

Swirling Flow Visualisation in a Square Section Test Duct by Particle Image Velocimetry (PIV) System

Omprakash Yadav¹ and Pradeep Gaikwad²

^{1,2}*Department of Mechanical Engineering, Sharda University, Greater Noida, India.*
E-mail: ¹omprakash.yadav@sharda.ac.in, ²pradeepravindra.gaikwad@sharda.ac.in

Abstract

The purpose of this work is to investigate swirling flow in a square section test duct at section 1 and 2 experimentally, one foot and one foot and 7cm from front respectively. The two components of the velocity i.e. velocity field in a plane, vorticity, strain rate, Reynolds shear stress and total turbulence are visualised with their respective fluctuations by Particle Image Velocimetry (PIV) system. A new setup for swirling flow in a square section test duct in the PIV laboratory is designed which is four feet long with height $D=1$ foot and width $H=1$ foot. The aspect ratio of test duct is defined as ratio of larger to smaller dimension of the cross section of the test duct having value one. Venturimeter is incorporated, one at the section 1 and one at section 2 to measure the discharge. Water is supplied to sections through two branches of pipe line and the nozzles. The swirling in the test duct is created by the nozzles incorporated at four faces with the help of supply of water tangentially into the section. Pure water loaded with seeding particle known as tracer is used to trace the path of flow. The flow is visualised by Particle Image Velocimetry system. The PIV system consists of laser, CCD camera, synchronizer, computer etc. Two pulses of laser illuminate the seed particle at the section and two photographs are taken by high speed CCD camera which is analysed by PIV using INSIGHT3G software to get one velocity vector. The laser and CCD camera are perpendicular to each other. INSIGHT software measures velocity using one of three correlation processes: Autocorrelation, 1-Frame Cross-Correlation and 2-Frame Cross-Correlation.

Keyword: Swirling flow, Particle Image Velocimetry (PIV), square section test duct, venturimeter and nozzle.

1. Introduction

PIV is a planer measurement technique wherein a pulse laser light sheet is used to illuminate a flow field seeded with tracer particle small enough to follow the flow. The position of particle are recorded on CCD camera at each instant the light sheet is pulsed. The data processing consists of either determining the average displacement of the particle over the small interrogation region in the image or the individual particle displacement between the pulse of light sheet. Knowledge of time interval between light sheet pulses then permits computation of velocity field. While the method of adding particles or objects to a fluid in order to observe its flow is likely to have been used from time to time through the ages no sustained application of the method is known. The first to use particles to study fluids in a more systematic manner was Ludwig Prandtl, in the early 20th century. PIV is used for swirling flow visualisation. Such swirling flow finds its applications in combustion chamber of the boiler furnace, chemicals mixing and combustor of gas turbine. The objective of this experiment is to find out velocity field, vorticity, shear strain rate, Reynolds stress and total turbulence at the nozzle and at the section 1 and section 2 for swirling flow in square section duct by particle image velocimetry system.

Particle image velocimetry (PIV) is a two-dimensional quantitative instantaneous velocity measurement technique. In contrast to single-point measurements, a two-dimensional velocity distribution can provide local velocity gradients. These gradients determine certain properties of the turbulent flow that affect mixing, flame wrinkling, and the burning rate in combusting environments. In the PIV technique, a light sheet i.e. pulse from the laser is passed through a seeded flow field, illuminating the particles at time, t . At a known time later, $t + \Delta t$, a second sheet of light i.e. pulse is sent through the same plane in the flow field. The images of the particles from both laser sheets are stored on a recording medium. Measurement of the separation between two images of the same particle throughout the field of view by autocorrelation can provide the local fluid velocities as depicted in Fig. 1.

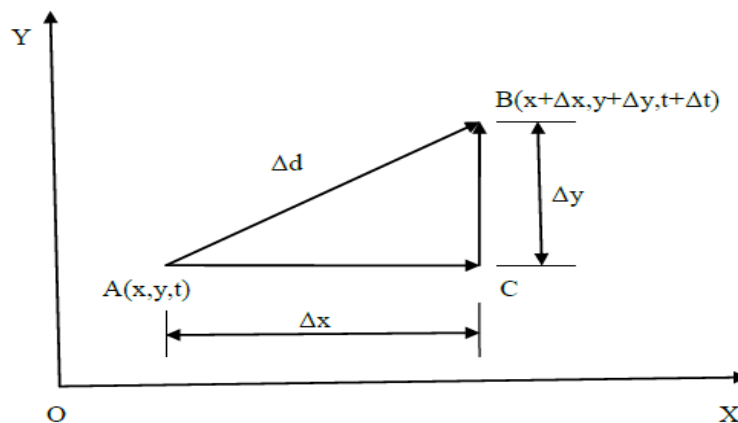


Fig. 1: Principle of Particle Image Velocimetry.

$$u(x,t) = \frac{\Delta x(x,t)}{\Delta t} \quad (1)$$

$$v(y,t) = \frac{\Delta y(y,t)}{\Delta t}$$

The velocity vector field is given by,

$$\vec{V} = \vec{u} \cdot \hat{i} + \vec{v} \cdot \hat{j} \quad (2)$$

Knowing the component of velocity in x and y direction, we can find the rotation i.e. vorticity of swirling flow along z-direction as follows.

$$\Omega_z = \left[\frac{\partial v}{\partial x} - \frac{\partial u}{\partial y} \right] \quad (3)$$

A test duct having square cross section has to be designed in which water is supplied tangentially at two sections one feet and two feet from the front. A swirling is a spinning, often turbulent, flow of fluid. The flow of a fluid along a curved path or the flow of a rotating mass of fluid is known as vortex or swirling flow. Swirling flow has many interesting features and occurs frequently in nature and technology. Intensity of swirling flow is specified by swirl number or swirl intensity. In this project, swirling is created by nozzle tangentially fitted to the square cross section. Knowing the component of velocity in x and y direction, shear strain is given as follows.

$$\phi_{xy} = \frac{\partial v}{\partial x} + \frac{\partial u}{\partial y} \quad (4)$$

The equations of free vortex flow and forced vortex are respectively,

$$v \cdot r = \text{const}, \quad v = r \times \omega \quad (5)$$

Reynold shear stress can be defined as,

Reynold shear stress = $-u'v'$

$$u(x,t) = \bar{u} + u' \quad (6)$$

Turbulence intensity or degree of turbulence,

$$I = \sqrt{\frac{1}{3}(u'^2 + v'^2 + w'^2)} / U_\infty \quad (7)$$

Where,

$$\text{Stream wise Reynolds stress } u'u' = -2 \frac{\nu_t}{R_e} \frac{du}{dx} + \frac{2}{3} k \quad (8)$$

$$\text{Normal Reynolds stress, } v'v' = -2 \frac{\nu_t}{R_e} \frac{dv}{dy} + \frac{2}{3} k \quad (9)$$

$$\text{Reynolds shear stress, } u'v' = -\frac{\nu_t}{R_e} \left[\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \right] \quad (10)$$

$$\text{Turbulent kinetic energy, } k = \frac{1}{2}(u'^2 + v'^2 + w'^2) \quad (11)$$

2. Experimental Setup and Particle Image Velocimetry (PIV) system

2.1 Experimental test duct

The whole of test duct is made of Perspex sheet (transparent) to enable visual inspection of the flow as well as flow visualizations and the PIV measurements at the section 1 and 2. The other side of chamber is vertical and open to the atmosphere. The test duct is full of water loaded with seeding particle. The test duct is fitted with 4 nozzles at section 1 and 4 nozzles at section 2 tangentially to supply the water into test duct such that the flow is swirling. The experimental test duct is as shown in figures 2 and 3.

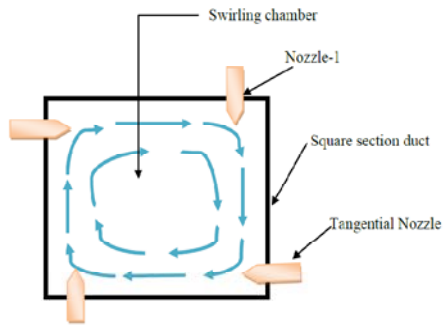


Fig. 2: Swirling flow in a square chamber.

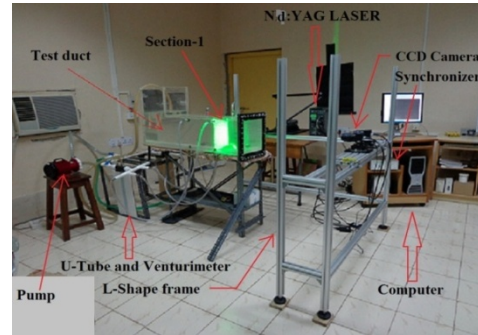


Fig. 3: Experimental test ducts.

2.2 Pump and Nozzle

The water is driven through the flow circuit by a magnetic centrifugal pump with a capacity of 125 lpm at a head of 12m. The same water is circulated in a close cycle. In order to run the experiments efficiently, the pump was adjusted with help of the two venturimeters and kept fixed thereafter. Convergent external threaded Nozzle made of brass is used. In the experimental setup, total eight nozzles are used out of which four nozzles are at section 1 and four nozzles are at section 2. Each nozzle is having orifice diameter of 1/4 inches. The nozzles are incorporated at the section face in such a way that flow at each section is swirling flow.



Fig. 4: Nozzle.

2.3 Design of Venturimeter

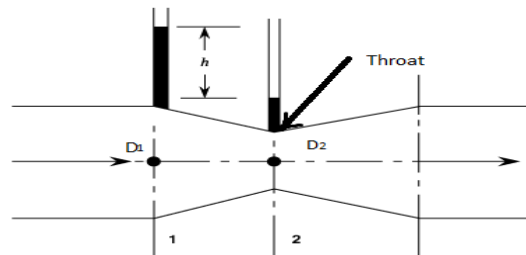


Fig. 5: Design of venturimeter.

Input parameters are as follows,

$$D_1 = 20\text{mm} \quad A_1 = 31.4 \times 10^{-5} \text{m}^2$$

$$D_2 = 12\text{mm} \quad A_2 = 1.1304 \times 10^{-4} \text{m}^2$$

$$Q = 40\text{rpm} = 6.66667 \times 10^{-4} \text{m}^3/\text{s}$$

From the Bernoulli equation discharge through the venturimeter is given by,

$$Q = A_1 A_2 \sqrt{\frac{2gh}{A_1^2 - A_2^2}}, C_d \approx 1 \tag{12}$$

By putting the value in the equation 12,

Head of water $h = 154.4\text{cm}$

$$h = x \left[\frac{S_m}{S_w} - 1 \right] \tag{13}$$

From the above relation between head of water h and head of mercury x ,

Head of mercury, $x = 12.35\text{cm}$

Length of U-Tube is 55cm, so approximately 45cm deflection of mercury is allowed in this design of venturimeter. The deflection of mercury in the design of venturimeter is only 12.35cm which is less than 45cm (maximum deflection).

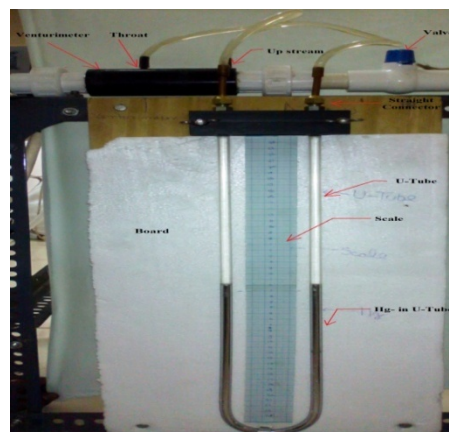


Fig. 6: Venturimeter.

2.4 Particle Image Velocimetry (PIV) system

Particle image velocimetry (PIV) is an optical method of flow visualization used in education and research. It is used to obtain instantaneous velocity measurements in two dimensional and related properties in the fluids. The fluid is seeded with tracer particles which, for sufficiently small particles, are assumed to follow the flow dynamics (the degree to which the particles follow the flow is represented by the Stokes number). The fluid with entrained particles is illuminated by laser so that particles are visible. The motion of the seeding particles is used to calculate speed and direction i.e. the velocity field of the flow being studied. A schematic diagram of particle image velocimetry system is as shown in Fig. 7.

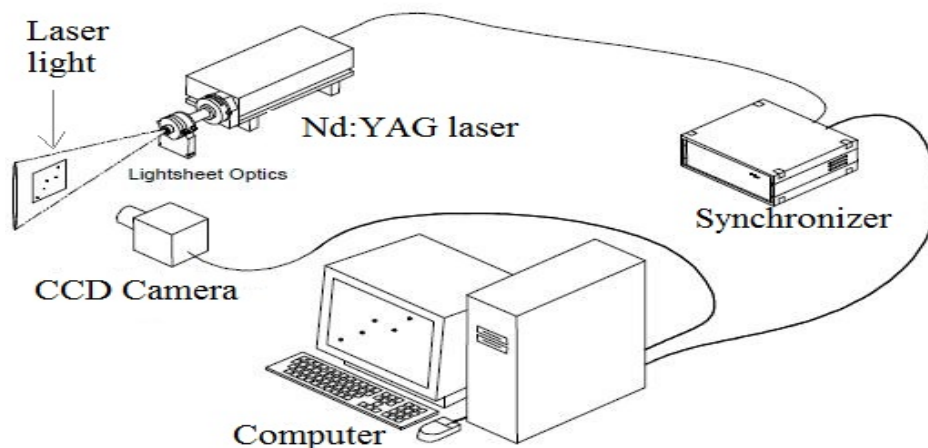


Fig. 7: The schematic diagram of particle image velocimetry (PIV) system.

Simple particle image velocimetry system uses INSIGHT 3G software for the manipulation of flow field. Simple particle image velocimetry system mainly consists of following components:

1. Light sources i.e. Laser.
2. High speed CCD Camera.
3. Synchronizer.
4. Computer.

2.5 Seeding particle

These are solid particle which are added with water before doing the experiment. The correct choice of seed particle is critical to the successful execution of particle image velocimetry experiment. Thus, TSI offers a full range of seed particles to satisfy even the most difficult measurement requirements. Hollow particles are also available for improved density matching with the flow medium. Coated particles are also available for maximizing the reflected light. Standard particle size ranges from 1 micron to 12 microns are available. In this PIV experiment, Nylon as the seeding particle is used because density of Nylon (1.14 g/cc) is close to the water. Size and refractive index of Nylon respectively is 4 microns and 1.53.

3. Working Procedure

A pump circulates the water through the piping system and venturimeter to nozzles which are tangentially fitted to the test duct at section 1 and at section 2. The same water is again circulated to the pump. The sequence of events for capturing a series of frames is as follows.

1. Synchronizer triggers the camera to start exposure.
2. Camera starts exposure and triggers the Synchronizer that the shutter is open with the flash sync output.
3. Synchronizer sends fire signals to the laser for the first pulse.
4. Synchronizer waits the selected pulse separation time.
5. Synchronizer sends signals for the second pulse of light.
6. The camera shutter closes at the end of the exposure time.
7. Camera outputs the video data.
8. Repeat the sequence for the number of frame to capture. The camera must be ready for the next exposure trigger before the frame rate time or an error will occur.

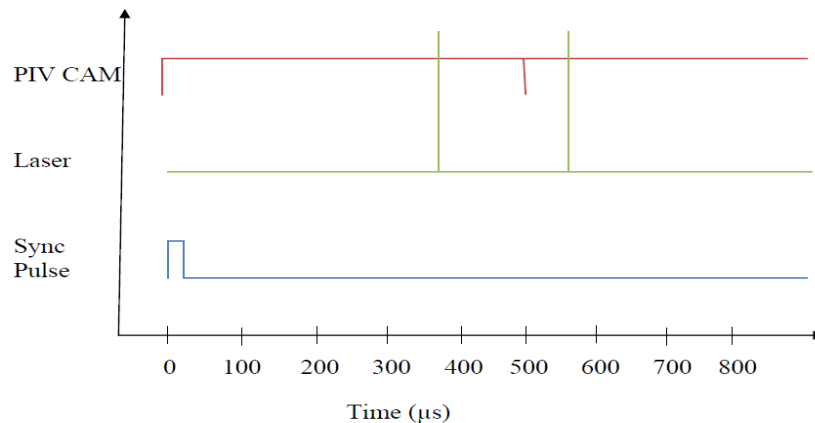


Fig. 8: Capture timing diagram.

3.1 Post Processing

Post Processing refers to the analysis of the velocity vector field after the vectors have been extracted from the PIV image. Post processing consists of two basic functions, vector editing and computing flow properties. Vector editing is necessary because some wrong peaks may be chosen as the velocity peak. In vector fields with 1,000 points, 99% correct vectors still give 10 wrong vectors. In post processing, the vectors are compared with the neighbouring vectors. Vectors that vary by more than the validation tolerance from the neighbourhood average are removed. This neighbourhood check enforces continuity of the flow. Places that are left empty can be filled in by interpolating the neighbouring vectors to get the best estimate of the velocity at that point. After the vector has been validated and the missing points filled in, the properties of the flow can be computed. The post processing module computes,

1. Vorticity.
2. Strain rate.

3. Velocity magnitude and direction.
4. Stream line.
5. Reynolds stress
6. Total turbulence

These parameters can be displayed by colour coding the arrows or by contour displays.

4. Result and Discussion

4.1 Flow field at the Nozzle

Discharge is increased from lower to higher value and effect on flow field is visualised by PIV. At different discharge result for velocity vector, vorticity, strain rate, total turbulence, Reynolds stresses etc are taken by PIV as shown in figures 9,10,11,12 and 13 respectively.

4.2 Flow field at high discharge

To visualise the flow field at nozzle, CCD Camera is set 20mm below the nozzle exit. The above is average of 300 frames and taken at speed of 15frames/s. The maximum velocity measured by venturimeter and measured by PIV are approximately same. For total discharge, $Q_{total}=52.38$ lpm and discharge through one nozzle, $Q_1=13.10$ lpm, Reynolds number at nozzle exit, $Re=43783.56$ (from venturimeter).

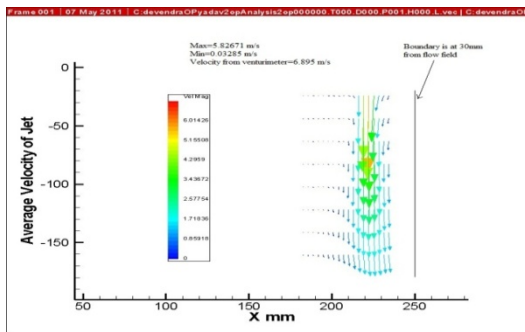


Fig. 9. Average velocity vector.

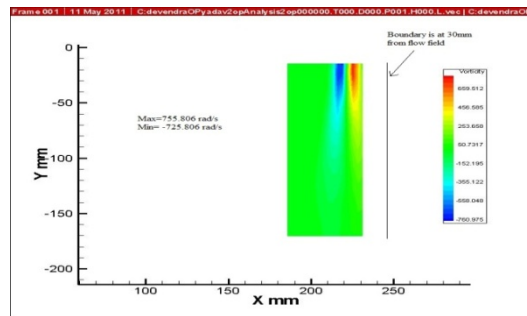


Fig. 10: Average vorticity contour.

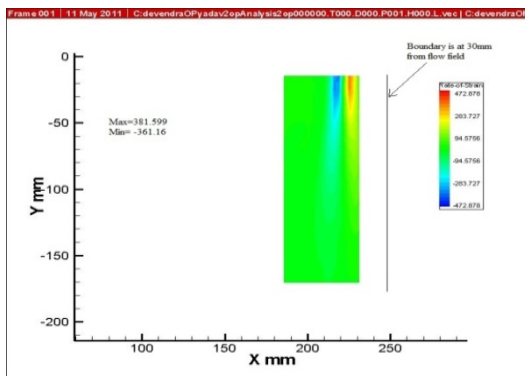


Fig. 11: Average rate of strain.

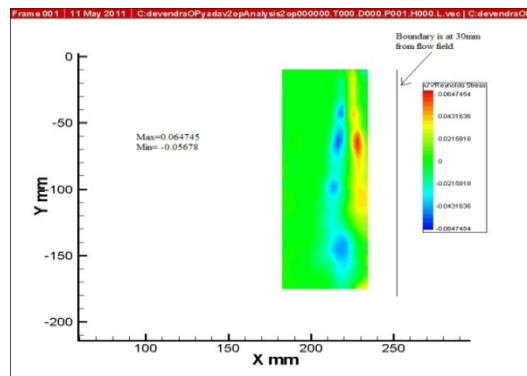


Fig. 12: Average Reynolds stress.

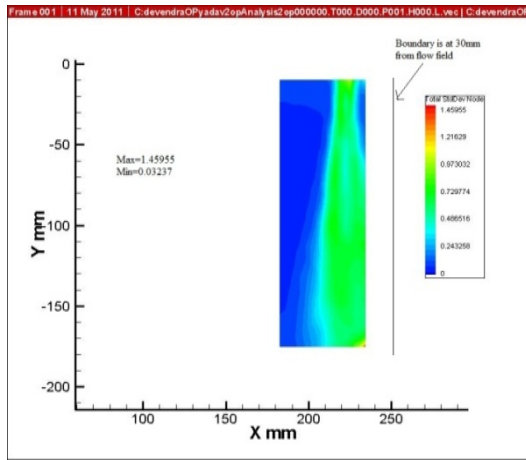


Fig. 13: Average total turbulence.

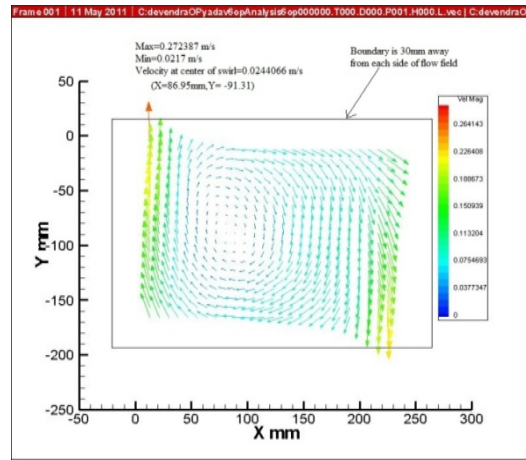


Fig. 14: Average velocity vector.

4.3 Whole flow field at Section-1

The Laser is set to flash on section 1 and CCD Camera is focused at section 1 to visualise the flow field. The above is average of 500 frames and taken at speed of 15frames/s. On moving from centre to boundary, velocity increases like in forced vortex flow. Total discharge, $Q_{total}=52.38$ lpm and discharge through one nozzle, $Q_1=13.10$ lpm. Reynolds number at nozzle 1 exit, $Re=43783.56$ (from venturimeter). (Refer Figures 14, 15, 16, 17, 18)

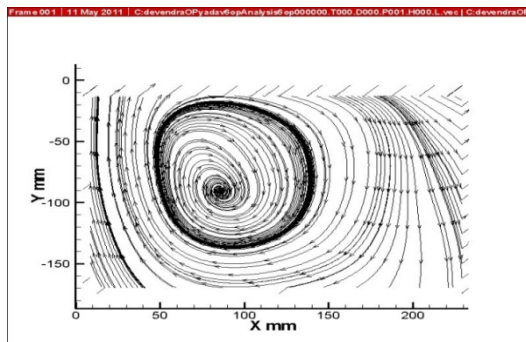


Fig. 15: Stream lines for average field.

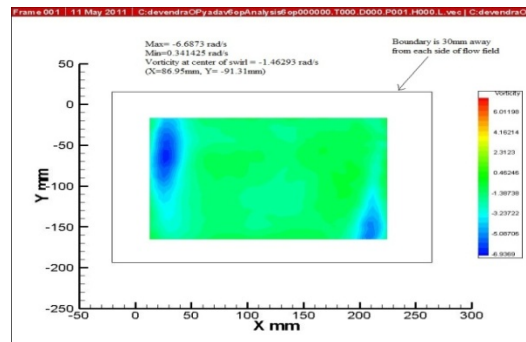


Fig. 16: Average vorticity contour.

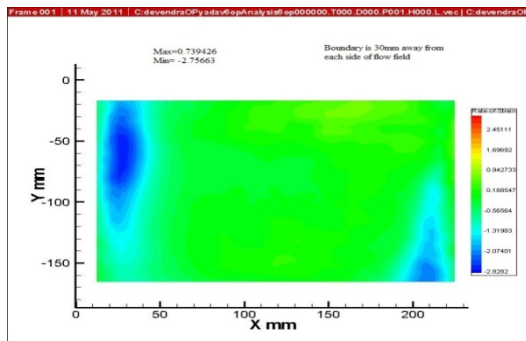


Fig. 17: Average rate of strain.

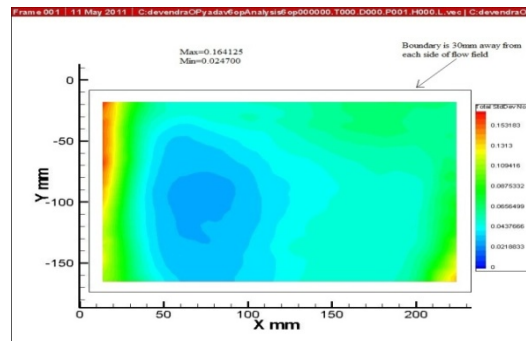


Fig. 18: Average total turbulence.

5. Conclusion

From the PIV, the resulting velocity is maximum at nozzle exit for all range of discharges. The maximum velocity measured from two approaches is approximately same. Small error is due to density of seed particle, calibration, light etc. As the discharge increases maximum velocity also increases. At the section 1 velocity is minimum at the centre of the swirl and increases towards the boundary. Shear stress is maximums near the wall. There is decay of velocity, vorticity and swirl from section 1 to section 2.

References

- [1] Kazuyoshi Matsuzaki, Yasutake Haramoto, Munekata and Hideki Ohba (2001), A study on swirling flow in a rectangular channel, *Journal of thermal science*, **10**,3.
- [2] Michael J. Stucky, Enrico Nino, Boguslaw Gajdeczko and Philip Felton (1994), Two colour Particle image velocimetry technique for an internal combustion engine, *Experimental thermal and fluid science*, **8**, pp. 305-314.
- [3] Ing Kiet Toh, Damon Honnery, Julio Soria (2010), Axial plus tangential entry jet, *Journal of experimental fluid*, **48**, pp. 309-325.
- [4] Tanja Weller, Martin Oberlack, Ingo Recktenwald, and Wolfgang Schroder (2005), DNS and experiment of a Turbulent Channel flow with streamwise rotation - study of the cross flow phenomena, *Journal of applied mathematics and mechanical*, **5**, pp. 569-570.
- [5] Jan Visscher, Helge I. Andersson, Mustafa Barri, Henri Didelle, Samuel Viboud, Damien Sous and Joel Sommeria (2011), A new set-up for PIV measurements in rotating turbulent duct flows. *Flow measurement and instrumentation*, **22**, pp.71-80.
- [6] Fude Guo, Bin Chen, Liejin Guo and Ximin Zhang (2010), Investigation of turbulent mixing layer flow in water channel by piv. *The Canadian journal of chemical engineering*, **88**, pp. 919-928.
- [7] Nakabayashi K, Kitoh O (1996), Low Reynolds number fully developed two dimensional turbulent channel flow with system rotation. *Journal of Fluid Mechanics*, **315**, pp. 1-29.
- [8] M. Passtrapanska, J. Jovanovic, H. Lienhart and F. Durst (2006), Turbulence measurements in a swirling pipe flow. *Journal of experimental fluids*, **41**, pp. 813-827.
- [9] S.V.Alekseenko, P.A Kuibin, V.L Okulov and S.I Shtork (1999), Helical vortices in swirl flow. *Journal of fluid mechanics*, Vol. **382**, pp. 195-243.
- [10] Yehia A. Eldrainy, Hossam S. Aly, Khalid M. Saqr, and Mohammad Nazri Mohd Jaafar (2009), A multiple inlet Swirler for Gas Turbine Combustors. *World Academy of Science, Engineering and Technology* **53**.