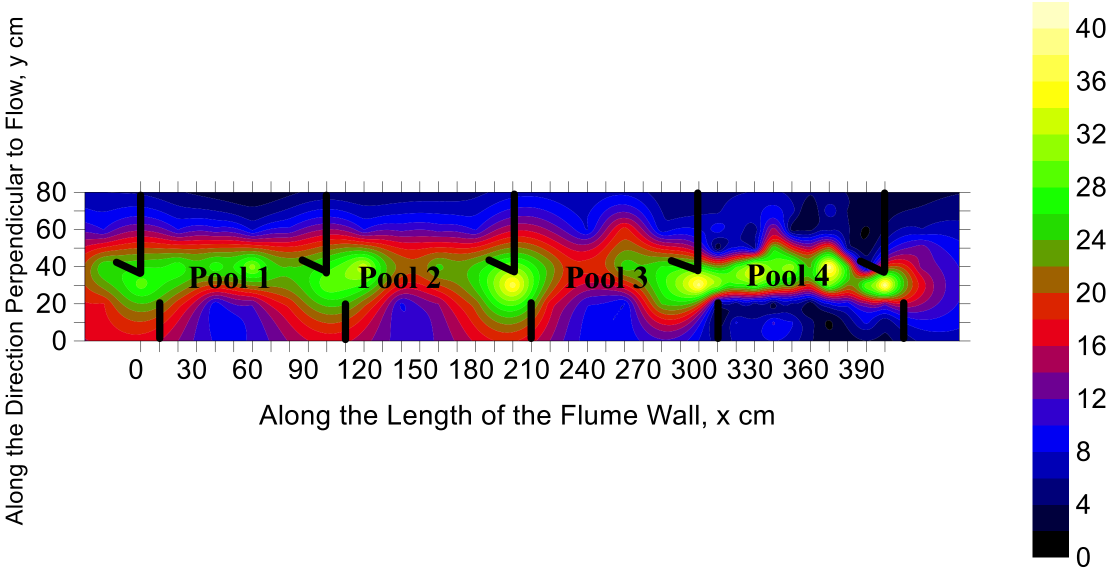
(a)

(b)

Figure 5.64: (a) Plane velocity field and (b) Velocity contour map in pool 1 to pool 4 for experiment run 10



(a)



(b)

Figure 5.65: (a) Plane velocity field and (b) Velocity contour map in pool 1 to pool 4 for experiment run 17

increased form pool 1 to pool 4due to head drop per pool. The flow pattern has been found almost same in pool 1 to pool 4.

5.4 Observation of the Fish Behaviour in the Fish Pass

Three types of fish species (e.g. Rui, Catla and Mrigel) of fry size (0-1mm body length), fingerling size (4-5cm) and juvenile size (8-10cm) have been used in this study to observe the fish behavior. It has been found that the hydrodynamic condition was unfavorable in most of the cases except some low velocity conditions for fry and fingerling size of the three species. But in case of Juvenile size hydrodynamic condition was favorable in most of the cases except some high velocity conditions. Behaviour and cruising velocities of fish species have been presented on Table 5.19-5.27.

Table 5.19: Behaviour of Rui (*Labeo rohita*) of fry size under different experimental runs

Experiment Run No.	U/S Water Level (cm)	Discharge, Q (m^3/hr)	Approx. Velocity at D/s Opening of Pool 4, m/s	Passing U/S Slot	Passing D/S Slot	Resting Behaviour
1	50	81	0.5	No	No	U.F.
2	50	94	0.6	No	No	U.F.
3	50	104	0.7	No	No	U.F.
4	50	118	0.8	No	No	U.F.
5	50	55	0.3	Yes	Yes	F
6	50	68	0.4	Yes	Yes	F
7	40	65	0.5	No	No	U.F.
8	40	75	0.6	No	No	U.F.
9	40	87	0.7	No	No	U.F.
10	40	96	0.8	No	No	U.F.
11	40	37	0.3	No	No	U.F.
12	40	52	0.4	No	No	U.F.
13	60	100	0.5	No	No	U.F.
14	60	110	0.6	No	No	U.F.
15	60	125	0.7	No	No	U.F.
16	60	145	0.8	No	No	U.F.
17	60	70	0.3	Yes	Yes	F
18	60	84	0.4	Yes	Yes	F

Note: U.F. = Unfavorable F. = Favourable

Table 5.20: Behaviour of Rui (*Labeo rohita*) of fingerling size under different experimental runs

Experiment Run No.	U/S Water Level (cm)	Discharge, Q (m^3/hr)	Approx. Velocity at D/s Opening of Pool 4, m/s	Passing U/S Slot	Passing D/S Slot	Resting Behaviour
1	50	81	0.5	No	No	U.F.
2	50	94	0.6	No	No	U.F.
3	50	104	0.7	No	No	U.F.
4	50	118	0.8	No	No	U.F.
5	50	55	0.3	Yes	Yes	F
6	50	68	0.4	Yes	Yes	F
7	40	65	0.5	No	No	U.F.
8	40	75	0.6	No	No	U.F.
9	40	87	0.7	No	No	U.F.
10	40	96	0.8	No	No	U.F.
11	40	37	0.3	No	No	U.F.
12	40	52	0.4	No	No	U.F.
13	60	100	0.5	No	No	U.F.
14	60	110	0.6	No	No	U.F.
15	60	125	0.7	No	No	U.F.
16	60	145	0.8	No	No	U.F.
17	60	70	0.3	Yes	Yes	F
18	60	84	0.4	Yes	Yes	F

Note: U.F. = Unfavorable F. = Favourable

Table 5.21: Behaviour of Rui (*Labeo rohita*) of juvenile size under different experimental runs

Experiment Run No.	U/S Water Level (cm)	Discharge, Q (m^3/hr)	Approx. Velocity at D/s Opening of Pool 4, m/s	Passing U/S Slot	Passing D/S Slot	Resting Behaviour
1	50	81	0.5	Yes	Yes	F
2	50	94	0.6	Yes	Yes	F
3	50	104	0.7	Yes	Yes	F
4	50	118	0.8	No	No	U.F.
5	50	55	0.3	Yes	Yes	F
6	50	68	0.4	Yes	Yes	F
7	40	65	0.5	Yes	Yes	F
8	40	75	0.6	Yes	Yes	F
9	40	87	0.7	No	No	U.F.
10	40	96	0.8	No	No	U.F.
11	40	37	0.3	Yes	Yes	F
12	40	52	0.4	Yes	Yes	F
13	60	100	0.5	Yes	Yes	F
14	60	110	0.6	Yes	Yes	F
15	60	125	0.7	Yes	Yes	F
16	60	145	0.8	No	No	U.F.
17	60	70	0.3	Yes	Yes	F
18	60	84	0.4	Yes	Yes	F

Note: U.F. = Unfavorable F. = Favourable

Table 5.22: Behaviour of Catla (*Catla catla*) of fry size under different experimental runs

Experiment Run No.	U/S Water Level (cm)	Discharge, Q (m^3/hr)	Approx. Velocity at D/s Opening of Pool 4, m/s	Passing U/S Slot	Passing D/S Slot	Resting Behaviour
1	50	81	0.5	No	No	U.F.
2	50	94	0.6	No	No	U.F.
3	50	104	0.7	No	No	U.F.
4	50	118	0.8	No	No	U.F.
5	50	55	0.3	Yes	Yes	F
6	50	68	0.4	Yes	Yes	F
7	40	65	0.5	No	No	U.F.
8	40	75	0.6	No	No	U.F.
9	40	87	0.7	No	No	U.F.
10	40	96	0.8	No	No	U.F.
11	40	37	0.3	No	No	U.F.
12	40	52	0.4	No	No	U.F.
13	60	100	0.5	No	No	U.F.
14	60	110	0.6	No	No	U.F.
15	60	125	0.7	No	No	U.F.
16	60	145	0.8	No	No	U.F.
17	60	70	0.3	Yes	Yes	F
18	60	84	0.4	Yes	Yes	F

Note: U.F. = Unfavorable F. = Favourable

Table 5.23: Behaviour of Catla (*Catla catla*) of fingerling size under different experimental runs

Experiment Run No.	U/S Water Level (cm)	Discharge, Q (m^3/hr)	Approx. Velocity at D/s Opening of Pool 4, m/s	Passing U/S Slot	Passing D/S Slot	Resting Behaviour
1	50	81	0.5	No	No	U.F.
2	50	94	0.6	No	No	U.F.
3	50	104	0.7	No	No	U.F.
4	50	118	0.8	No	No	U.F.
5	50	55	0.3	Yes	Yes	F
6	50	68	0.4	Yes	Yes	F
7	40	65	0.5	No	No	U.F.
8	40	75	0.6	No	No	U.F.
9	40	87	0.7	No	No	U.F.
10	40	96	0.8	No	No	U.F.
11	40	37	0.3	No	No	U.F.
12	40	52	0.4	No	No	U.F.
13	60	100	0.5	No	No	U.F.
14	60	110	0.6	No	No	U.F.
15	60	125	0.7	No	No	U.F.
16	60	145	0.8	No	No	U.F.
17	60	70	0.3	Yes	Yes	F
18	60	84	0.4	Yes	Yes	F

Note: U.F. = Unfavorable F. = Favourable

Table 5.24: Behaviour of Catla (*Catla catla)* of juvenile size under different experimental runs

Experiment Run No.	U/S Water Level (cm)	Discharge, Q (m^3/hr)	Approx. Velocity at D/s Opening of Pool 4, m/s	Passing U/S Slot	Passing D/S Slot	Resting Behaviour
1	50	81	0.5	Yes	Yes	F
2	50	94	0.6	Yes	Yes	F
3	50	104	0.7	Yes	Yes	F
4	50	118	0.8	No	No	U.F.
5	50	55	0.3	Yes	Yes	F
6	50	68	0.4	Yes	Yes	F
7	40	65	0.5	Yes	Yes	F
8	40	75	0.6	Yes	Yes	F
9	40	87	0.7	No	No	U.F.
10	40	96	0.8	No	No	U.F.
11	40	37	0.3	Yes	Yes	F
12	40	52	0.4	Yes	Yes	F
13	60	100	0.5	Yes	Yes	F
14	60	110	0.6	Yes	Yes	F
15	60	125	0.7	Yes	Yes	F
16	60	145	0.8	No	No	U.F.
17	60	70	0.3	Yes	Yes	F
18	60	84	0.4	Yes	Yes	F

Note: U.F. = Unfavorable F. = Favourable

Table 5.25: Behaviour of Mrigel (*Cirrhinus mrigala*) of fry size under different experimental runs

Experiment Run No.	U/S Water Level (cm)	Discharge, Q (m^3/hr)	Approx. Velocity at D/s Opening of Pool 4, m/s	Passing U/S Slot	Passing D/S Slot	Resting Behaviour
1	50	81	0.5	No	No	U.F.
2	50	94	0.6	No	No	U.F.
3	50	104	0.7	No	No	U.F.
4	50	118	0.8	No	No	U.F.
5	50	55	0.3	Yes	Yes	F
6	50	68	0.4	Yes	Yes	F
7	40	65	0.5	No	No	U.F.
8	40	75	0.6	No	No	U.F.
9	40	87	0.7	No	No	U.F.
10	40	96	0.8	No	No	U.F.
11	40	37	0.3	No	No	U.F.
12	40	52	0.4	No	No	U.F.
13	60	100	0.5	No	No	U.F.
14	60	110	0.6	No	No	U.F.
15	60	125	0.7	No	No	U.F.
16	60	145	0.8	No	No	U.F.
17	60	70	0.3	Yes	Yes	F
18	60	84	0.4	Yes	Yes	F

Note: U.F. = Unfavorable F. = Favourable

Table 5.26: Behaviour of Mrigel (*Cirrhinus mrigala*) of fingerling size under different experimental runs

Experiment Run No.	U/S Water Level (cm)	Discharge, Q (m^3/hr)	Approx. Velocity at D/s Opening of Pool 4, m/s	Passing U/S Slot	Passing D/S Slot	Resting Behaviour
1	50	81	0.5	No	No	U.F.
2	50	94	0.6	No	No	U.F.
3	50	104	0.7	No	No	U.F.
4	50	118	0.8	No	No	U.F.
5	50	55	0.3	Yes	Yes	F
6	50	68	0.4	Yes	Yes	F
7	40	65	0.5	No	No	U.F.
8	40	75	0.6	No	No	U.F.
9	40	87	0.7	No	No	U.F.
10	40	96	0.8	No	No	U.F.
11	40	37	0.3	No	No	U.F.
12	40	52	0.4	No	No	U.F.
13	60	100	0.5	No	No	U.F.
14	60	110	0.6	No	No	U.F.
15	60	125	0.7	No	No	U.F.
16	60	145	0.8	No	No	U.F.
17	60	70	0.3	Yes	Yes	F
18	60	84	0.4	Yes	Yes	F

Note: U.F. = Unfavorable F. = Favourable

Table 5.27: Behaviour of Mrigel (*Cirrhinus mrigala*) of juvenile size under different experimental runs

Experiment Run No.	U/S Water Level (cm)	Discharge, Q (m^3/hr)	Approx. Velocity at D/s Opening of Pool 4, m/s	Passing U/S Slot	Passing D/S Slot	Resting Behaviour
1	50	81	0.5	Yes	Yes	F
2	50	94	0.6	Yes	Yes	F
3	50	104	0.7	Yes	Yes	F
4	50	118	0.8	No	No	U.F.
5	50	55	0.3	Yes	Yes	F
6	50	68	0.4	Yes	Yes	F
7	40	65	0.5	Yes	Yes	F
8	40	75	0.6	Yes	Yes	F
9	40	87	0.7	No	No	U.F.
10	40	96	0.8	No	No	U.F.
11	40	37	0.3	Yes	Yes	F
12	40	52	0.4	Yes	Yes	F
13	60	100	0.5	Yes	Yes	F
14	60	110	0.6	Yes	Yes	F
15	60	125	0.7	Yes	Yes	F
16	60	145	0.8	No	No	U.F.
17	60	70	0.3	Yes	Yes	F
18	60	84	0.4	Yes	Yes	F

Note: U.F. = Unfavorable F. = Favourable

5.5 Velocity of Fish Species

Fingerling and juvenile size of *Labeo rohita* species were released in the flume to observe the velocity of fish for several experimental runs. The results are shown in Table 5.28 and 5.29. Velocity of fish species have been measured while they were passing from upstream to downstream. Cruising velocities of fish species can be measured by deducting the water velocity from velocity of fish species.

Table 5.28: Observed velocity of fish for fingerling species of *Labeo rohita*

Experiment Run No.	U/s Water Level (cm)	Pump Discharge (m^3/hr)	Approx. Velocity at D/s Opening of Pool 4 (m/s)	Velocity of water in Pool without Strc. (m/s)	Velocity of Fish (m/s)
1	50	81	0.5	0.042	0.38
4	50	118	0.8	0.096	0.31
5	50	55	0.3	≅ 0.0	0.44
7	40	65	0.5	≅ 0.0	0.67
10	40	96	0.8	0.095	0.64
11	40	37	0.3	≅ 0.0	0.38
13	60	100	0.5	0.055	0.43
16	60	145	0.8	0.06	0.29
17	60	70	0.3	≅ 0.0	0.43

Table 5.29: Observed velocity of fish for juvenile species of *Labeo rohita*

Experiment Run No.	U/s Water Level (cm)	Pump Discharge (m^3/hr)	Approx. Velocity at D/s Opening of Pool 4 (m/s)	Velocity of water in Pool without Strc. (m/s)	Velocity of Fish (m/s)
1	50	81	0.5	0.042	0.6
4	50	118	0.8	0.096	0.32
5	50	55	0.3	≅ 0.0	0.49
7	40	65	0.5	≅ 0.0	0.69
10	40	96	0.8	0.095	0.38
11	40	37	0.3	≅ 0.0	0.31
13	60	100	0.5	0.055	0.67
16	60	145	0.8	0.06	0.38
17	60	70	0.3	≅ 0.0	0.53

5.6 Summary

The findings and results of each of 18 experimental runs have been presented clearly in this chapter and relevant discussions have been made. Velocity fields, vertical velocity profiles have been presented and Reynolds numbers and Froude numbers have been calculated for the experiment runs. Furthermore, an attempt has been made to represent the response of fish behavior of selected species with the flow pattern and hydrodynamic conditions inside the fish pass.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

6.1 General

The performance of a fish pass like vertical slot mostly depends on ensuring the favourable condition of fish species so that the species can pass through the obstacles to the spawning ground with minimum or no injury. The velocities at the pool opening should be such that it can attract fish species. A vertical slot fish pass allows for variations in discharge and permits fish to ascend the fish pass at any depth they choose. In addition, the path of a fish ascending the fish pass is not tortuous and the fish pass provides resting locations for fish (Clay, 1995). The outcomes of this research work match with the theory of vertical slot fish pass.

6.2 Conclusions of the Study

By conducting detail and rigorous experimental investigations, data analysis and observations of fish behaviour presented at the previous chapters, the synopsis of the study can be represented as follows:

1. It was observed that in this study the flow pattern inside the pool follows the pattern 1 type of vertical slot fish pass i.e. the flow from the slot travels through the center of the pool to the next slot with two large recirculation regions located on either side of the jet which agrees with the theory.
2. The maximum velocity occurred at the opening of the slots in most of the cases continuing the mainstream along the center of the pool which indicates that the opening of the slot is a critical section in a vertical slot fish pass.
3. The vertical velocity profiles that have been presented show that the pool openings are the places of maximum velocities where attractive velocity of fishes can be observed.
4. The velocity profiles at the resting places of fish at the recirculation region just before the partition wall represents lower magnitude of velocities which matches with the theory.
5. From the values of Froude numbers which are in the range of 0.006 to 0.584 it is found that the flow is subcritical through the pool which indicates that the

gravitational forces are dominant and no hydraulic jump or hydraulic drop can develop inside the pool.

6. During the observation of fish behavior, the hydrodynamic conditions were found favourable for fry size and fingerling size in experiment run 5 to 6 and 17 to 18; for juvenile size in experiment run 1 to 3 and 5 to 8 and 11 to 15 and 17 to 18. But the hydrodynamic conditions were unfavourable for fry and fingerling sizes in experiment run 1 to 4 and 7 to 16 and for juvenile size in experiment run 4, 9, 10 and 16. Recirculation regions were not so well developed in experiment runs 4, 9, 10 and 16 which caused the injury to the fish species by creating a tendency to hitting them to the flume walls and baffles.
7. The magnitude and distribution of velocity inside the pool of the fish pass is the governing factor for smooth passage of fishes.
8. The resting places were mainly identified at the recirculation regions created at the side of the long baffles just before the partition walls which also agrees with the theory. And the cruising velocities at these places for the fish species were also observed.

6.3 Recommendations for Further Study

Based on the knowledge and experience gathered form the present research work some recommendations for further study can be suggested as follows:

1. Further laboratory studies based on other designs of vertical slot fish pass can be tested with different Bangladeshi fish species.
2. Detailed research works can be performed to understand the biological characteristics of different fish species.
3. Further study related to the water quality parameters can also be performed to find the fish response to the water quality parameters.

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APPENDIX-A

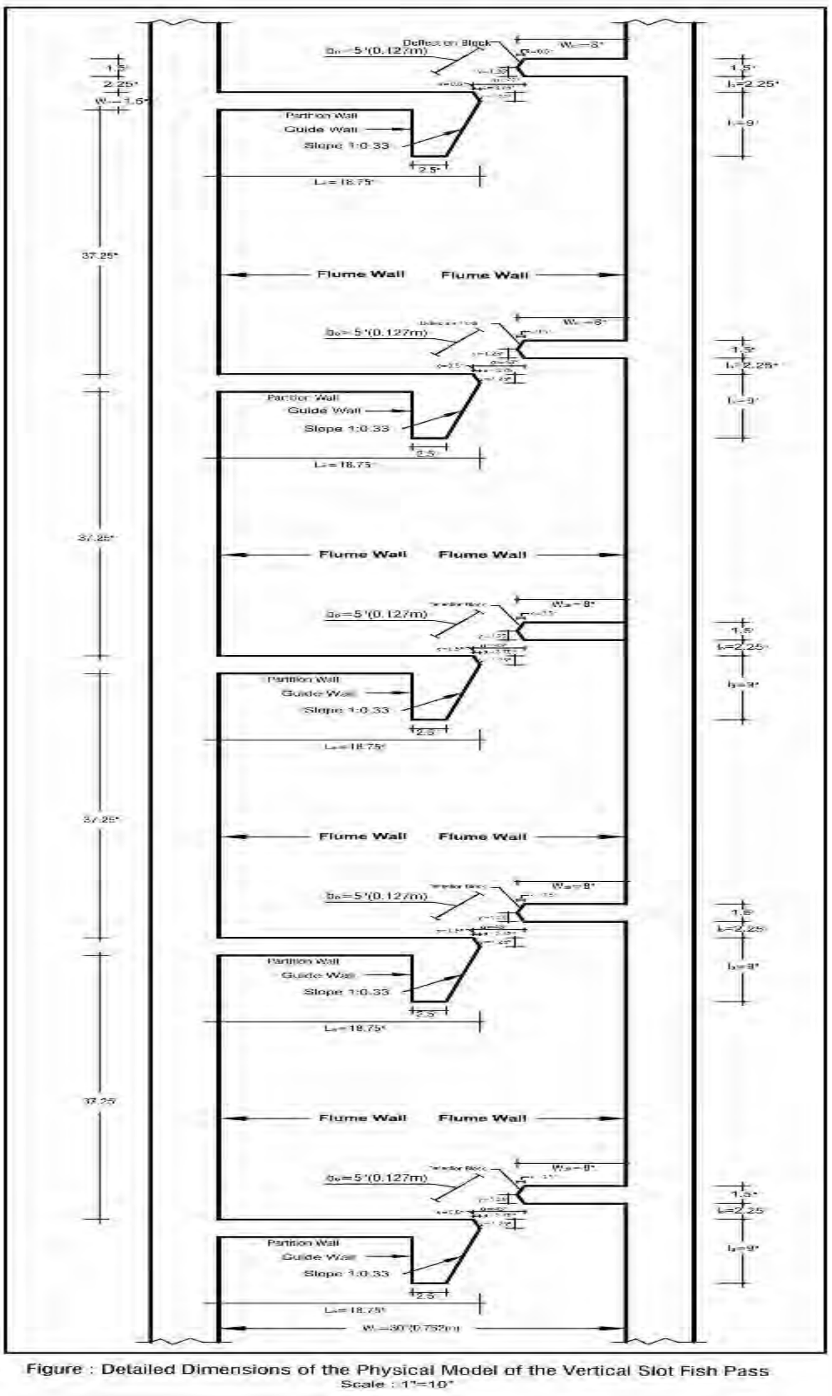

Figure A.1: Detailed dimensions of the physical model developed in the laboratory flume

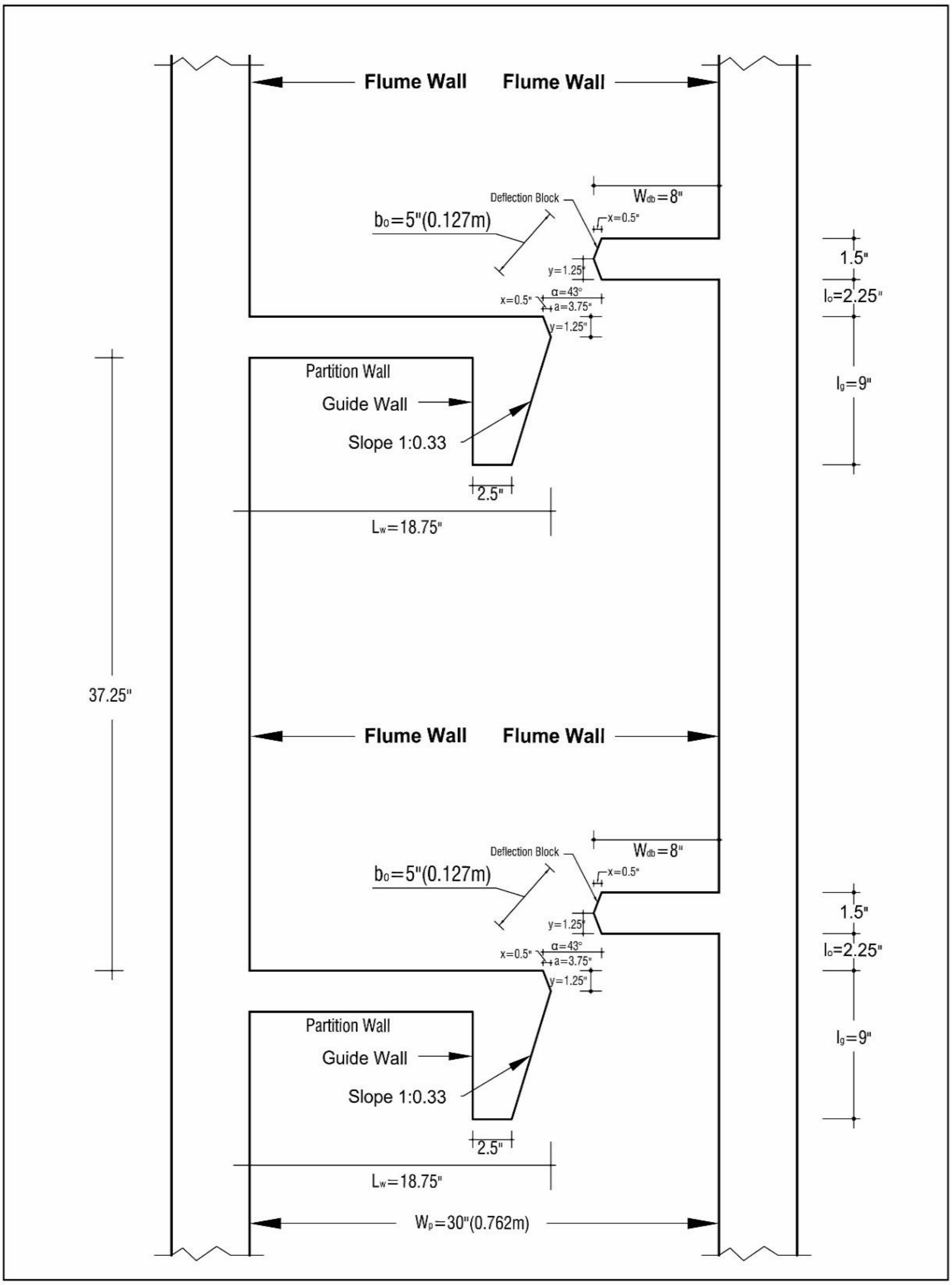

Figure : Detailed Dimensions of the Physical Model of the Vertical Slot Fish Pass
Scale : 1"=10"

Figure A.2: Detailed dimensions of a pool of the physical model developed in the laboratory flume