GROWTH OF BOUNDARY LAYER THICKNESS AND LENGTH OF FULLY DEVELOPED FLOW IN OPEN CHANNEL

A Thesis submitted in partial Fulfillment of the requirement for the degree of

BACHELOR OF TECHNOLOGY

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CERTIFICATE

This is to certify that the project entitled **Growth of Boundary layer thickness and Length of fully developed flow in open channel** submitted by Mr. **CHIKKAM RAMAKRISHNA BALAJI** (Roll No. **110CE0347)** and Mr. **BICHITRANANADA BEHERA** (Roll. No.**110CE0348**) in partial fulfillment of the requirements for the award of Bachelor of Technology Degree in Civil Engineering at NIT Rourkela is an authentic work carried out by him under my supervision and guidance.

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ABSTRACT

The aim of the present work was to study the growth of boundary layer thickness and length of fully developed flow in an open channel flow which has a great applications in fields like, hydrodynamics (ships, torpedoes, submarines), wind engineering (buildings, water towers, bridges), aerodynamics (airplanes, rockets, projectiles), ocean engineering (buoys, breakwaters, cables) and transportation (trucks, automobiles, cycles). Boundary layer thickness and length of fully developed flow is crucial for solving many engineering problems such as management of rivers and floodplains, it is important to understand the behavior of flows within compound channels for designing of flood control, hydraulic structure, sedimentation, water management and excavation. In pipe flow, where boundary layer thickness is equal to radius of pipe which can be obtained easily whereas one finds difficulty in obtaining boundary layer thickness in open channels due to the presence of free surface. This challenge motivated us to study the growth of boundary layer thickness and length of fully developed flow in open channel flow. Experiments were performed to measure the characteristics of a boundary layer and fully developed flow by making use of velocity profiles developing on a rough concrete surface placed in an open channel flow from bottom to close proximity to the free surface. Section wise velocity measurements were made with a pitot tube-manometer combination and Acoustic Doppler velocimeter system along the flow depth ranging from 0, 0.2h, 0.4h, 0.6h, 0.8h.

Keywords

- Open channel flow
- Boundary layer thickness
- Developed flow
- Pitot tube
- ADV

CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER-1

INTRODUCTION

1.1 OPEN CHANNEL FLOW

The flow of liquid with a free surface is known as open channel flow. Free surface experiences a constant pressure such as atmospheric pressure. In open channel flow, as the pressure is atmospheric, the flow happens under the force of gravity which means the flow is due to the slope of the bed of the channel only.

1.2 CLASSIFICATION OF FLOWS IN CHANNEL

1. Laminar flow and turbulent flow.
2. Sub-critical, critical and super critical flow.
3. Steady flow and unsteady flow.
4. Uniform flow and non-uniform flow.

Laminar Flow and Turbulent Flow

The flow in open channel is said to be laminar if Reynolds number (Re) is less than 500 or 600 and if the Reynolds number is more than 2000, the flow is said to be turbulent in open channel flow. If Re lies between 500 and 2000, the flow is considered to be in transition state.

Sub-critical, Critical and Super Critical Flow

The flow in open channel is said to be sub-critical if the Froude number (Fe) is than 1.0. The flow is called critical if Fe = 1.0 and if Fe > 1.0, the flow is called sinusoidal.

Pre-critical or shooting or rapid or torrential.

Froude number is defined as:

Fe = V/ (g*D)1/2 …(1.1)

Where

V = Mean velocity of flow

D = Hydraulic depth of channel = A/T

A=Wetted area

T=Top width of channel.

Steady Flow and Unsteady Flow

If the flow parameters such as depth of flow, velocity of flow, rate of flow at any point in open channel flow do not change with respect to time, the flow is said to be steady flow. If at any point in open channel flow, the velocity of flow, depth of flow or rate of flow changes with respect to time, is said to be unsteady flow.

Uniform Flow and Non-uniform Flow

If the velocity of flow, depth of flow, slope of the channel and cross-section remain constant for a given length of the channel the flow is said to be uniform. If the velocity of flow, depth of flow etc., for a given length of the channel does not remain constant, the flow is said to be non-uniform flow.

1.3 CONCEPT OF FULLY DEVELOPED FLOW AND BOUNDARY LAYER

Due to the viscous shear that takes place between the layers of fluid immediately above it and the surface, Skin friction drag will be generated. This is predominantly seen on surface of objects that are very long in the direction of flow compared to their height. Such bodies/objects are called **STREAMLINED BODIES**. Over a solid surface when a fluid flow, layer next to the surface might become attached to it (it wets the surface). This is known as 'no slip condition'. The layers of fluid above the surface are moving so between the layers of the fluid shearing takes place. The shear stress which acts between the wall and the first moving layer next to it is known as *the wall shear stress* and denoted by τ . The result of this action is that the velocities of the fluid u increases with height y. The distance required for the velocity to reach 99% of u, free stream velocity is taken as the boundary layer thickness δ . This layer is known as **BOUNDARY LAYER** and δ is the **BOUNDARY LAYER THICKNESS**.

The boundary layer, which may be laminar at the upstream end, steadily thickens up to a certain point in the channel length L_e in which the flow is called "developing flow" .Beyond this point the flow is called "**FULLY DEVELOPED FLOW**."

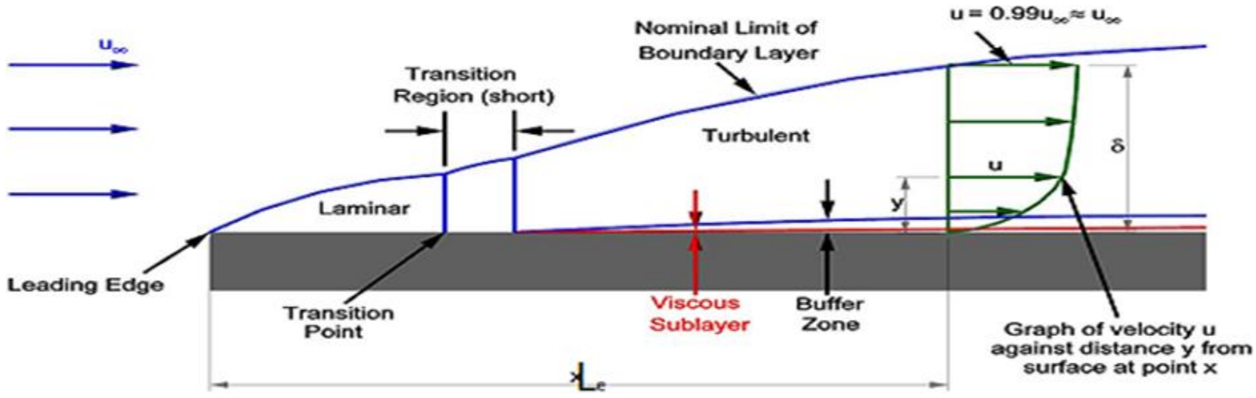


Figure-1

When a fluid starts to flow over a rough/smooth surface the boundary layer grows from zero. More fluid is slowed down by frictional force between the layers of fluid close to the boundary, as it passes over a greater length. Therefore the thickness of the slower layer increases significantly.

OBJECTIVES

Our interest in the boundary layer is that its presence greatly affects the flow through or round an object. Some of the phenomena associated with the boundary layer, length of fully developed flow and discuss the effect of it on open channel flow are examined.

1. Conducting experiments in determining boundary layer thickness in open channel and pipe flow

2. Variation of boundary layer thickness due to different flow and geometry conditions in open channel and pipe flow.

3. To study the variation of boundary layer thickness due to different laminar and turbulent flow conditions

CHAPTER-2

LITERATURE SURVEY

Iehisa Nezu and Wolfgang Rodi (1986) had used two colors Laser Doppler Anemometer (LDA) system with direct digital signal processing to measure the longitudinal and vertical velocity components in fully developed flow over smooth beds. They had re-examined the law of the wall and the velocity defect law as the log law had often been applied to open channels without detailed verification and was found that log law strictly can be applied to the near wall region only. The friction velocity can be evaluated accurately from velocity measurements by applying the log-law with Von Karman constant K = 0.412 and A = 5.29 to the near-wall region.

M. Salih Kirkgoz (1989) had measured the velocity profiles using a laser-doppler anemometer in a fully developed, rectangular, subcritical open channel flow on smooth and rough beds. The "rough" surfaces, used in the experiments had average roughness heights of 1 mm, 4 mm, 8 mm, and 12 mm and the shear velocities are determined from velocity profiles measured close to the bed. This shows that as the wall roughness increases the calculated shear velocities determined from the velocity profiles are in increasing tendency. The overall data represented in terms of law-of-the-wall distribution was reasonable; however, the velocity-defect distribution was not satisfactory. From the study of mean velocity distributions the following conclusions are drawn.

- As the average uniform roughness height increases from 1 mm to 12 mm the non-dimensional velocity distribution becomes increasingly non-uniform in the inner region of turbulent flow.
- The thickness of the inner region of flow on a "smooth" bed is about 50-60% of the entire boundary-layer thickness. This value decreases with an increase in Reynolds number.
- The corresponding boundary layer thickness and length of developed flow for different discharge were calculated and found that
    a. There is a linear relationship between the dimensionless length *L/h* of the turbulent flow developing zone of open channel flow and the ratio R/F.
    b. At the axis of a fully developed turbulent flow section the boundary layer extends to the water surface if the channel aspect ratio *b/h* =3.

Vito Ferro and Giorgio Baiamonte(1994) had done the velocity measurement in a rectangular flume having gravel bed for four different bed shapes, characterized from different concentration of coarser elements and for two conditions of small and large scale roughness to establish how the velocity profile varies with the concentration of coarse bed elements and the ratio between the depth h and a characteristic bed diameter.

R.N.Parthasarathy and M.Muste(1994) confirmed the non-coincidence of the planes of maximum velocity and zero Reynolds stress. Significant diffusion of momentum and kinetic energy took place from rough to the smooth surface. AS the roughness of the cover was increased; the vertical transfer of vertical velocity fluctuations of the cover was decreased, resulting in a decrease in the sediment-suspension mechanism. The proper length scale in the outer region was the height of the plane of zero total stress from the corresponding surface. When the distance from each surface was normalised with the log law, and the measured stream wise and vertical velocity fluctuations agreed with the exponential variations formulated in 1986 by Nezu and Rodi.

T. Song and W.H. Graf (1996) studied unsteady flow properties in an open channel with a rough bed. A recently developed acoustic Doppler velocity profiler (ADVP) is used to obtain instantaneously the flow profiles. From these measurements, using the Fourier components method, the mean velocities, the turbulence intensities and the Reynolds-stress profile, are obtained.

Graeme M. Smart (1999) investigated vertical profiles of turbulent stream wise velocities in gravel bed rivers. Field measurements made at high and low flows with electronic pitot tubes show logarithmic velocity profiles to extend over much of the flow depth. For the gravel bed rivers studied the velocity at 0.6 of the total depth was generally a good indicator of depth-averaged flow velocity. An unambiguous definition of flow depth is adopted to deal with situations where the bed is uneven or moving. When hydraulic roughness Z_0 is defined as a fitted parameter of a logarithmic velocity profile, the river data indicate that the profile origin displacement below the tops of roughness elements scales with Z_0. No direct relation between Z_0 and bed material size is evident under mobile bed conditions. For these conditions a relation between hydraulic roughness and U^{*2} is identified (with U^* also derived as a log profile parameter). A flow resistance equation using this relation is verified by comparison with mobile bed laboratory measurements in which U^* is not fitted from velocity profiles.

Ram Balachandar and V. C. Patel (2002) had performed experiments to measure the characteristics of a turbulent boundary layer developing on a rough surface for an open channel flow at close proximity to the free surface. Stream wise velocity measurements were made with a one component laser Doppler velocimeter system at the top of the spherical roughness elements. Measurements at three stations downstream of the plate leading edge showed the growth of the boundary layer on the rough wall and its interaction with the exterior open-channel flow and the free surface. Resorting to the turbulence profile provides an alternative definition of the boundary layer thickness.

Xingwei Chen and Yee-Meng Chiew (2004), they investigated theoretically and experimentally the velocity distributions of turbulent open channel flow with bed suction. A velocity profile with a slip velocity at the bed surface and an origin displacement under the bed surface is proposed and discussed. Based on this assumption, a modified logarithmic law is derived. The measured experimental velocity distribution verifies the accuracy of the theoretically derived profile. The data show a significant increase in the near bed velocity and a velocity reduction near the water surface, resulting in the formation of a more uniform velocity distribution. The values of the origin displacement slip velocity and shear velocity are found to increase with increasing relative suction. The measured data show the occurrence of two flow regions in the suction zone: a transitional region in which the velocity readjusts rapidly; and an ‘‘equilibrium’’ region.

CHAPTER-3

3.1 Layout of experiment

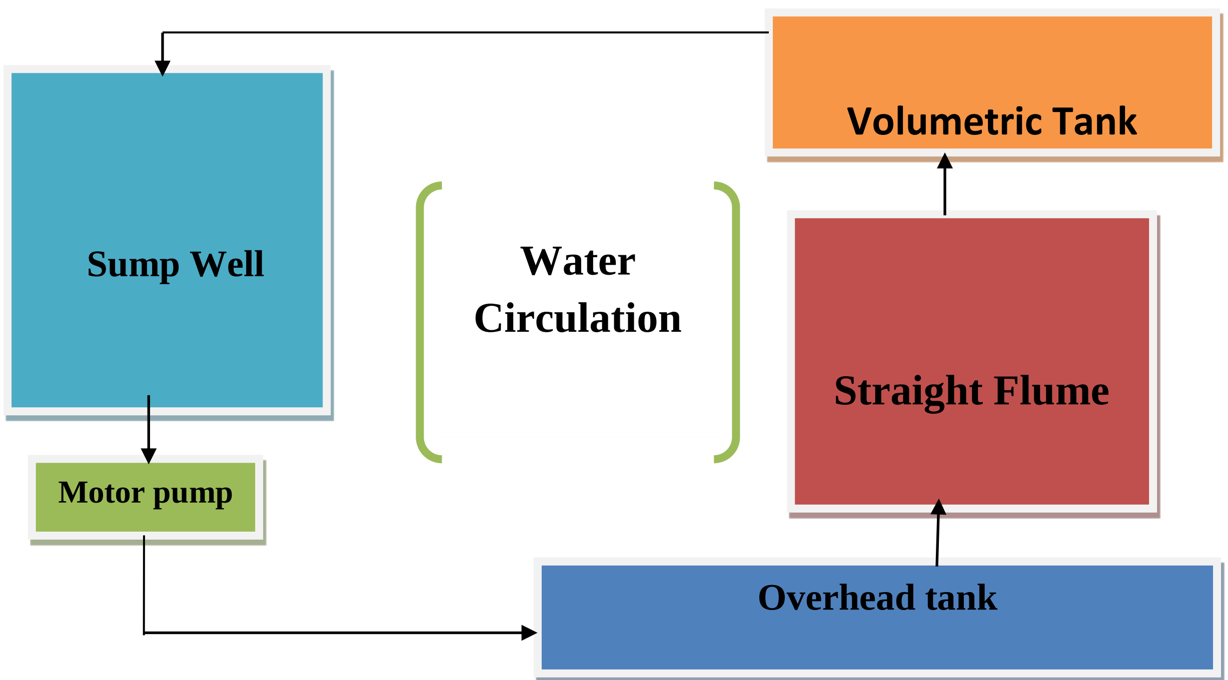


Figure-2

3.2 EXPERIMENTAL SETUP:

3.2.1 Straight Flume

A Flume is an open artificial channel or chute carrying a stream of water. In a way a flume is a model of a river/canal/water body for conducting experiments and observing its behavior. Making use of flume real conditions of rivers/canal/water bodies can be generated virtually. Flume also helps in obtaining the parameters of river/canal/any water bodies experimentally in laboratory.

One shouldn't be confused with flumes and aqueducts, which are built with the goal of transporting the water, whereas a flume would use the flowing water to transport other materials.

There are different types of flume basing on geometry or shape

1. Straight flume
2. Meandering flume

But here we are concerned with the straight flume only.

The experimental flume which is straight in shape and having a rigid bed made of cement mortar is shown in figure-3.

Figure-3

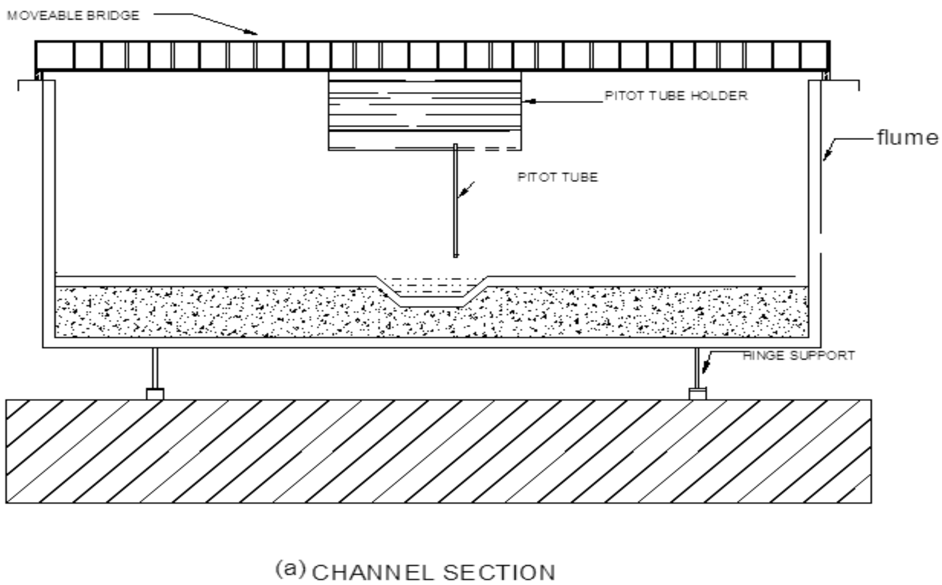


Figure-4 Sectional view of flume

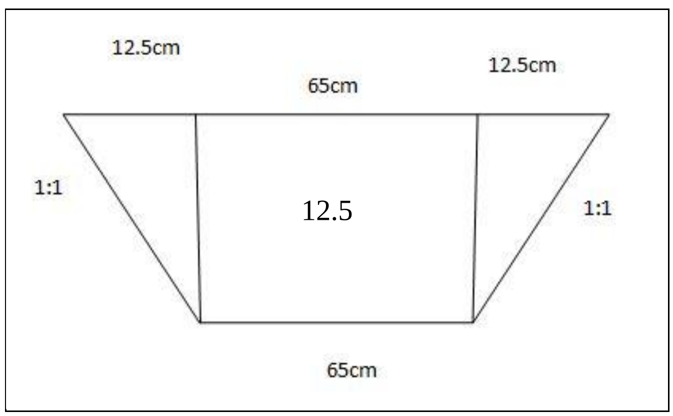


Figure-5 Sectional view-In bank

Construction of channel is done with the use of M15 concrete mix and finished smoothly.

3.2.2 Volumetric Tank

It is a tank where water is temporarily stored for discharge calculations.

Area of Volumetric Tank, A=20.928784 m^2

Outlet of volumetric tank is closed and water is allowed to fill the tank. Around 20-30 minutes later, time taken for 1 cm rise of water in volumetric tank is measured. This procedure is repeated for 4-5 times and average time (T) is evaluated.

Volume of water collected in T sec, V= A* H = A*(1cm).

Discharge, Q=V/T

= (A*1)/T m^3/s

Figure-6

3.2.3 Sump well and Overhead tank

An underground tank where water from volumetric tank is collected and stored permanently and making use of motors pumped into overhead tank for experimental usage. Overhead is a rectangular tank placed over a certain height from ground level. Input water of overhead tanks comes from sump well and output from overhead tank flows to flume.

3.2.4 Motor System

Laboratory is equipped with 2 types of motors having capacity 1HP 2HP

1. Submergible motors
2. Priming motors

Care has to be taken such that water level in overhead tank during the experiments should be more-less constant.

3.3 INSTRUMENTS USED:

3.3.1 Pitot tube

A Pitot-tube is a device used for measuring the velocity of flow at any point in a pipe or a channel. Its principle is based on the fact that if the velocity of flow at a point becomes zero, the pressure there is increased due to the conversion of kinetic energy into pressure energy.

The Pitot-tube consists of a steel tube bent at right angle. The lower end, which is bent through 90 º, is directed opposite to flow direction of the water. The kinetic energy is converted to pressure energy so the liquid rises up in the tube, with this velocity of water at a point can be evaluated. . Diameter of pitot tube is D=4.07 mm.

The theoretical velocity is given by:

$$\mathbf{V_{th} = (2gh)^{1/2}}$$

Where,

h = difference of pressure head which is calculated from the manometer

The actual velocity is given by:

$$V = C_v(2gh)^{1/2}$$

C_v= coefficient of pitot-tube

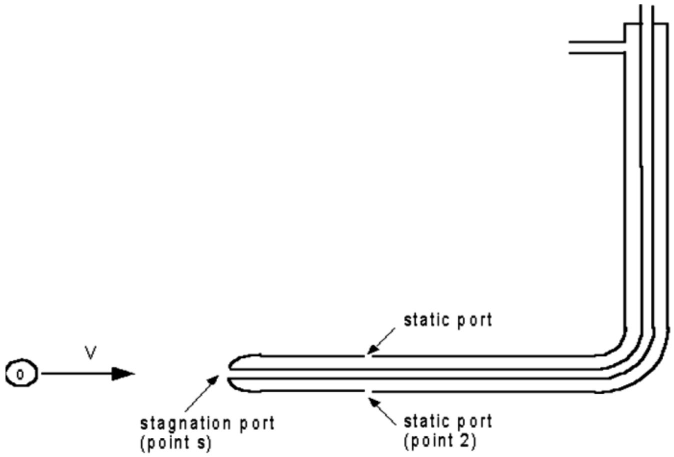


Figure-7

Pressure difference at various locations in a straight channel for different depth was recorded. The data recorded was used for the further calculation of velocity distribution.

3.3.2 ADV (acoustic Doppler velocimeter)

16-MHz Micro ADV (Acoustic Doppler Velocimeter) from the original Son-Tek, San Diego, Canada, is the most significant and efficient breakthrough in 3-axis (3D) Velocity meter Technology. The higher acoustical frequency of 16 MHz enables the Micro-ADV the optimal instrument for laboratory-research orientated study. After setup of the Micro ADV with the software package it is used for taking high-quality 3-D Velocity data at various points. This data of flow area are received to the ADV-processor. Raw data after compilation by software package of the processor is shown by the computer. For a minute, at every point the instrument records a number of velocity data. The mean value of the point velocities (3-D) were recorded for each flow depths using the statistical analysis using the installed software.

The Doppler shift principle is used by the Micro ADV to measure the velocity of small particles, assumed to move at velocities similar to the fluid. Velocity is resolved into 3orthogonal components like vertical, Tangential and radial and measured in a volume five centimeters below the probe head, minimizing interference of the flow field, and allowing measurements/observations to be made close to the bed.

The Micro ADV has the Features like

- Three-axis velocity measurement
- Small sampling volume -- less than 0.1 cm3
- High sampling rates -- up to 50 Hz
- Small optimal scattered -- excellent for low flows
- Comprehensive software
- Large velocity range: 1 mm/s to 2.5 m/s
- High accuracy: 1% of measured range
- No recalibration needed
- Excellent low-flow performance

ADV (down probe) is unable to read the velocity of upper layer up to 5 cm below the free surface so Preston tube technique in which the standard pitot tube in conjunction with a inclined manometer is used for the measurement of point velocity readings at some specified positions for the upper 5cm region from free surface across the channel.

Down probe

Up probe

Figure-8

3.3.3 Derivation for velocity of flow

Velocity of flow can be calculated from Bernoulli's equation

$$z + \frac{p}{\rho g} + \frac{v^2}{2g} = h$$

Z= Datum height

$\frac{p}{\rho g} =$ Pressure head

$\frac{V^2}{2g} =$ Kinetic head

h= Total head

$$z_1 + \frac{p_1}{\rho g} + \frac{v_1^2}{2g} = z_2 + \frac{p_2}{\rho g} + \frac{v^2{}_2}{2g}$$

Here point 1 is located just outside of opening of pitot tube

Point 2 is located just before the 90^0 bent.

As, $z_1 = z_2 = 0$

And $V_2 = 0$ (velocity of water inside the pitot tube is zero)

Difference in pressure heads, $\frac{P_2}{\rho g} - \frac{P_1}{\rho g} = \Delta h * \sin\theta$

$\Delta h =$ Height difference in manometer tubes.

θ = angle of inclination of manometer

Therefore, $\frac{V_1^2}{2g} = \Delta h * \sin\theta$

$V = \sqrt{2g\Delta h \sin\theta}$ Eq. (1)

3.4 EXPERIMENTAL PROCEDURE

Evaluation of slope of flume

A long transparent thin pipe is taken and is filled with water. Desired length of channel is selected where slope has to be evaluated with thin pipe, placed along the lengths with two ends fixed at two points so as to make no vertical deflection of water in the thin pipe. Vertical height difference of water in the thin pipe is measured making use of scale/tape, say A and the length between the desired points is also measured, say B.

Slope of flume, $\theta = \tan^{-1}\left(\frac{A}{B}\right)$ Eq. (2)

3.4.1 Method adopted

3.4.1.1 Longitudinal Boundary Layer

- Water from overhead tank with a controlled discharge is allowed to flow over the surface of channel for about 30-45 minutes for obtaining a steady flow in the channel.
- Within this interval, one should make sure Pitot tube is free from bubbles. If present they should be carefully bubbled out. Otherwise, presences of bubbles lead to erroneous reading in manometer.
- The choice of discharge should be such that overflow from main channel does not take place.
- Water level is checked with the help of needle so as to ensure constant discharge. Any small fluctuations in the flow should be avoided for practical purposes. This may be due to undulations in the channel bed preparations.
- Channel is divided for ease in experimental approach. The division can be of 0.5m or 1m.

- Now the setup of experiment is brought to the position where velocity profile has to be found, say x=0 m.
- Depth of flow is found by placing needle at various points (say, 5 points) in a particular cross-section; average depth of flow in a particular cross-section is evaluated.
- For obtaining rough picture of velocity profile at a section, depth of flow is divided into five equal divisions such as 0, 0.2h, 0.4h, 0.6h, 0.8h. Reading at height H can't be taken as bubbles may enter into manometer.
- Pitot tube is placed along the center line of section and varied from various position 0, 0.2h, 0.4h, 0.6h, 0.8h.
- Readings of manometer are taken at individual depths for velocity after 3 minutes interval of change in position of pitot tube for different depths.
- From these data, Δh is calculated which in term gives the value of velocity at that particular depth from eq. (1).
- Above procedure is followed for next sections to find the desired boundary layer thickness and length of fully developed flow.

3.4.1.2 TRANSVERSE BOUNDARY LAYER

- Once the length of fully developed flow is known, velocity profiles of complete transverse section are to be measured.
- As Boundary layer thickness is symmetric about center line of transverse section only half of the sections velocity profiles are measured.
- Now half the length of transverse section is divided equally and named, say Y_1, Y_2, Y_3 etc.
- The velocities at 0, 0.2h, 0.4h, 0.6h, 0.8h are measured by making use of pitot tube-manometer combination at specified position of transverse section.
- From the above data velocity profiles of transverse section to be drawn and Growth of boundary layer thickness along the transverse can also be found out.

3.5 EXPERIMENTAL DATA:

FOR LONGITUDINAL DIRECTION (ALONG THE FLOW)

TABLE-1

For depth of flow=7.1cm, $\theta = 28.7^0$

X(in m)	Y(in cm)	H_1(cm)	H_2(cm)	ΔH (cm)	$V = \sqrt{2g\Delta h \sin\theta}$ (in m/s)
2	0	56.9	56.9	0	0
	0.2h	56.9	59.4	2.5	0.485
	0.4h	56.5	59.5	3	0.532
	0.6h	56.5	59.5	3	0.532
	0.8h	56.5	59.5	3	0.532
2.5	0	55.7	55.7	0	0
	0.2h	55.7	58.3	2.6	0.495
	0.4h	55.5	58.5	3	0.532
	0.6h	55.5	58.8	3.3	0.540
	0.8h	55.5	58.5	3.3	0.540
3	0	56.5	56.5	0	0
	0.2h	56.4	58.9	2.5	0.485
	0.4h	56.5	59.5	3	0.532
	0.6h	56.5	59.5	3	0.532
	0.8h	56.5	59.5	3	0.532
3.1	0	56.3	56.3	0	0
	0.2h	56.4	59.4	3	0.53
	0.4h	56.5	59.6	3.1	0.54
	0.6h	56.5	59.8	3.3	0.56
	0.8h	56.7	60.0	3.3	0.56
3.2	0	56.2	56.2	0	0
	0.2h	56.4	59.3	2.9	0.52
	0.4h	56.4	59.6	3.2	0.56
	0.6h	56.3	59.7	3.4	0.57
	0.8h	56.3	59.7	3.4	0.57
3.5	0	58.9	56.5	2.4	0
	0.2h	59.6	56.5	3.1	0.54
	0.4h	59.7	56.4	3.3	0.56
	06h	59.6	56.2	3.4	0.57
	0.8h	59.8	56.3	3.5	0.57
4	0	56.0	56.0	0	0
	0.2h	56.0	59.1	3.1	0.54
	0.4h	56.3	59.7	3.4	0.57
	0.6h	56.2	59.8	3.6	0.58
	0.8h	55.9	59.5	3.6	0.58

TABLE-2

For flow depth=5.3cm, $\theta = 28.6^0$

X	Y	H_1	H_2	ΔH (cm)	$V = \sqrt{2g\Delta h \sin\theta}$ (in m/s)
2	0	52.1	52.1	0	0
	0.2h	52.0	53.3	1.3	0.35
	0.4h	52.5	54.3	1.8	0.41
	0.6h	52.9	54.9	2	0.43
	0.8h	52.9	54.9	2	0.43
2.5	0	51.8	51.8	0	0
	0.2h	51.5	52.9	1.4	0.36
	0.4h	51.9	53.3	1.4	0.36
	0.6h	51.9	53.8	1.9	0.41
	0.8h	52.4	54.2	2	0.42
3	0	52.0	52.0	0	0
	0.2h	52.1	53.5	1.4	0.360
	0.4h	52.1	53.8	1.7	0.399
	0.6h	52.0	53.8	1.8	0.41
	0.8h	52.0	53.8	1.8	0.41
3.3	0	51.6	51.6	0	0
	0.2h	51.7	52.7	1	0.31
	0.4h	51.7	52.8	1.1	0.32
	0.6h	51.7	52.8	1.1	0.32
	0.8h	51.6	52.8	1.2	0.335
3.4	0	51.4	51.4	0	0
	0.2h	51.3	52.4	1.1	0.32
	0.4h	51.3	52.5	1.2	0.335
	0.6h	51.3	52.6	1.3	0.35
	0.8h	51.5	52.8	1.3	0.35
3.5	0	51.1	51.1	0	0
	0.2h	51.2	52.6	1.4	0.360
	0.4h	51.1	52.8	1.7	0.399
	0.6h	51.1	52.8	1.7	0.399
	0.8h	51.0	52.8	1.8	0.399
4	0	51.2	51.2	0	0
	0.2h	51.2	52.7	1.5	0.375
	0.4h	51.2	52.8	1.6	0.387
	0.6h	51.1	52.8	1.7	0.399
	0.8h	50.9	52.7	1.8	0.41

TABLE-3

Flow depth= 8.8cm, $\theta = 30.5$

X(in m)	Y(in cm)	H_1(cm)	H_2(cm)	ΔH (cm)	$V = \sqrt{2g\Delta h \sin\theta}$ (in m/s)
2.5	0	62	62	0	0
	0.2h	62	60.6	1.4	0.373
	0.4h	62.1	60.5	1.6	0.399
	0.6h	62.2	60.5	1.7	0.411
	0.8h	62.2	60.5	1.7	0.411
3	0	62	62	0	0
	0.2h	62	60.4	1.6	0.399
	0.4h	62.4	60.5	1.7	0.411
	0.6h	62.4	60.5	1.7	0.411
	0.8h	62.5	60.6	1.7	0.411
3.3	0	62.1	62.1	0	0
	0.2h	62.1	60.6	1.5	0.386
	0.4h	62.3	60.6	1.7	0.411
	0.6h	62.4	60.6	1.7	0.411
	0.8h	62.4	60.6	1.7	0.411
3.4	0	61.9	61.9	0	0
	0.2h	61.9	60.4	1.5	0.385
	0.4h	62.1	60.4	1.7	0.411
	0.6h	62.1	60.4	1.7	0.411
	0.8h	62.2	60.5	1.7	0.411
3.5	0	62.1	62.1	0	0
	0.2h	62.1	60.4	1.7	0.411
	0.4h	62.2	60.3	1.9	0.435
	0.6h	62.3	60.4	1.9	0.435
	0.8h	62.5	60.6	1.9	0.435
4	0	62.2	62.2	0	0
	0.2h	62.2	60.5	1.7	0.411
	0.4h	62.1	60.1	2	0.446
	06h	62.1	60.1	2	0.446
	0.8h	62	60	2	0.446

TABLE-4

Flow depth= 7.7 cm, $\theta = 30.5$

X(in m)	Y(in cm)	H_1(cm)	H_2(cm)	ΔH (cm)	$V = \sqrt{2g\Delta h \sin\theta}$ (in m/s)
2	0	61.5	61.5	0	0
	0.2h	61.5	59.3	2.2	0.468
	0.4h	61.7	59.3	2.4	0.489
	0.6h	61.9	59.3	2.6	0.509
	0.8h	62	59.3	2.7	0.519
2.5	0	59	59	0	0
	0.2h	61.5	59	2.5	0.499
	0.4h	61.6	58.9	2.7	0.519
	0.6h	61.8	58.9	2.9	0.537
	0.8h	61.9	59	2.9	0.537
3	0	61.3	61.3	0	0
	0.2h	61.3	59.1	2.2	0.468
	0.4h	61.6	59.1	2.5	0.499
	0.6h	61.7	59.1	2.6	0.509
	0.8h	61.8	59.2	2.6	0.509
3.3	0	61.2	61.2	0	0
	0.2h	61.2	58.9	2.3	0.479
	0.4h	61.6	58.9	2.7	0.519
	0.6h	61.7	58.9	2.8	0.528
	0.8h	61.7	58.9	2.8	0.528
3.5	0	61.5	61.5	0	0
	0.2h	61.6	59.1	2.4	0.489
	0.4h	61.7	58.9	2.7	0.519
	0.6h	61.7	59.1	2.8	0.528
	0.8h	61.8	59.2	2.8	0.528
4	0	61.3	61.3	0	0
	0.2h	61.3	58.9	2.4	0.489
	0.4h	61.5	58.8	2.7	0.519
	06h	61.7	58.9	2.8	0.528
	0.8h	61.7	58.9	2.8	0.528

TABLE-5

Using Acoustic Doppler Velocimeter

X (m)	Depth of Flow	Velocity (m/s)
3	0	0
	0.2h	0.25
	0.4h	0.38
	0.6h	0.38
	0.8h	0.38
3.3	0	0
	0.2h	0.37
	0.4h	0.39
	0.6h	0.39
	0.8h	0.39
3.5	0	0
	0.2h	0.37
	0.4h	0.39
	0.6h	0.39
	0.8h	0.39
4	0	0
	0.2h	0.37
	0.4h	0.39
	0.6h	0.39
	0.8h	0.39
4.5	0	0
	0.2h	0.38
	0.4h	0.40
	0.6h	0.40
	0.8h	0.40

FOR TRANSVERSE DIRECTION AT THE POINT WHERE THE FLOW IS FULLY DEVELOPED

TABLE-6

For depth of flow=7.1cm, $\theta = 28.7^0$

Y	Depth of flow(cm)	H_2(cm)	H_2(cm)	ΔH (cm)	$V = \sqrt{2g\Delta h \sin\theta}$ (in m/s)
35	0.2h	56.3	59	2.7	0.504
	0.4h	56.3	59.4	3.1	0.540
	0.6h	56.3	59.6	3.3	0.557
	0.8h	56.3	59.6	3.3	0.567
25	0.2h	56.4	59.1	2.7	0.504
	0.4h	56.4	59.4	3	0.532
	0.6h	56.4	59.5	3.1	0.54
	0.8h	56.4	59.5	3.1	0.54
15	0.2h	56.4	58.9	2.5	0.485
	0.4h	56.5	59.2	2.7	0.504
	0.6h	56.4	59.2	2.8	0.512
	0.8h	56.4	59.2	2.8	0.512

TABLE-7

For flow depth=5.3cm, $\theta = 28.6^0$

Y	Depth of flow(cm)	H_2(cm)	H_2(cm)	ΔH (cm)	$V = \sqrt{2g\Delta h \sin\theta}$ (in m/s)
35	0.2h	51.9	52.8	0.9	0.291
	0.4h	51.9	53	1.1	0.321
	0.6h	51.8	53	1.2	0.336
	0.8h	51.8	53	1.2	0.336
25	0.2h	51.7	52.6	0.9	0.291
	0.4h	51.7	52.7	1	0.306
	0.6h	51.7	52.7	1	0.306
	0.8h	51.7	52.7	1	0.306
15	0.2h	51.5	52.5	1	0.306
	0.4h	51.5	52.5	1	0.306
	0.6h	51.5	52.5	1	0.306
	0.8h	51.6	52.6	1	0.306

TABLE-8

Flow depth= 8.8cm, $\theta = 30.5^0$

Y	Depth of flow(cm)	H_2(cm)	H_2(cm)	ΔH (cm)	$V = \sqrt{2g\Delta h \sin\theta}$ (in m/s)
35	0.2h	61.9	60.3	1.6	0.399
	0.4h	62.3	60.5	1.8	0.423
	0.6h	62.5	60.7	1.8	0.423
	0.8h	62.5	60.7	1.8	0.423
25	0.2h	62.1	60.6	1.5	0.386
	0.4h	62.2	60.6	1.6	0.399
	0.6h	62.2	60.6	1.6	0.399
	0.8h	62.3	60.6	1.7	0.411
15	0.2h	61.9	60.4	1.5	0.386
	0.4h	62.1	60.4	1.7	0.411
	0.6h	62.4	60.7	1.7	0.411
	0.8h	62.4	60.7	1.7	0.411

TABLE-9

Depth of flow =7.7 cm, $\theta = 30.5^0$

Y	Depth of flow(cm)	H_2(cm)	H_2(cm)	ΔH (cm)	$V = \sqrt{2g\Delta h \sin\theta}$ (in m/s)
35	0.2h	61.3	58.9	2.4	0.489
	0.4h	61.6	58.9	2.7	0.519
	0.6h	61.8	59	2.8	0.528
	0.8h	61.8	59	2.8	0.528
25	0.2h	61.1	58.8	2.3	0.479
	0.4h	61.5	58.9	2.6	0.509
	0.6h	61.6	58.9	2.7	0.519
	0.8h	61.6	58.9	2.7	0.519
15	0.2h	61.3	58.9	2.4	0.489
	0.4h	61.6	58.9	2.7	0.519
	0.6h	61.6	58.9	2.7	0.519
	0.8h	61.6	58.9	2.7	0.519

CHAPTER-4

Results and discussion

As soon as observations (velocities using either pitot tube-manometer combination or ADV) are taken, one have to tentatively find the thickness of Boundary layer at each section of consideration.

Then by applying the definition of Boundary layer thickness i.e.., depth from bottom (rough surface) to the point where velocity is 99% of free stream velocity.

Velocity at 99% of free stream velocity can be found out by using method of Interpolation between two known points.

Example: **Depth of flow, h=7.7**

Depth	Velocity
0	0
0.2h	0.489
0.4h	0.519
0.6h	0.519
0.8h	0.519

Here Free Stream velocity, V= 0.519 m/s

99% of free stream velocity, V^1 = 0.99* V

V^1 =0.51381 m/s

So, Depth at V^1 can be found by using method of Interpolation

At 0.2h depth, velocity is 0.489

At 0.4h depth, velocity is 0.519

Let Y be the depth, velocity is 0.51381

$$Y = \frac{0.51381 - 0.489}{0.519 - 0.489}(0.4h - 0.2h) + 0.2h$$

$$= \frac{0.02481}{0.03}(0.2h) + 0.2h$$

= 0.1654h+0.2h =0.3654h =2.81358 cm.

For rest of Observation tables above method of interpolation is being followed.

Analysis of Results

In the graph of Boundary layer thickness in longitudinal direction, increasing trends is seen from starting point (leaving the disturbances caused by various agents near the entrance) to length of fully developed flow

The graph of transverse boundary layer which is being shown is only half the transverse length of section. As the growth of Boundary layer thickness along transverse direction is symmetric about the center-line so other half can be evaluated by taking mirror image across the center-line of transverse section.

For rest of graphs the Growth of Boundary Layer thickness along the Transverse section is shown from center-line to periphery i.e.., half of Transverse section.

Growth of Boundary Layer in Longitudinal direction

From the Table-1 data it is observed that the flow is fully developed after 3.1m from the entrance of the channel. So the experimental data for the length of fully developed flow is found to be 3.1m from where the boundary layer thickness remains almost same along the direction of flow. The thickness of the boundary layer is found to be 0.4h=2.8cm from the bottom of the channel. Initially it is being affected by various agents but finally following the trend of increasing in the direction of flow.

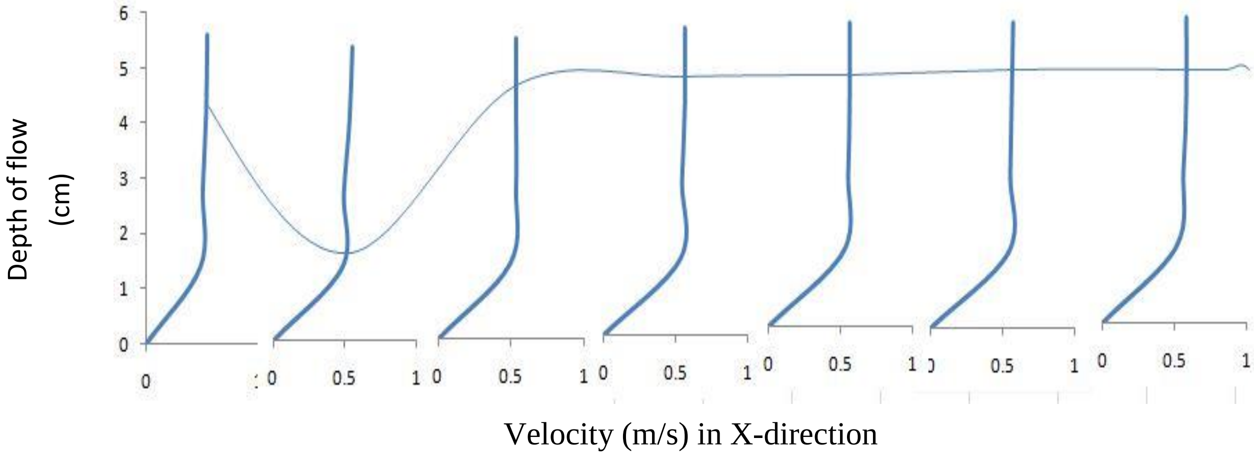


Figure-9

Growth of Boundary Layer in Transverse direction

At x=3.1m the velocity of flow is measured along the transverse section and the velocity profile is given below.

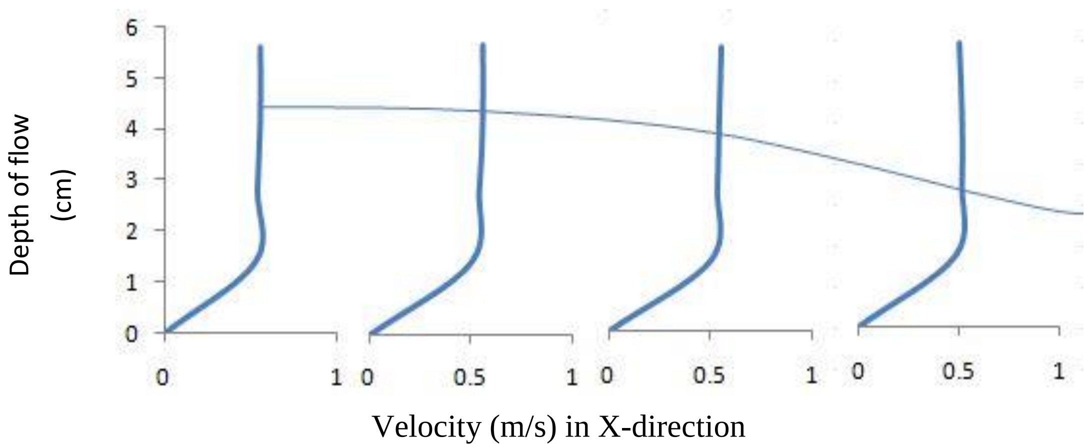


Figure-10

Growth of Boundary Layer in Longitudinal direction

Boundary Layer thickness is 2.12cm for depth of flow 5.3 cm.

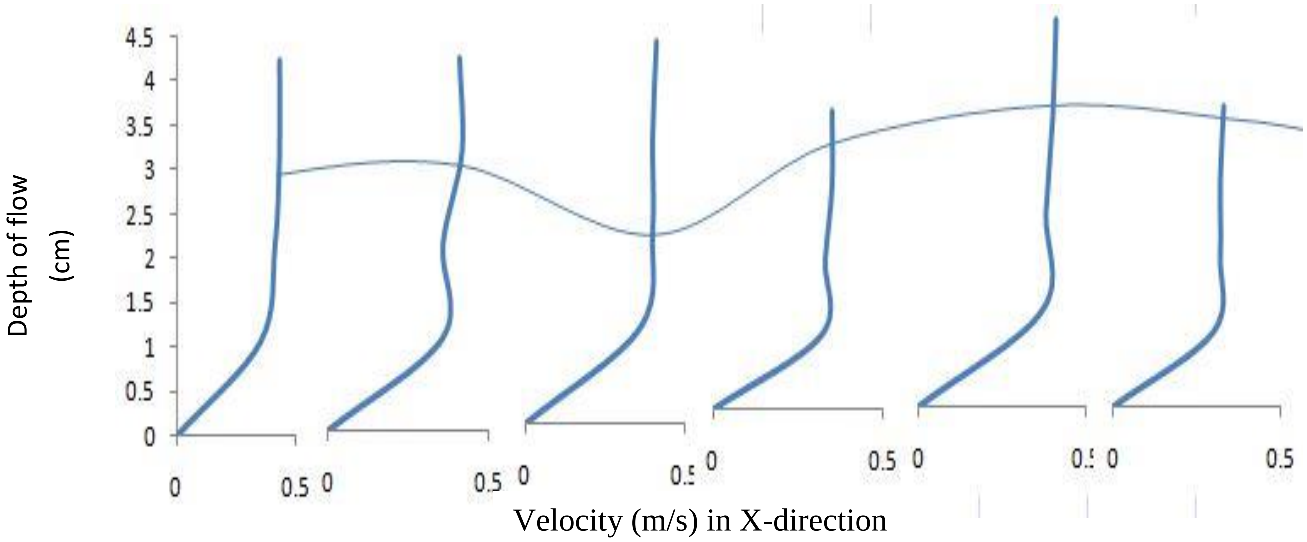


Figure-11

Growth of Boundary Layer in Transverse direction

Length of fully developed flow is 3.5 m for depth of flow 5.3 cm

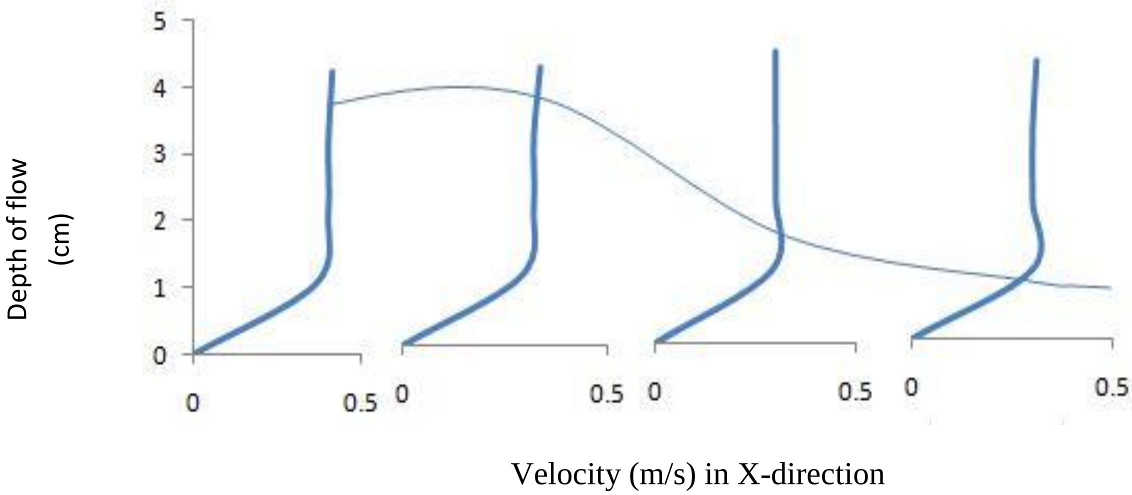
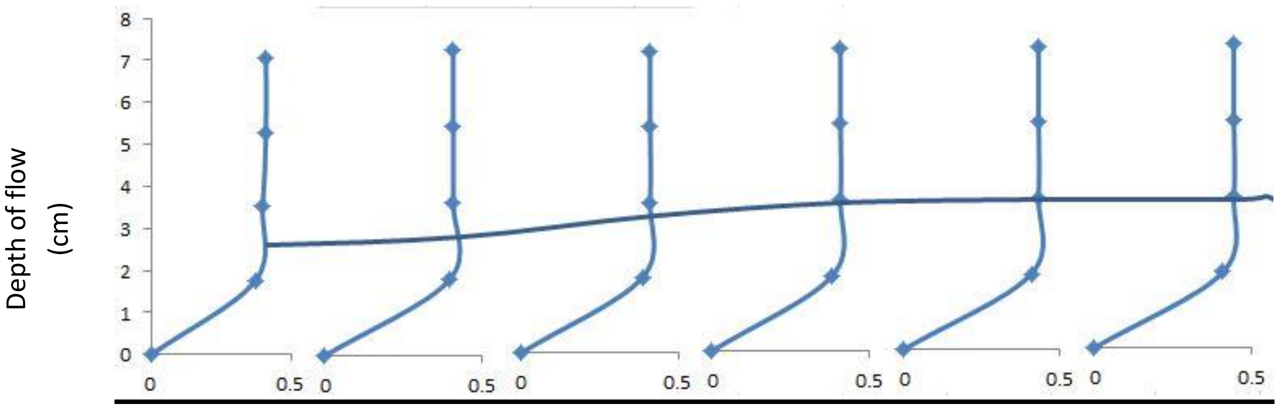


Figure-12

Growth of Boundary Layer in Longitudinal direction

Boundary layer thickness is 3.2 cm for depth of flow 8.8 cm.

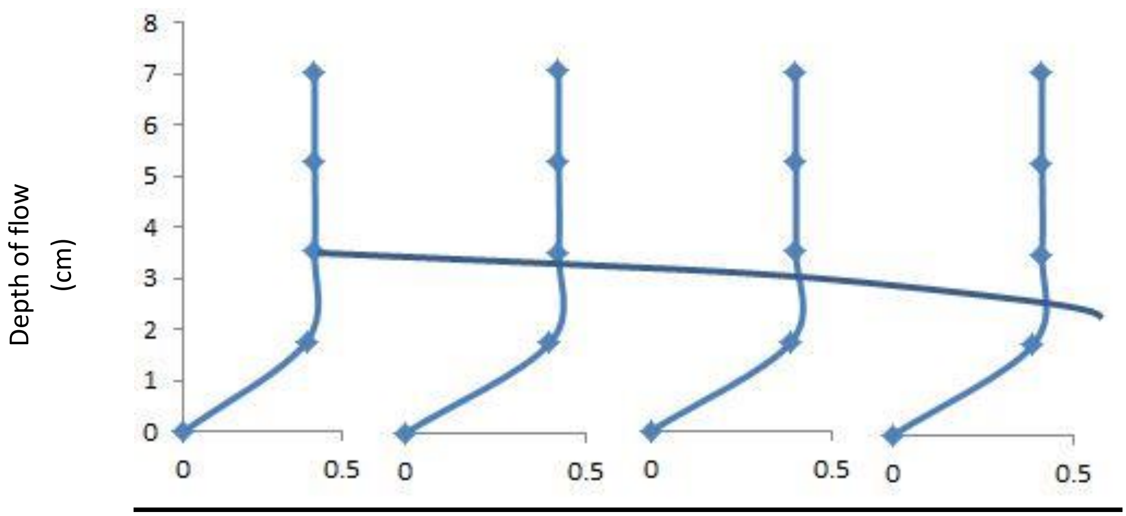


Velocity (m/s) in X-direction

Figure-13

Growth of Boundary Layer in Transverse direction

Length of fully developed flow is 3.4 m for depth of flow 8.8 cm

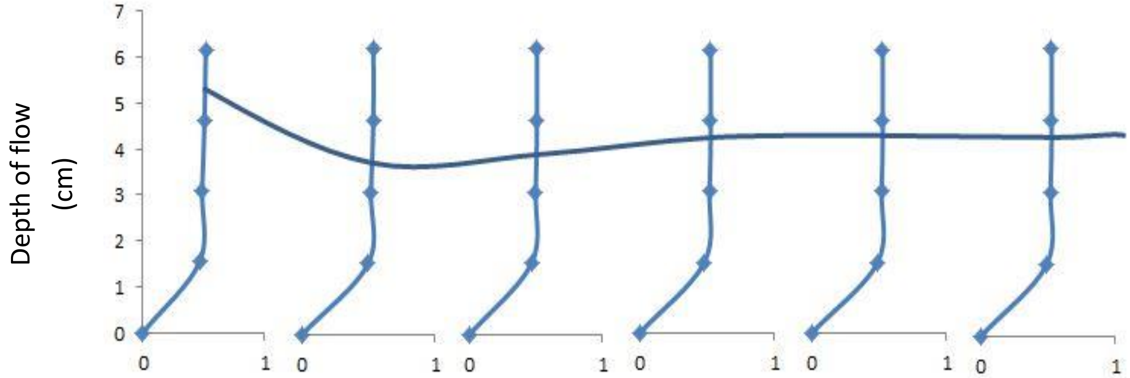


Velocity (m/s) in X-direction

Figure-14

Growth of Boundary Layer in Longitudinal direction

Boundary layer thickness 3.7 cm for depth of flow 7.7 cm

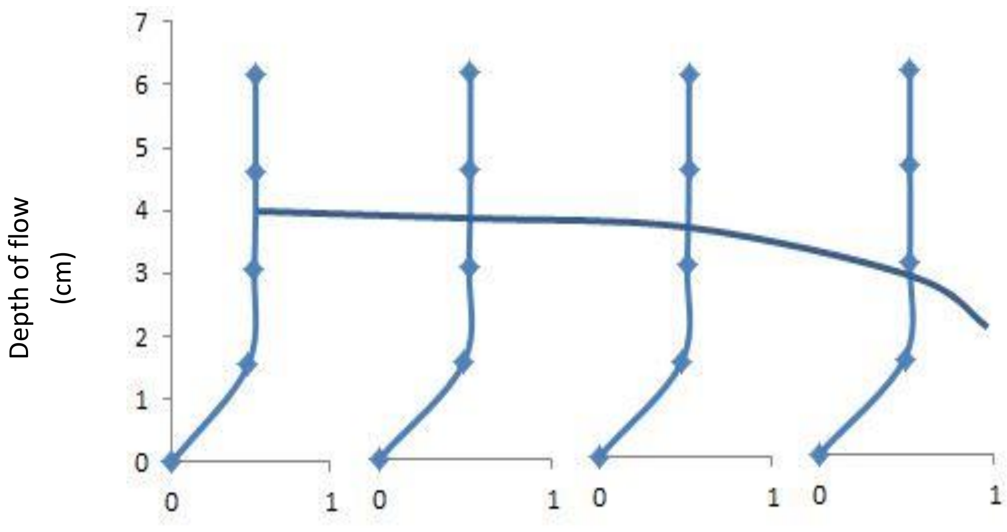


Velocity (m/s) in X-direction

Figure-15

Growth of Boundary Layer in Transverse direction

Length of fully developed flow is 3.3m for depth of flow =7.7 cm



Velocity (m/s) in X-direction

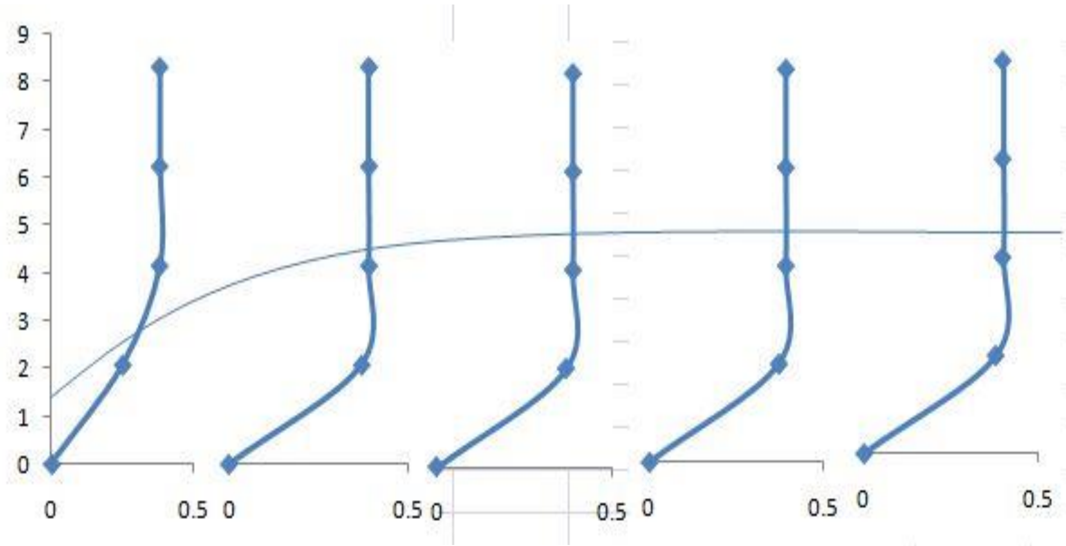
Figure-16

Using Acoustic Doppler Veloci meter (ADV)

Growth of Boundary Layer in Longitudinal direction

Boundary layer thickness is 4.2cm and length of fully developed flow is 3.3m.

Depth of flow (cm)



Velocity (m/s) in X-direction

Figure-17

COMPARISON WITH THEORITICAL VALUE

According to Bauer's investigations (1951),

$$\frac{\delta}{x} = \frac{0.024}{\left(\frac{x}{k}\right)^{0.13}} \qquad \text{Eq. (3)}$$

Where δ =Boundary layer thickness at x

x = distance from inlet in the direction of flow where boundary layer thickness is required.

k =roughness height (for cement surface 0.004 ft.)

Putting the respective values for x (i.e. the length of developed flow) and k the theoretical values obtained are shown in the table.

Table-10

Discharge	Length of developed flow(x)	Experimental value (Boundary Layer thickness)	Theoretical value (Boundary Layer thickness)
1	3.1m	2.8 cm	2.7 cm
2	3.5m	2.1 cm	3.0 cm
3	3.4m	3.2 cm	2.9 cm
4	3.3m	3.7 cm	2.8 cm

Here expiremental obtained are compared with theorticial values from Bauer's equation.

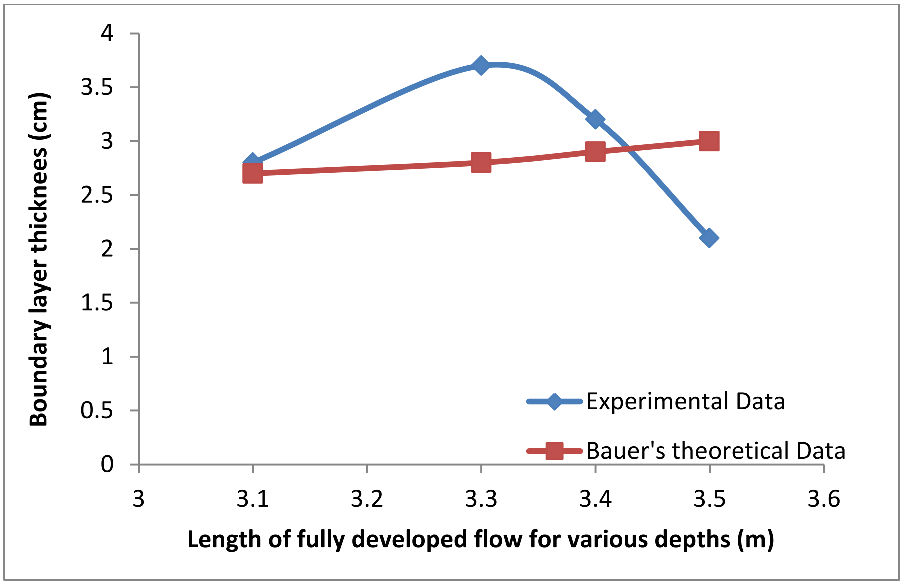


Figure-18

From the above graph, it is observed that experimental data of boundary layer thickness obtained increases to a maximum value and then decreases with length of fully developed flow for various discharges (flow depths). Whereas according to Bauer's equation there is a slight increase in boundary layer thickness with length of fully developed flow for various discharges (flow depths).

Similarly, from US Army Corps of engineers by Campbell et al. (1965)

$$\frac{\delta}{x} = 0.08\left(\frac{x}{k_s}\right)^{-0.233} \qquad \text{Eq. (4)}$$

Where, parameters hold the same definitions as Bauer's equation

Table-11

Discharge	Length of developed flow(x)	Experimental value (Boundary Layer thickness)	Theoretical value (Boundary Layer thickness)
1	3.1 m	2.8 cm	3.9
2	3.5 m	2.1 cm	4.3
3	3.4 m	3.2 cm	4.2
4	3.3 m	3.7 cm	4.1

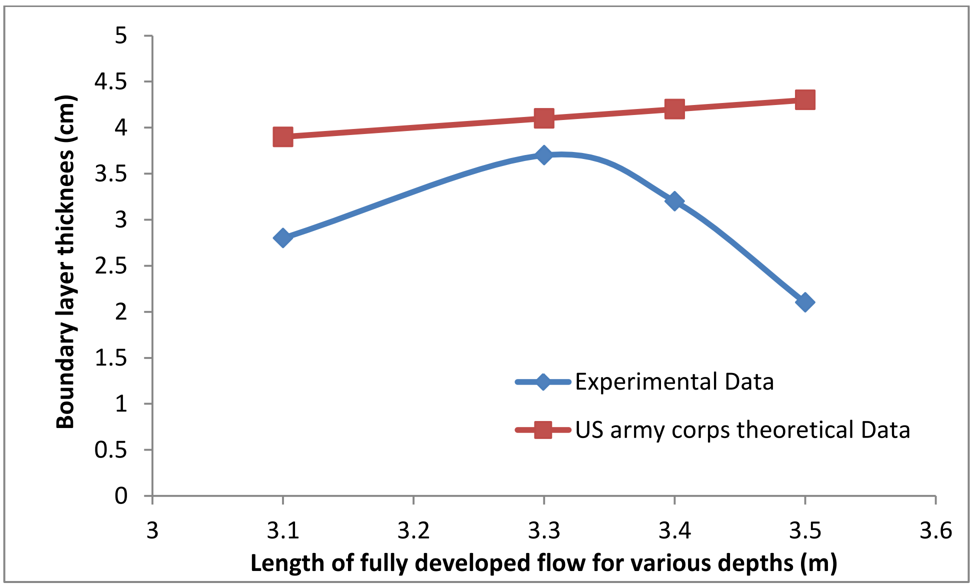
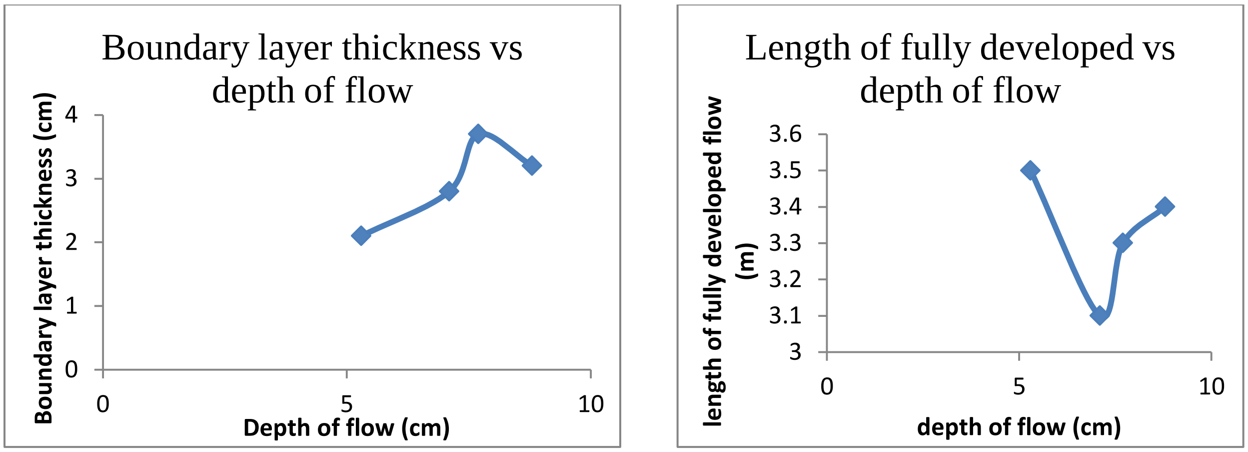


Figure-19

From the above graph, as stated above experimental data od boundary layer thickness increases to a maximum value then decreases with length of fully developed flow for various discharges (flow depths). But according to US Army Corps theoretical equation there is a linear increase in boundary layer thickness with length of fully developed flow for various discharges (flow depths).

Relation between boundary layer thickness and length of fully developed flow with discharge



(I) (II)

Figure-20

From the above figure-20 (I) boundary layer thickness increases initially and reaches a maximum value at a depth of 8cm,then decreases gradually and remain constant with depth of flow increases.

Also from the figure-20 (II) length of fully developed flow decreases initially reaches a minimum value and then increases with depth of flow (discharge).

CHAPTER-5

CONCLUSION

A completely new method, dividing the length of flume into various sections and evaluating velocities at each section is adopted. Here finding velocities at each section include observations at 0, 0.2h, 0.4h, 0.6h,0.8h depths where h is the depth of flow.

From the various experimental data, the boundary layer thickness and length of fully developed flow are calculated.

- Near the inlet section, due to the presence of turbulence and eddies, proper correlation with theoretical study is not observed. One can find the momentum transfer among the layers which leads to haphazard values in the growth of boundary layer thickness. So it is suggested not to consider these velocity profiles in evaluating boundary layer thickness and length of fully developed flow.
- Experimentally, for various depths of flow 5.3 cm, 7.1 cm, 7.7 cm and 8.8 cm respective boundary layer thickness are 2.1 cm, 2.8cm, 3.7 cm and 3.2 cm.
- Also for various depths of flow 5.3 cm, 7.1 cm, 7.7 cm and 8.8 cm respective length of fully developed flow are 3.5 m, 3.1 m, 3.3 m and 3.4 m.
- Theoretically, boundary layer thickness increases from inlet section to section where flow is fully developed and remains constant afterwards.

- Also from the above experimental data it is validated that, boundary layer thickness increasing from inlet section to section where flow is fully developed. From the section where flow is fully developed to outlet section thickness of boundary layer remains constant. But if adjustment of Tail gate of flume is not done properly, one can find erroneous data which will not correlate with theoretical value of boundary layer thickness.

- Theoretically, Boundary layer thickness along the transverse section is maximum at center line of section with decreasing near the wall side of channels. From the series of experiments above statement is validated from above figures.

- Discharge of flow (flow depth) is having greater impact on boundary layer thickness and length of fully developed flow which is discussed in comparison part.

- Section parameters like length, breadth, aspect ratio, friction coefficient, roughness of section, type of surface (smooth/rough), and type of material used in section preparation will affect boundary layer thickness and length of fully developed flow in various ways.

CHAPTER-6

REFERENCE

1. Bansal R.K., Fluid Mechanics and Hydraulic machines, Laxmi publication.
2. Iehisa Nezu and Wolfgang Rodi (1986), Open-channel flow measurements with a laser doppler anemometer, *J. Hydraulic. Eng.* 112:335-355.
3. M. F. Karim and John F. Kennedy (1987), Velocity and sediment-concentration profiles in river flows, *J. Hydraulic Eng.* 113:159-176.
4. M. Salih Kirkgoz (1989),Turbulent velocity profiles for smooth and rough open channel flow, *J. Hydraulic. Eng*.115:1543-1561.
5. Graeme M. Smart (1999) Turbulent velocity profiles and boundary shear in gravel bed rivers, *J. Hydraulic. Eng.* 1999.125:106-116.
6. Ram Balachandar and V. C. Patel (2002), Rough Wall Boundary Layer on Plates in Open Channels, *J. Hydraulic. Eng*. 2002.128:947-951.
7. Yen, B. C. (2002), Open-channel flow resistance. *J. Hydraulic Engineering, ASCE*. 128(1): 20-39.
8. Xingwei Chen and Yee-Meng Chiew(2004),Velocity Distribution of Turbulent Open-Channel Flow with Bed Suction, *J. Hydraulic. Eng*. 2004.130:140-148.

9. Shu-Qing Yang, Soon-Keat Tan, and Siow-Yong Lim (2004),Velocity Distribution and Dip-Phenomenon in Smooth Uniform Open Channel Flows, *J. Hydraulic. Eng*. 2004.130:1179-1186.
10. Noor Afzal1, Abu Seena, and Afzal Bushra(2007),Power Law Velocity Profile in Fully Developed Turbulent Pipe and Channel Flows, *J. Hydraulic. Eng.* 2007.133:1080-1086.
11. Oscar Castro-Orgaz (2010), Drawdown curve and turbulent boundary layer development for chute flow, *Journal of Hydraulic Research Vol. 48, No. 5 (2010), pp. 591–602.*