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STUDY OF BOUNDARY LAYER GROWTH IN STRAIGHT OPEN RECTANGULAR CHANNEL

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ABSTRACT
Open channel flow, a branch of fluvial hydraulics, fluid flow within a conduit having free surface is an example of such flow.Whereasthe other type of flow within a closed conduit, is termed as pipe flow. Pipe flow is due to external pressure which is replaced by gravity force in open-channel flow. If we consider the open channel flow it is essential to make a study of velocity and its others characteristics is very essential for knowing various aspects of flow. Boundary layer is expressed as the fluid layer alongside to the surface of solid boundary where the effect of viscous forces is prevalent. This paper presents, the variation of boundary layer alongside the centerline of the rectangular straight channel which extends up to the free surface of a flow having aspect ratio $b/h \geq 3$, measured along and across the direction of flow of the straight simple rectangular channel and has been methodically analyzed at different test sections of the channel. The investigation is done thoroughly to encounter changes in the shape of the velocity profile all through the simple straight path, which helps in studying the thickness of boundary layer along the channel as well as across the channel. Velocity profile can be further used for identifying the growth of boundary layer, change in flow direction, accelerated or decelerated flow description. Using a pitot tube along with U-tube manometer, longitudinal velocities are measured in different cross section which is used to signify the development of completely developed open channel flow as per the variation in boundary layer thickness.

KEYWORDS: India**,** Boundary Layer; Velocity Profile; fully developed zone.

INTRODUCTION
Based on the velocity distribution the primitive difference between turbulent and laminar flow is that the maximum velocity is found at some distance lower to the surface of water for turbulent flows, but in case of laminar flows it occurs at the water surface. The presence of secondary flow cells plays important role behind this concept of velocity distribution. Velocity distribution study helps to know about the magnitude of velocity at each point

across the cross-section of flow. A lot of studies have been conducted by various authors. Nezu and Rodi(1986) had used two colours Laser Doppler Anemometer (LDA) apparatus with direct digital signal processing over smooth beds to compute thevelocity components in longitudinal and verticaldirection in a fully developed flow.M. Salih Kirkgoz (1989)had computed the velocity profiles using a laser-Doppler anemometer in a fully developed, rectangular, subcritical open channel flow on smooth and rough beds. Theaverage roughness heights used in the experiments over rough surfaces were of 1 mm, 4 mm, 8 mm, and 12 mm. Ferro and Baiamonte (1994) had done the velocity measurement in a rectangularflume having gravel bed for four distinct bed shapes, which was characterized from non-identical concentrationof coarser elements and small and large scale roughness as two condition. T. Song and W.H. Graf (1996) studied unsteady flow properties in an open channel with a rough bed. A newly developed acoustic Doppler velocity profiler (ADVP) is used to obtainthe flow profiles. The mean velocities, the turbulence intensities and the Reynolds-stress profile, are found using the Fourier components method. Graeme M. Smart (1999) investigated vertical profiles of turbulent stream wise velocities in gravel Bed Rivers. With the help of electronic pitot tubes that show logarithmic velocity profiles made at high and low flows to extend over much of the flow depthmeasurements.

A quick development took place inunderstanding the fluid flow phenomena at the starting of twentieth century. In this view, Prandtl (1932) and Von Karman (1930) published their work, covering various aspects of boundary layer theory and turbulence. Coles (1956) and Coleman (1981) developed velocity equation for sediment-laden flow in open channel. After years, Tominaga and Nezu (1992) studied velocityprofile in steep open channel. Julien (1995) presented a logarithmic form ofvelocity profile equation which is mostly used to assess depth-averaged velocities in wide channels with rough bed.M. Salih Kirkgoz*et al*. **(**1997**)** measured mean velocities using a Laser Doppler Anemometer (LDA) in developing and fully developed turbulent subcritical smooth open channel flows. From the experiments it is found that the boundary layer along the centre line of the channel develops up to the free surface for a flow aspect ratio.At the upstream end the boundary layer may be laminar, but steadily thickens up to a certainpoint in the channel length L where the flow is called "developing flow"; after this position the flow is known to be "fullydeveloped flow”. The investigations with Experimental set up onmeasurements of velocity for completely developed open channel flow are available. In this study,a pitot tube along with U-tube manometer is used to measure the longitudinal velocities in fully developed open channel flow.

METHODOLOGY

FORMULAS FOR VELOCITY DISTRIBUTION

Many semi empirical models have been developed in the past with the help of which the velocity profiles of fully developed turbulent open channel flow is represented.

The wall shear stress$\tau_0$along with the wall separation$z$ and the kinematic viscosity factor ν of the fluid regulates the flow velocities of a smooth wall inner to the position of the turbulent boundary layer. The velocity distribution in the viscous sub layer generally is acknowledged linear. In case of completely turbulent layer of the inner region, the logarithmic velocity distribution of von Kanmln (1930), Prandtl (1932), is popularly described as the law of the wall, is the universally accepted formula

$$\frac{u}{u_*} = {}^1/_\chi \ \ln \frac{u_* z}{\nu} + B \qquad \textbf{(1)}$$

Where $\boldsymbol{\chi}$ is Von Karman constant; B is constant, u_*=($\sqrt{\tau_0/\rho}$) = shear velocity; and ρ = density.
The value of B based on the nature of the wall surface, but the value of A does not depend on it.(Schlichting 1968). Nikuradse (1932), in their experiments, found that the value of A= 2.5 and B = 5.5 in the case of hydraulically "smooth" pipe flow. Thesame values can be used for smooth open channel flow as well, which was assumed by Keulegan (1938). These results were confirmed by Kirkgoz(1989) in a study done by him. However, various investigators have obtained different values for A and B.The value of A has a range of variation between 2.43 (Nezu and Rodi 1986) and 2.5 (Steffleretal.1985) and *B* between 4.9 (Klebanoff 1954) and 7 (Townsend1956).
Coles (1956) introduced the wake hypothesis in (1) to extend the law of the wall to the outer region of boundary layer.He gave the expression in the form

$$\frac{u}{u_*} = \frac{1}{\chi} ln \frac{u_* z}{\nu} + B + \frac{\Pi}{\chi} w(\frac{z}{\delta}) \quad (2)$$

Where Π = a "profile" parameter; and w(z/δ) = an empirical "wake" function or, as "law of the wake" denoted by $2\,sin^2(\frac{\pi z}{2\delta})$. Coles (1956) showed that for $\boldsymbol{\chi}$ = 0.4, B = 5.1, and Π = 0.55 there was reasonable agreement between the experiments conducted by him and (2)
In the outer region of boundary layer where the flow velocities mainly are controlled by turbulent shear, the velocitydefect law is suitable for both smooth and "rough" walls(Prandtl 1925).

$$\frac{u_m - u}{u_*} = -\frac{1}{\chi} \ln \frac{z}{\delta} \quad (3)$$

whereu_m= maximum velocity in the distribution. Some correction terms were added to (3) for a better fit with experimental data; for instance, a correction value of 2.5 was added by Clauser(1956).
From an analysis of the Reynolds-averaged Navier-Stokes (RANS) equations and by assuming a parabolic profile for the eddy viscosity, Yang et al. (2004) proposed this law. They found that the velocity deviation from the log law is linearly proportional to the logarithmic distance from the free surface.

$$\frac{u}{u^*} = \frac{1}{k} [\ln\left(\frac{y}{y_0}\right) + \alpha \ln(1 - \frac{y}{h}) \quad (4)$$

In 3D open-channel flows with secondary currents, the log-wake law is unable to predict velocity dip phenomenon. A suitable simple law is possible by adding to log law both Coles' wake function and the term linearly proportional to the logarithmic distance from the free surface as:

$$\frac{\mathrm{u}}{\mathrm{u}_*} = \frac{1}{\kappa} [\ln\left(\frac{\mathrm{y}}{\mathrm{y}_0}\right) + 2\Pi \sin^2\left(\frac{\pi}{2}\frac{\mathrm{y}}{\mathrm{h}}\right) + \alpha \ln(1 - \frac{\mathrm{y}}{\mathrm{h}}) \quad (5)$$

The first term in parentheses is the logarithmic law of the wall; the sine-square term is the law of the wake that expresses the effects of the constant pressure-gradient in pipes or the convective inertia in ZPG boundary layers; and dip-correction function (Guo and Julien, 2003).

According to Vedula and Rao (1985) the junction point from which the parabolic law is applicable up to the free surface ranges from 0.2 to 0.3 for sediment-laden flows. Later (Sarma et al., 2000) proposed the limitations and the region of validity of the parabolic law. From the experimental investigations it was found that for the tangential parabola, the maximum value of the junction point is 0.5 when there is no dip-phenomenon and the value decreases with the presence of dip phenomenon.

$$\frac{u-u_{max}}{u_*} = 6.3\left(1-\frac{\eta}{\eta_{dip}}\right) \qquad (6)$$

THEORETICAL BACKGROUND

The variation of velocity profile is along a flow line at right angles to the general flow direction. It not only shows magnitude, but also shows characteristics of the flow like direction of flow, changes caused by the varying shape of domain or increase and decrease in the magnitude of velocity regard to the geometry & more. So generally, it makes us understand how the fluid behaves while being transported through the domain. It can also be used for identifying the growth of boundary layer.

Boundary layer

At the boundary surface the fluid velocity will be zero in case of stationary boundary condition. Hence the fluid layer is subjected to retardation near the surface of the boundary. Further, this retarded layer of fluid causes retardation for the fluid in the adjacent layers, thereby growing a small region in the immediate vicinity of the boundary surface. The zone is noted as boundary layer. Farther away from the boundary this retardation due to presence of viscosity is negligible and the velocity there will be equal to that of the mainstream.

Thickness of boundary layer

Within the boundary layer the velocity increases asymptotically from zero at boundary surface to the velocity of the main stream. Therefore, the boundary layer thickness represented by "δ" is arbitrarily defined as that distance from the boundary surface in which the velocity reaches 99% of the velocity of the main stream. This definition nonetheless gives a value of the thickness boundary layer approximately and thus δ is commonly termed as nominal thickness.

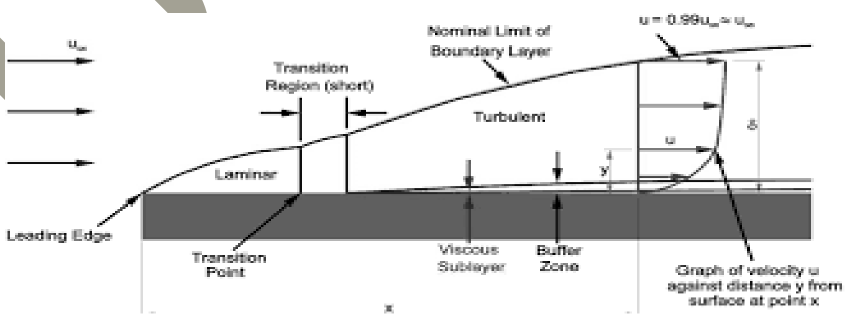

Fig.1 showing the thickness of boundary layer

EXPERIMENTAL SETUP

Experiments were conducted utilizing the flume facility that is available in the Department Civil Engineering Hydraulics lab, Veer Surendra Sai University of Technology, Burla. The Experiments are performed in a straight simple rectangular flume made up of iron whose length is 2.5 m, width 0.3 m, and 0.3 m deep. The Water supply is from a storage sump which is again lifted by number of parallel pumps to an overhead tank. The water is then supplied to the flume through a metal pipe and discharge is controlled through a valve. The Head gate is lifted fully to allow the water to enter the flume. Baffle walls are provided in series before the head gate so as to decrease the effect turbulence of the incoming water. The Pointer gauge is first checked for its smooth moving over the flume and its least count is noted. Water is allowed to flow through a tilting type tailgate towards the finish of the experimental channel, and is accumulated in a metal volumetric tank from where it is again redirected to the sump. From the sump, water is then transported back to the overhead tank by a pump installed in the laboratory, thus setting a complete re-circulating water supply system for the experimental flume. Here the role of tailgate is to maintain the flow to be uniform in the flume. To attain a steady and uniform flow conditions every single experimental run of the flume is done by maintaining the water surface slope parallel to the bed slope

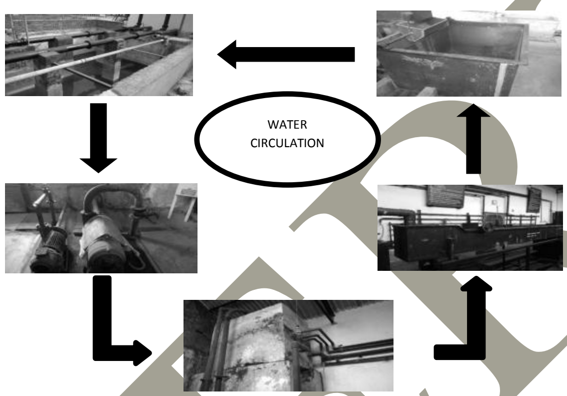

Fig. 2 showing the experimental setup for the experiments.

The velocities of the flow carried out in the experiment were measured at 6 mid-verticals (x = 0.25,0.5,0.75,1,1.25 and 1.5 m) alongside the flow developing region and 6 mid-horizontals (y = 0.03,0.06,0.09,0.12,0.15 and 0.18 m) across the flow developing zone across half width of the flow section. This is for a single water flow depth. In this way, the same procedure is repeated for multiple flow depths starting from bed of the channel (0.06, 0.1, 0.14, 0.18, 0.22 m).

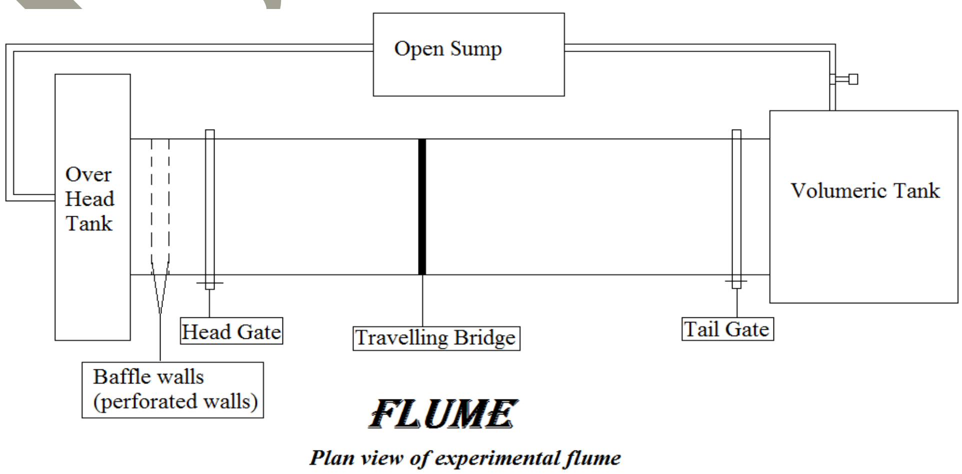

Fig.3 showing the plan view of experimental flume

Table 1. Details of the Experimental Conditions

Test No.	Flow Discharge Q (cm^3/s)	Height h(m)	Aspect Ratio b/h	Length of flow developing zone L (m)	Froude number F_r	Reynolds number R_e
1	19.55	0.06	5	0.25	0.29	10,853
2	27.2	0.1	3	0.5	0.323	21,573
3	38.25	0.14	2.14	0.75	0.384	36,404
4	51	0.18	1.66	1	0.451	54,606
5	67.15	0.22	1.36	1.5	0.537	79000

The table above indicates the detail position of the points where the velocity measurements have been conducted. The x = 0 refers the position of the head of the gate of the channel from which the start of the effective length of the channel begins. So this can be described as the starting position for the developing zone of flow. The finish point of the development of flow was found by observing and comparing the velocity profiles that are measured across the channel. It was seen that length of the flow developing zone changes between 0.25 to 1.25 m which varies depending on the flow conditions. Henceforth, at the end of section at 1.25 m it was assumed to represent the fully developed flow section for all tests. The details of the test conditions are given in table 1. F_r is the Froude number (= $V/\sqrt{gh}$), V is the average velocity of flow, R is the Reynolds number (=VR/v) and R is the hydraulic radius.

RESULTS AND ANALYSIS

Table 2. Showing details of the stage-discharge relationship

RUNS	Discharge (Q) ($in cm^3/s$)	Flow Depth (h) (in m)
1	19.55	0.06
2	27.2	0.1
3	38.25	0.14
4	51	0.18
5	67.15	0.22

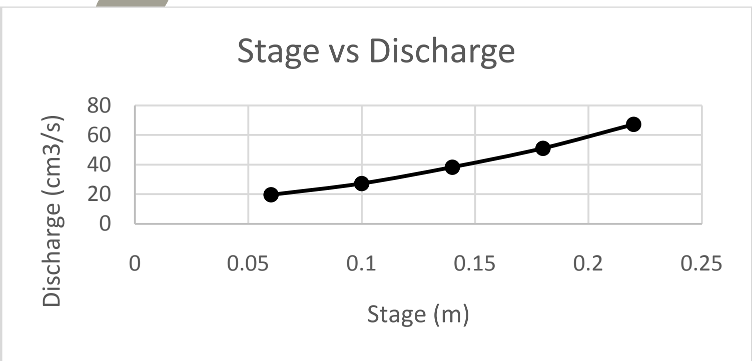

Fig. 4 showing the Plot of Stage vs Discharge

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The above graph has been plotted with the data obtained from the experimental observations performed in the laboratory. In the Horizontal axis the value represents the discharge in cm^3/sec and the vertical axis represents the Stage in mm i.e. the height of flow.

LENGTH OF FLOW DEVELOPING ZONE

Depending on the flow parameters like flow discharge, flow height, flow aspect ratio, length of flow developing zone, Froude number, Reynolds number given in table 1, a graph is plotted between dimensionless length of the flow developing zone L/h (Y axis) against the ratio R/F (in the Xaxis). The correlation between the dimensionless length of the developing zone with Reynolds number and Froude number are shown in Fig 5.

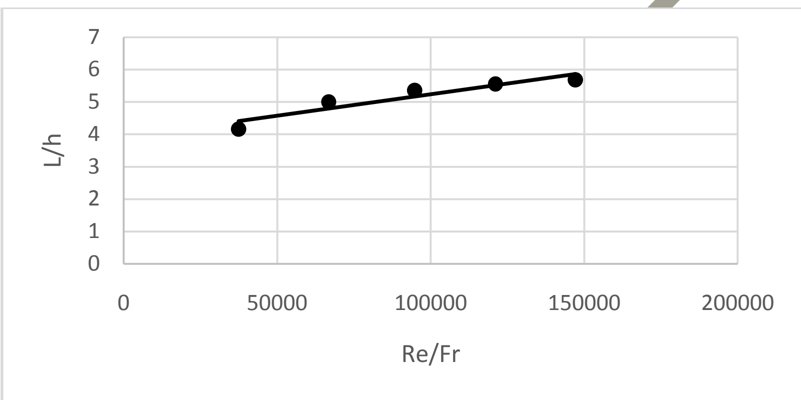

Fig. 5Plot between Dimensionless Lengths of Flow (L/h) with [Re/Fr]

The boundary layer thickness varies along a plate. As we move upward from the bottom of the flume towards free surface or if we move sidewise from the wall of the flume towards centre line, the boundary layer thickness varies. It increases from the edge of the sidewall to the centre of the flume. In case of this experiment also the thickness of boundary layer is seen to be increasing from sidewall to the center. This variation of boundary layer growth continues till it attains 99% of the freestream velocity. At certain distance from the walls, the velocity profile shape remains constant. Till this region, the flow the is considered as developing flow. After that region as the velocity profile has a constant shape, the flow is assumed to be fully developed.

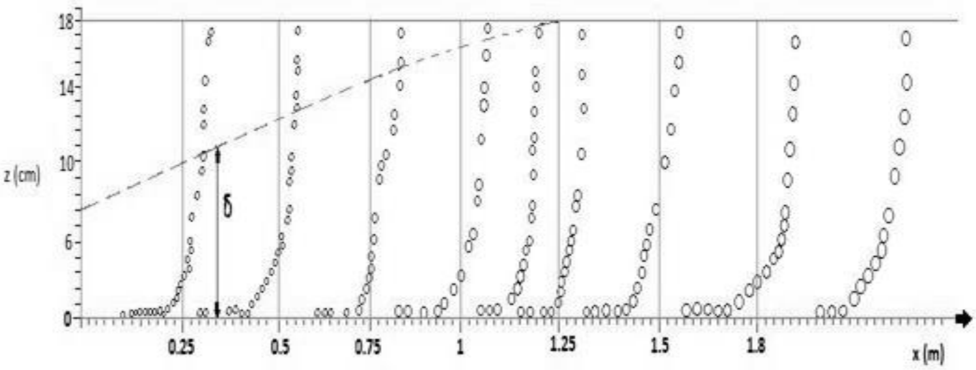

Fig 6. Measured velocity profiles along Developing Flow

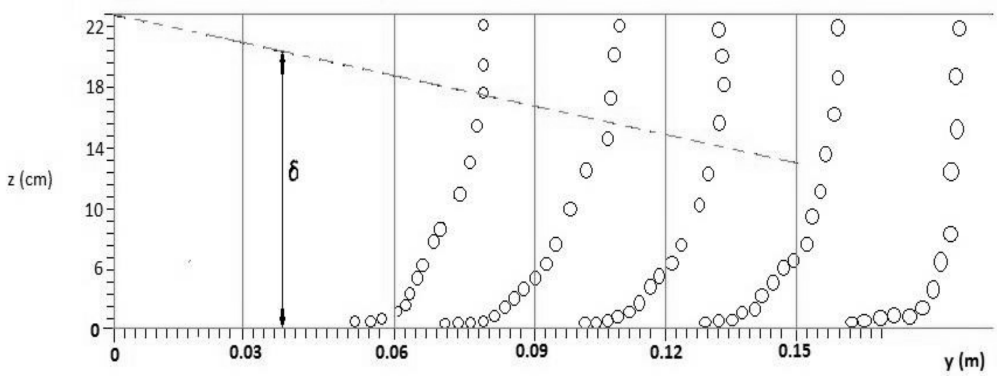

Fig 7.Measured velocity profiles along Developing Flow

ANALYSIS

The measured velocity profiles for test 5 are indicated in Fig.6. The measured velocity profiles of the entire stream of flow are recorded during the conduct of the experiment. Fig. 6shows the velocity profiles alongside the centreline of the region of developing flow. Verifying the velocity profiles inFig. 6 it is possiblyobserved that the distribution of thevelocities in vertical direction remains nearly unaltered and accordingly theflow is considered fully developed for*x*>=1.25 m, in test5 of the experimental procedure. Thus, for this exact experiment thedevelopment of boundary layer length is *L*= 1.25 m.Fig.5 denotesthat at the end of the developing zone δthe thickness of boundary layer δ increasesprogressivelyand equals to the flowdepth *h.* The velocity profiles across the flowsection at *x* = 1.8 m is shown in Fig 7. It is seen that the boundary layer thickness goes on decreasinginvariablytowards the sidewall direction. The dip created in the velocityprofiles alongside the rectangular channel is related with the secondary currents which is generated by the mixed action of the bed and boundary layers of sidewallexisting at the corner area.

CONCLUSION

The thickness of boundary layer varies along a plate. As we move upward from the bottom of the flume towards free surface or if we move sidewise from the wall of the flume towards centre line, the boundary layer thickness varies. It increases from the edge of the sidewall to the center of the flume. In case of this experiment also the thickness of boundary layer is seen to be increasing from sidewall to the center. This variation of boundary layer growth continues till it attains 99% of the freestream velocity. In case of developing zone in an open channel flow, the velocity profile shapes vary and the boundary layer thickness also goes on increasing gradually. When the velocity profile attains constant shape, it can be concluded that boundary layer thickness becomes maximum and then the flow is termed as fully developed flow.

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