CE 319F Elementary Mechanics of Fluids

Department of Civil, Architectural and Environmental Engineering
The University of Texas at Austin

Turbulence Laboratory

Objective:

The objective of this laboratory is to demonstrate the use of Particle Image Velocimeter (PIV) system to measure and study the velocity variations in a boundary layer.

Introduction to Turbulent flow:

Turbulence is an irregular motion superimposed on the main stream flow of the fluid. The fluctuating motion is quite complex and almost inaccessible to mathematical treatment. It must be noted that the mixing motion is very important for the course of flow and for the equilibrium of forces. When the Reynolds number is increased, internal flows and boundary layers formed on solid bodies undergo a remarkable transition from the laminar to turbulent regime. The effects of turbulence are as if the viscosity were increased by factors of thousands. At large Re, a continuous transfer of energy occurs from the main flow into large eddies. However, energy is dissipated preponderantly by small eddies, and the process occurs in a narrow strip inside the boundary layer, near the wall.

Turbulent Boundary layer:

The turbulent boundary layer can be broadly classified into three zones of velocity distribution. The zone immediately adjacent to the wall remains relatively smooth, is very thin and obeys Newton's law of viscosity. It is known as the viscous sublayer. From experimental results, the thickness of the viscous sublayer, δ' is given by

$$\delta' = \frac{5\,\nu}{u*}$$

The nondimensional velocity distribution in the viscous sublayer:

$$\frac{u}{u*} = \frac{y}{\nu/u*}$$

The viscous sublayer becomes larger along the wall in the direction of the flow as the shear stress decreases in the downstream direction. Beyond this layer, turbulence significantly alters the flow regime. The mixing action of turbulence causes the velocities at a given point in the flow to fluctuate with time. In laminar flow, the longitudinal pressure gradient which maintains the motion is proportional to the first power of the velocity, whereas in turbulent flow it becomes proportional to the square of the mean flow velocity. From Prandtl Mixing length it can be derived that beyond the viscous sublayer a logarithmic velocity distribution exists.

$$\frac{u}{u*} = 2.44\, ln \frac{y\, u*}{\nu} + 5.56$$

The logarithmic law is valid for values of $y^{+} = \frac{y\, u*}{\nu}$ ranging from 30 to 500. Beyond 500 no specific expression can be developed and hence this outer region is denoted by a third zone called velocity defect law. The combination of the viscous and logarithmic velocity profile for the range of y^{+} from 0 to approximately 500 is called *law of the wall*

For a wide range of Reynolds numbers (10^5<Re<10^7), the velocity profile in the turbulent boundary layer on a flat plate is approximated by the *power-law* equation

$$\frac{u}{\bar{u}} = \left(\frac{y}{\delta}\right)^{1/7}$$

The formula applies to about 90% of the boundary layer ($0.1 < y/\delta < 1$). For the inner 10% of the boundary, we need to resort to the equations for the law of the wall.

Reynolds' Stresses:

The theory of stability of flows decomposes the motion into a mean flow and a disturbance superimposed on it. In the resultant motion the velocity components are given by:

$$u = \overline{u} + u', \qquad v = \overline{v} + v', \qquad w = \overline{w} + w'$$

- *u*, *v*, and *w* are the instantaneous velocities in the x, y, and z directions respectively
- $\bar{u}$, $\bar{v}$, $\overline{w}$ and are the mean velocities (time averaged)
- *u*', *v*', and *w*' are the velocity fluctuations (deviation of the instantaneous velocities from the mean) and represent turbulence

The non steady disturbances or fluctuations in the velocities are a result of the mixing action of turbulence. Measurement of these fluctuating velocity components can be made with the help of PIV system. The fluctuations cause momentum exchange into and from the boundary layer. This has an effect as if shear stresses were applied to the fluid. Hence, in turbulent flow these stresses are known as apparent shear stresses or Reynolds stresses. An equation can be derived for evaluating the Reynolds stresses in the form

$$\tau = -\rho\overline{u'v'}$$

Where, $\overline{u'v'}$ denotes the product of the fluctuating components averaged over a period of time. The total shear stress in the flow is equal to the sum of the Reynolds stress and the viscous stress:

$$\tau^{total} = \tau^{viscous} + \tau^{\mathrm{Re}ynolds}$$

Where, $\tau^{\mathrm{Re}ynolds} = -\rho\overline{u'v'}$ and $\tau^{viscous} = \mu\frac{du}{dy}$

Experiment performed with PIV:

An experiment was conducted in the flume test facility at the Fluids & Hydraulics lab of the University of Texas at Austin to observe and measure the development of boundary layer at the flume bottom. A steady flow with the depth of 0.3 meter was running in the flume.

The flow field in area near the boundary was measured by a 2D Particle Image Velocimetry (PIV) system. The PIV system consists of a light source (a Nd:YAG Laser) and a nano sense camera, which takes pictures at the time interval of 0.00333 sec for a set of 100 images in this study. The images were processed through a sequence of analyses viz. adaptive correlation and average filter to get field velocities output. Further analysis of the measurements yields instantaneous and mean velocity profiles, turbulence, etc

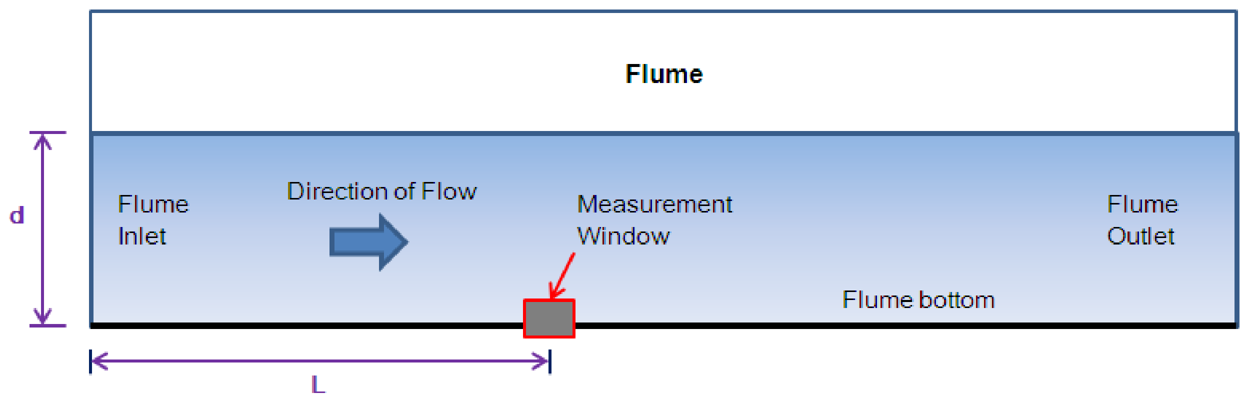


Fig 1. Schematic diagram of experimenalt setup

The distance from the inlet of the flume to the point of measurement is 3.2m. The thickness of the boundary layer at the point of measurement can be calculated as:

$$\delta = \frac{0.37\,x}{Re_x^{\frac{1}{5}}}$$

Mean flow Velocity $\overline{u}$ = 0.066 m/s

Characteristic dimension L= 3.2 m

$$Re = \frac{\overline{u}\,L}{\nu}$$

At 20°C for water, $\nu = 10^{-6}$ m^2/s

A comparison of the mean velocity with the instantaneous velocity is shown in Figures 2 and 3.

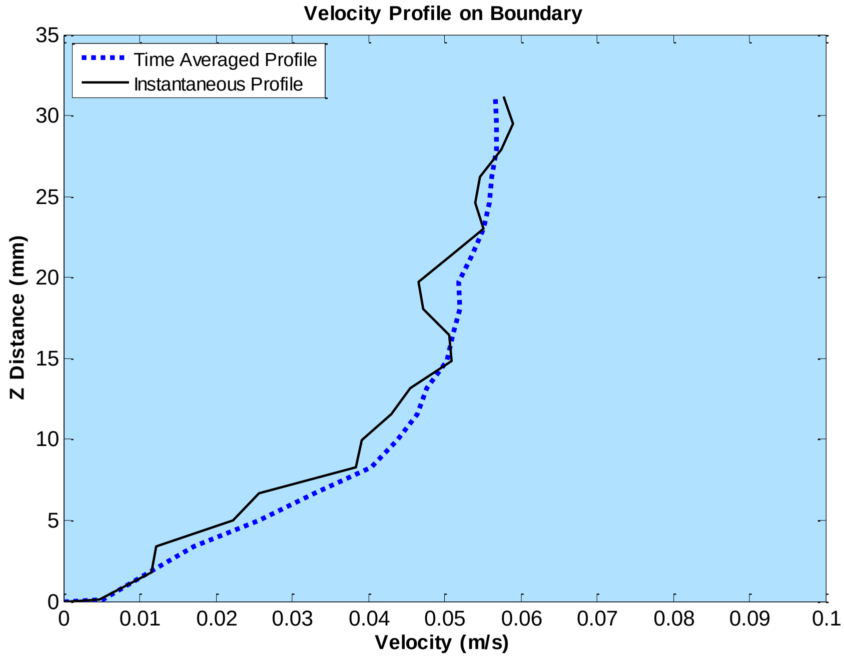


Fig 2. Mean and Instantaneous Velocity (longitudinal)

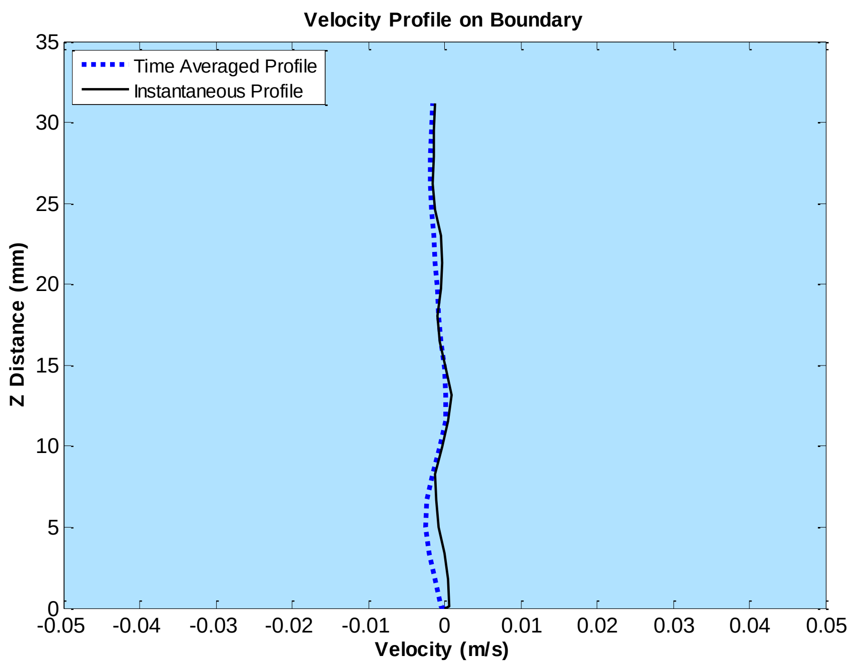


Fig 3. Mean and Instantaneous Velocity (transverse)

It can be clearly seen that **both u and v are zero at the flume bottom. The horizontal velocity u increases sharply from zero from the wall and then grows steadily at lower rate with greater distance above the wall. The vertical velocity component seems to be almost negligible.**

From the PIV measurements, we obtain the velocity gradient at the wall $\frac{du}{dy} = 6.5$

The shear stress at the wall is:

$$\tau_0 = \mu \frac{du}{dy}$$

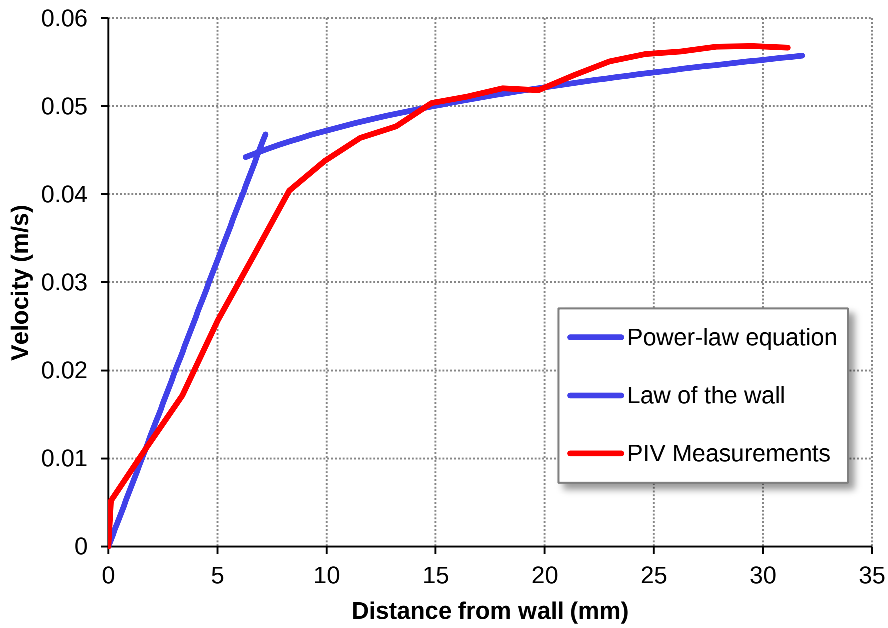


Fig 4. Velocity profiles by measurements and theoretical prediction

The PIV measurement of the longitudinal velocity profile is compared with the theoretical prediction by the power-law and the law of the wall over different distance above wall. The experimental results are in good agreement with the predicted ones.

Mean motion and fluctuations:

Upon close investigation it appears that the most striking feature of turbulent motion consists in the fact that the velocity and pressure at a fixed point in space do not remain constant with time but perform very irregular fluctuations of high frequency. The fluctuations so observed with the help of PIV have been depicted in Fig 5.

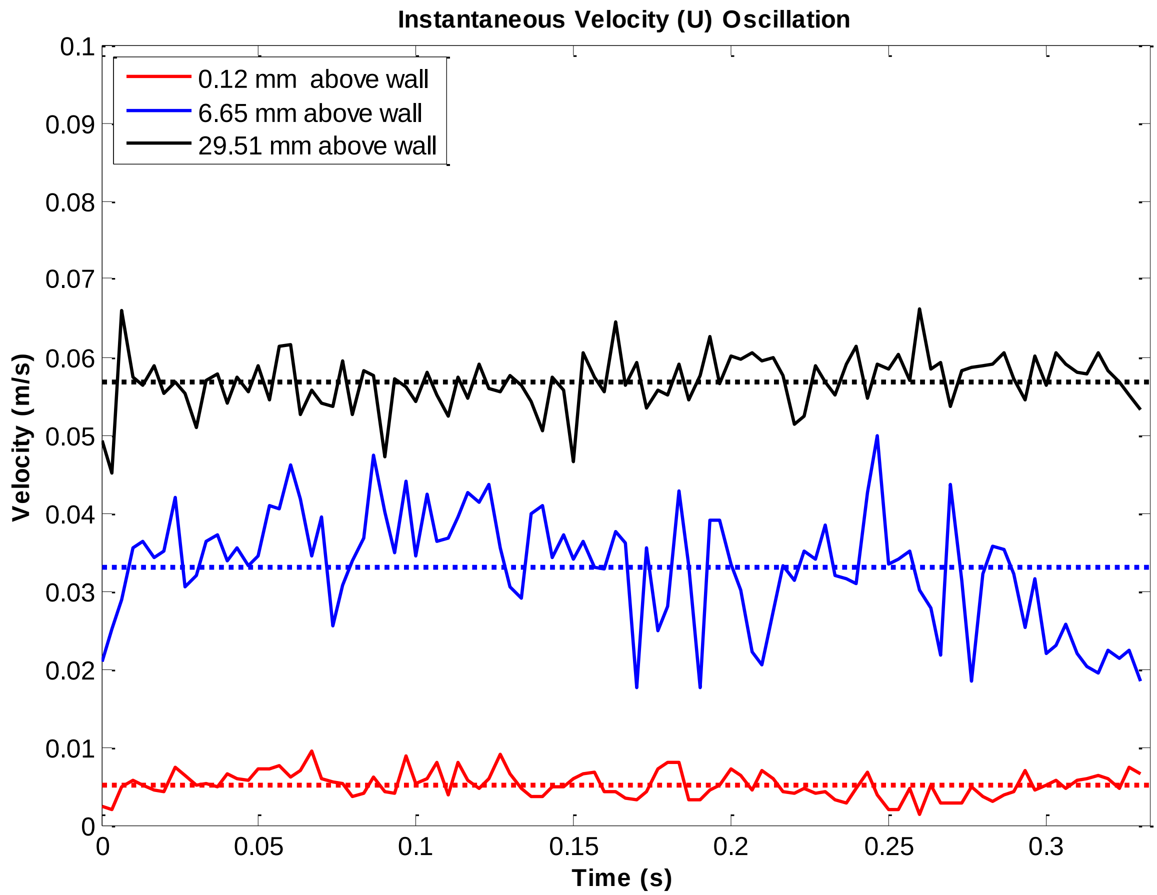


Fig 5. Velocity fluctuations at different heights above the wall

It can be clearly seen from the figure that the fluctuations are less near the wall (at 0.12 mm). However, the fluctuations are the most significant for the measurements made at 6.65 mm. Thus, the measurements suggest the presence of a very thin viscous sublayer near the plate and higher fluctuations indicate the presence of turbulence.

Turbulence Intensity

The degree of disturbance in the flow can be quantitatively evaluated in terms of turbulent intensity of the flow. The turbulence intensity of a stream can be defined in terms of the time averages of the three fluctuating velocity components or each individual ones. But, generally the Turbulence Intensity is expressed in terms of the root-mean-square of fluctuations normalized with mean flow velocity.

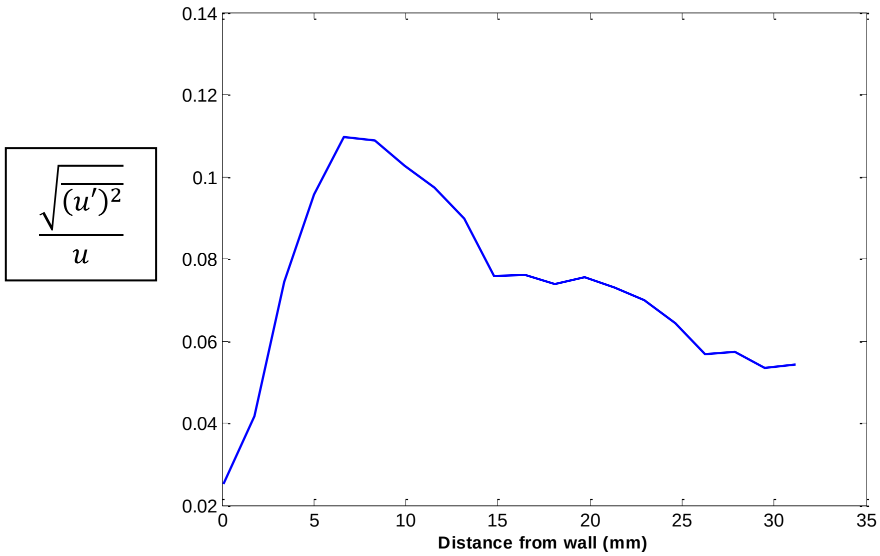
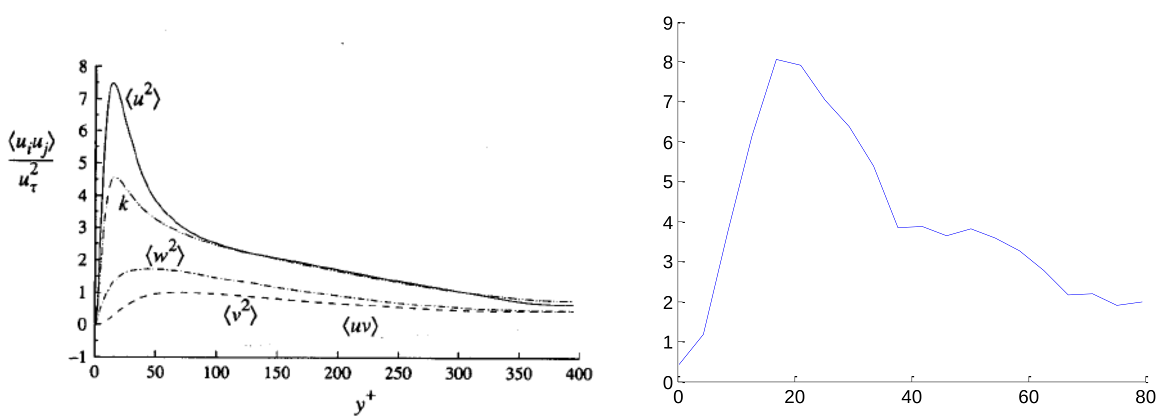


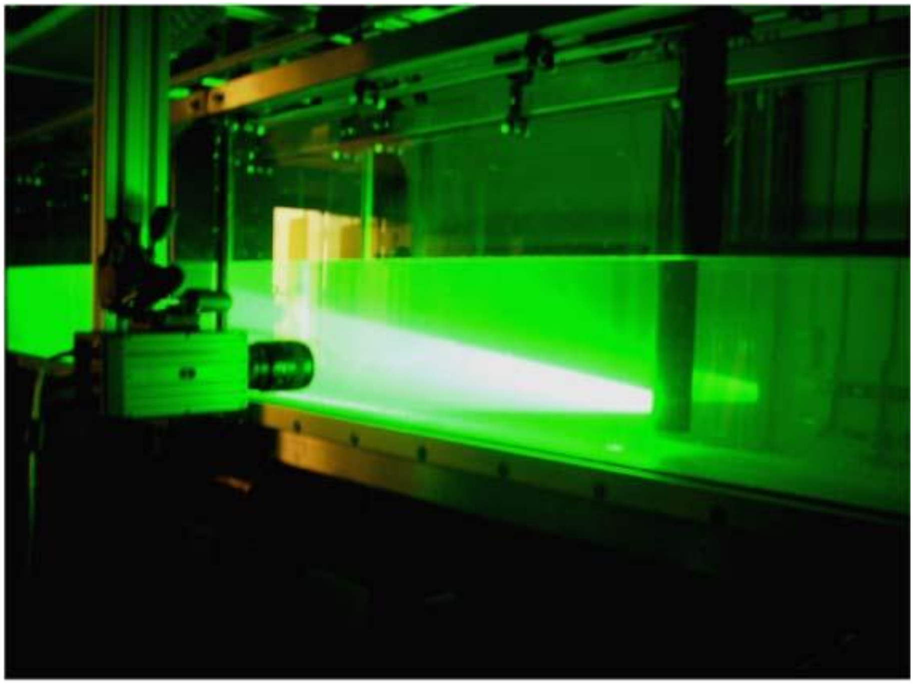
Fig 6. Turbulence Intensity

A comparison of the turbulence intensity of the longitudinal components is made between the PIV measurement and the DNS numerical results of Spalart (1st Ed ,Fig 7.33, Pope, S., Turbulent) with the same normalization. A remarkable agreement can be observed between them. It is noted that the maximum value occurs very near to the wall, it is zero at the wall since the fluctuations die out.

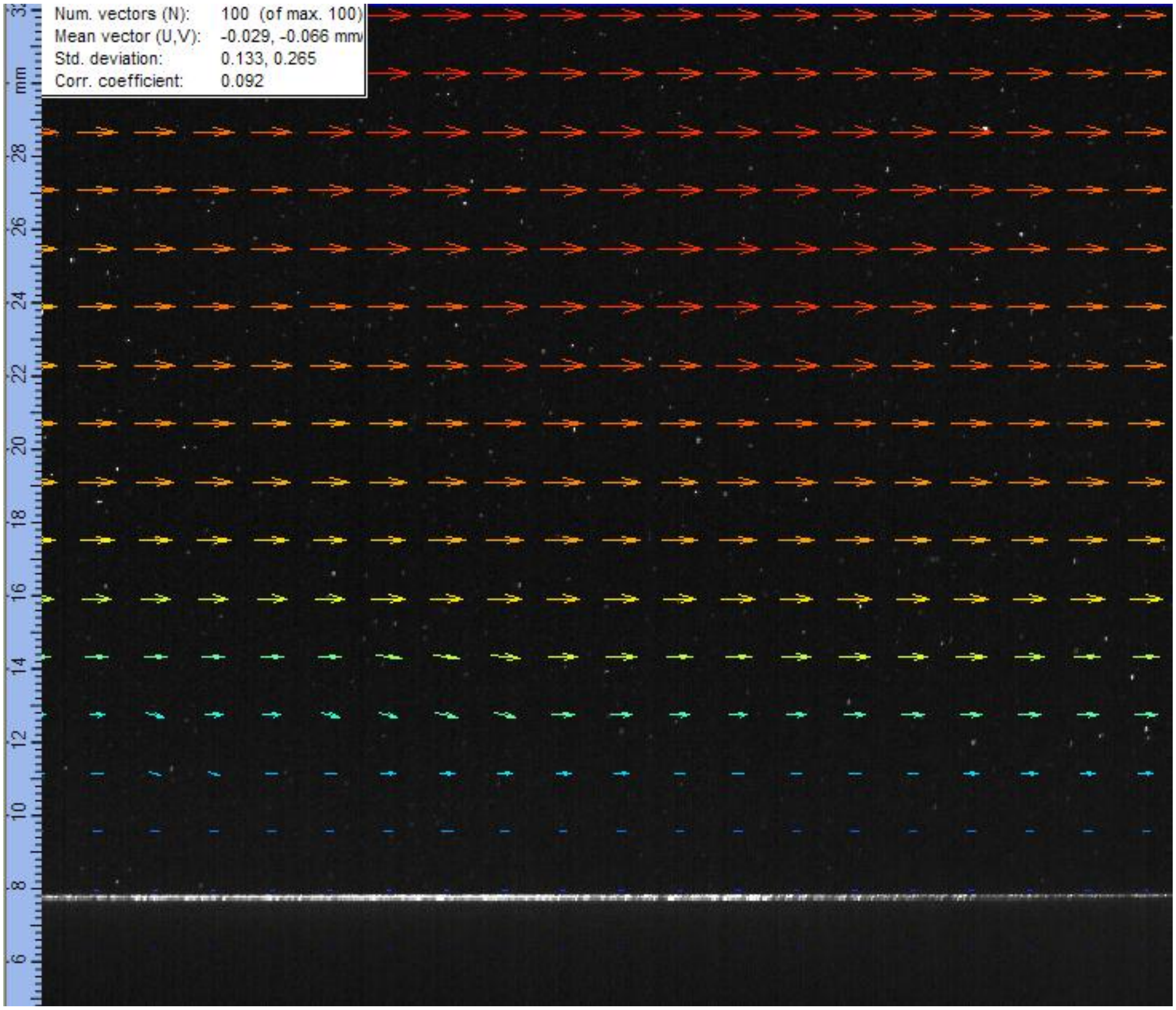


(a) Numerical Result (b) PIV measurements

Fig 7. Comparison of Turbulence Intensity between PIV measurements and DNS Data of Spalart



Picture of the PIV system being used for measurement of boundary layer at flume bottom.



Vector Map representing the velocity distribution in the boundary layer.