VELOCITY MEASUREMENTS IN A HIGH-SPEED FLOW THROUGH A SQUARE DUCT CONTAINING A 90° BEND

A Thesis in
Mechanical Engineering
by
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Abstract

This investigation is aimed at better understanding the nature of bend effects in a high Reynolds number duct flow. Bend effects have been previously studied using laser Doppler velocimetry and hot wire anemometry, but these are point measurement techniques, which limits the amount and type of data that can be obtained. The current work employs particle image velocimetry to present detailed field measurements of the flow velocity throughout the bend, including upstream and downstream sections. Additionally, velocity measurements have been carried out at three different Reynolds numbers to establish the dependence or independence of the bend effects on the flowrate. Associated turbulence quantities have also been calculated and presented in an intuitive, graphical manner.

The test section is a square cross-sectioned duct, containing a $90^\circ$ bend preceded by an $5D_h$ upstream section and a $10D_h$ downstream straight section, where $D_h$ is the hydraulic diameter. Turbulent flow entering the upstream section is fully-developed to allow the isolation of the bend effects. At $Re = 2.76 \times 10^5$, detailed velocity measurements are acquired at 12 streamwise locations in three streamwise-radial planes at different heights (top, middle and bottom). Complementary data are obtained in a more limited set of locations at $Re = 1.76 \times 10^5$ and $Re = 3.20 \times 10^5$ to allow comparison of the bend effects at different flowrates. Turbulence intensities and the Reynolds shear stress components are calculated and presented for all three Reynolds numbers.

One of the major aims of this work is to provide a benchmark for computational codes developed to study bend effects in a turbulent pipe flow. To allow easy comparison of these codes to the results of the current study, all the measured and calculated quantities are plotted in a curvilinear coordinate system in addition to the native cartesian (global) coordinate system.
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<td>Cross-sectional Area</td>
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<tr>
<td>D</td>
<td>Characteristic length</td>
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<tr>
<td>$D_h$</td>
<td>Hydraulic diameter, in inches</td>
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<tr>
<td>$De$</td>
<td>Dean Number = $Re\sqrt{\frac{D_h}{2R_{mid}}}$</td>
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<tr>
<td>EL</td>
<td>Entrance length required to allow flow to be fully-developed</td>
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<td>$F_i$</td>
<td>Factor representing the in-plane loss of pairs</td>
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<tr>
<td>$F_o$</td>
<td>Factor representing the out-of-plane loss of pairs</td>
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<tr>
<td>HWA</td>
<td>Hot wire anemometry</td>
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<tr>
<td>I</td>
<td>Turbulence Intensity</td>
</tr>
<tr>
<td>LDV</td>
<td>Laser Doppler velocimetry</td>
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<tr>
<td>$M$</td>
<td>Magnification factor = $\frac{\text{Size of image plane}}{\text{Size of object plane}}$</td>
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<tr>
<td>N</td>
<td>Number of files that contain the valid velocity data for a location</td>
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<td>$N_i$</td>
<td>Effective particle image pair density within the interrogation spot</td>
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<tr>
<td>$O_{global}$</td>
<td>Origin of the cartesian coordinate system, also center of $90^\circ$ bend</td>
</tr>
<tr>
<td>$O_{local}$</td>
<td>Origin for the local coordinate system of an image taken in Insight</td>
</tr>
<tr>
<td>P</td>
<td>Perimeter</td>
</tr>
<tr>
<td>PIV</td>
<td>Particle image velocimetry</td>
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<tr>
<td>$Re$</td>
<td>Reynolds Number = $\frac{U_hD}{\nu}$</td>
</tr>
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\[ R^* = \frac{R_{\text{mid}}}{D_h} \]

- **\( R_{\text{inst}} \)**: Radius of a particular point from \( O_{\text{global}} \), in mm
- **\( R_{\text{mid}} \)**: Radius of bend middle (axis of symmetry) from \( O_{\text{global}} \), in inches

- **\( U_{av}, U_b \)**: Bulk velocity of the flow, in m/s
- **\( U_{\text{global}} \)**: Velocity component parallel to \( X_{\text{global}} \), in m/s
- **\( U_{\text{local}} \)**: Velocity component parallel to \( X_{\text{local}} \), in m/s
- **\( U_{\text{pixel}} \)**: Flow displacement component parallel to \( X_{\text{local}} \), in pixels
- **\( U_s \)**: Streamwise mean velocity parallel to \( s \), in m/s
- **\( V_n \)**: Radial mean velocity parallel to \( n \), in m/s
- **\( V_{\text{global}} \)**: Velocity component parallel to \( Y_{\text{global}} \), in m/s
- **\( V_{\text{local}} \)**: Velocity component parallel to \( Y_{\text{local}} \), in m/s
- **\( V_{\text{pixel}} \)**: Flow displacement component parallel to \( Y_{\text{local}} \), in pixels
- **\( W_z \)**: Velocity component parallel to \( z \), in m/s

- **\( X_{\text{global}} \)**: Cartesian coordinate system X-axis, in mm
- **\( X_{\text{local}} \)**: X-axis for the local coordinate system of an image taken in Insight, in pixels
- **\( Y_{\text{global}} \)**: Cartesian coordinate system Y-axis, in mm
- **\( Y_{\text{local}} \)**: Y-axis for the local coordinate system of an image taken in Insight, in pixels
- **\( dT \)**: Time between two laser pulses for single exposure/double-frame PIV recordings
- **\( f^\# \)**: \( f \) number of the lens

- **\( n \)**: Curvilinear coordinate system axis perpendicular to the streamwise direction, directed towards the ducts outer (positive \( n \)) and inner walls (negative \( n \)) of the duct. Also referred to as radial axis or normal axis, normalized
- **\( s \)**: Curvilinear coordinate system axis along the streamwise direction, normalized
- **\( u \)**: Streamwise velocity fluctuations
- **\( u_{\text{RMS}} \)**: Root mean square of the streamwise velocity component
- **\( u_{sd} \)**: Standard deviation of the streamwise velocity fluctuations
- **\( \tilde{u}(t) \)**: Instantaneous Velocity
\( u_{var} \) Variance of the streamwise velocity fluctuations

\( \overline{uv} \) Reynolds shear stress

\( v \) Normal velocity fluctuations

\( v_{RMS} \) Root mean square of the normal velocity component

\( v_{sd} \) Standard deviation of the normal velocity fluctuations

\( v_{var} \) Variance of the normal velocity fluctuations

\( z \) Coordinate axis perpendicular to the streamwise and radial direction, directed towards the top and bottom of the duct, normalized

\( \Theta \) Angle between a point in the bend and the \( X_{global} \) axis, in degrees

\( \alpha \) Angle made between the edge of the image frame perpendicular to the streamwise flow with the \( X_{global} \) axis, in degrees

\( \beta \) Angle made by vector from \( O_{global} \) to any point in the bend with \( X_{global} \) axis, in radians

\( \delta z \) Depth of focus of the camera

\( \theta \) Anti-clockwise angle of rotation of \( X_{local} \) axis for it to be parallel to \( X_{global} \) axis, in degrees

\( \lambda \) Wavelength of the laser

\( \nu \) Kinematic viscosity
Acknowledgments

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Andrew Stordahl did a fantastic job in building a well-designed experimental setup. Although he works full time in another part of the state, he remained accessible and was always quick to answer any queries I had about the setup. Andrew Knisely joined me in the Spring of 2009 to help develop MATLAB codes to process data and he quickly proved to be a valuable resource to the project. I would like to express my appreciation and gratitude to both of them.

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Finally, I would like to express my heartfelt gratitude to my family and friends who have been with me every step of my academic journey and molded me into the person I am today.
Introduction

Fluid flow through a pipe containing a bend is a phenomenon that finds enormous practical application in all walks of life. HVAC pipes, fuel lines, turbomachinery, and even the human circulatory system are some everyday examples of where this sort of phenomenon is found (Figure 1.1).

![Example images of curved pipes](image1.png)

(a) HVAC pipes  (b) Space Shuttle Main Engine. *(Note the fuel lines)*  (c) Human Circulatory System.

**Figure 1.1.** Examples of applications of curved pipes.

Flow through a curved pipe has a highly three-dimensional structure that is distinctly different from flow through a straight duct. This three dimensionality, caused by “secondary flow”, contributes to increased pressure losses and heat transfer. Hence knowledge of this flow structure is important to allow the engineers to design efficient piping systems. Secondary flow is the term attributed to a flow that is perpendicular to
the direction of the mean flow. A typical secondary flow in a bend, such as that shown in Figure 1.2, is set up by pressure gradients; velocities therein are much lower than mean free stream velocities. For flow moving through a 90° bend, the main secondary motion comes in the form of a counter-rotating vortex pair as illustrated in Figure 1.2.

![Figure 1.2. Schematic of the test section geometry and coordinate system. Also shown is the primary vortex pair of the secondary motion in the bend. Adapted from Stordahl et al.](image)

The strength of the vortices is dependent on several factors including the bulk velocity and the radius of curvature of the duct. The Dean number, $De$, named after W. R. Dean [1] who developed it in 1928, is a nondimensional parameter that helps to classify flows around bends. Several variations on the original nondimensional parameter developed by Dean have been used and although no standardized form has been adopted, all involve a ratio of the mean bend radius and a length scale of the duct and the Reynolds number. Equation 1.1 lists the form used in the current work.

$$De = Re \sqrt{\frac{D_h}{2R_{mid}}}$$  \hspace{1cm} (1.1)

The present work is an experimental study of high speed flow in a moderately curved (radius ratio $R^* = 4$), square cross-sectioned pipe. Particle Image Velocimetry (PIV) is
used to conduct field measurements, while previous studies, listed in Chapter 2 used point measurement techniques such as Laser Doppler Velocimetry and Hot Wire Anemometry. The use of a field technique, along with the comprehensiveness of the present measurements upstream, through the bend and downstream, allows the authors to present a complete visual picture of the bend effects aiding intuitive understanding of the phenomenon. Simultaneously, numerous detailed velocity measurements and turbulent statistics have been calculated to allow for the benchmarking of computational codes, including those with a fine mesh. Measurements at three flow rates have been performed to establish the dependence of the flow characteristics on the Reynolds’ number.
2.1 Introduction

Flow in a pipe bend has been studied quite extensively since the early 1900’s. Experimental studies on pipes having different cross sections were carried out. The main focus of the earliest research on flow through ducts with bends was to understand the pressure losses for the design of pipe systems. Although this research was helpful in developing simple correlations to determine pressure drop, it contained very little information on the flow structure. Information on the flow structure is required to properly design inlets of machinery that are preceded by a bend to allow the equipment to achieve maximum efficiency.

As experimental techniques developed, they contributed to bettering our understanding of bend effects. Computational models also began to be developed and that helped examine and predict flow patterns for various cases by differing parameters such as bend angle, flowrates, bend curvature and so on. Advanced experimental techniques, flow visualization, hot-wire anemometry and laser Doppler velocimetry helped examine bend effects not only in the fluid core but also in the boundary layers. These were used to validate newer and more advanced numerical models. Detailed below, with a focus on flow through a square duct, is a review of the important experimental and computational
work done over the years that has contributed to our understanding of flow through a curved pipe.

# 2.2 Experimental Work

Basic experiments on flexible and fixed curved tubes were conducted by Eustice [2] in 1910. Using a colored dye injected into the flow, he observed the flow structure of fluid flowing through a pipe. He experimented with flexible pipes, allowing him to vary the curvature and cross-section of the pipe and study the effect of each change on the fluid velocity.

The work published by Dean [1, 3] can be considered to be seminal work in the study of fluid flow through curved pipes. With the help of theoretical equations, he explained the presence and structure of secondary flows present in flows through a curved pipe. He also matched his theory to the observations of Eustice [2]. The secondary flow is a pair of counter-rotating vortices set-up in the cross-section of the pipe; these are often referred to as “Dean’s vortices” after him. These vortices are also referred to as secondary flow of the first kind.

G.I Taylor [4] conducted visual dye based experiments using a glass tube coiled in a helix and verified White’s claim [5] that a higher flow speed is required to maintain the turbulence in a curved pipe when compared with a straight one. The velocity of flow at which the flow turned turbulent from “steady state” [implied laminar] was referred to as “critical velocity”. Eustice [2] noted the absence of a definite critical velocity for curved pipes and Dean [1, 3] accepted this. However, White said that there exists a definite critical velocity and this claim was found to be true by Taylor [4] in his study.

As it became evident that flow through curved pipes cause higher pressure losses than flow through straight ducts, it became imperative to understand in detail the nature of these losses. The ability to calculate pressure-based losses in pipes was critical to the design of efficient piping systems. Ito [6] comprehensively studied the pressure loss
in a bend and developed an empirical relation to calculate the bend-loss coefficients. Ward-Smith’s book [7], summarized the loss coefficients for different types of bends and pipe systems. These loss coefficients are a key tool for developing pipe systems and determining pump sizes.

Laufer [8] was one of the first authors to provide an in-depth study of the flow structure in a curved bend. Using hot wire anemometry (HWA), he studied fully developed turbulent flow near the wall as well as in the mean flow field. His results included mean velocity values as well as turbulence statistics such as Reynolds stresses, triple correlations, turbulence dissipation and energy spectra.

An important phenomenon that has been observed in straight ducts needs to be discussed at this point since it affects flow in curved pipes. It is called secondary flow of the second kind. This secondary flow is observed in flows through long non-circular ducts. Gessner et al. [9] detailed it extensively, obtaining experimental data for flow through a straight square duct 22m long. A pair of counter-rotating vortices centered about each corner bisector are set up. For turbulent flow, the flow direction of these vortices is from the center of the duct along the sidewall bisector to the bounding walls, along which they move to get back to the corner. Since each corner has a pair of vortices, a square duct typically has eight corner vortices driven by cross-stream normal stresses. These stresses are set up due to flow along the walls of a non-circular duct (Figure 2.1).

In the late seventies and early eighties, Humphrey et al. [10, 11] investigated laminar and turbulent flows in square ducts with a strong curvature \( R^* = \frac{R_{mid}}{D_h} = 2.3 \). Laser Doppler velocimetry (LDV) was used as the primary measurement technique in these studies as well as subsequent studies by Taylor et al. [12], Enayet et al. [13], H. Sun and T. Feng [14], and Liou and Liu [15, 16]. Humphrey et al. [11] measured the longitudinal and radial components of velocities as well as the Reynolds stress tensor. They discussed the dominance of secondary flow of the first kind over secondary flow of the second kind as the fluid flows through a bend, its structure, and the factors that cause it, such as
Taylor et al. [12] studied the importance of inlet flow boundary layer thickness. They used the same experimental set-up and flow Reynolds numbers as Humphrey et al. [10, 11] and obtained pressure and velocity data. Taylor et al. [12] compared their results with the fully developed inlet flow condition studied by Humphrey et al. [10, 11] and concluded that with thin boundary layers, the influence of the streamwise vorticity was not noticeable until much later. They also noted the absence of any influence of secondary flows of the second kind on the flow development through the bend. Taylor et al. [12] compared their work to Enayet et al. [13] who used a milder bend geometry ($R^* = 7$).

Secondary flows of the first kind are set up due to the cross-stream pressure gradient which is caused by the presence of a bend in the pipe. The tighter the bend, the lower its radius ratio $R^*$ and the higher the velocities of the secondary flow. Enayet et al. [13] studied the effect of having a circular cross-section in a strongly curved test bend ($R^* = 2.8$) and then compared it with a technical note [17] Enayet published as a postscript to his study. This technical note measured the turbulence in a moder-
ately curved \((R^* = 7)\) square duct. Measurements included the streamwise and radial mean velocity components, the corresponding turbulence intensities and the Reynolds’ shear stress. It was concluded that the flow is qualitatively similar to previous studies conducted for similar test sections and \(\text{Re}\), but quantitatively secondary cross-stream velocities in moderate bends were one-half of those measure in strongly curved bends. They also noted the presence of a very weak second vortex pair of the opposite sense near the outer wall of the bend in the latter portion of the bend (Figure 2.2(a)).

Sun and Feng [14] measured velocity data very near to the wall surface for both laminar and turbulent flow through a square duct with a 90° bend. They also measured the pressure distribution along the wall in an attempt to discuss the relationship between the velocity field and the pressure drop. The linear law of velocity distribution in sublayer was verified and the shear stresses on the duct wall were evaluated. Also, a direct physical relation between wall shear stress and the near-wall pressure field was suggested by the comparison of the pressure gradient fluctuation to the variation of local coefficient of skin friction. Total bend loss coefficients were calculated and it was shown that the effect of curvature was higher for a laminar flowfield. Another near-wall study was conducted more recently Mokhtarzadeh-Dehghan and Yuan [18] using HWA. With air as the working fluid, quantitative measurements of the mean velocity profiles, mean turbulence quantities such as turbulence intensities and turbulence shear stress and the response of bursting period were obtained in the convex and concave walls boundary layers.

Laminar or low speed turbulent flows generally give rise to a pair of Dean’s vortices in the bend. However, as the flow speed increases, multiple pairs of Dean vortices are seen to develop. Liou and Liu [15, 16] showed the presence of 4-vortex and 6-vortex structures in the secondary motion in 1986 [15] and studied them in greater detail in 1987 [16]. Mean streamwise and radial velocity components and their corresponding turbulent intensities were measured in [15] using LDV and it was shown that the turbulence intensity was anisotropic in the bend as well as downstream of the bend exit. Also, high levels of
turbulence intensity were found near the duct walls and in the regions where Dean vortices appear. Liou and Liu [16] is essentially the same study but has very clear figures and also includes pressure measurements for the bend region. It is seen that the two additional pairs of vortices have a sense of rotation opposite to that of the primary pair of Dean’s vortices. As discussed later in Section 2.3, Crawford et al. [19] also noticed an additional pair of Dean’s vortices but with the same sense of rotation as the primary Dean’s vortices. Liou’s 6-vortex structure is shown in Figure 2.2(b) while Crawford’s observations are adapted in Figure 2.2(c).

Sudo et al. [20] studied the development of a steady turbulent flow in a curved pipe with a square cross-section. Using hot wire anemometry, they obtained the longitudinal and lateral components of the mean and fluctuating velocities and the Reynolds’ stresses. These data support a similar flow pattern as seen in the previous works, [11, 12, 13, 14, 15, 16]. Specifically: (i) the bend effect was visible approximately two diameters upstream of the bend inlet; (ii) the flow near the inner wall has a higher velocity than the outer wall. This is switched around just before the bend exit and a higher velocity can be seen near the outer wall than near the inner wall until the secondary flow starts dying out downstream; and (iii) turbulence intensity was reported to have the highest value two hydraulic diameters from the bend exit, confirming what Liou and Liu [15, 16] observed.

Ondore [21] used smoke-based flow visualization to check the convex wall near the bend exit for recirculation as predicted by the numerical computation performed by him. Hot wire anemometry was used to measure mean flow velocities, turbulence intensities and Reynolds’ stresses. The main turbulence model used for the numerical part of the investigation was the Reynolds Stress Model. His findings verified separation near the convex wall. However, he also concluded that more accurate experimental techniques, including PIV were needed to support the improvement of turbulence modeling.

Table 2.1 provides an organized summary of the articles discussed in this section. It compares the experimental techniques used, Reynolds number, Dean number, radius ratio, inlet conditions and the experimental set-up of past experimental studies conducted
(a) 4-vortex structure as observed by Enayet et al. Two pairs of Dean vortices are seen. The pair near the outer wall has clockwise rotation, opposite that of the primary pair of Dean vortices.

(b) 6-vortex structure as observed by Liou and Liu. Three pairs of Dean vortices are seen. The pairs near the axis of symmetry have clockwise rotation, opposite that of the primary pair of Dean vortices.

(c) 4-vortex structure as observed by Crawford et al. Two pairs of Dean vortices are seen. Both pairs of Dean vortices have the same sense of rotation.

**Figure 2.2.** Comparison of stated observations of more than one pair of Dean vortices. Refer to Tables 2.1 and 2.2 for flow conditions. *Figures adapted from Enayet et al., Liou and Liu and Crawford et al.*

on flow through a curved pipe containing a bend.

*The present PIV data present the most comprehensive picture to date of the mean flow structure, turbulent intensity and Reynolds stresses of high Reynolds number flow through a square sectioned 90° bend.* This data set has been compiled at $\text{Re} \approx 2.76 \times 10^5$ using PIV with a total of 12 streamwise locations in each of the three planes: top, middle and bottom of the test section. Additionally, for four streamwise fields-of-view along the
horizontal midplane of the test section, more PIV data were obtained at Re \(\approx 1.76 \times 10^5\) and Re \(\approx 3.2 \times 10^5\).
Table 2.1. Summary of experimental conditions of previous and present work.

<table>
<thead>
<tr>
<th>Author(s)</th>
<th>Year</th>
<th>Primary Measurement Technique</th>
<th>Re</th>
<th>De</th>
<th>$R^*$</th>
<th>Inlet Conditions</th>
<th>Set-up</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laufer [8]</td>
<td>1953</td>
<td>HWA</td>
<td>5.00 x 10^4</td>
<td>5.07 x 10^4</td>
<td>0.486</td>
<td>FD T</td>
<td>A, V, SQ, 90°</td>
</tr>
<tr>
<td>Humphrey et al. [10]</td>
<td>1977</td>
<td>LDV</td>
<td>790</td>
<td>368</td>
<td>2.3</td>
<td>FD L</td>
<td>W, V, SQ, 90°</td>
</tr>
<tr>
<td>Humphrey et al. [11]</td>
<td>1981</td>
<td>LDV</td>
<td>4.00 x 10^4</td>
<td>1.87 x 10^4</td>
<td>2.3</td>
<td>FD T</td>
<td>W, V, SQ, 90°</td>
</tr>
<tr>
<td>Taylor et al. [12]</td>
<td>1982</td>
<td>LDV</td>
<td>790</td>
<td>368</td>
<td>2.3</td>
<td>DL</td>
<td>W, H, SQ, 90°</td>
</tr>
<tr>
<td>Humphrey et al. [11]</td>
<td>1981</td>
<td>LDV</td>
<td>4.00 x 10^4</td>
<td>1.87 x 10^4</td>
<td>2.3</td>
<td>DL</td>
<td>W, H, SQ, 90°</td>
</tr>
<tr>
<td>Enayet et al. [13]</td>
<td>1982</td>
<td>LDV</td>
<td>4.3 x 10^4</td>
<td>1.81 x 10^4</td>
<td>2.8</td>
<td>DT</td>
<td>W, H, C, 90°</td>
</tr>
<tr>
<td>Enayet et al. [17]</td>
<td>1982</td>
<td>LDV</td>
<td>3.52 x 10^4</td>
<td>9.41 x 10^3</td>
<td>7</td>
<td>DT</td>
<td>W, H, SQ, 90°</td>
</tr>
<tr>
<td>Sun and Feng [14]</td>
<td>1985</td>
<td>LDV, P</td>
<td>6 x 10^3</td>
<td>1.9 x 10^3</td>
<td>5</td>
<td>FD L</td>
<td>to W, H, SQ, 90°</td>
</tr>
<tr>
<td>Liou and Liu [15, 16]</td>
<td>1986</td>
<td>LDV, P</td>
<td>4.70 x 10^4</td>
<td>2.71 x 10^4</td>
<td>1.5</td>
<td>DT</td>
<td>A, V, SQ, 90°</td>
</tr>
<tr>
<td>Sudo et al. [20]</td>
<td>2001</td>
<td>HWA</td>
<td>4.00 x 10^4</td>
<td>2.00 x 10^4</td>
<td>2</td>
<td>FD T</td>
<td>A, H, SQ, 90°</td>
</tr>
<tr>
<td>Mokhtarzadeh-Dehghan and Yuan [18]</td>
<td>2002</td>
<td>HWA</td>
<td>3.60 x 10^5</td>
<td>2.35 x 10^5</td>
<td>1.17</td>
<td>DT</td>
<td>A, V, SQ, 90°</td>
</tr>
<tr>
<td>Stordahl et al. [22]</td>
<td>2007</td>
<td>P</td>
<td>5.00 x 10^5</td>
<td>1.77 x 10^5</td>
<td>4</td>
<td>DT</td>
<td>A, V, SQ, 90°</td>
</tr>
<tr>
<td>Sheth et al.</td>
<td>2009</td>
<td>PIV</td>
<td>1.76 x 10^5</td>
<td>6.223 x 10^4</td>
<td>4</td>
<td>FD T</td>
<td>W, H, SQ, 90°</td>
</tr>
<tr>
<td>(present work)</td>
<td></td>
<td></td>
<td>2.76 x 10^5</td>
<td>9.76 x 10^4</td>
<td>4</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>3.2 x 10^5</td>
<td>11.314 x 10^4</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

HWA = Hot wire anemometry, LDV = Laser Doppler velocimetry, PIV = Particle image velocimetry, P = Pressure
D = Developing flow, FD = Fully developed flow, L = Laminar, T = Turbulent, C = Circular cross-section, SQ = Square cross-section
A = Air, W = Water, H = Bend in horizontal plane, V = Bend in vertical plane


2.3 Computational Work

There can be various permutations of pipe cross-sections, bend angles, curvature ratios, flowrates and fluids being carried by the pipe. Experimental data collection for every configuration of interest is impractical because of the large set-up costs, specialized experimental techniques and the time involved in the whole process. A computational or numerical model goes a long way in helping model flow for different configurations. Hence, it has always been an important component of the study of bend effects on fluid flow through a pipe. However, detailed computations and simulations are not always possible due to the limits of computing ability, too many parametric dependencies or the closure problem. This review shows, partly, how computational models have grown over the years to paint a more accurate picture of what we can expect to see when high speed fluid flows through a bend, with an emphasis on square ducts.

An early demonstration of the capabilities of the k-\(\epsilon\) model was performed by Launder and Spalding [23] who applied it to 9 different kinds of turbulent flows including flow through square ducts and twisted pipes. However, while the model was successful in a few applications, the authors highlight the need for further improvements required in the model. The need to replace the isotropic viscosity formula by more universal expressions that relate the stress and strain in a turbulent field was one of the major areas of improvement identified due to the anisotropic nature of turbulent flow.

Patankar et al. [24] solved the three dimensional time averaged Navier-Stokes equations using a two-equation k-\(\epsilon\) model turbulence model. They studied turbulent flow in a square sectioned U-bend and found good agreements with experimental data.

Using a simple closure model, Kresvosky [25] successfully predicted laminar and turbulent flow in a curved bend with a rectangular cross-section. The model improved on a previously developed primary-secondary velocity approach. This improved solution provided for the solution of the equations governing secondary vorticity and vector potential as a coupled system, using an iterative linearized block implicit scheme. While
it predicted the secondary flows for turbulent flows correctly qualitatively, some quantitative discrepancies were observed near the inner wall, especially at 60° and 77.5° from the bend entry when compared with the experimental results of Taylor et al. [12].

Iacovides et al. [26] detail finite volume, semi-elliptical computations of the three dimensional flow around a 90° square sectioned bend to predict the experimental results of Taylor et al. [12] and obtain excellent agreement. A two-equation turbulent flow model was used. The mean flow was simulated using a standard $k$-$\epsilon$ eddy viscosity model (EVM) while near wall flow was modeled using the mixing length hypothesis instead of extending the standard $k$-$\epsilon$ EVM to the wall.

Flow prediction of the secondary flow for turbulent fluid flow in a long straight duct as well as a curved duct using a non-linear k-\(l\) model was reported by Hur et al. [27]. They successfully predicted the eight counter-rotating vortices generated by the secondary flow of the second kind as flow develops in a straight duct with a square cross-section. For fully-developed flow through curved ducts with a square cross-section, a typical double vortex structure was obtained. As the $R^*$ of the pipe was decreased, the subsequent increase in centrifugal force caused the 2-vortex structure to change into a 4-vortex structure with the strengthening of 2 counter-rotating vortices near the outer wall. They called for future research to be directed towards a full non-linear $k$-$\epsilon$ model since a standard $k$-$\epsilon$ model was not able to model the interactions of turbulent flow with the secondary flows of the second kind.

Liu et al. [28] presented a three dimensional model for turbulent flow within a 90° square bend and a flat duct. A body-fitted coordinate system and standard $k$-$\epsilon$ equations were used. The authors supported Hur et al. [27] in calling for further research in developing a non-linear k-l or k-$\epsilon$ model. They also suggested the development of a multiscale k-$\epsilon$ model.

Using direct numerical simulation (DNS), Huser et al. [29] presented a description of turbulent flow in a square duct with emphasis on the origin of secondary flows. The terms of the Reynolds’ stress budget are calculated and presented. A detailed discussion
of the secondary flow of the second kind is seen. Data from the DNS was also used to evaluate the non-linear k-ε Speziale model.

A very detailed study of the developing turbulent flow in a 90° square bend was presented by Hitoshi et al. [30, 31]. An algebraic Reynolds stress model and a boundary fitted coordinate system were adopted by the authors. In reference [30], this method predicted the mean and secondary flow distributions well. It is observed that the secondary flow of the first kind is maintained for 1\(D_h\) from the bend exit after which it decays and gradually transforms to secondary flow of the second kind nearly 10\(D_h\) downstream of the exit. In Hitoshi et al. [31] attention was paid to the comparison of calculated results with the distribution of Reynolds stresses. These papers were published in Japanese and English translations were not found; hence a more detailed description of the work cannot be provided.

Large Eddy Simulation (LES) was adopted by Boersma et al. [32] to compute fully developed turbulent flow in a curved pipe. It is a comprehensive study detailing how the curvature influences the mean velocity profile, the various turbulent statistics and the secondary motion in the pipe cross-section that is typical of flow in a bend. Comparing their results with previous experimental work done by Adler [33], the authors have reported a good match for the core region, while mentioning small differences in data near the wall.

Raisee et al. [34] applied two different low-Reynolds-number eddy viscosity models to examine developing turbulent flow through a square and a rectangular 90° bend. A Launder and Sharma low-Re k-ε model and a cubic nonlinear low-Re k-ε model are employed to predict the velocity and pressure fields in the flow. One of the most important results was the distinct presence of a counter-rotating pair of additional vortices near the concave wall. A reasonable match was obtained between the numerical results and the experimental results obtained by Taylor et al. [12].

The most recent work in numerical investigation of flow structures has been carried out by Crawford et al. [19]. Four turbulent models were studied using a circular pipe
with three different bend curvatures ($R^* = 1.3, 5, 20$) to determine their accuracy in predicting pressure loss data. The standard k-$\epsilon$ model, realizable k-$\epsilon$ model, k-$\omega$ model and a Reynolds stress model (RSM) were studied. The RSM model performed the best in predicting the pressure data. The authors also plotted some interesting figures of the secondary flow. For the bends with a strong and moderate curvature, the RSM model observed a 4 vortex structure different from the ones mentioned previously. This 4-vortex structure was made up of 2 pairs of counter rotating vortices i.e in the top half of the pipe cross-section, 2 vortices with the same sense of rotation existed. This is different from the experimental observations of Enayet et al. [13] and Liou and Liu [15, 16].

Table 2.2 summarizes the computational literature reviewed in this section and provides a basis of comparison based on computational model used, Reynolds number, inlet conditions and geometry of the pipe modelled.

Since field measurements using PIV allow the mapping of the complete bend region as opposed to limited slices at fixed angles when data are obtained using point measurement techniques, the present study provides a more complete experimental data set to computational scientists. Also, the high resolution data obtained in the current work allows for a more thorough comparison of the results obtained using computational codes.
Table 2.2. Summary of previous computational work.

<table>
<thead>
<tr>
<th>Author(s)</th>
<th>Year</th>
<th>Model</th>
<th>Re</th>
<th>Inlet Conditions</th>
<th>Set-up</th>
</tr>
</thead>
<tbody>
<tr>
<td>Launder and Spalding [23]</td>
<td>1974</td>
<td>$k$-$\epsilon$</td>
<td>$6 \times 10^3$ and $&gt; 2 \times 10^4$</td>
<td>FD L,T</td>
<td>SQ, twisted pipes</td>
</tr>
<tr>
<td>Patankar et al. [24]</td>
<td>1975</td>
<td>Parabolic N-S equation solution</td>
<td></td>
<td>D T</td>
<td>SQ, 180°</td>
</tr>
<tr>
<td>Kresvosky [25]</td>
<td>1981</td>
<td>Simple closure model</td>
<td>$1 \times 10^4$ and $4 \times 10^4$</td>
<td>FD L T</td>
<td>R, 90°</td>
</tr>
<tr>
<td>Iacovides et al. [26]</td>
<td>1987</td>
<td>$k$-$\epsilon$, $k$-$\epsilon$ EVM (near wall)</td>
<td>790</td>
<td>D L</td>
<td>SQ, 90°</td>
</tr>
<tr>
<td>Hur et al. [27]</td>
<td>1990</td>
<td>non-linear $k$-$l$</td>
<td>$4.2 \times 10^4$</td>
<td>FD T</td>
<td>SQ, straight, curved</td>
</tr>
<tr>
<td>Liu et al. [28]</td>
<td>1992</td>
<td>$k$-$\epsilon$, BFCS</td>
<td>790 and $5.0 \times 10^3$</td>
<td>L T</td>
<td>SQ, 90°</td>
</tr>
<tr>
<td>Huser et al. [29]</td>
<td>1994</td>
<td>DNS</td>
<td>$1.032 \times 10^4$</td>
<td>FD T</td>
<td>SQ</td>
</tr>
<tr>
<td>Hitoshi et al. [30, 31]</td>
<td>1995</td>
<td>RSM, BoFCS</td>
<td>$4 \times 10^4$</td>
<td>D T</td>
<td>SQ, 90°</td>
</tr>
<tr>
<td>Raisee et al. [34]</td>
<td>2006</td>
<td>Launder and Sharma low-Re $k$-$\epsilon$</td>
<td>4$ \times 10^4$</td>
<td>D T</td>
<td>SQ, R, 90°</td>
</tr>
<tr>
<td>Crawford et al. [19]</td>
<td>2009</td>
<td>$k$-$\epsilon$, realizable $k$-$\epsilon$ k-$\omega$ RSM</td>
<td>$1.98 \times 10^4$-$1.26 \times 10^5$</td>
<td>FD T</td>
<td>C, 90°</td>
</tr>
</tbody>
</table>

EVM = Eddy Viscosity Model, RSM = Reynolds’ Stress Model, DNS = Direct Numerical Simulation, BoFCS = Boundary fitted Co-ordinate System, BFC = Body-fitted Co-ordinate System, Re* = Reynolds number based on mean friction velocity, FD = Fully developed flow, L = Laminar, T = Turbulent, R = Rectangular cross-section, SQ = Square cross-section, C = Circular cross-section
2.4 Conclusions

Various other studies, both experimental and computational have been carried out over the years for different cross-sections, bend angles, flow conditions and other parameters.

The aim of this work is to obtain a visual and quantitative representation of the flow especially the secondary flow using a non-intrusive optical technique. When compared with LDV or HWA, which are point measurement techniques, PIV allows us to map flow almost continuously from upstream of the bend to a place sufficiently downstream of the bend exit. In other words, PIV makes field measurements compared to the point measurements made by LDV or HWA. The field data collected also allow us to present the data in a highly intuitive visual form which allows the reader to understand, at a glance, the way the bend influences fluid flow within the pipe. Also, the data generated can be further processed to obtain the turbulent statistics of the flow as well as to benchmark future numerical codes since the high-speed turbulent flow is fully developed before it enters the test section. Finally, with data collected for a flow having the Reynolds number order of magnitude of $10^5$, which is 1-2 orders of magnitude higher than most of the previous experimental studies, the amount of data available for high-speed flow through a square duct containing a $90^\circ$ bend is substantially improved.
Chapter 3

Experimental Setup

3.1 Flow Facility

This flow facility was primarily designed by A. Stordahl as part of his graduate thesis. A detailed description can be found in Stordahl [22]. Some modifications were made to the facility to adapt it for the current data collection exercise. A section was added to the original flow facility to allow the flow to be fully-developed before it enters the test section. This section was a 54” long stainless steel square-sectioned duct that was placed in between the shape changer section and the test section inlet. The design details have been included in Appendix C. Also, the polycarbonate honeycomb flow straightener was replaced with a stainless steel (304SS) honeycomb custom manufactured for this application by Benecor Inc (based in Wichita, KS). This change allowed the removal of the stainless steel screen downstream of the flow straightener. With these modifications, currently the closed loop flow system is capable of a maximum flowrate of 190 gallons per minute which gives a Reynolds number of 470,000.

A 200 gallon tank serves as the fluid reservoir for the experiment. The fluid is initially filtered through a stand-alone filtration system consisting of a UV lamp and a 5µm filter to remove any foreign material and to prevent biological growth in the tank. After this initial treatment, this filtration loop is closed and the working fluid is pumped through
a secondary filtration loop consisting of a 40µm particulate filter for removal of larger foreign particles, rust and other deposits added to the fluid by the pump, pipelines and other components in the closed loop system.

The outlet of this filter loop leads to the flow-conditioning section of the experimental setup. This is made up of a flow straightener, a nozzle, a shape-change section and a section to fully-develop the flow. The flow straightener is a customized stainless steel honeycomb which has a nominal outer diameter of 2.415” ± 0.05” and a thickness of 5.79” ± 0.03” and sits within a 6” stainless steel flow straightener section. On exiting this section, the fluid enters a nozzle which reduces the pipe inner diameter from 2.065” to 1.5” and leads it to the shape-change section. Here, the pipe cross-section changes from 1.5” circular to 1” by 1” square. Finally, the flow is allowed to become fully developed in a 54” long duct having a 1” square cross-section, leading to the test section inlet.

The test section has an upstream section of length 5$D_h$ where $D_h$ is the hydraulic diameter (1” in this case from Equation 3.1), followed by a 90 degree bend having a mean radius 4$D_h$. The downstream portion of the test section is 10$D_h$ long and leads into a diffuser followed by an outlet pipe that leads back into the water tank.

A schematic of the diagram can be seen in Figure 3.1 while the actual experimental setup is labeled in Figure 3.2(a). The test-section has an optically-accessible acrylic bottom half and can be fitted with different tops. Depending on the type of measurement that needs to be made, the test-section can be fitted with either an aluminium top containing pressure taps for static and dynamic pressure measurements or an optically-accessible acrylic top for PIV measurements. These are shown in Figure 3.2(b).

$$D_h = 4 \frac{A}{P}$$ (3.1)
3.2 PIV System

As mentioned earlier, velocity measurements are obtained using Particle Image Velocimetry (PIV). The system components used for this particular application are detailed in this section while the PIV set-up for a typical data collection run is shown in Figure 3.3.

A New Wave Research Solo 120 15Hz laser is used as the illumination source. This dual head Nd-Yag laser is used to obtain a beam of wavelength $\lambda = 532$ nm. It is
(a) Experimental Setup

(b) Test section fitted with optically accessible PIV top (left) and pressure measurement top (right)

Figure 3.2. Experimental set-up and possible test section configurations.
fitted with an optical system consisting of a cylindrical lens ($F = -15 \text{ mm}$) followed by a spherical lens ($F = 500 \text{ mm}$) oriented such that the laser sheet is horizontal. This lens system can be easily rotated by $90^\circ$ to obtain a lightsheet in the vertical plane, if desired. The light sheet has a finite thickness ($\simeq 1 \text{ mm}$) which is referred to as the “waist” at the point of minimum thickness. The laser sheet is positioned such that its waist is in the channel’s vertical plane of symmetry. Hence a thin, horizontal plane is illuminated and light is reflected off the particles in that plane, allowing them to be captured by the camera system.

A TSI Powerview Camera 4M with a resolution of 2048 x 2048 pixels with a pixel size of 7.4 $\mu m \times 7.4 \mu m$ is used to capture flow images. It operates at a maximum frequency of 17 frames per second and provides a 12-bit output. The CCD chip output is transmitted to the PIV processing software, TSI Inc’s Insight 5-5, by means of a high speed frame grabber card. An AF Micro-Nikkor 105 mm f/2.8D lens is attached to the camera and the assembly is mounted on a camera stand. This customized camera stand can be moved along the test section and can be bolted down while taking PIV images to eliminate accidental movement and ensure that all the images are taken at the same location. Fine adjustments in the X, Y and Z direction can be made to maneuver the camera to look exactly at the location desired. The camera is focused onto a plane illuminated by the laser sheet. However, particles that are slightly above or below the focal plane may also be captured by the camera. The particles are illuminated by the light scattered from the particles within the laser plane. This is known as depth of focus and it is discussed in further detail in Section 4.5.1.

The seed particles used are hollow glass spheres of mean diameter 12 - 20 $\mu m$. With density for the glass spheres given as 1.1 g/cc, they are expected to be able to follow the flow faithfully based on Mei [35]. They are added directly into the tank at the start of each run after the filtration loops have been closed. A dense particle field is essential for good PIV images. However too many particles may cause specular reflection of the laser light within the flow field under observation and this causes saturation of the pixels.
Saturated pixels are seen as pink flashes in the image. Saturation has two primary ill-effects. First, repeated saturation at the same location can cause the pixels on a CCD chip looking at such a location to “burn-out”. Secondly, saturation cause “bleeding” of light into neighboring locations in the PIV image causing particles to be masked and making it impossible for the software to generate vectors in those region. This gives rise to empty spaces or “holes” in the flow field, where there are no generated vectors. This discontinuity causes a loss of information that could otherwise have been captured. Hence, care must be taken to avoid saturation while at the same time maintaining a satisfactorily densely seeded flow field.

A TSI Synchronizer is used to synchronize the camera and the laser system. It is connected to a computer on which TSI’s image processing software, Insight 5-5 is installed. Parameters such as the number of images obtained, the delay time, dT, between
the two frames of each image, shutter open time and the laser intensity can be entered as input into Insight 5-5. Pressing the “Laser Fire” button on the software sends an input to the synchronizer which then controls the firing of the dual heads of the laser as well as the shutter exposure based on the inputs given to Insight 5-5. Transferring the acquired images back to Insight for storage in the computer’s hard-drive is also performed by the synchronizer.

Once images are acquired, they are transferred to an external hard drive and further backed up in another hard drive. The data in the primary drive are then used for further processing.

### 3.3 Instrumentation

One Setra 204 0-100 psig static pressure transducer is placed upstream of the flow straightener while another one is placed downstream after the diffuser. A T-type thermocouple located at the same location as the upstream pressure transducers helps monitor the water temperature within the flow system. A turbine flowmeter is placed in the return loop and it measures the flowrate in gpm.

All the instrumentation data input is scaled into the appropriate units and output using LABVIEW. The pressure transducers are connected through a National Instruments BNC-2110 connector block to a DAQCard-6036E PCMCIA data acquisition card in a PC. There is also a PCI-4130 data acquisition card from National Instruments which uses the output from the thermocouple as an input. A Newport iDRN-PR converts the 4-20mA signal from the flowmeter output into a 0-5 VDC signal that can be used in the DAQCard 6036E-board. Details of the connections and circuit diagrams may be found in Stordahl [22]. For the static pressure measurements, the optically accessible PIV top is replaced by a pressure top which has 20 pressure taps. These taps are $0.2D_h$ from the inside and outside walls. All of these taps go to a single stream selector valve from Valco Instrument Corporation Inc., model C35Z-31826EMH which can take up to 26 channels
as input. This stream selector valve is connected to a Setra 204 0-100psig static pressure transducer. A clicker allows the user to switch sequentially through all the channels and read the pressure output at the selected location through the data acquisition system. Each port is sampled sequentially at a rate of 100 Hz for 10 seconds.
Chapter 4

Data Collection

4.1 Locations

One of the major aims of this project is to extensively map the flow field within the pipe at a high Reynolds number. This serves many purposes, the two most important ones being obtaining a visual representation of the flow within the pipe as well as collecting information on the nature of the flow, such as velocity and turbulent statistics at a large number of locations. Visually mapping the flow allows better understanding of the propagation of the bend effects through the flow field. The velocity data collected at a large number of spatial points can be processed to obtain turbulence statistics at those locations and this in turn, quantitatively tells us how the bend is influencing flow through the pipe.

To achieve these aims, extensive amounts of contiguous data are required so as to minimize loss of information. Also, since the flow is highly turbulent, we need to obtain data at three \( z \)-locations within the field for the same \( X-Y \) location. Data are obtained at twelve stations along the bend and three \( z \)-locations at each station. The stations are as follows: (1) one station upstream 1.75\( D_h \) from the start of the bend, (2) six stations throughout the bend where each station looks at a sector with 15° as the included angle and (3) five stations downstream of the bend starting 0.75\( D_h \) after the bend exit and
Figure 4.1. 12 stations for PIV: 1 upstream (UP1), 6 in the bend from 0° to 90° (BND1 - BND6), 5 downstream of the bend (DN1 - DN5).

providing continuous data until $7D_h$ downstream of the bend exit. The station locations are shown in Figure 4.1.

At each of the above 12 stations, velocity measurements are acquired at 0.125”, 0.5” and 0.875” from the top of the channel. These locations are referred to as top, middle, and bottom respectively. The z-axis has its origin in the center of the test section that is 0.5” from the top of the channel. The top plane has a $z = 0.375D_h$, the middle plane $z =$
0 and the bottom plane is noted as \( z = -0.375D_h \). For a Reynolds number of \( 2.76 \times 10^5 \), 500 pairs of images have been obtained at each location, with the exception of the station upstream. Here, 300 image pairs have been obtained.

Additional data at \( \text{Re} = 1.76 \times 10^5 \) and \( 3.2 \times 10^5 \) are obtained at the upstream location, bend entry (\( 0^\circ \) to \( 15^\circ \)), bend exit (\( 75^\circ \) to \( 90^\circ \)) and a location downstream of the bend exit. 500 pairs of image are obtained at each of the four locations. All of these data are taken in the middle plane. As will be seen in Section 6.2.5, these data allow us to compare the bend effects at different Reynolds numbers.

Each image is approximately 8 MB in size. For the 45 locations, a total of 21,900 image pairs were obtained. Hence nearly 350 GB of raw data have been collected for processing.

### 4.2 Calibration

For each station, the camera has a different point of reference (Figure 4.1). That is, at each location, the local origin of the image varies with respect to the global coordinate system. PIV processing is carried out using the local coordinate system (in pixels). This gives us the displacement vectors whose components, \( U_{\text{pixel}} \) and \( V_{\text{pixel}} \), are parallel to the local \( X \) and local \( Y \) axes respectively. After PIV processing is complete, all the stations need to have their local origins (\( O_{\text{local}} \)) shifted to a common origin \( O_{\text{global}}(0,0) \) located at the center of the arc that forms the inner edge of the bend. The transformation also requires a corresponding rotation and translation for the \( U_{\text{pixel}} \) and \( V_{\text{pixel}} \) displacement components into \( U_{\text{global}} \) and \( V_{\text{global}} \) velocity components which are in m/s and are parallel to the \( X_{\text{global}} \) and \( Y_{\text{global}} \) axes respectively. We have a third coordinate system which has the \( s-n \) co-ordinates as its axes. This is a curvilinear coordinate system, where \( s \) is the axis that is along the axis of symmetry of the test section and \( n \) is perpendicular to \( s \), positive when pointing towards the outer side of the bend. The origin for the curvilinear co-ordinates is in the middle of the test section at the start of the bend. The
calculation of $U_{global}$ and $V_{global}$ velocities is an intermediate step in transforming the local displacement vector components obtained from PIV to velocity vector components in the curvilinear coordinate system. As a final step, the cartesian coordinates are also transformed into curvilinear coordinates.

Due to the coordinate transformations that includes either rotation or translation or both, it is essential to know the orientation of the camera with respect to $O_{global}$ for each station. To facilitate this, a “calibration” image is taken before each set of PIV data is obtained. This calibration image provides a reference with respect to a known location or dimension of the test-section, enabling calculation of the exact orientation and offset of $O_{local}$ with respect to $O_{global}$. These offset values, listed in Table 4.1, are later used for the coordinate transformation operations. Calibration is an important step in order to ensure that data integrity is maintained. The exact distance from the reference point is entered in datasheets for each location. The complete datasheets can be found in Appendix A. The equations for the actual coordinate transformations can be found in Section 5.3.1.

### 4.3 Settings

PIV data are obtained using the Frame Straddle mode in Insight 5-5. This mode captures two frames: Frame A and Frame B which are separated by the user determined time interval $dT$. The successive images taken by the camera are then displayed by the software. Magnification (in pixels/mm) for a particular station is obtained by measuring the distance between the channel walls in the image in pixels and dividing by the known channel width $D_h=25.4$ mm. Using this magnification and the flowrate reading from the turbine flowmeter, Equation 4.1 can be used to obtain the estimated speed of the particles within the flow in pixels per second.
Table 4.1. Data to calculate global coordinates

<table>
<thead>
<tr>
<th>Reynolds Number</th>
<th>Location</th>
<th>dT (µs)</th>
<th>Magnification (pixels/mm)</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>2.81×10^5</td>
<td>UP1</td>
<td>26</td>
<td>48.937</td>
<td>180</td>
<td>90</td>
<td>-0.50</td>
<td>4.82</td>
</tr>
<tr>
<td>2.64×10^5</td>
<td>BND1</td>
<td>15</td>
<td>49.096</td>
<td>182</td>
<td>90</td>
<td>1.58</td>
<td>4.72</td>
</tr>
<tr>
<td>2.88×10^5</td>
<td>BND2</td>
<td>15</td>
<td>49.370</td>
<td>193</td>
<td>73.5</td>
<td>2.68</td>
<td>4.12</td>
</tr>
<tr>
<td>3.04×10^5</td>
<td>BND3</td>
<td>10</td>
<td>48.346</td>
<td>211</td>
<td>60.5</td>
<td>3.66</td>
<td>3.10</td>
</tr>
<tr>
<td>2.29×10^5</td>
<td>BND4</td>
<td>10</td>
<td>48.497</td>
<td>252</td>
<td>46</td>
<td>4.27</td>
<td>1.84</td>
</tr>
<tr>
<td>2.50×10^5</td>
<td>BND5</td>
<td>10</td>
<td>49.058</td>
<td>243</td>
<td>30</td>
<td>4.85</td>
<td>0.95</td>
</tr>
<tr>
<td>2.70×10^5</td>
<td>BND6</td>
<td>10</td>
<td>49.016</td>
<td>259.5</td>
<td>15</td>
<td>4.93</td>
<td>-0.23</td>
</tr>
<tr>
<td>3.05×10^5</td>
<td>DN1</td>
<td>15</td>
<td>48.189</td>
<td>270</td>
<td>0</td>
<td>4.99</td>
<td>-2.00</td>
</tr>
<tr>
<td>2.69×10^5</td>
<td>DN2</td>
<td>15</td>
<td>48.189</td>
<td>270</td>
<td>0</td>
<td>4.90</td>
<td>-3.25</td>
</tr>
<tr>
<td>2.94×10^5</td>
<td>DN3</td>
<td>15</td>
<td>48.189</td>
<td>270</td>
<td>0</td>
<td>5.00</td>
<td>-4.50</td>
</tr>
<tr>
<td>3.11×10^5</td>
<td>DN4</td>
<td>15</td>
<td>48.189</td>
<td>270</td>
<td>0</td>
<td>5.01</td>
<td>-5.75</td>
</tr>
<tr>
<td>2.54×10^5</td>
<td>DN5</td>
<td>15</td>
<td>48.189</td>
<td>270</td>
<td>0</td>
<td>4.93</td>
<td>-7.00</td>
</tr>
<tr>
<td>1.76×10^5</td>
<td>UP1</td>
<td>20</td>
<td>49.567</td>
<td>180</td>
<td>90</td>
<td>-0.50</td>
<td>5.02</td>
</tr>
<tr>
<td>1.84×10^5</td>
<td>BND1</td>
<td>20</td>
<td>48.268</td>
<td>183</td>
<td>90.5</td>
<td>1.49</td>
<td>4.67</td>
</tr>
<tr>
<td>1.76×10^5</td>
<td>BND6</td>
<td>20</td>
<td>49.685</td>
<td>257</td>
<td>15</td>
<td>5.01</td>
<td>-0.23</td>
</tr>
<tr>
<td>1.84×10^5</td>
<td>DN1</td>
<td>20</td>
<td>49.213</td>
<td>270</td>
<td>0</td>
<td>4.79</td>
<td>-4.50</td>
</tr>
<tr>
<td>3.63×10^5</td>
<td>UP1</td>
<td>10</td>
<td>49.567</td>
<td>180</td>
<td>90</td>
<td>-0.50</td>
<td>5.02</td>
</tr>
<tr>
<td>3.74×10^5</td>
<td>BND1</td>
<td>10</td>
<td>48.268</td>
<td>183</td>
<td>90.5</td>
<td>1.49</td>
<td>4.67</td>
</tr>
<tr>
<td>3.67×10^5</td>
<td>BND6</td>
<td>10</td>
<td>49.685</td>
<td>257</td>
<td>15</td>
<td>5.01</td>
<td>-0.23</td>
</tr>
<tr>
<td>3.75×10^5</td>
<td>DN1</td>
<td>10</td>
<td>49.213</td>
<td>270</td>
<td>0</td>
<td>4.79</td>
<td>-4.50</td>
</tr>
</tbody>
</table>

\[ U_b(\text{pix/s}) = 97.8 \times \text{Flowmeter output (gpm)} \times \text{Magnification (pix/mm)} \]  
(4.1)

where 1 gpm = 97.8 mm/s

This value, along with an estimated pixel displacement between Frames A and B in Insight 5-5, can be used to calculate the user-specified dT. A good value of dT ensures sufficient time between two laser pulses such that we get distinct images of particle displacement in Frame A and Frame B. A trial image pair is captured at every data collection location to verify the calculated value of dT.

This data collection exercise is spread over several days and each run has a fresh
supply of water and particles. Hence, it is necessary to examine and if necessary, readjust the Q-switch delay in each laser head to minimize bleeding due to saturation for each set of data collection. Thus, after confirming the dT value for the particular run, further trials are carried out to ensure optimum Q-switch settings. Each Q-switch setting is then recorded into the datasheets, attached in Appendix A.

4.4 PIV Hardware Set-up

The laser and the camera are adjusted for each location at which PIV data are acquired. The laser is aimed such that the laser sheet is parallel to the station where the PIV is to be performed. The height of the laser is adjusted so the laser sheet plane matches the $z=0.375''$ plane. Following this adjustment, the camera stand is moved to the location and bolted down. The height is adjusted so that the field of view is as desired, followed by finer $X$-$Y$ adjustments if required. All metallic and shiny components around the location are covered in black felt to prevent reflections acting as multiple secondary illumination sources. After this procedure has been completed, the calibration image is obtained and stored and the lens is focussed on the top or $z=0.375''$ plane. Following PIV in the top plane at a station, the laser is simply adjusted to match the $z=0''$ and $z=-0.375''$ plane and the camera lens is refocused in each case.

4.5 Experimental Accuracy

4.5.1 PIV System

The measurement accuracy of an experiment is a sum of various factors including the set-up design, instrumentation and data collection techniques. Similarly, the accuracy of data recorded by a PIV system is dependent on various factors from the recording technique to the final evaluation methods. One of the possible ways to assess this uncertainty in PIV systems is to conduct a PIV analysis on a known flow and then compare the results to determine the total error associated with the technique. This, however,
may not possible in all cases, including the present study. Hence we base these estimates
of accuracy on the basis of results generated by numerical simulation.

Varying one parameter at a time, researchers can generate artificial particle image
recordings which can be compared with the known original result. In one such use of
computational techniques, Monte Carlo simulations were used to determine the RMS-
uncertainty (in pixels) in PIV measurements based upon the particle image diameter in
the PIV image. For the current work, the average particle image diameter is $\simeq 2$ pixels.
This translates to an uncertainty of $\simeq 0.012$ pixels or nearly 0.052 m/s for each PIV
measurement. Details on this technique can be found in the book by Raffel et al. [36]
who has provided a good compilation of the various studies conducted.

As mentioned before, a dual head laser is used for the PIV recording. This can be
another source of inaccuracies. If the beams are misaligned, then each frame of the
dual exposure illuminates a slightly different plane in the flow field. Processing images
from such a recording would provide spurious or incorrect vectors and hence the laser
was periodically aligned to make sure that the laser beams from each laser head were
coincident.

Secondary flow is highly three dimensional, while the laser sheet coming into the
test section is two dimensional. This may lead to loss of particles that move out-of-
plane. The camera can capture all the particles, including out-of-plane particles if they
are illuminated by the laser sheet and are within its depth of focus. Depth of focus is
calculated using Equation 4.2.

$$\delta z = 4(1 + M^{-1})^2(f_{\#})^2\lambda$$ (4.2)
where

\[
\delta z = \text{Depth of focus} \\
M = \text{Magnification factor} \\
= \frac{\text{Size of image plane}}{\text{Size of object plane}} \\
f_\# = f \text{ number of the lens} \\
\lambda = \text{Wavelength of the laser}
\]

In this case, out-of-plane motion is when the particles move in the \( z \)-direction along the sidewalls of the test section. For the experimental set-up that we have, the typical secondary flow velocity along the sidewall is about 40% of the mean flow velocity. For a typical image, we have the following parameters:

Secondary flow velocity in \( z \)-direction \((W_z)\) = 0.006455 \( \leq W_z \leq 0.01301 \) mm/\( \mu s \)

\[
M = \frac{15.2}{41.2} \text{ mm} \\
f_\# = 11 \\
\lambda = 532 \text{ nm}
\]

This gives a depth of focus \( \delta z = 3.545 \) mm. Assuming the laser sheet thickness to be 1 mm, for a particle to be lost to out-of-plane motion, \( dT \) has to be greater than 77 \( \mu s \). For all the measurements, we have a \( dT \) less than 30 \( \mu s \). This minimizes the chances of any out-of-plane loss of image pairs, increasing the chances of generating valid vectors and hence the accuracy of the PIV processing.

In-plane losses are avoided by choosing a bigger interrogation region size for Frame B than for Frame A. Also, the Grid Engine offsets the image field, allowing for higher accuracy. These are discussed in detail in Sections 5.2.3.1 and 5.2.3.2 respectively.
Keane and Adrian [37] defined three quantities: \( N_i, F_o, \) and \( F_i \). The number of image pairs captured in an interrogation area depends on these 3 quantities. \( N_i \) is the effective particle image pair density within the interrogation spot, \( F_o \) is a factor representing the out-of-plane loss of pairs, \( F_i \) is a factor representing the in-plane loss of pairs and the product of these three factors, \( N_i F_o F_i \) expresses the mean effective number of particle image pairs. For a single exposure/double frame recording, if \( N_i F_o F_i > 5 \), then the valid detection probability exceeds 95\%. We have a typical \( N_i \) of 10 and with minimal or no loss of pairs either in-plane or out-of-plane, the values of \( F_i \) and \( F_o \) tend to 1. Hence, for our study, \( N_i F_o F_i \approx 10 \) which is greater than the baseline requirement and should allow the detection of \( \geq 95\% \) of all the image pairs captured.

Background noise is eliminated using background subtraction discussed in Section 5.2.2 allowing for a higher signal to noise ratio and more valid vectors.

The placement of hardware such as the camera and laser system is accurate to the nearest 1/16th of an inch since a regular foot-scale was used to measure distances.

### 4.5.2 Instrumentation

<table>
<thead>
<tr>
<th>Type</th>
<th>Company</th>
<th>Model</th>
<th>Range</th>
<th>%/FS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow rate</td>
<td>Sponsler</td>
<td>SP2-CB-PHL-A-4X</td>
<td>20-220 gpm</td>
<td>±0.25</td>
</tr>
<tr>
<td>Temperature</td>
<td>Omega</td>
<td>TMQSS-062G-12</td>
<td>−250°C to 350°C</td>
<td>±0.75</td>
</tr>
<tr>
<td>Mean pressure</td>
<td>Setra</td>
<td>204</td>
<td>0-100 psig</td>
<td>±0.11</td>
</tr>
</tbody>
</table>

The experimental set-up has a thermocouple, two pressure transducers and a turbine flowmeter to provide information about the working fluid. Upstream of the test section, right after the filtration loop a thermocouple and a pressure transducer provide us with the initial state of the flow. A pressure transducer placed downstream of the flow measures the pressure after the fluid has gone through the bend, following which the turbine flowmeter placed further downstream measures the flowrate. The accuracy of each instrument, as quoted by the manufacturers, is provided in Table 4.2. The Reynolds
number of the flow, calculated on the basis of the readings of these instruments, has an accuracy of \( \pm 9\% \).
Chapter 5

Data Processing

5.1 Introduction

The voluminous PIV data collected are stored in an external hard drive. This is due to lack of storage space in a regular lab PC as well as the mobility advantage that an external drive provides. The raw image data are then processed using two distinct platforms, proprietary TSI software Insight 3-G and customized MATLAB codes. Each software enables many different processes which allow us to extract meaningful data from the raw image files obtained using PIV. Using the current processing techniques, we can obtain the (a) instantaneous velocities, (b) mean velocities and (c) turbulent fluctuations at each point in each location, (d) average velocities and (e) root mean square velocities at each location and other turbulent statistics such as (f) standard deviation, (g) variance, (h) turbulence intensity and (i) Reynolds shear stresses. Each step of the processing has been detailed in this chapter along with relevant equations, wherever applicable. A quick overview of the process is shown in the flowchart (Figure 5.1).
Figure 5.1. Overview of Data Processing.

- **External storage**
  - 3G processed
    - Transfer to MATLAB
      - Process *.vec files
        - Backup
          - Tecplot
            - Process *.vec files
            - Remap intensity
            - Run background average intensity generator
              - Perform background subtraction
                - Determine processing parameters
                  - Process images to get *.vec files
  - 3G compatible
    - Transfer to MATLAB processing computer
    - Rename using MATLAB file
5.2 Generating Vector Files

5.2.1 Compatibility with Insight 3-G

TSI’s Insight 5-5 is the software available pre-installed on the lab PIV acquisition computer hence it is used to collect the PIV data. However, for processing the image files to obtain vector files Insight 3G (a more powerful and updated version of Insight 5-5) is used. Since 3G requires the image filename to be in a certain format which is different from the filename generated by 5-5, the first step is renaming the files. Insight 3G has a function that allows you to do so but that had a maximum limit of 200 files at a time. Since we have thousands of files that need to be renamed, a MATLAB code was written to perform the task. The code can be found in Appendix B.

Following renaming, the files also need to have their intensity values remapped to be zero based. This is because the camera used for capturing images is a 12-bit camera that stores the image information with the bits shifted high in Insight 5-5. Insight 3G, however, stores this 12-bit information in the 12 highest bits of a 16-bit file format, causing the intensity information range to be 16 to 65535 instead of from 0 to 4095. The Image Tool Remap function of Insight 3G remaps the intensities to have a low bit =0 and high bit = 11 allowing the 12-bit information to be stored in the lowest 12 bits of a 16-bit format. With this shift, the intensity values have the correct range (from 0 to 4095) in a 16-bit format and the images can be used correctly with Insight 3G.

5.2.2 Image Pre-processing

After conditioning the files to be compatible with Insight 3G, an “Experiment” is created in the working directory of 3G. This is followed by the creation of a new “Run”. The Experiment folder now has two subfolders - Run and Settings. The Run folder is divided further into two subfolders - RawData and Analysis. As the name suggests, RawData is the folder where the raw image files are imported to and stored while the Analysis folder is used store any background subtraction files, background subtracted image files and
the vector files. The \textit{Settings} folder stores details that can be shared across runs. This includes files such as capture parameters, processing and validation parameters.

Raw images can contain noise in the form of light from unwanted sources such as reflections, bleeding due to saturation of pixels on the CCD chip and edges of the test section. The greater the noise in an image, the higher the chances of losing information, either by the generation of spurious vectors or the absence of valid vectors due to a low signal to noise ratio (SNR). It was realized that the best way to get rid of noise was by using Insight 3G’s \textit{“AverageIntensityImageProcessor”} to generate an average of the intensity at each pixel over the whole data set and subtract that average from each image. This allows the subtraction of static objects such as walls and edges, light due to constant reflections and bleeding effects due to saturation (Figure 5.2). A stark contrast is seen between the bright, light-scattering tracer particles and the black background, which makes it easier for the crosscorrelation functions to calculate the displacement vectors. These “cleaned” images are stored in the \textit{Analysis} folder.

\section*{5.2.3 Image Processing}

A typical PIV image that is obtained has a resolution of 2048 by 2048 pixels. It needs to be processed to be able to obtain the displacement information about the particles that have been captured in the image. The most common way of obtaining this information is
to divide the image plane into a number of smaller squares and then cross-correlating the two frames obtained from the two shutter exposures. A detailed explanation, including mathematical treatment, of the steps in PIV processing can be found in the book by Raffel et al. [36].

5.2.3.1 Interrogation Regions

These smaller squares are known as “interrogation regions” or “spot size” and are typically of the size 32 by 32 pixels. However, the interrogation regions used in processing these PIV images have been customized depending on the location of the image being processed relative to the bend. For example, if the image is upstream of the bend, then displacement in the cross-stream direction would be very small compared to the stream-wise displacement. Hence we can use a rectangular interrogation region instead of a square to improve accuracy and processing speed. However, in the bend, a square interrogation region is used since a rectangular one would cause loss of information as both, streamwise and cross-stream flows are significant. The typical interrogation regions used in processing the current information have been listed in Table 5.1. The window overlap is 50% in all cases.

<table>
<thead>
<tr>
<th>Location</th>
<th>Initial Spot Size</th>
<th>Final Spot Size</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Spot A Width</td>
<td>Spot B Width</td>
</tr>
<tr>
<td>Upstream</td>
<td>120</td>
<td>128</td>
</tr>
<tr>
<td>Bend</td>
<td>120</td>
<td>128</td>
</tr>
<tr>
<td>Downstream</td>
<td>120</td>
<td>128</td>
</tr>
</tbody>
</table>

The interrogation region for Frame A (Spot A) is typically slightly smaller than that for Frame B (Spot B). This is to prevent loss of displacement data at the edges of the interrogation regions. For example, if the flow is moving from right to left, the particle at the left edge of Frame A will travel out of Frame B and Insight 3G will generate holes
at that location. Having Frame B larger than Frame A allows Insight 3G to generate
displacement vectors even for particles that are very near the edge of Frame A. For
multipass grid generation, we also specify a final interrogation region or Final spot size
which is smaller than the Initial spot size.

5.2.3.2 Correlation of Images

Insight 3G breaks the actual vector field generation into four steps. For each of these
steps, depending the users application, there are various options that can be chosen and
these options can be further customized using plug-ins. The relevant options that have
been used in this study are presented below while a complete list can be found in the
Insight 3G manual [38] provided by TSI Inc.

1. Grid Engine

The Grid Engine breaks up the image into the interrogation windows as specified
by the user and initializes the vector field. The RecursiveNyquistGrid is a multipass
grid engine that was used to generate the vector field. The initial vector field is
the result of a regular Nyquist type processing pass. This field is then edited using
a PassValidation macro and the results are used to optimize spot offsets for the
second processing pass. The second pass is half the spot size than the one used in
the initial pass. This is repeated until the final processing pass spot size matches
the user defined Final spot size. The RecursiveNyquistGrid was chosen since its
recursive process and validation after each pass using the PassValidation macro
provide higher accuracy than the typical single pass NyquistGrid. The vector field
is analyzed by the Final Validation macro after the final pass has been completed.

2. Spot Mask Engine

The Spot Mask Engine conditions the image spots before sending them to the
Correlation Engine. It is dependent on the type of correlation engine that is being
used. NoMask has been used in this study since the correlation engine chosen does
not require the spots to be conditioned. No changes have been made to the image spots and they are passed directly to the Correlation Engine.

3. Correlation Engine

This engine computes the correlation function of Spot A and B and returns the result as a correlation map. The highest correlation map pixel is assumed to be the particle image displacement while the other peaks may be considered as noise peaks cause by random pairings. The HartCorrelator \[39\] is used to generate the correlation map for all images in this study. It is a direct correlation method that processes only the most significant pixels to improve the processing speed. In fact, among all the available options, this engine is the fastest and is also quite accurate. The DirectCorrelator provides higher accuracy and a greater number of vectors but is very slow and unsuitable for the large amounts of data that need to be processed. Measurement accuracies for correlation maps generated by the engine may be improved by matching the Peak Engine.

4. Peak Engine

The Peak Engine finds the location of the peak in the correlation map generated for it by the Correlation Engine. It does this by finding the highest intensity pixel in the correlation map and then applying an interpolation algorithm to the peak pixel and its neighbours to locate the peak with sub-pixel accuracy. The Bilinear Peak Engine matches up with the HartCorrelator and hence, is used.

5.2.3.3 Vector Validation

Processing parameters such as spot sizes are chosen depending on whether the image location is upstream, in the bend or downstream. A “test group” of 5 to 10 cleaned image from the Analysis folder are opened up and processed using the parameters chosen for that particular location. After processing, the “Validation Set-up” tab allows us to see the average, range and standard deviation of the calculated “u” and “v” displacements.
If there is a large standard deviation, or a very large range which does not make physical sense, then the vectors generated for the flow field may contain spurious vectors. Additionally, a visual inspection of the vector map allows us to detect any obviously incorrect vector. An incorrect vector is typically a stand-alone vector that is considerably different in direction and magnitude than its neighbours. Depending on the statistical values as well as the visual inspection of the flowfield, a validation macro is recorded.

Typical validation macros for all locations in the current study have included a Standard Deviation based validation and a Neighborhood Mean Filter. The Standard Deviation removed any velocity vectors larger than a specified number of standard deviations away from the global mean vector values. A typical value of three standard deviations was used for each location. The Neighborhood Mean Filter checks the magnitude of each vector with the average magnitude of its neighboring vectors in a $5 \times 5$ neighborhood. If the absolute magnitude of the difference of the vector in question and the average over its neighbors is greater than a certain threshold value (two, for each location), the vector is rejected. Insight 3G allows the user to interpolate vectors to fill the holes generated by the vectors that have failed to be validated, but this option was not used. This recorded validation macro can then be used as PassValidation, FinalValidation or both to dynamically clean the flowfield of spurious vectors while they are being processed (PassValidation) as well as go back and clean it post-processing (FinalValidation).

Once the processing parameters are established, they are used to analyze all image pairs for that location. All the images for a particular location are loaded into a current window in Insight 3G from the Analysis folder and processed. The vector files generated are text files that have the extension *.vec and are stored back into the Analysis folder.

The total time taken for all the procedures and processes listed in this section is about 13 to 15 hours per location.
5.3 Data Interpretation and Extraction

The vector files obtained after 3G processing are known as the raw data files. These files contain the following variables as information:

\( X_{local} \) - This is the local \( x \) coordinate in pixels. Its domain is 0 to 2048.

\( Y_{local} \) - This is the local \( y \) coordinate in pixels. Its domain is 0 to 2048

\( U_{pixel} \) - This is the distance, in pixels, traveled by a particle in time “dT” parallel to the \( X \) axis

\( V_{pixel} \) - This is the distance, in pixels, traveled by a particle in time “dT” parallel to the \( Y \) axis

\( \text{CHC} \) - CHC or Choice Code is an identifier that stores processing information about the vector. Only the positive CHC codes are chosen (1 to 4) since CHC=0 or lower indicate that either no particles existed in that area and hence no vector could be calculated or an existing vector was removed during validation. Further details can be found in the Insight 3G User Manual.

These basic files are then processed with MATLAB to obtain mean velocity, turbulent fluctuations, RMS velocity, standard deviation, variance and turbulence intensity values.

5.3.1 Coordinate Transformations

As mentioned earlier, each location has its own local coordinate axis and local origin with respect to the global coordinate axis. The local values of \( X_{local} \) and \( Y_{local} \) are made to undergo an origin and unit transformation to obtain their coordinates in the global system in millimeters (mm). The \( U_{pixel} \) and \( V_{pixel} \) values are also transformed so that they can be expressed in units of m/s. The coordinate transformation equations are listed in Equation 5.1 while the velocity equations can be found in Equation 5.2.
\[ X_{\text{global}}(\text{mm}) = X_{\text{offset}} + \frac{X_{\text{local}} \cos \theta + Y_{\text{local}} \sin \theta}{\text{Magnification (pix/mm)}} \]  

\[ Y_{\text{global}}(\text{mm}) = Y_{\text{offset}} + \frac{-X_{\text{local}} \sin \theta + Y_{\text{local}} \cos \theta}{\text{Magnification (pix/mm)}} \]  

(5.1)

where

\[ X_{\text{offset}} = X \text{ component of spatial vector from } O_{\text{global}} \text{ to } O_{\text{local}} = (25.4 \times 3.5 \cos \alpha) + \frac{X_{\text{local}} \cos(\theta - 180) + Y_{\text{local}} \sin(\theta - 180)}{\text{Magnification (pix/mm)}} \]

\[ Y_{\text{offset}} = Y \text{ component of spatial vector from } O_{\text{global}} \text{ to } O_{\text{local}} = (25.4 \times 3.5 \sin \alpha) - \frac{X_{\text{local}} \sin(\theta - 180) - Y_{\text{local}} \cos(\theta - 180)}{\text{Magnification (pix/mm)}} \]

\[ \theta = \text{Anti-clockwise angle of rotation of } X_{\text{local}} \text{ axis for it to be parallel to } X_{\text{global}} \text{ axis} \]

\[ \alpha = \text{Angle made between the edge of the image frame perpendicular to the streamwise flow with the } X_{\text{global}} \text{ axis.} \]

\[ U_{\text{global}}(\text{m/s}) = U_{\text{local}} \cos \theta + V_{\text{local}} \sin \theta \]

\[ V_{\text{global}}(\text{m/s}) = -U_{\text{local}} \sin \theta + V_{\text{local}} \cos \theta \]  

(5.2)

where

\[ U_{\text{local}}(\text{m/s}) = \frac{1000 \times U_{\text{pixel}}}{dT(\mu s) \times \text{Magnification (pix/mm)}} \]

\[ V_{\text{local}}(\text{m/s}) = \frac{1000 \times V_{\text{pixel}}}{dT(\mu s) \times \text{Magnification (pix/mm)}} \]

\[ \theta = \text{Anti-clockwise angle of rotation of } X_{\text{local}} \text{ axis for it to be parallel to } X_{\text{global}} \text{ axis} \]

Following this transformation, all the points are also transformed to obtain their location in a curvilinear coordinate system containing \( s \) and \( n \) as its axes. The \( s \) coor-
(a) Detailed geometry used for coordinate transformations for a typical window.

(b) All coordinate systems are labeled here. Also, it shows how images are taken in the bend and highlights the need for coordinate transformations.

**Figure 5.3.** Coordinate transformation geometry.
The coordinate is along the streamwise flow of the fluid while the \( n \) coordinate is perpendicular to \( s \) that is, along the radial direction of the test section. The transformations for \( s \) and \( n \) are listed in Equation 5.3 while the velocity equations can be found in Equation 5.4.

\[
s \text{ (in mm)} = \begin{cases} 
X_{\text{global}} & \text{Upstream} \\
R_{\text{mid}} \ast \left( \frac{\Pi}{2} - \beta \right) & \text{Bend} \\
R_{\text{mid}} \ast \frac{\Pi}{2} - Y_{\text{global}} & \text{Downstream}
\end{cases}
\]

\[
n \text{ (in mm)} = \begin{cases} 
Y_{\text{global}} - R_{\text{mid}} & \text{Upstream} \\
R_{\text{inst}} - R_{\text{mid}} & \text{Bend} \\
Y_{\text{global}} - R_{\text{mid}} & \text{Downstream}
\end{cases}
\]  

(5.3)

where

\( R_{\text{mid}} \) (mm) = Radius of bend middle (axis of symmetry) from \( O_{\text{global}} \)

\( R_{\text{inst}} \) (mm) = Radius of a particular point from \( O_{\text{global}} \)

\[
= \sqrt{X_{\text{global}}^2 + Y_{\text{global}}^2}
\]

\( \beta \) = Angle made by vector from \( O_{\text{global}} \) to any point in the bend with \( X_{\text{global}} \) axis

\[
= \arctan \frac{Y_{\text{global}}}{X_{\text{global}}}
\]

\[
U_s \text{ (in m/s)} = U_{\text{global}} \sin \beta - V_{\text{global}} \cos \beta \\
V_n \text{ (in m/s)} = U_{\text{global}} \cos \beta + V_{\text{global}} \sin \beta
\]  

(5.4)

These coordinate transformations are carried out by code written in MATLAB. The actual file containing the code identifier.m is listed in Appendix B. Copies of the original raw vector data files are populated with the new coordinate and velocity values and these
processed files are used for all further analysis.

### 5.3.2 Average Velocity

Flow through the test section is highly turbulent. One of the defining characteristics of a turbulent flow quantity is that the instantaneous value can be represented as a sum of the average flow quantity and the turbulent fluctuations. In our case, the flow quantity under consideration is velocity. Instantaneous velocity at a point can be represented as the summation of the ensemble average of instantaneous flow velocity at that point and the turbulent fluctuations as shown in Equation 5.5

\[
\tilde{u}(t) = \frac{1}{N} \sum_{i=1}^{N} \tilde{u}_i(t) + u
\]  

(5.5)

where

\[ \tilde{u}(t) = \text{Instantaneous Velocity} \]

\[ N = \text{Number of files that contain the valid velocity data for a location} \]

\[ u = \text{Velocity fluctuation} \]

All the processed files containing the instantaneous velocity information at a particular location are averaged and a single file containing the average velocity information for that location is generated. This file contains the average velocity components for each point within that location in both, the cartesian and curvilinear coordinate system as well as the ‘average count’ for each point. For a particular location, each processed file may not have valid vectors at each point. The points are given a very large velocity value (\(\approx 9.9 \times 10^9\)) and are considered to be invalid data points. The invalid data points are skipped during the averaging process and the number of files that contained valid data used in averaging is stored in ‘average count’ (\(N\) in Equation 5.5).
5.3.3 Statistics

The Root Mean Square or RMS velocity has been calculated using the formula listed in Equation 5.6. It is defined as the square root of the mean of the squares of the instantaneous velocity components.

\[
\begin{align*}
    u_{RMS} &= \sqrt{\bar{u}^2} \\
    v_{RMS} &= \sqrt{\bar{v}^2}
\end{align*}
\]

(5.6)

(5.7)

Options to calculate the standard deviation and variance of the fluctuations is also provided based on Equations 5.8 and 5.9 respectively.

\[
\begin{align*}
    u_{sd} &= \sqrt{\bar{u^2}} \\
    v_{sd} &= \sqrt{\bar{v^2}}
\end{align*}
\]

\[
\begin{align*}
    u_{var} &= \bar{u^2} \\
    v_{var} &= \bar{v^2}
\end{align*}
\]

(5.8)

(5.9)

Turbulent intensity characterizes the intensity or “violence” of the turbulent fluctuations. It characterizes the turbulence in the flow and is calculated using Equation 5.10

\[
    I = \sqrt{\frac{\frac{1}{2} (u^2 + v^2)}{U_s^2 + V_n^2}}
\]

(5.10)

Reynolds shear stresses are also calculated using the formula \( \overline{uv} \). These stresses are discussed in detail in Section 6.5.

All the formulae discussed in Sections 5.3.2 and 5.3.3 are adapted from discussions in the book by Tennekes and Lumley [40] as well as Kundu and Cohen [41]. The MATLAB codes written to calculate each of these parameters can be found in Appendix B.
6.1 Inlet Conditions

Knowledge of the inlet conditions is very important for predicting the flow of fluid through a curved pipe. As seen in Table 2.1, most of the work done on a square 90° pipe bend had developing flow at the inlet due to its likelihood of occurrence in most real-life piping situations. However, the streamwise independence of flow velocity, as seen in a fully-developed flow, helps isolate and study the effects of the curvature and resultant secondary flows on the mean flow. Thus, the present study of fully-developed flow is more broadly useful for the fundamental understanding of bend effects and for benchmarking computational codes.

In the current experimental set-up, a section designed to enable the fully-developed condition precedes entry to the test inlet. Details on this section can be found in Appendix C. Data from measurement location UP1 (refer to Figure 4.1) are used to assess the inlet conditions. Figure 6.1 shows the inlet flow velocity profiles for a flowrate of 100 gpm (Re = 2.76×10^5). Velocity profiles are extracted for each of the three horizontal (constant z) planes: top (\( \frac{s}{D_h} = 0.375 \)), middle (\( \frac{s}{D_h} = 0 \)) and bottom (\( \frac{s}{D_h} = -0.375 \)) at the following streamwise positions: (i) The entry to the measurement station UP1 (\( \frac{s}{D_h} = -2.1 \)); (ii) streamwise midpoint of UP1 (\( \frac{s}{D_h} = -1.3 \)) and (iii) just before the flow
enters the bend ($\frac{s}{D_h} = -0.55$). These inlet profiles are compared with a fully-developed turbulent flow profile described by the following empirical power law equation:

\[
\frac{U}{U_{av}} = \frac{(n + 1)(2n + 1)}{2n^2} \left( \frac{y}{R} \right)^{\frac{1}{n}}
\]

where

\[
n = -1.7 + 1.8 \log(ReU_{max})
\]

\[y = \text{Height from the wall}
\]

\[R = \frac{D_h}{2}
\]

Note the discontinuity in slope $\frac{d(U/U_{av})}{d(n/D_h)}$ at the centerline $\frac{n}{D_h} = 0$ for the predicted fully-developed flow velocity profile. The empirical power law is defined only for one half of the pipe as fully-developed flow is assumed to be symmetrical. To be able to compare the experimental PIV data that has been obtained over the complete $D_h$ with the predicted fully developed profile, the half-pipe profile given by Equation 6.1 is mirrored across the centerline. Since the the empirical power law does not have a zero slope at the centerline, we see a distinct point of discontinuity at the center line where the slope changes abruptly.

A more commonly used alternative to this law for predicting the fully-developed profile is Spalding’s equation since it gives a logarithmic profile with a slope that tends to zero at the center. However, it too gave a point of inflection at the center of the pipe. Additionally, the calculations that would have to be performed on the experimental data are more complex and involve assumptions about quantities that are not known in the present set-up, such as the shear stress at the wall, $\tau_w$. Hence, the empirical power law is favored for comparison to the present data. Spalding’s equation and further explanation and comparison with the empirical power law may be obtained in the book on fundamental Fluid Mechanics by Schetz and Fuhs [42].
6.1.1 Middle Plane

The three velocity profiles shown in Figure 6.1 in the middle plane $\frac{s}{D_h}=0$ are within $\pm 3\%$ of the empirical power law prediction. Furthermore, the profiles collapse to within $\pm 0.8\%$ as we move along the streamwise co-ordinates ($\frac{\partial U}{\partial s}=0$). Thus the fully developed condition is validated. A slight bulge towards the inner wall is noticed in the velocity profile nearest to the bend entry ($\frac{s}{D_h}=-0.57$). This is due to the acceleration of the fluid in the presence of an adverse pressure gradient near the inner wall. The effect, (referred to as "bend effect" here onwards) of the centrifugal force driven radial pressure gradient that is present at the bend entry has traveled upstream and causes the flow to bulge out near the inner wall. The first valid point closest to the wall is at a distance of $0.04D_h$ from it and has a velocity that is 85% of the theoretical bulk velocity. $\frac{U}{U_b}$ at the center of the duct is seen to be 1.15 and is in line with the calculations from the empirical power law curve. Flow data very near to the wall are not obtained reliably due to the higher noise caused by light reflected off the imperfections on the walls of the test section as well as the inability of the PIV processor to detect particle images in the region due to the significantly lower particle velocities. Hence, these near-wall data are not included in the diagram.

6.1.2 Top Plane

The velocity profiles in the top plane show distinct bulges near each wall for each of the three streamwise profiles. $\frac{U}{U_b}$ in the center is 1.05, while it is 1.07 at the peak of each bulge. The distinct shape of the velocity profile indicates that the distortion is caused due to secondary flow of the second kind, discussed previously in Section 2.2.

An additional bulge is noticed near the inner wall in the velocity profile nearest to the bend entry ($\frac{s}{D_h} = -0.57$). This can be reasoned to be due to the bend effects as explained earlier. The most reliable point of measurement is at a distance of $n = 0.04D_h$ from the wall and has a velocity value of 91% of the average velocity. All three profiles collapse on top of each other and show no indication of varying with increase in $s$. Hence
Figure 6.1. Comparison of inlet profiles of each plane with theoretical fully-developed profile flow in the top plane can also be considered fully-developed.

6.1.3 Bottom Plane

The velocity profiles in the bottom plane are qualitatively similar to those found in the top plane. Bulges at each end near the walls due to the secondary flow of the second kind are prominent. However, there is a decrease in velocity with increase in $s$. Along the centerline of the duct, we see that the velocity profile farthest away from the bend entry has $\frac{U}{U_b} = 0.94$ which decreases to 0.91 for the profile nearest to the bend entry. Neither the normal stress driven secondary flow nor the pressure driven bend effect is strong enough to cause flow to slow down. Thus, it may be due to a slight deformation
or manufacturing defect along the test section floor.

### 6.1.4 Constant Plane, Different Reynolds Numbers

The normalized inlet velocity profiles shown in Figure 6.2 are upstream of the bend and in the middle plane for each of the three different flowrates: 66 gpm (Re = $1.76 \times 10^5$), 100 gpm (Re = $2.76 \times 10^5$), and 133 gpm (Re = $3.2 \times 10^5$). As can be clearly seen from the velocity profiles in the figure the flow is considered to be fully-developed for each flowrate. This allows us to assume that the boundary layer at the inlet of the flow has no effect on the flow structure. Any change in the flow structure can be attributed to be due to the bend. As expected in the middle plane, a bulge near the inner wall for the velocity profile closest to the bend entry is observed. For example, at $\frac{n}{D_h} = -0.475$ for Re = $1.76 \times 10^5$, velocity near the bend entry ($\frac{s}{D_h} = -0.91$) is 6% higher than the velocity at the entry to the upstream section ($\frac{s}{D_h} = -1.70$). This bulge is caused due to the bend effect that propagates upstream of the bend. The effect of the secondary flows of the second kind, which causes a slight bulging of the velocity profiles at the corners, is absent and this absence is in line with our expectations from the previous observation.

### 6.1.5 Discussion of Inlet Conditions

Gessner et al. [9] carried out an extensive study on entrance region of a square duct. The flow conditions were very similar to one of the cases (100 gpm / Re = $2.76 \times 10^5$) in the current experiment. Fluid flowed through a square duct of $D_h = 1”$ with an Re = $2.5 \times 10^5$. Thus, we can compare the flow in the entrance region to the results in Gessner et al. [9]. He noted that the boundary layers from opposite walls had interacted with each other just beyond $\frac{x}{D_h} \simeq 32$. Velocity measurements in the center of the duct at length $\frac{x}{D_h} \simeq 60$ yielded $\frac{U}{U_b} = 0.96$ for $z=0.1”$ from the bottom wall, and $\frac{U}{U_b} = 1.15$ for $z = 0.5”$ from the bottom wall. In comparison, we have $\frac{U}{U_b} = 0.91$ and 1.17 for a $z=0.125”$ and 0.5” from the bottom wall, respectively. The measurements are also at the center of the duct, at $\frac{s}{D_h} = -0.57$. By this point, the fluid has traveled for $\simeq 59D_h$ in a
Figure 6.2. Comparison of inlet profiles for each flowrate with theoretical fully-developed profile
square duct of uniform cross-section including both the fully developed section and the
test section upstream. A reasonably close match is seen between the inlet flow observed
in Gessner et al. [9] and the current work.

Qualitative matches between the velocity profiles seen here can also be obtained in
the study of turbulent flow through a square duct by Humphrey et al. [10]. The bulging
effects due to the secondary flows and the adverse pressure gradients are clearly evident.
Since a lower Reynolds number flow was studied in Humphrey et al. [10], the presence
of the bulges in both the studies show them to be characteristic of the set-up.

Since a complete field measurement of the upstream section from \( \frac{s}{D_h} \simeq -2.10 \) to
\( \frac{s}{D_h} \simeq -0.55 \), for three different streamwise planes for \( \text{Re} = 2.76 \times 10^5 \) is obtained in the current work, it shows exactly how the bend effects affect the incoming flow in each plane, providing a more complete picture of the flow entering the bend. Also, the data are obtained in the middle plane at different Reynolds numbers allowing the verifications of the previous bend effect observations.

6.2 Mean Velocities

The mean velocity, \( U_{av} \), near the bend entrance is biased towards the inner wall. The bulge or slight increase in velocity, as explained in Section 6.1, tells us that there is some bend effect that is propagating upstream of the bend entrance and affecting the flow. This effect, mentioned briefly earlier, is examined in detail here.

The basic effect of introducing a curvature in a pipe is an outward pointed centrifugal force in the radial direction, as illustrated in Figure 6.3. The centrifugal force tends to increase the pressure on the outer wall of the bend and decrease it on the inside of the bend, causing an adverse pressure gradient at the outer wall in the radial direction. The adverse radial pressure gradient causes some fluid near the outer wall to flow radially from the outer wall to the inner wall in all the horizontal \( z \)-planes, which, in turn, causes the mean flow to shift towards the inner part of the bend. This negative radial velocity (flowing from the outer to inner wall) is opposed by the vortices set-up by the secondary flow of the second kind near the outer wall while near the inner wall it is supported by the secondary flow of the second kind generated vortices. To compensate for this complex interaction in the radial direction while conserving mass, the streamwise flow slows near the outer wall and accelerates near the inner wall. As a result, the velocity profile near the outside wall is flattened while an additional bulge in the profile is seen near the inner wall.

Figure 6.4 is a scaled representation of the normalized streamwise flow velocities in the actual test section. A clear picture of the influence of a bend in a pipe on the fluid
Figure 6.3. Direction of centrifugal and pressure forces acting on the fluid at bend entry and the interactions between the resultant motion of the fluid and the secondary flow of the second kind set-up due to the straight square duct flowing through the bend is shown. However, since most computations and simulations in literature are carried out using a curvilinear coordinate system, Figure 6.5 maps out the normalized streamwise flow velocities in the s-n coordinates to allow for easy comparison. This also provides a convenient basis of explanation of the different effects of the bend on the flow.

Similarly, Figure 6.6 shows the influence of the bend on the radial velocity in the cartesian coordinate system to aid intuitive understanding while Figure 6.7 is in the curvilinear coordinate system and is referred to in the subsequent sections to point out various flow characteristics.
Figure 6.4. Normalized streamwise velocity \( U_s \) distribution in the cartesian coordinate system \( X, Y \) for the horizontal planes: Top \( (\bar{z}_D = 0.375) \), Middle \( (\bar{z}_D = 0) \) and Bottom \( (\bar{z}_D = -0.375) \) \([Re = 2.76 \times 10^5]\).
Figure 6.5. Normalized streamwise velocity $U_s$ distribution in the curvilinear coordinate system $s-n$ for the horizontal planes: Top($z_{Dh}=0.375$), Middle($z_{Dh}=0$) and Bottom($z_{Dh}=-0.375$) [$Re = 2.76 \times 10^5$]
Figure 6.6. Normalized radial velocity $V_n$ distribution in the cartesian coordinate system $X-Y$ for the horizontal planes: Top $(z_D = 0.375)$, Middle $(z_D = 0)$ and Bottom $(z_D = -0.375)$ [$Re = 2.76 \times 10^5$]
Figure 6.7. Normalized radial velocity $V_n$ distribution in the curvilinear coordinate system $s-n$ for the horizontal planes: Top($\frac{z}{D_h}$ = 0.375), Middle($\frac{z}{D_h}$ = 0) and Bottom($\frac{z}{D_h}$ = -0.375) [$Re = 2.76 \times 10^5$]
6.2.1 Middle Plane

The streamwise velocity ($U_s$), shown in the middle plane in Figure 6.5, initially decelerates near the outer wall. A slim layer near the outer wall between $\Theta \simeq 0^\circ$ to $30^\circ$ ($\frac{s}{D_h} \simeq 0$ to 2.06) slows down to $0.71U_b$. For the region bound by $\frac{s}{D_h} \simeq 0$ to $\frac{s}{D_h} \simeq 2.06$, $U_s$ is less than $U_b$ till $0.355D_h$ ($\frac{n}{D_h} \simeq 0.245$) from the outer wall but higher than $U_b$, with a distinctly visible fluid core, from $\frac{n}{D_h} \simeq 0.245$ to $\frac{n}{D_h} \simeq -0.5$. As secondary flow of the first kind starts developing from $\Theta \simeq 45^\circ$ ($\frac{s}{D_h} \simeq 3.12$), the streamwise flow starts to move outwards. By the time the bend exit is reached, the flow has almost shifted beyond the central axis towards the outer wall. Downstream of the bend, the flow has crossed the axis of the duct and is strongly biased towards the outer wall. Until our last measurement is taken at $\frac{s}{D_h} \simeq 13.15$, we see that effects of the bend are still very evident and the flow is still strongly biased towards the outside of the duct.

Referring to Figure 6.7, in the middle plane at the bend entry, we have a spanwise (along $n$) negative radial velocity ($V_n$) only from $\frac{s}{D_h} = 0$ to 0.44. After $\frac{s}{D_h} \simeq 0.44$, the negative $V_n$ is pushed against the inner wall by the rapidly developing secondary flow of the first kind (explained previously in 2.2). From $\frac{s}{D_h} = 1$, this band of negative $V_n$ is constant at $\frac{n}{D_h} = -0.4$ until it further thins out to approximately $\frac{n}{D_h} = -0.48$ at bend angle $\Theta \simeq 35^\circ$ ($\frac{s}{D_h} \simeq 2.45$). At $\Theta \simeq 72^\circ$ ($\frac{s}{D_h} \simeq 5.03$), negative $V_n$, starts rising again and thickens out to $\frac{n}{D_h} = -0.45$ at the bend exit. This may be the additional pair of Dean vortices reported by Liou and Liu [16] as the third Dean vortex pair, illustrated schematically earlier in Figure 2.2(b). This pair has a clockwise sense of rotation (when viewed from downstream of the bend), opposite to that of the primary pair of Dean vortices. For the additional pair of vortices, $V_n$ is approximately $\frac{1}{10}$th of the radial velocity of the primary Dean vortices. This additional pair is further discussed in Section 6.4 under Turbulent Intensities. Not much can be made out of the additional vortex pair downstream of the bend due to the lack of valid data very near to the wall ($\frac{n}{D_h} < -0.46$). However, where data exist, it seems that the layer has again thinned out to $\frac{n}{D_h} = -0.48$. 
6.2.2 Top Plane

In the top plane in Figure 6.5, we see that at the bend entry the streamwise flow decelerates to approximately $0.9U_b$. This is to compensate for the negative radial flow directed towards the inner wall, as discussed earlier in this section. Further, due to the motion of the radial flow, the streamwise flow is pushed towards the inner wall for the entire length of the bend. The mean streamwise flow is higher towards the inner wall even in the $\Theta = 75^\circ$ to $90^\circ$ ($\frac{s}{D_h} \simeq 5.24$ to $6.28$) location. However, as soon as the flow exits the bend, the mean streamwise flow is pushed up against the outer wall.

Refer to Figure 6.7. In the top plane, the radial velocity ($V_n$) is almost always directed from the outer wall to the inner. In the upstream inlet section, fluid moves from the duct center to the outer wall (positive radial velocities) and from the duct center to the inner wall (negative radial velocities), which is indicative of the presence of cross-stream, normal-stress-driven secondary flows of the second kind. The introduction of the pressure driven radial flows near the bend entry, though, completely overwhelms the normal-stress-driven secondary flow and introduces a uniform pressure-driven negative radial secondary flow. From $\Theta = 0^\circ$, to the bend exit, most of the $s-n$ area is occupied by the radial negative flow. The radial flow from the outer to inner wall suddenly increases in magnitude at $\Theta \simeq 45^\circ$ ($\frac{s}{D_h} \simeq 3.12$) due to the presence of secondary flows of the first kind. Radial velocity($V_n$) is strongest from $\Theta = 75^\circ$ to $90^\circ$ ($\frac{s}{D_h} \simeq 5.24$ to $6.28$) and has a maximum of $0.245U_b$ near $\Theta \simeq 76^\circ$ and $\frac{n}{D_h}=-0.2604$.

From $\Theta \simeq 4^\circ$ ($\frac{s}{D_h} \simeq 0.28$) to $\Theta \simeq 30^\circ$ ($\frac{s}{D_h} \simeq 2.09$), there is a small band of radial velocity directed towards the outer wall, at $\frac{n}{D_h} \simeq 0.23$. However, beyond $\Theta \simeq 30^\circ$, this band is swept away into the stronger secondary flow of the first kind. A thinner band reappears between $\Theta = 60^\circ$ to $75^\circ$ ($\frac{s}{D_h} \simeq 4.20$ to $5.24$), disappears near the bend exit and reappears downstream. In the downstream section, positive radial velocity is present along the outer wall until approximately $0.12D_h$ away from it and may be due to the weakening of the secondary flow of the first kind and the recurrence of the secondary flow of the second kind.
6.2.3 Bottom Plane

Refer to the bottom plane in Figures 6.5 and 6.7. The flow structure of the streamwise and radial direction in the bottom plane is very similar to the top plane. We see a deceleration in $U_s$ similar to that in the top plane near the outer wall in the first 30° ($\frac{\Delta P}{D_h} \approx 2.06$) of the bend. Since the radial velocities are directed from the outer wall towards the inner wall within the bend, the faster moving fluid in the streamwise direction is pushed to the inner wall. As soon as this high velocity fluid exits the bend, it snaps towards the outer wall. The velocity magnitudes, $U_s$ and $V_n$ are lower in this plane than in the top plane, but this can be attributed to the slower $U_{av}$ of the fluid entering the bottom plane.

6.2.4 Discussion of Mean Velocities

The observations detailed above in each of the planes show that even though the secondary velocities are only about 20% of $U_b$, they have a substantial effect on the mean flow through a curved pipe. Figure 6.8 is a composite image that shows the effect of the radial velocities $V_n$ on the streamwise velocities $U_s$. The background flooding is based on the magnitude of $V_n$ while the lines are a representation of the magnitude of $U_s$. Figure 6.9 uses the curvilinear coordinate system to present the effect of $V_n$ on $U_s$. Figures 6.10 and 6.11 detail the velocity magnitude of the fluid as it flows through the bend in the global and curvilinear coordinate systems respectively.

Starting at the bend entrance, the fluid tends to move from the outer wall to the inner wall due to the radial pressure gradient that is directed from the outside of the bend to the inside. This tendency is countered by the centrifugal force that is directed outwards. The pressure gradient is dominant from $\Theta = 0^\circ$ to $45^\circ$, causing the streamwise acceleration of the fluid near the inner wall. However, from $45^\circ$, the radial pressure gradient starts decreasing, due to a rise in pressure at the inner wall. The acceleration of the fluid streamwise velocities on the inner side switches suddenly to a deceleration while a higher acceleration is seen on the outer wall.
Mass is conserved by the pair of counter-rotating vortices that have been developing in the cross-stream. These vortices, known as Dean’s vortices, are solely responsible for the secondary flows in the bend. They carry the slow moving fluid away from the inner wall along the axial plane of symmetry to the outer wall. The slow moving fluid moves away from the middle plane, along the outer wall, towards the top and bottom of the pipe, gaining velocity. These Dean’s vortices carry the faster fluid from the outer wall of the bend to the inner wall along the top and bottom sidewalls and back towards the plane of symmetry along the inner wall. Hence, if a viewer was to look at a cross-sectional slice of the bend from the bend exit, he/she would see a counter-clockwise rotation of fluid in the top half of the slice and a clockwise rotation in the bottom.

At the bend exit, the pressure gradient due to lateral curvature vanishes and the flow suddenly has to adjust for uniform pressure. In the absence of the adverse pressure gradient, the inertia due to the centrifugal force causes the mean flow in the top and bottom planes to move towards the outer wall. The fluid in the middle plane, which has started moving towards the outer wall in the bend itself, continues towards the downstream outer wall after the bend exit. Eventually, the flow in all planes tends to even out and slowly move back towards the center of the duct. The secondary vortices start decreasing while the cross-stream normal stresses re-appear in the straight duct. The direction of radial velocity due to the secondary flow of the second kind near the outer wall opposes the radial velocity due to the secondary flow of the first kind, decelerating the flow there while it strengthens the radial velocity near the inner wall accelerating fluid close to it. If a long enough downstream section is provided, then the flow regains its fully developed structure. However, due to the short length of the downstream test section in the current experimental set-up there was ample evidence that the bend effects were not overcome.

Humphrey et al. [10] describes similar qualitative results of flow structure through out. However, data are rather limited since the radial velocities were measured only at $\Theta = 0^\circ$ and $\Theta = 90^\circ$. Liou and Liu [16] however provide an excellent basis for
comparison. They have recorded similar observations. The mean radial velocities in the top and bottom planes are pushed to the inner wall near the bend exit while the middle plane radial velocity has shifted to the outer edge. The largest value of radial velocity was $0.35U_b$ at $\Theta = 75^\circ$. They took additional pressure measurements for the cross-stream circumferential pressure gradient. Starting from the axial plane of symmetry near the inner wall, they took the pressure data along the inner wall through the top wall and back to the axial symmetry plane along the outer wall. These measurements were taken at three locations upstream of the bend, at every $15^\circ$ in the bend and four locations downstream of the bend. They clearly show that the adverse pressure gradient develops near the outer wall near the bend entry but it switches sides and exists near the inner wall through the bend. The highest pressure drop is from the outer wall to the inner along the top sidewall in the regions of $\Theta = 60^\circ$ to $90^\circ$. They also noticed doubly peaked mean velocity profiles along the inner wall. The peaks are near the top and bottom sidewall which match what we notice in Figure 6.5.

The current work significantly adds to the available data on flow through a pipe containing a $90^\circ$ bend since field velocity data in the streamwise and radial directions are available at all points throughout the bend as well as $\approx 7D_h$ downstream of the bend in three different planes: $\frac{z}{D_h} = 0.375, 0, \text{ and } -0.375$. 
Figure 6.8. Velocity magnitude (normalized) streamlines superimposed on distribution of radial velocity (normalized) in the cartesian coordinate system $X$-$Y$ for the horizontal planes: Top($\frac{z}{D_h}=0.375$), Middle($\frac{z}{D_h}=0$) and Bottom($\frac{z}{D_h}=-0.375$) [Re = $2.76 \times 10^5$]
Figure 6.9. Velocity magnitude (normalized) streamlines superimposed on distribution of radial velocity (normalized) in the curvilinear coordinate system $s-n$ for the horizontal planes: Top($\frac{z}{D_h}=0.375$), Middle($\frac{z}{D_h}=0$) and Bottom($\frac{z}{D_h}=-0.375$) [Re = $2.76 \times 10^5$]
Figure 6.10. Normalized in-plane velocity magnitude in the cartesian coordinate system $X-Y$ for the following horizontal planes: Top($\frac{z}{D_h} = 0.375$), Middle($\frac{z}{D_h} = 0$) and Bottom($\frac{z}{D_h} = -0.375$). $[Re = 2.76 \times 10^5]$
Figure 6.11. Normalized in-plane Velocity Magnitude in the streamwise coordinate system $s-n$ for the following horizontal planes: Top($\frac{s}{D_h} = 0.375$), Middle($\frac{s}{D_h} = 0$) and Bottom($\frac{s}{D_h} = -0.375$) [Re = $2.76 \times 10^5$]
6.2.5 Constant Plane, Different Reynolds Numbers

Figures 6.12 and 6.13 show the normalized streamwise velocity component $\frac{U}{U_b}$ and the normalized radial velocity component $\frac{V}{U_b}$ for three different flowrates and hence different Reynolds number flows in the middle plane ($\frac{s}{D_h} = 0$). In Figure 6.12, we see that the qualitative structure of the streamwise flow velocity remains the same for each case. Each time the flow enters the bend, the fluid core is pushed towards the inner wall due to the negative radial velocities that are moving from the outer wall to the inner wall. This is reversed towards the bend exit where the flow is pushed towards the outer wall by the secondary flow moving from the inner to the outer wall. At the bend exit, the plot for the highest Reynolds number $Re = 3.2 \times 10^5$ (flowrate = 133 gpm) shows a distinct point ($\frac{s}{D_h} \simeq 6.25$) at which the streamwise flow suddenly makes a steep turn towards the outer wall. This is the bend exit and thus the point where the bend induced pressure gradient is removed and the inertia due to the centrifugal force is the only force acting on the flow. This effect is present in both the slower flows, but the transition is more gradual in the flow with $Re = 2.76 \times 10^5$ (100 gpm) while it is almost indistinguishable in the flow with $Re = 1.76 \times 10^5$ (66 gpm). We also see that for a lower Reynolds number flow, there is a thicker fluid core where the velocity is nearly equal to the value it had when it entered the test section. For $Re = 1.76 \times 10^5$, the core was approximately $0.355D_h$, flow with $Re = 2.76 \times 10^5$ had a core $\simeq 0.24D_h$ and the highest $Re = 3.2 \times 10^5$ had the thinnest core $\simeq 0.21D_h$.

Figure 6.13 shows that the basic structure of the radial velocity is also independent of the Reynolds number. A higher Reynolds number appears to cause simply a difference in the velocity magnitude. An important observation can be made from the figure. As mentioned earlier in Section 6.2.1, a smaller pair of Dean vortices are observed in the middle plane near the inner wall for a flow with $Re = 2.76 \times 10^5$ (100 gpm). Figure 6.13 shows that these vortices are also present in $Re = 1.76 \times 10^5$ (66 gpm) and $Re = 3.2 \times 10^5$ (133 gpm) flows at $5.12 \leq \frac{s}{D_h} \leq 6.51$, alongside the inner wall. This establishes the additional vortex pair as a characteristic of the flow. The band of negative radial velocity
seen at the bend entry is slowly pushed to the inner wall by the secondary flow that develops around $\frac{s}{Dh} \simeq 0.64$. The secondary flow increases in strength while the band of negative radial velocities gets thinner as the flow goes around the bend. This may be the smaller vortex pair that is seen by Liou and Liu [16] or it may be a remanent of the negative radial velocity that is seen at the bend entry.

Figure 6.14 profiles the normalized radial velocities at various constant $\frac{s}{Dh}$ for each of the three flowrates. At $\frac{s}{Dh} = 0.2756$ which is right at the bend entrance, the radial velocity is moving from the outer wall to the inner wall for the whole section. At the bend exit $\frac{s}{Dh} = 6.1811$ most of the bend has a positive radial velocity while a thin band ($\frac{n}{Dh} = -0.47$ to -0.50) near the inner wall is negative. This is, again, suggestive of the existence of a smaller vortex pair near the central plane. Discussions of Section 6.2.1 can be verified using the 100 gpm profile plotted in this figure.

Figure 6.15 shows the velocity magnitude of the flow as it goes around the bend while Figure 6.16 presents a composite image of streamwise and radial velocities. It shows us how the streamwise velocities are modified due to the action of the radial velocities.

A quick note on the trapezoidal shape of the bend locations in figures such as Figure 6.12. Referring to the station between $\Theta = 75^\circ$ to $\Theta = 90^\circ$ in Figure 4.1, we see that using a square window to capture the slice extends in a triangle beyond $\Theta = 90^\circ$. This protrusion causes the trapezoidal shape of the window when the coordinates are transformed from cartesian to curvilinear. For $Re = 2.76 \times 10^5$ (100 gpm) the window is cut to a rectangular size since contiguous data is available but due to the limited amount of information on the flow rates other than 100 gpm, it was decided to leave the imaging window in a trapezoidal form.
Figure 6.12. Normalized streamwise velocity $U_s$ distribution in the curvilinear coordinate system $s-n$ for the flow rates: 66 gpm ($Re = 1.76 \times 10^5$), 100 gpm ($Re = 2.76 \times 10^5$), and 133 gpm ($Re = 3.2 \times 10^5$) [Middle Plane ($\frac{z}{D_h}=0$)]
Figure 6.13. Normalized radial velocity $V_n$ distribution in the curvilinear coordinate system $s$-$n$ for the flow rates: 66 gpm (Re = $1.76 \times 10^5$), 100 gpm (Re = $2.76 \times 10^5$), and 133 gpm (Re = $3.2 \times 10^5$) [Middle Plane ($\frac{s}{D_h} = 0$)]
Figure 6.14. Normalized radial velocity $V_n$ distribution at various values of $\frac{s}{D_h} = \text{constant}$ for the flow rates: 66 gpm ($\text{Re} = 1.76 \times 10^5$), 100 gpm ($\text{Re} = 2.76 \times 10^5$), and 133 gpm ($\text{Re} = 3.2 \times 10^5$) [Middle Plane ($\frac{z}{D_h} = 0$)]
Figure 6.15. Normalized in-plane velocity magnitude in the curvilinear coordinate system $s-n$ for the flow rates: 66 gpm ($Re = 1.76 \times 10^5$), 100 gpm ($Re = 2.76 \times 10^5$), and 133 gpm ($Re = 3.2 \times 10^5$) [Middle Plane ($\frac{z}{D_h} = 0$)]
Figure 6.16. Velocity magnitude (normalized) streamlines superimposed on distribution of radial velocity (normalized) in the curvilinear coordinate system $s-n$ for the flow rates: 66 gpm ($Re = 1.76 \times 10^5$), 100 gpm ($Re = 2.76 \times 10^5$), and 133 gpm ($Re = 3.2 \times 10^5$) [Middle Plane ($\frac{D}{D_0} = 0$)]
6.3 Flow Development Through Test Section

6.3.1 Deviation of Flow Profiles from Fully-developed Profile

Figure 6.17 describes the deviation of the velocity profile at a particular $s$ from the fully-developed profile. Equation 6.2 is used to calculate the deviation of the profile at each $s$ location. The velocity vector profiles shown in Figure 6.18 show clearly that the flow deviates significantly over the initial blunt fully-developed flow profile it had when it entered the flow. The deviation $Dev_{FD}$ is calculated using Equation 6.2.

$$Dev_{FD} = \sqrt{\frac{1}{N_s} \sum_{i=1}^{N_s} \left[ \left( \frac{U}{U_b} \right)_{\text{exp}} - \left( \frac{U}{U_{av}} \right)_{\text{theo}} \right]^2}$$

(6.2)

where

$$N_s = \text{Number of points along a constant } s$$

Figure 6.17 shows that the middle plane has the least deviation from the fully-developed profile at entrance to the test section which steadily increases until the bend entrance. It deviates further within the initial part of the bend, but then attempts to get back to a fully-developed shape, reaching a minimum deviation just after $\Theta = 45^\circ \left( \frac{s}{D_h} \simeq 3.12 \right)$. At $\Theta = 49^\circ$ corresponding to point $\frac{s}{D_h} \simeq 3.425$, the influence of the secondary flow kicks in and the velocity profiles show a high rate of change from the fully-developed profile, reaching a maximum of 0.25 downstream of the bend at $\frac{s}{D_h} \simeq 8.15$. After that, the effect of the secondary flows weakens and the deviation starts dropping.

The top plane deviation is qualitatively similar to that of the middle plane until $\Theta = 49^\circ$. After that point, it continues to decrease until $\Theta \simeq 71^\circ \left( \frac{s}{D_h} \simeq 5 \right)$. It increases again, continuing beyond the bend exit till $\frac{s}{D_h} \simeq 8.89$ in the downstream section and then again drops towards till the end of the test section. However, this is not a uniform drop. It consists of plateaus and sudden slopes, indicating that while the secondary flows of the first kind are reducing, the secondary flows of the second kind are reappearing.
Figure 6.17. Streamwise deviation of local velocity profiles from theoretical fully-developed profile

The bottom plane has a high deviation from the mean fully-developed profile to start with. Bend effects, seen in Figure 6.1 cause the ‘$Dev_{FD}$ versus $s/D_h$’ plot to be very jerky with multiple points of inflection. It has a trend similar to the top plane except for a sudden rise in deviation at $\Theta = 49^\circ$. The profile shows an increase in deviation towards the end of the test section which may again be attributed to the development of cross-stream normal stresses as well as possible downstream effects.
6.3.2 Vector Profiles of Mean Flow

Figure 6.18 shows the development of velocity profiles as flow moves through a bend with a square cross-section. Vectors representing the mean velocity magnitude have been plotted from $\frac{s}{D_h} = -2.1$ to $\frac{s}{D_h} = 12.48$. These vectors are uniformly distributed for the most part. At some locations, however, profiles have been plotted closer together so as to show the change in flow structure. Also, for the sake of clarity, every fourth vector has been plotted. The background flooding represents the mean radial velocity profile as it moves through the bend.

The inlet flow has been thoroughly discussed previously in Section 6.1. Carrying on from that discussion, we see that the bulging of contours near the inner and outer walls, as seen in inlet flow for the top and bottom planes, is still evident in the location defined by $\Theta = 0^\circ$ to $15^\circ$ ($\frac{s}{D_h} \simeq 0$ to 1.05). However, the bulge near the outer wall has substantially reduced while the near the inner wall the bulge shows a definite increase. This is due to the negative values of radial velocity (seen in Figure 6.6) over almost the entire cross-section which opposes the radial velocities due to the secondary flow of the second kind near the outer wall, but supports the radial velocities near the inner wall. The bulge near the inner wall is seen until $\Theta = 45^\circ$ ($\frac{s}{D_h} \simeq 3.12$). The effect of the cross-stream normal stress near the outer wall vanishes very near to the bend entrance and the flow decelerates until $\Theta = 45^\circ$. In the middle plane, you see a deviation from the blunt fully-developed profile that enters the bend in the form of an acceleration near the inner wall and a deceleration at the outer wall. The core of the fluid is seen to shift to the inner side.

From $\Theta = 45^\circ$ to $60^\circ$, ($\frac{s}{D_h} \simeq 3.12$ to 4.20) we see that the mean velocity profile in the middle plane fills out near the outer wall and reduces the bulge cause by acceleration near the inner. In the top and bottom planes, while no significant reduction in bulge near the inner wall is seen, the velocity profile of fluid near the outer part of the bend shows a distinct acceleration. This is due to the increase in pressure near the inner wall and change in favorable radial pressure gradient as mentioned earlier.
At $\Theta = 60^\circ$ in the middle plane, we see a distinct jump in the mean velocity profile. The velocities near the inner wall have slowed significantly due to the shift of the core to the outer side of the bend under the secondary flow. This band of slowing mean flow grows towards the outer wall far downstream of the bend reaching a maximum at $\frac{s}{D_h} \simeq 11.15$. At this point, the high speed mean flow occupies only 23% of the bend near the outer wall. 77% of the bend area is filled with decelerated fluid. This is significant, since it shows that if a flowmeter, such as a differential pressure flowmeter, was used to measure the velocity at this position of $s$, it would possibly give an output that is not entirely accurate since the velocity across the cross-section is not uniform, which may not allow for an accurate pressure drop across the flowmeter. After $\frac{s}{D_h} \simeq 11.15$, the fluid starts accelerating again, and the velocity profile near the inner wall start filling out. It is very evident, however, that the flow is far from developed at the last measured location in the downstream section and would require a longer straight section.

In the top and bottom planes, after $\Theta = 60^\circ$, we still see a bias towards the inner wall which has been explained to be a result of the direction of the secondary flows in those planes. The immediate shift of the mean flow just downstream of the bend exit to the outer wall is due to the removal of the lateral curvature induced pressure gradient. Evidence that the secondary flow is pressure driven is emphasized by the fact that is rapidly loses intensity downstream of the bend where there are no centrifugal effects. The reappearance of radial velocities due to the secondary flow of the second kind help even out the flow profile quicker in these planes than in the middle plane. We can compare Figure 6.18 to Figure 6.19 which is adapted from a paper by Liou and Liu [16].

As seen from Figure 6.20, the velocity field in the same horizontal plane is qualitatively independent of the Reynolds number. All three flowrates have similar velocity profiles at a particular streamwise location.
Figure 6.18. Vector profiles for various values of constant $\frac{s}{D_h}$ superimposed on a flow field flooded by bulk velocity normalized normal vectors to show the effect of a bend on high-speed flow structure. Curvilinear coordinate system $s-n$ used for the horizontal planes: Top($\frac{s}{D_h}=0.375$), Middle($\frac{s}{D_h}=0$) and Bottom($\frac{s}{D_h}=-0.375$) [Re = $2.76 \times 10^5$]
Figure 6.19. Vector profiles for various values of constant $\frac{s}{\rho_h}$ along a bend. Image adapted from: Liou and Liu
Figure 6.20. Vector profiles for various values of constant $\frac{D_h}{s}$ superimposed on a flow field flooded by bulk velocity normalized normal vectors to show the effect of a bend on high-speed flow structure. Curvilinear coordinate system $s$-$n$ used for the flow rates: 66 gpm ($Re = 1.76 \times 10^5$), 100 gpm ($Re = 2.76 \times 10^5$), and 133 gpm ($Re = 3.2 \times 10^5$) [Middle Plane ($\frac{D_h}{s}=0$)]
6.4 Turbulence Intensities

Turbulence intensities are a measure of the turbulence in the flow. A highly turbulent flow has a high turbulent intensity. In the pressure driven bend flow in the bend, studying the turbulent intensities can help better understand the flow. A region of high turbulence intensities indicates a high velocity gradient \( \frac{\partial U_i}{\partial x_i} \) [40]. Figures 6.21 and 6.22, referenced in the discussions below are maps of the turbulence intensity at all locations in the test section in the cartesian and curvilinear coordinate systems respectively.

6.4.1 Middle Plane

Refer to the middle plane in Figure 6.22. At the inlet, we see a flow coming in with very low intensity in the fluid core \( \simeq 3\% \). This low turbulence intensity follows the fluid core (mean flow) in the bend. It is low near the inner wall in the initial part of the bend. Adjoining the outer wall, a band of thickness \( \simeq 0.13D_h \) has a turbulence intensity of \( \simeq 8\% \) right at the bend entrance, decreasing to \( \simeq 7.4\% \) at the exit. The higher initial value is due to the streamwise deceleration of the flow due to the adverse radial pressure gradient while the acceleration in the flow near the outer wall due to the influence of the secondary flow helps reduce the value of the intensity near the bend exit. As the mean flow starts moving towards the outer wall, the turbulence intensities near the inner wall show evidence of increasing up to \( \simeq 8\% \) at the bend exit.

After the bend exit, the low turbulence intensity region moves up against the outer wall while the higher turbulence region growing from the inner wall exists outside it. An intense region of turbulence of magnitude \( \simeq 17\% \) is observed at a distance \( \simeq 0.5D_h \) from the bend exit near the inner wall. This region is a very good indicator that there is a steep velocity gradient in that region which proves the existence of an additional counter-rotating pair of Dean’s vortices exists near the inner wall. As discussed briefly earlier, the magnitude of this pair is much smaller than that of the primary pair of Dean’s vortices which exist just alongside it. Liou and Liu [16] and Sudo et al. [20]
observe similar high turbulent intensity values and in this region. Liou and Liu detected
the highest turbulence intensity $0.5D_h$ away from the bend exit while Sudo notices it
$1D_h$ from the bend exit.

6.4.2 Top Plane

The flow for the top plane in Figure 6.22 has low intensities $\simeq 6\%$ for the upstream
and downstream sections. Higher intensities ($\simeq 8\%$) can be seen downstream at either
wall near $y^+ \simeq 9.25$. This may be due to the effects of the cross-stream normal stresses
gaining in strength as the flow moves along the straight downstream pipe. In the bend,
turbulent intensities $\simeq 8\%$ exist near the outer wall at the bend entrance and decrease
radially across the cross-section. The higher value near the outer wall is due to the
velocity gradient set up by the flow of fluid from the outer to the inner wall and the
resultant deceleration of the streamwise flow near the outer wall.

6.4.3 Bottom Plane

The bottom plane (in Figure 6.22) has turbulent intensity profiles similar to the top
plane for the most part. In the section upstream of the bend, a central region of higher
instabilities is noticed which confirms the observation of $U_a v$ decreasing as the flow moves
towards the bend entrance along $s$, seen in Figure 6.1. In the bend, high turbulent
intensities ($\simeq 8\%$) are seen near the outer wall and they fan out into the bend as the flow
moves towards the bend exit. Downstream of the bend, higher intensities are seen near
the outer wall. Near the inner wall, a lot of data is not available due to higher noise
from reflected light and hence no definite conclusions can be put forward.

6.4.4 Discussion of Turbulence Intensities

Humphrey et al. [10] used the terminology “destabilizing” and “stabilizing” for the outer
and inner walls respectively. This is seen from the distribution of turbulence intensities
within the bend for each of the planes. Fluid with high turbulence intensity is transported
by the secondary flow from the outer wall to the inner in the top \((\frac{z}{D_h} = 0.375)\) and bottom \((\frac{z}{D_h} = -0.375)\) planes. This fluid moves along the inner wall to the mid plane \((\frac{z}{D_h} = 0)\) where you see that low turbulence fluid exists. Hence, the inner wall has a stabilizing effect by reducing the turbulence intensity of the fluid. In the middle plane, low intensity fluid is carried to the outer wall where it is seen to have a higher intensity, or has been “destabilized”. This can be seen in Figures 6.21 and 6.22

6.4.5 Constant Plane, Different Reynolds Numbers

Similar to the velocity field, the turbulence intensity in the same horizontal plane for different flowrates is independent of the flow Reynolds number (Figure 6.23). This is useful since it allows comparison between experiments that may have been conducted at different flowrates and Reynolds number but for a similar flow regime.
Figure 6.21. Turbulence intensity in the cartesian coordinate system $X-Y$ for the following horizontal planes: Top($z_Dh=0.375$), Middle($z_Dh=0$) and Bottom($z_Dh=-0.375$). 

[Re = $2.76 \times 10^5$]
Figure 6.22. Turbulence intensity in the curvilinear coordinate system $s-n$ for the following horizontal planes: Top($\frac{z}{D_h}=0.375$), Middle($\frac{z}{D_h}=0$) and Bottom($\frac{z}{D_h}=-0.375$). $[Re = 2.76 \times 10^5]$
Figure 6.23. Turbulence intensity in the curvilinear coordinate system $s-n$ for the flow rates: 66 gpm ($Re = 1.76 \times 10^5$), 100 gpm ($Re = 2.76 \times 10^5$), and 133 gpm ($Re = 3.2 \times 10^5$) [Middle Plane ($\frac{s}{D_h}=0$)]
6.5 Reynolds Shear Stress

The Reynolds shear stress is given by the off-diagonal component of the Reynolds stress 
\[-\rho_0 \bar{u}_i \bar{v}_j \frac{\partial U_i}{\partial x_j}.\] For this study, we have the shear stress = \(\bar{u} \bar{v}\) where \(u\) and \(v\) are the turbulent fluctuations in the streamwise and radial directions respectively. The calculated shear stress has been shown in Figures 6.24 and 6.25. The increase in turbulent kinetic energy represents the loss of energy from the mean flow. As is shown below, when fluid flows through a pipe containing a bend there is a high amount of production of the turbulent kinetic energy due to shear, causing transfer of energy from the mean flow into turbulence.

6.5.1 Middle Plane

In the location upstream of the bend in the middle plane in Figure 6.25, a positive \(\bar{u} \bar{v}\) from the center of the duct to the outer wall works with the negative \(\frac{\partial U_z}{\partial n}\) near the outer wall to increase the flow turbulence. In the same upstream location of the middle plane, a negative \(\bar{u} \bar{v}\) between the center and the inner wall works with the positive \(\frac{\partial U_z}{\partial n}\) near the inner wall, also to increase the flow turbulence. Overall, what this means is that the turbulent kinetic energy of the flow has started increasing before it has even entered the bend.

Within the bend region, we see a distinct region of positive \(\bar{u} \bar{v}\) near the outer wall. However, \(\frac{\partial U_z}{\partial n}\) is negative for that region. Hence, the outer wall region in the middle plane also represents a positive addition to the turbulent kinetic energy. \(\bar{u} \bar{v}\) decreases in magnitude along the cross-section (that is, radially) towards the inner wall, but is still slightly positive. From the bend entrance to \(\Theta = 23^\circ\) \(\left(\frac{s}{D_h} \simeq 0.60\right)\), the area between the center of the duct and the inner wall has negative shear stress values. Due to the negative radial velocities that exist in this region and drive the mean flow towards the inner wall, the positive value of \(\frac{\partial U_z}{\partial n}\) is negative, allowing the destruction of some turbulent energy. Near the inner wall, however, \(\frac{\partial U_z}{\partial n}\) switches to a positive value because
of the boundary layer effects and thus the flow is made more turbulent in this region. This is supported by the turbulence intensities mapped in the middle plane of Figure 6.22. Similarly, a thin band of negative $\overline{uv}$ begins near the inner wall from $\Theta = 31^\circ \left( \frac{s}{D_h} \simeq 2.16 \right)$ and moves towards the outer wall till the bend exit. $\frac{\partial U_s}{\partial n}$ in this region is positive due to the effect of the secondary flow, causing an addition in the turbulent kinetic energy. Another thin band that grows near the inner wall from $\Theta = 65^\circ \left( \frac{s}{D_h} \simeq 4.54 \right)$ towards the bend exit serves to destroy some kinetic energy since it has a positive value of $\overline{uv}$ corresponding to the positive $\frac{\partial U_s}{\partial n}$.

Downstream of the bend exit, $\overline{uv}$ is negative almost everywhere except near the outer wall and a small central island that begins at $\frac{s}{D_h} \simeq 8.82$ till $\frac{s}{D_h} \simeq 11.92$. Since $\frac{\partial U_s}{\partial n}$ is entirely positive downstream, the regions of negative $\overline{uv}$ serve to add to the flow’s turbulence while the areas of positive $\overline{uv}$ serve to reduce the overall turbulent kinetic energy of the flow.

### 6.5.2 Top Plane

In the top plane in Figure 6.25, the shear stresses at the inlet are similar to the mid plane inlet. Most of the bend region has a negative $\frac{\partial U_s}{\partial n}$. However, near the inner wall there exists a positive $\frac{\partial U_s}{\partial n}$. The positive values of $\overline{uv}$ near the outer wall serve to add to the kinetic energy while the negative terms in the center and near the inner wall decrease the turbulent kinetic energy. Downstream of the bend, this is reversed. Turbulent kinetic energy is reduced near the outer wall and is increased near the inner wall and the center of the duct. This region, which tends to reduce the kinetic energy quickly shrinks and occupies only 20% of the duct by $\frac{s}{D_h} \simeq 8.93$.

### 6.5.3 Bottom Plane

The bottom plane shear stresses are very similar to the top plane and can be compared in Figure 6.25.
Figure 6.24. Reynolds shear stress components $\bar{u}\bar{v}$ in the cartesian coordinate system $X-Y$ for the following horizontal planes: Top($\frac{z}{D_h} = 0.375$), Middle($\frac{z}{D_h} = 0$) and Bottom($\frac{z}{D_h} = -0.375$). [Re = $2.76 \times 10^5$]
Figure 6.25. Reynolds shear stress components \( \bar{uv} \) in the curvilinear coordinate system \( s-n \) for the following horizontal planes: Top \( \left( \frac{z}{D_h} = 0.375 \right) \), Middle \( \left( \frac{z}{D_h} = 0 \right) \) and Bottom \( \left( \frac{z}{D_h} = -0.375 \right) \).

\[ \text{Re} = 2.76 \times 10^5 \]
6.5.4 Constant Plane, Different Reynolds Numbers

Increasing the Reynolds number of the flow increases the Reynolds shear stress quantitatively. However, the distribution of the stress does not change. The outer wall has regions of high positive Reynolds shear stress while the region neighboring the inner wall has negative Reynolds shear stress. Figure 6.26 details the distribution of $\overline{uv}$ for the middle horizontal plane $\frac{z}{D_h} \simeq 0$ for different Reynolds number flows.

6.5.5 Discussion of Reynolds Shear Stresses

To summarize, the upstream sections of the bend serve to add to the total turbulent kinetic energy. The outer wall also adds to the turbulent kinetic energy but the inner wall of the top and the bottom planes tend to destroy it. The inner wall in the middle plane destroys some of the energy after $\Theta = 65^\circ$. Hence, it is shown yet again that the inner wall provides a stabilizing effect while the outer wall tends to destabilize the flow. Downstream of the bend, in all the three planes turbulent kinetic energy is added to the flow. This is one of the prime reasons as to why the flow does not return to its fully developed state immediately after exiting the bend. The only way to destroy this added turbulent energy is through viscous dissipation and hence a long downstream section is required to return to a fully-developed flow profile. This also means that a higher Reynolds number flow will take longer to “shake off” the effects of the bend due to the higher turbulent kinetic energy added to the flow.
Figure 6.26. Reynolds shear stress components $\bar{uv}$ in the curvilinear coordinate system $s$-$n$ for the flow rates: 66 gpm ($Re = 1.76 \times 10^5$), 100 gpm ($Re = 2.76 \times 10^5$), and 133 gpm ($Re = 3.2 \times 10^5$) [Middle Plane ($\frac{s}{D_h} = 0$)]
Summary

7.1 Conclusions

As mentioned earlier in Chapter 4, 350 GB of raw image data are collected. These raw data generate an additional 350 GB of data when they are pre-processed. Processing these image files using Insight 3G and the in-house MATLAB codes generates data-rich *.vec files for each image pair which are stored in a folder named Processed data while the statistics are stored in a separate Statistics folder. These folders are approximately 3.3 GB for each location, totalling to nearly 150 GB for all the data sets obtained.

The present measurements serve to map the flow in the streamwise plane in much greater detail than any previous study on the effects of a bend in a square cross-sectioned pipe at high Reynolds number. The field velocity measurements over three planes: top, middle and bottom and at 12 streamwise locations (fields-of-view) in each plane have generated a large volume of spatial velocity data which was further processed to generate mean velocities, turbulent fluctuations, turbulent intensities and Reynolds shear stress components. Also, since the flow was fully-developed at the inlet, it effectively isolated the bend effects. This aids in developing a thorough, yet intuitive understanding of the complex bend effects and fluid dynamics in a curved pipe. Additionally, the extensive data can be used to benchmark Computational Fluid Dynamics (CFD) codes. For this
purpose, the data will be made freely available to the scientific community through an online database linked via a website.

The inlet velocity profiles are within ±3% of the theoretical fully-developed flow profile. The slope at the center of the duct for the experimental data is very near to zero, as would be expected from flow that is fully-developed. The effect of traveling through a long straight non-circular pipe is seen in the form of cross-stream normal stress generated corner vortices in a plane perpendicular to the streamwise flow direction. This is known as secondary flow of the second kind and it causes the streamwise velocity profile in the top and bottom planes to bulge slightly outwards near the inner and outer walls. No noticeable effect of the secondary flow of the second kind is seen in the middle plane in the straight upstream section.

As the flow draws closer to the bend, bend effects that have traveled upstream cause the streamwise velocity profile in all planes to bulge out near the inner wall. This bulge is indicative of a slight acceleration near the inner wall. At the bend entry, a distinct acceleration of the streamwise flow near the inner wall is seen, while the flow near the outer wall decelerates. These changes in velocity are caused by the radial pressure gradient that is directed from the outer wall to the inner wall; fluid in all planes moves radially from the outer to the inner wall. As the flow goes around the bend and the main Dean’s vortices (secondary flow of the first kind) start developing, this negative radial flow in all planes is concentrated towards the middle plane near the inner wall and eventually appears to form the additional pair of Dean’s vortices that have been observed in Figure 6.7. Conclusive evidence of the origin of the small additional Dean’s vortices at the inner wall would only be obtained by mapping the flow in the vertical plane along the inner wall of the bend.

The secondary flow of the first kind is clearly evident from $\Theta \simeq 45^\circ \left( \frac{s}{D_h} \simeq 3.12 \right)$ and is the strongest from $\Theta = 75^\circ$ to $90^\circ \left( \frac{s}{D_h} \simeq 5.24 \text{ to } 6.28 \right)$ in all planes. Pressure losses in a bend are caused due to this strong secondary flow are in a plane perpendicular to the streamwise flow direction. Also, if a pipe was carrying a heated fluid, in this region, the
heat transfer to the walls would be greater in the region of strong secondary flows. Now, if this pipe is supposed to retain the heat it can be insulated in these regions to the loss of heat to the outside while if it supposed to dissipate the heat, then greater cooling can be provided near the bend exit. This is a prime example of how knowledge of the flow structure can aid in designing a better and more efficient piping system.

After the bend exit, the streamwise flow is pushed to the outer wall. The primary pair of Dean’s vortices are present throughout the downstream section, even as secondary flow of the second kind makes a distinct reappearance along the walls. From the turbulence intensities in Figure 6.22 and Reynolds shear stress in Figure 6.25, we see that the downstream section adds to the turbulent kinetic energy of the flow, justifying the need for a longer downstream section if the bend effects and the three-dimensionality of the flow within it are undesirable.

Limited experimental data in the middle horizontal plane was acquired at different flowrates to observe the dependence of the flow structure on the Reynolds number. It was seen that as the Reynolds number increased, the qualitative structure of the streamwise and the radial flow remained unchanged while the magnitude of velocities increased with increasing flowrate, as would be expected. Turbulence intensities are shown to be independent of the flow rate since qualitatively and quantitatively they remained the same. The Reynolds shear stress increased with increasing flowrate since a higher velocity fluid would add to the turbulent kinetic energy due to the higher values of shear stresses across the flow.

Previous authors such as Humphrey et al. [11], Liou and Liu [16] have limited point measurement data in the bend in the n-z plane. Humphrey has data only at $\Theta \simeq 0^\circ$ and $\Theta \simeq 90^\circ$ while Liou and Liu have data at every $15^\circ$ slices. The field data collected in this work maps the complete bend from $\Theta \simeq 0^\circ$ to $\Theta \simeq 90^\circ$, as well as to $\simeq 6.5D_h$ downstream of the bend exit. The final interrogation region in the PIV measurements of this study are 32 by 32 pixels, with a 50% overlap. This essentially means data such as velocity components, turbulence intensities and Reynolds shear stress components are
available at every 16 pixels (≈0.013”) over the whole test section. Since PIV is a field measurement techniques, it can be safely said that the current work is, to date, the most extensive field mapping of fluid flow in the horizontal (s-n) plane in a curved bend.

7.2 Future Work

As advances in PIV allow three dimensional field mapping, field data can be obtained in the n-z plane if compensation for the optical distortion due to the bend is provided. These measurements can be combined with the present work to present a true three dimensional image of the effect of a bend in a pipe on the flow within it.
A.1 Introduction

To recap, for a flowrate of 100 gpm (Re = 2.76×10^5), data were obtained 12 locations in each of the three planes: top, middle and bottom. Data were collected at 4 locations in the middle plane for both the flowrates, 66 gpm (Re = 1.76×10^5) and 133 gpm (Re = 3.20×10^5). The raw image and vector data are too voluminous (∼ 850 GB in all) to be made available online. Hence a condensed version of the data is categorized and will be made available to the scientific and technical community via a website. These files will be data files in the *.vec format which can be easily opened by any text-editing program such as Notepad. These vec files are also formatted to be easily opened in any version of Tecplot to allow for easy data manipulation and representation. For each location, files containing: (i) the spatial mean velocity components, (ii) turbulence intensities, (iii) Reynolds shear stress components, (iv) RMS of velocity components, (v) standard deviation, (vi) variance, (vii) skewness and (viii) kurtosis.

These data are categorized according to the Reynolds number. Within each Reynolds number folder, there will be a group of folders based on the stations (UP1, BND1, BND5, and so on) at which the data was taken. Within the station folders, each plane (top, middle and bottom) will be allotted a separate folder which will contain the above
mentioned data files for that location. Tecplot files used for the figures in Chapter 6 will also be provided to allow the user to see the detailed data. The datasheets, listed below, will also be provided in the relevant location-based folder to provide a reference about the experimental conditions to the user.
A.2  66 gpm

Date: 07/02/2009
Flow Rate: 66gpm

**Camera:**
Distance /Exact Location : 3.25"

*Ruler (8”mark) was placed at face of black oxidized flange towards test section. Look at calibration image mark on rightmost top side of the image and that will give you distance from the flange. Add the flange thickness to it.*

Location: Upstream
Z-Location: Middle
Station: 01
F #: 11
Zoom: 1\frac{1}{4} ft.
Field of View (from calib): 1.25"

**Set-up:**
Pump Frequency: 23.30Hz
Upstream Pressure: 8.48 psig
Downstream Pressure: 5.53 psig
Water Temperature(S/End): 21.79/ 22.3 deg C
Seed: Hollow Glass Spheres
Amount: 3 caps.

**Insight:**
Data Source: Camera
Exposure Mode: Frame Straddle
Capture Mode: Sequence
No. of Images: 500
Start number: 0

dT : 20 us

YAG1 : High

Q-switch1 : 160 us

YAG 2: High

Q-switch 2 : 175 us

Pulse Delay : 0.3048

Rep Rate: 1 Hz
Date: 07/02/2009
Flow Rate: 66gpm

**Camera:**
Distance /Exact Location : 0 to 15

*The calibration image “a” will give the exact demarcations of the 0 degree and 15 lines since it is focused on the metal strips. Calibration image “b” serves as a check since it is focused on the channel boundaries*

Location: Bend
Z-Location: Middle
Station: 01
F #: 11
Zoom: 1\(\frac{1}{4}\) ft.
Field of View (from calib): 1.25"

**Set-up:**
Pump Frequency: 23.3Hz
Upstream Pressure: 8.36 psig
Downstream Pressure: 5.45 psig
Water Temperature(S/End): 23.8 / 23.99 deg C
Seed: Hollow Glass Spheres
Amount: 3 caps.

**Insight:**
Data Source: Camera
Exposure Mode: Frame Straddle
Capture Mode: Sequence
No. of Images: 500
Start number: 0
dT : 20 us
YAG1 : High
Q-switch1 : 175us
YAG 2: High
Q-switch 2 : 175 us
Pulse Delay : 0.3048
Rep Rate: 1 Hz
Date: 07/05/2009
Flow Rate: 66gpm

**Camera:**
Distance /Exact Location: 75 to 90 deg window

*The calibration image “a” will give the exact demarcations of the 75 degree and 90 lines since it is focused on the metal strips. Calibration image “b” serves as a check since it is focused on the channel boundaries*

Location: Bend
Z-Location: Middle
Station: 06
F # : 11
Zoom: 1\(\frac{1}{4}\) ft.
Field of View (from calib): 1 ”

**Set-up:**
Pump Frequency: 23.3 Hz
Upstream Pressure: 8.42 psig
Downstream Pressure: 5.08 psig
Water Temperature(S/End): 22.12 / 22.29 deg C
Seed: Hollow Glass Spheres
Amount: 3 caps.

**Insight:**
Data Source: Camera
Exposure Mode: Frame Straddle
Capture Mode: Sequence
No. of Images: 500
Start number: 0
dT : 20 us
YAG1 : High
Q-switch1 : 175 us
YAG 2: High
Q-switch 2 : 175 us
Pulse Delay : 0.3049
Rep Rate: 1 Hz
Date: 01/02/2009
Flow Rate: 66gpm

**Camera:**
Distance /Exact Location : 5.5”
[0” of the Ruler was placed at join of black oxidized flange and SS flange towards the outer side. Look at calibration image mark on leftmost bottom side of the image and that will give you distance from the join .The outer side is towards the bottom of the image.]

Location: Downstream
Z-Location: Middle
Station: 03
F # : 11
Zoom: 1 1/4 ft.
Field of View (from calib): 1.25”

**Set-up:**
Pump Frequency: 23.3 Hz
Upstream Pressure: 8.17 psig
Downstream Pressure: 5.14 psig
Water Temperature(S/End): 24.09 / 24.11 deg C
Seed: Hollow Glass Spheres
Amount: 3 caps.

**Insight:**
Data Source: Camera
Exposure Mode: Frame Straddle
Capture Mode: Sequence
No. of Images: 500
Start number: 0
dT : 20 us
YAG1 : High
Q-switch1 : 165 us

YAG 2: High
Q-switch 2 : 175 us
Pulse Delay : 0.3049
Rep Rate: 1 Hz
A.3 100 gpm

Date: 12/24/2008
Flow Rate: 100gpm

**Camera:**
Distance /Exact Location : 3.25"

*Ruler (8”mark) was placed at face of black oxidized flange towards test section. Look at calibration image mark on rightmost top side of the image and that will give you distance from the flange. Add the flange thickness to it.*

Location: Upstream

Z-Location: Top

Station: 01

F #: 11

Zoom: 1\(\frac{1}{4}\) ft.

Field of View (from calib): 1.25"

**Set-up:**
Pump Frequency: 32.45Hz

Upstream Pressure: 17.5 psig

Downstream Pressure: 09.1 psig

Water Temperature(S/End): 22.3/22.7 deg C

Seed: Hollow Glass Spheres

Amount: 3 caps.

**Insight:**
Data Source: Camera

Exposure Mode: Frame Straddle

Capture Mode: Sequence

No. of Images: 300
Start number: 0

dT : 26 us

YAG1 : High

Q-switch1 : 175 us

YAG 2: High

Q-switch 2 : 175 us

Pulse Delay : 0.3049

Rep Rate: 1 Hz
Date: 12/24/2008
Flow Rate: 100gpm

**Camera:**
Distance /Exact Location : 3.25" 
[[Ruler (8”mark) was placed at face of black oxidized flange towards test section. Look at calibration image mark on rightmost top side of the image and that will give you distance from the flange. Add the flange thickness to it.]
Location: Upstream
Z-Location: Middle
Station: 01
F # : 11
Zoom: 1 1/4 ft.
Field of View (from calib): 1.25"

**Set-up:**
Pump Frequency: 32.45Hz
Upstream Pressure: 17.5 psig
Downstream Pressure: 09.1 psig
Water Temperature(S/End): 24.23/ 24. 50 deg C
Seed: Hollow Glass Spheres
Amount: 3 caps.

**Insight:**
Data Source: Camera
Exposure Mode: Frame Straddle
Capture Mode: Sequence
No. of Images: 300
Start number: 0
dT : 26 us
YAG1 : High
Q-switch1 : 175 us
YAG 2: High
Q-switch 2 : 175 us
Pulse Delay : 0.3048
Rep Rate: 1 Hz
Date: 12/24/2008
Flow Rate: 100gpm

**Camera:**

Distance /Exact Location : 3.25"  
*Ruler (8”mark) was placed at face of black oxidized flange towards test section. Look at calibration image mark on rightmost top side of the image and that will give you distance from the flange. Add the flange thickness to it.*

Location: Upstream  
Z-Location: Bottom  
Station: 01  
F #: 11  
Zoom: 1\frac{1}{4} ft.  
Field of View (from calib): 1.25"

**Set-up:**

Pump Frequency: 32.45Hz  
Upstream Pressure: 17.5 psig  
Downstream Pressure: 09.1 psig  
Water Temperature(S/End): 24.64/24.79 deg C  
Seed: Hollow Glass Spheres  
Amount: 3 caps.

**Insight:**

Data Source: Camera  
Exposure Mode: Frame Straddle  
Capture Mode: Sequence  
No. of Images: 300  
Start number: 0  
\(dT : 26 \text{ us}\)  
YAG1 : High
Q-switch1 : 175 us
YAG 2: High
Q-switch 2 : 175 us
Pulse Delay : 0.3048
Rep Rate: 1 Hz
Date: 11/09/2009
Flow Rate: 100gpm

**Camera:**
Distance /Exact Location : 0 to 15 deg window

*The calibration image “a” will give the exact demarcations of the 0 degree and 15 lines since it is focused on the metal strips. Calibration image “b” serves as a check since it is focused on the channel boundaries*

Location: Bend
Z-Location: Top
Station: 01
F #: 11
Zoom: 1¾ ft.
Field of View (from calib): N/A

**Set-up:**
Pump Frequency: 32.40 Hz
Upstream Pressure: 17.6 psig
Downstream Pressure: 09.2 psig
Water Temperature(S/End): 19.76 / 20.59 deg C
Seed: Hollow Glass Spheres
Amount: 3 caps.

**Insight:**
Data Source: Camera
Exposure Mode: Frame Straddle
Capture Mode: Sequence
No. of Images: 500
Start number: 0
dT : 15 us
YAG1: High
Q-switch 1: 155 us*

YAG 2: High
Q-switch 2: 175 us
Pulse Delay: 0.3049
Rep Rate: 1 Hz

*: 155 gave the best values of Choice 1 and SNR fail and least u-vel SD
Date: 11/09/2009
Flow Rate: 100gpm

**Camera:**
Distance /Exact Location : 0 to 15 deg window

*The calibration image “a” will give the exact demarcations of the 0degree and 15 lines since it is focused on the metal strips. Calibration image “b” serves as a check since it is focused on the channel boundaries*

Location: Bend
Z-Location: Middle
Station: 01
F # : 11
Zoom: 1\(\frac{1}{4}\) ft.
Field of View (from calib): N/A

**Set-up:**
Pump Frequency: 32.40 Hz
Upstream Pressure: 17.6 psig
Downstream Pressure: 09.2 psig
Water Temperature(S/End): 21.48 / 21.89deg C
Seed: Hollow Glass Spheres
Amount: 3 caps.

**Insight:**
Data Source: Camera
Exposure Mode: Frame Straddle
Capture Mode: Sequence
No. of Images: 500
Start number: 0
dT : 15 us
YAG1: High
Q-switch1: 175 us*

YAG 2: High
Q-switch 2: 175 us
Pulse Delay: 0.3049
Rep Rate: 1 Hz

*: 175 gave the best values of Choice 1 and SNR fail. The flare towards the bottom centre
was of approximately same size for Q-switch values 145 to 175. It reduced marginally
for Q-switch 125 to 135 but that reduced number of vectors by a larger number.
Date: 11/09/2009
Flow Rate: 100gpm

**Camera:**
Distance /Exact Location : 0 to 15 deg window

*The calibration image “a” will give the exact demarcations of the 0 degree and 15 lines since it is focused on the metal strips. Calibration image “b” serves as a check since it is focused on the channel boundaries*

Location: Bend
Z-Location: Bottom
Station: 01
F # : 11
Zoom: $1\frac{1}{4}$ ft.
Field of View (from calib): N/A

**Set-up:**
Pump Frequency: 32.40 Hz
Upstream Pressure: 17.6 psig
Downstream Pressure: 09.2 psig
Water Temperature(S/End): 22.12 / 22.78 deg C
Seed: Hollow Glass Spheres
Amount: 3 caps.

**Insight:**
Data Source: Camera
Exposure Mode: Frame Straddle
Capture Mode: Sequence
No. of Images: 500
Start number: 0
dT : 15 us
YAG1 : High
Q-switch1 : 175 us*

YAG 2: High
Q-switch 2 : 175 us
Pulse Delay : 0.3049
Rep Rate: 1 Hz

* : 175 gave the best values of Choice 1 and least SNR fail.
Date: 1/09/2009  
Flow Rate: 100gpm  

**Camera:**  
Distance /Exact Location : 15 to 30 deg window  
*The calibration image “a” will give the exact demarcations of the 15 degree and 30 lines since it is focused on the metal strips. Calibration image “b” serves as a check since it is focused on the channel boundaries*  

Location: Bend  
Z-Location: Top  
Station: 02  
F # : 11  
Zoom: $1\frac{1}{4}$ ft.  
Field of View (from calib): N/A  

**Set-up:**  
Pump Frequency: 32.40 Hz  
Upstream Pressure: 17.6 psig  
Downstream Pressure: 09.2 psig  
Water Temperature(S/End): 25.91/ 26.29 deg C  
Seed: Hollow Glass Spheres  
Amount: 3 caps.  

**Insight:**  
Data Source: Camera  
Exposure Mode: Frame Straddle  
Capture Mode: Sequence  
No. of Images: 500  
Start number: 0  
$dT : 15$ us
YAG1 : High
Q-switch1 : 175 us*

YAG 2: High
Q-switch 2 : 175 us
Pulse Delay : 0.3049
Rep Rate: 1 Hz

* : 175 gave the best values of Choice 1 and least SNR fail.
Date: 1/09/2009
Flow Rate: 100gpm

**Camera:**
Distance /Exact Location : 15 to 30 deg window

*The calibration image “a” will give the exact demarcations of the 15 degree and 30 lines since it is focused on the metal strips. Calibration image “b” serves as a check since it is focused on the channel boundaries*

Location: Bend
Z-Location: Middle
Station: 02
F #: 11
Zoom: 1 1/4 ft.
Field of View (from calib): N/A

**Set-up:**
Pump Frequency: 32.40 Hz
Upstream Pressure: 17.6 psig
Downstream Pressure: 09.2 psig
Water Temperature(S/End): 25.21 / 25.71 deg C
Seed: Hollow Glass Spheres
Amount: 3 caps.

**Insight:**
Data Source: Camera
Exposure Mode: Frame Straddle
Capture Mode: Sequence
No. of Images: 500
Start number: 0
dT : 15 us
YAG1 : High
Q-switch1 : 175 us*

YAG 2: High
Q-switch 2 : 175 us
Pulse Delay : 0.3049
Rep Rate: 1 Hz

* : 175 gave the best values of Choice 1 and least SNR fail.
Date: 1/09/2009

Flow Rate: 100gpm

**Camera:**

Distance /Exact Location : 15 to 30 deg window

*The calibration image “a” will give the exact demarcations of the 15 degree and 30 lines since it is focused on the metal strips. Calibration image “b” serves as a check since it is focused on the channel boundaries*

Location: Bend

Z-Location: Bottom

Station: 02

F #: 11

Zoom: 1.25 ft.

Field of View (from calib): N/A

**Set-up:**

Pump Frequency: 32.40 Hz

Upstream Pressure: 17.6 psig

Downstream Pressure: 09.2 psig

Water Temperature(S/End): 24.54 / 25.13 deg C

Seed: Hollow Glass Spheres

Amount: 3 caps.

**Insight:**

Data Source: Camera

Exposure Mode: Frame Straddle

Capture Mode: Sequence

No. of Images: 500

Start number: 0

dT : 15 us
YAG1: High
Q-switch1: 175 us*

YAG 2: High
Q-switch 2: 175 us
Pulse Delay: 0.3049
Rep Rate: 1 Hz

*: 175 gave the best values of Choice 1 and least SNR fail.
Date: 1/09/2009
Flow Rate: 100gpm

**Camera:**

Distance /Exact Location : 30 to 45 deg window

*The calibration image “a” will give the exact demarcations of the 30degree and 45 lines since it is focused on the metal strips. Calibration image “b” serves as a check since it is focused on the channel boundaries*

Location: Bend
Z-Location: Top
Station: 03
F # : 11
Zoom: 1\(\frac{1}{4}\) ft.
Field of View (from calib): N/A

**Set-up:**
Pump Frequency: 32.40 Hz
Upstream Pressure: 17.6 psig
Downstream Pressure: 9.2 psig
Water Temperature(S/End): 26.97/ 27.52 deg C
Seed: Hollow Glass Spheres
Amount: 3 caps.

**Insight:**
Data Source: Camera
Exposure Mode: Frame Straddle
Capture Mode: Sequence
No. of Images: 500
Start number: 0
dT : 10 us
YAG1: High
Q-switch1: 175 us*

YAG 2: High
Q-switch 2: 175 us
Pulse Delay: 0.3049
Rep Rate: 1 Hz

*: 175 gave the best values of Choice 1 and least SNR fail.
Date: 1/09/2009
Flow Rate: 100gpm

**Camera:**
Distance /Exact Location : 30 to 45 deg window

*The calibration image “a” will give the exact demarcations of the 30degreee and 45 lines since it is focused on the metal strips. Calibration image “b” serves as a check since it is focused on the channel boundaries*

Location: Bend
Z-Location: Middle
Station: 03
F # : 11
Zoom: 1 1/4 ft.
Field of View (from calib): N/A

**Set-up:**
Pump Frequency: 32.40 Hz
Upstream Pressure: 17.6 psig
Downstream Pressure: 09.2 psig
Water Temperature(S/End): 27.66 / 28.21 deg C
Seed: Hollow Glass Spheres
Amount: 3 caps.

**Insight:**
Data Source: Camera
Exposure Mode: Frame Straddle
Capture Mode: Sequence
No. of Images: 500
Start number: 0
dT : 10 us
YAG1 : High
Q-switch1 : 175 us*

YAG 2: High
Q-switch 2 : 175 us
Pulse Delay : 0.3049
Rep Rate: 1 Hz

*: 175 gave the best values of Choice 1 and least SNR fail.
Date: 1/09/2009
Flow Rate: 100gpm

**Camera:**
Distance /Exact Location: 30 to 45 deg window

*The calibration image “a” will give the exact demarcations of the 30 degree and 45 lines since it is focused on the metal strips. Calibration image “b” serves as a check since it is focused on the channel boundaries*

Location: Bend
Z-Location: Bottom
Station: 03
F #: 11
Zoom: 1 1/4 ft.
Field of View (from calib): N/A

**Set-up:**
Pump Frequency: 32.40 Hz
Upstream Pressure: 17.6 psig
Downstream Pressure: 09.2 psig
Water Temperature(S/End): 28.37 / 28.60 deg C
Seed: Hollow Glass Spheres
Amount: 3 caps.

**Insight:**
Data Source: Camera
Exposure Mode: Frame Straddle
Capture Mode: Sequence
No. of Images: 500
Start number: 0
dT : 10 us
YAG1 : High
Q-switch1 : 175 us*

YAG 2: High
Q-switch 2 : 175 us
Pulse Delay : 0.3049
Rep Rate: 1 Hz

* : 175 gave the best values of Choice 1 and least SNR fail.
Date: 1/16/2009
Flow Rate: 100gpm

**Camera:**
Distance /Exact Location : 45 to 60 deg window

*The calibration image “a” will give the exact demarcations of the 45degree and 60 lines since it is focused on the metal strips. Calibration image “b” serves as a check since it is focused on the channel boundaries*

Location: Bend
Z-Location: Top
Station: 04
F # : 11
Zoom: 11/4 ft.
Field of View (from calib): N/A

**Set-up:**
Pump Frequency: 32.75 Hz
Upstream Pressure: 17.6 psig
Downstream Pressure: 09.2 psig
Water Temperature(S/End): 16.3 / 16.7 deg C
Seed: Hollow Glass Spheres
Amount: 3 caps.

**Insight:**
Data Source: Camera
Exposure Mode: Frame Straddle
Capture Mode: Sequence
No. of Images: 500
Start number: 0
dT : 10 us
YAG1: High
Q-switch 1: 175 us*

YAG 2: High
Q-switch 2: 175 us
Pulse Delay: 0.3049
Rep Rate: 1 Hz

*: 175 gave the best values of Choice 1 and least SNR fail.
Date: 1/16/2009

Flow Rate: 100gpm

**Camera:**

Distance /Exact Location: 45 to 60 deg window

*The calibration image “a” will give the exact demarcations of the 45degree and 60 lines since it is focused on the metal strips. Calibration image “b” serves as a check since it is focused on the channel boundaries*

Location: Bend

Z-Location: Middle

Station: 04

F #: 11

Zoom: 1 1/4 ft.

Field of View (from calib): N/A

**Set-up:**

Pump Frequency: 32.75 Hz

Upstream Pressure: 17.6 psig

Downstream Pressure: 9.2 psig

Water Temperature(S/End): 15.6 / 16.06 deg C

Seed: Hollow Glass Spheres

Amount: 3 caps.

**Insight:**

Data Source: Camera

Exposure Mode: Frame Straddle

Capture Mode: Sequence

No. of Images: 500

Start number: 0

dT : 10 us
YAG1 : High
Q-switch1 : 175 us*

YAG 2: High
Q-switch 2 : 175 us
Pulse Delay : 0.3049
Rep Rate: 1 Hz

* : 175 gave the best values of Choice 1 and least SNR fail.
Date: 1/16/2009

Flow Rate: 100gpm

**Camera:**

Distance / Exact Location: 45 to 60 deg window

*The calibration image “a” will give the exact demarcations of the 45 degree and 60 lines since it is focused on the metal strips. Calibration image “b” serves as a check since it is focused on the channel boundaries*

Location: Bend
Z-Location: Bottom
Station: 04
F # : 11
Zoom: 1 1/4 ft.
Field of View (from calib): N/A

**Set-up:**

Pump Frequency: 32.75 Hz
Upstream Pressure: 17.6 psig
Downstream Pressure: 09.2 psig
Water Temperature (S/End): 14.7 / 14.8 deg C
Seed: Hollow Glass Spheres
Amount: 3 caps.

**Insight:**

Data Source: Camera
Exposure Mode: Frame Straddle
Capture Mode: Sequence
No. of Images: 500
Start number: 0
dT : 10 us
YAG1: High
Q-switch 1: 175 us*

YAG 2: High
Q-switch 2: 175 us
Pulse Delay: 0.3049
Rep Rate: 1 Hz

*: 175 gave the best values of Choice 1 and least SNR fail.
Date: 1/16/2009
Flow Rate: 100gpm

**Camera:**
Distance /Exact Location: 60 to 75 deg window

*The calibration image “a” will give the exact demarcations of the 60 degree and 75 lines since it is focused on the metal strips. Calibration image “b” serves as a check since it is focused on the channel boundaries*

Location: Bend
Z-Location: Top
Station: 05
F #: 11
Zoom: 1 1/4 ft.
Field of View (from calib): N/A

**Set-up:**
Pump Frequency: 32.65 Hz
Upstream Pressure: 17.6 psig
Downstream Pressure: 09.2 psig
Water Temperature(S/End): 20.48 / 20.90 deg C
Seed: Hollow Glass Spheres
Amount: 3 caps.

**Insight:**

Data Source: Camera
Exposure Mode: Frame Straddle
Capture Mode: Sequence
No. of Images: 500
Start number: 0
dT : 10 us
YAG1 : High
Q-switch1 : 175 us
YAG 2: High
Q-switch 2 : 175 us
Pulse Delay : 0.3049
Rep Rate: 1 Hz
Date: 1/16/2009
Flow Rate: 100gpm

**Camera:**
Distance /Exact Location : 60 to 75 deg window

*The calibration image “a” will give the exact demarcations of the 60 degree and 75 lines since it is focused on the metal strips. Calibration image “b” serves as a check since it is focused on the channel boundaries*

Location: Bend
Z-Location: Middle
Station: 05
F #: 11
Zoom: 1\(\frac{1}{4}\) ft.
Field of View (from calib): N/A

**Set-up:**
Pump Frequency: 32.65 Hz
Upstream Pressure: 17.6 psig
Downstream Pressure: 09.2 psig
Water Temperature(S/End): 19.3 / 19.63 deg C
Seed: Hollow Glass Spheres
Amount: 3 caps.

**Insight:**
Data Source: Camera
Exposure Mode: Frame Straddle
Capture Mode: Sequence
No. of Images: 500
Start number: 0
dT : 10 us
YAG1: High
Q-switch 1: 175 us*

YAG 2: High
Q-switch 2: 175 us
Pulse Delay: 0.3049
Rep Rate: 1 Hz

*: 145 gave the highest SNR and Choice 1.
Date: 1/16/2009
Flow Rate: 100gpm

**Camera:**
Distance /Exact Location : 60 to 75 deg window

*The calibration image “a” will give the exact demarcations of the 60 degree and 75 lines since it is focused on the metal strips. Calibration image “b” serves as a check since it is focused on the channel boundaries*

Location: Bend
Z-Location: Bottom
Station: 05
F # : 11
Zoom: 1\(\frac{1}{4}\) ft.
Field of View (from calib): N/A

**Set-up:**
Pump Frequency: 32.65 Hz
Upstream Pressure: 17.6 psig
Downstream Pressure: 09.2 psig
Water Temperature(S/End): 19.89 / 20.24 deg C
Seed: Hollow Glass Spheres
Amount: 3 caps.

**Insight:**
Data Source: Camera
Exposure Mode: Frame Straddle
Capture Mode: Sequence
No. of Images: 500
Start number: 0
dT : 10 us
YAG1: High
Q-switch1: 175 us*

YAG 2: High
Q-switch 2: 175 us
Pulse Delay: 0.3049
Rep Rate: 1 Hz

*: 145 gave the highest SNR and Choice 1.
Date: 1/16/2009
Flow Rate: 100gpm

**Camera:**
Distance / Exact Location: 75 to 90 deg window

*The calibration image “a” will give the exact demarcations of the 75 degree and 90 lines since it is focused on the metal strips. Calibration image “b” serves as a check since it is focused on the channel boundaries*

Location: Bend
Z-Location: Top
Station: 06
F #: 11
Zoom: 1\frac{1}{4} ft.
Field of View (from calib): N/A

**Set-up:**
Pump Frequency: 32.5 Hz
Upstream Pressure: 17.6 psig
Downstream Pressure: 09.2 psig
Water Temperature (S/End): 21.65/22.01 deg C
Seed: Hollow Glass Spheres
Amount: 3 caps.

**Insight:**
Data Source: Camera
Exposure Mode: Frame Straddle
Capture Mode: Sequence
No. of Images: 500
Start number: 0
dT: 10 us
YAG1: High
Q-switch1: 175 us

YAG 2: High
Q-switch 2: 175 us
Pulse Delay: 0.3049
Rep Rate: 1 Hz
Reynold’s Number:
Date: 1/16/2009
Flow Rate: 100gpm

**Camera:**

Distance /Exact Location: 75 to 90 deg window

*The calibration image “a” will give the exact demarcations of the 75 degree and 90 lines since it is focused on the metal strips. Calibration image “b” serves as a check since it is focused on the channel boundaries*

Location: Bend
Z-location: Middle
Station: 06
F #: 8*
Zoom: 1 1/4 ft.
Field of View (from calib): N/A

**Set-up:**
Pump Frequency: 32.5 Hz
Upstream Pressure: 17.6 psig
Downstream Pressure: 9.2 psig
Water Temperature(S/End): 22.53 / 22.81 deg C
Seed: Hollow Glass Spheres
Amount: 3 caps.

**Insight:**
Data Source: Camera
Exposure Mode: Frame Straddle
Capture Mode: Sequence
No. of Images: 500
Start number: 0
dT : 10 us
YAG1 : High
Q-switch1 : 175 us
YAG 2: High
Q-switch 2 : 175 us
Pulse Delay : 0.3049
Rep Rate: 1 Hz

*: 8 gave more particles. The top had used 11 as f# and the seed dispersion was a bit sparse.
Date: 1/16/2009
Flow Rate: 100gpm

**Camera:**
Distance /Exact Location : 75 to 90 deg window

*The calibration image “a” will give the exact demarcations of the 75 degree and 90 lines since it is focused on the metal strips. Calibration image “b” serves as a check since it is focused on the channel boundaries*

Location: Bend
Z-Location: Bottom
Station: 06
F # : 8*
Zoom: 1 1/4 ft.
Field of View (from calib): N/A

**Set-up:**
Pump Frequency: 32.5 Hz
Upstream Pressure: 17.6 psig
Downstream Pressure: 09.2 psig
Water Temperature(S/End): 22.95 / 23.01 deg C
Seed: Hollow Glass Spheres
Amount: 3 caps.

**Insight:**
Data Source: Camera
Exposure Mode: Frame Straddle
Capture Mode: Sequence
No. of Images: 500
Start number: 0
dT : 10 us
YAG1 : High
Q-switch1 : 175 us

YAG 2: High
Q-switch 2 : 175 us
Pulse Delay : 0.3049
Rep Rate: 1 Hz

* : 8 gave more particles. The top had used 11 as f# and the seed dispersion was a bit sparse.
Date: 12/29/2008
Flow Rate: 100gpm

**Camera:**
Distance /Exact Location : 8”

[of the Ruler was placed at join of black oxidized flange and SS flange towards the outer side. Look at calibration image mark on leftmost bottom side of the image and that will give you distance from the join .The outer side is towards the bottom of the image.]

Location: Downstream
Z-Location: Top
Station: 01
F # : 11
Zoom: 1\(\frac{1}{4}\) ft.
Field of View (from calib): ~1.25”

**Set-up:**
Pump Frequency: 32.30Hz
Upstream Pressure: 17.5 psig
Downstream Pressure: 09.2 psig
Water Temperature(S/End): 27.22/ 27.54 deg C
Seed: Hollow Glass Spheres
Amount: 3 caps.

**Insight:**
Data Source: Camera
Exposure Mode: Frame Straddle
Capture Mode: Sequence
No. of Images: 500
Start number: 0
dT : 15 us
YAG1 : High
Q-switch1 : 160 us

YAG 2: High
Q-switch 2 : 160 us
Pulse Delay : 0.3049
Rep Rate: 1 Hz
Date: 12/29/2008
Flow Rate: 100gpm

**Camera:**
Distance /Exact Location : 8”

"0” of the Ruler was placed at join of black oxidized flange and SS flange towards the outer side. Look at calibration image mark on leftmost bottom side of the image and that will give you distance from the join. The outer side is towards the bottom of the image.

Location: Downstream
Z-Location: Middle
Station: 01
F # : 11
Zoom: 1 1/4 ft.
Field of View (from calib): ~1.25”

**Set-up:**
Pump Frequency: 32.30Hz
Upstream Pressure: 17.5 psig
Downstream Pressure: 09.2 psig
Water Temperature(S/End): 27.82/ 28.20 deg C
Seed: Hollow Glass Spheres
Amount: 3 caps.

**Insight:**
Data Source: Camera
Exposure Mode: Frame Straddle
Capture Mode: Sequence
No. of Images: 500
Start number: 0
dT : 15 us
YAG1 : High
Q-switch1 : 175 us
YAG 2: High
Q-switch 2 : 175 us
Pulse Delay : 0.3049
Rep Rate: 1 Hz
Date: 12/29/2008
Flow Rate: 100gpm

**Camera:**
Distance /Exact Location : 8”

[j0” of the Ruler was placed at join of black oxidized flange and SS flange towards the outer side. Look at calibration image mark on leftmost bottom side of the image and that will give you distance from the join. The outer side is towards the bottom of the image.]

Location: Downstream
Z-Location: Bottom
Station: 01
F #: 11
Zoom: 1 1/4 ft.
Field of View (from calib): ~1.25”

**Set-up:**
Pump Frequency: 32.30Hz
Upstream Pressure: 17.5 psig
Downstream Pressure: 09.2 psig
Water Temperature(S/End): 28.60/ 28.81 deg C
Seed: Hollow Glass Spheres
Amount: 3 caps.

**Insight:**
Data Source: Camera
Exposure Mode: Frame Straddle
Capture Mode: Sequence
No. of Images: 500
Start number: 0
dT : 15 us
YAG1 : High
Q-switch1 : 175 us
YAG 2: High
Q-switch 2 : 175 us
Pulse Delay : 0.3049
Rep Rate: 1 Hz
Date: 1/02/2009
Flow Rate: 100gpm

**Camera:**
Distance /Exact Location : 6.75”

[0” of the Ruler was placed at join of black oxidized flange and SS flange towards the outer side. Look at calibration image mark on leftmost bottom side of the image and that will give you distance from the join. The outer side is towards the bottom of the image.]

Location: Downstream
Z-Location: Top
Station: 02
F # : 11
Zoom: 1 1/4 ft.
Field of View (from calib): 1.25”

**Set-up:**
Pump Frequency: 32.35 Hz
Upstream Pressure: 17.9 psig
Downstream Pressure: 09.2 psig
Water Temperature(S/End): 20.59/21.03 deg C
Seed: Hollow Glass Spheres
Amount: 2.5 caps.

**Insight:**
Data Source: Camera
Exposure Mode: Frame Straddle
Capture Mode: Sequence
No. of Images: 500
Start number: 0
dT : 15 us
YAG1 : High
Q-switch1 : 145 us*

YAG 2: High
Q-switch 2 : 175 us
Pulse Delay : 0.3049
Rep Rate: 1 Hz

*: 145: least saturation and SNR Fail lower than all other tested values of dT (145, 155, 165, 175)
Date: 1/02/2009
Flow Rate: 100gpm

**Camera:**
Distance /Exact Location : 6.75”

0” of the Ruler was placed at join of black oxidized flange and SS flange towards the outer side. Look at calibration image mark on leftmost bottom side of the image and that will give you distance from the join. The outer side is towards the bottom of the image.

Location: Downstream
Z-Location: Middle
Station: 02
F # : 11
Zoom: 1 1/4 ft.
Field of View (from calib): 1.25”

**Set-up:**
Pump Frequency: 32.35 Hz
Upstream Pressure: 17.5 psig
Downstream Pressure: 09.2 psig
Water Temperature(S/End): 22.30/22.68 deg C
Seed: Hollow Glass Spheres
Amount: 2.5 caps.

**Insight:**
Data Source: Camera
Exposure Mode: Frame Straddle
Capture Mode: Sequence
No. of Images: 500
Start number: 0
dT : 15 us
YAG1 : High
Q-switch 1 : 145 us*

YAG 2: High
Q-switch 2 : 175 us
Pulse Delay : 0.3049
Rep Rate: 1 Hz

*: 155: not too many vectors – yet saturated.

175: Saturation, but most number of choice 1 vectors and almost equal SNR Fail to 145.
However Frame A generated too much background noise.

145: less saturation, less background noise. Almost equal choice 1 vectors to Q = 175
Date: 1/02/2009
Flow Rate: 100gpm

**Camera:**

Distance /Exact Location : 6.75"

[0” of the Ruler was placed at join of black oxidized flange and SS flange towards the outer side. Look at calibration image mark on leftmost bottom side of the image and that will give you distance from the join. The outer side is towards the bottom of the image.]

Location: Downstream
Z-Location: Bottom
Station: 02
F # : 11
Zoom: 1\frac{1}{4} ft.
Field of View (from calib): 1.25"

**Set-up:**

Pump Frequency: 32.35 Hz
Upstream Pressure: 17.5 psi psig
Downstream Pressure: 09.2 psig
Water Temperature(S/End): 23.35/ 23.81 deg C
Seed: Hollow Glass Spheres
Amount: 2.5 caps.

**Insight:**

Data Source: Camera
Exposure Mode: Frame Straddle
Capture Mode: Sequence
No. of Images: 500
Start number: 0
dT : 15 us
YAG1 : High
Q-switch1 : 165 us*

YAG 2: High
Q-switch 2 : 175 us
Pulse Delay : 0.3049
Rep Rate: 1 Hz

*: 155: Not too much better than 145 in terms of choice vecs, SNR fail and u-vel std deviation.

175: More saturation and BN than 165 – almost equal SNR fail and Choice 1 vectors.

145: Some Saturation, some BN. Almost equal choice 1 vectors to Q = 165, but higher std. deviation in u-vel
Date: 1/02/2009
Flow Rate: 100gpm

**Camera:**
Distance /Exact Location : 5.5”

0” of the Ruler was placed at join of black oxidized flange and SS flange towards the outer side. Look at calibration image mark on leftmost bottom side of the image and that will give you distance from the join. The outer side is towards the bottom of the image.

Location: Downstream
Z-Location: Top
Station: 03
F # : 11
Zoom: 1 1/4 ft.
Field of View (from calib): 1.25”

**Set-up:**
Pump Frequency: 32.35 Hz
Upstream Pressure: 17.9 psig
Downstream Pressure: 9.4 psig
Water Temperature(S/End): 26.84 / 27.21 deg C
Seed: Hollow Glass Spheres
Amount: 2.5 caps.

**Insight:**
Data Source: Camera
Exposure Mode: Frame Straddle
Capture Mode: Sequence
No. of Images: 500
Start number: 0
dT : 15 us
YAG1 : High
Q-switch 1 : 175 us*

YAG 2: High
Q-switch 2 : 175 us
Pulse Delay : 0.3049
Rep Rate: 1 Hz

*: 175 had more choice 1 vectors and lesser SNR fail than any other values. Saturation, BN was almost same for all cases.
Date: 1/02/2009
Flow Rate: 100 gpm

**Camera:**
Distance /Exact Location : 5.5”

[0” of the Ruler was placed at join of black oxidized flange and SS flange towards the outer side. Look at calibration image mark on leftmost bottom side of the image and that will give you distance from the join. The outer side is towards the bottom of the image.]

Location: Downstream
Z-Location: Middle
Station: 03
F #: 11
Zoom: 1 1\(\frac{3}{4}\) ft.
Field of View (from calib): 1.25”

**Set-up:**
Pump Frequency: 32.35 Hz
Upstream Pressure: 17.9 psig
Downstream Pressure: 9.4 psig
Water Temperature(S/End): 26.25 / 26.70 deg C
Seed: Hollow Glass Spheres
Amount: 2.5 caps.

**Insight:**
Data Source: Camera
Exposure Mode: Frame Straddle
Capture Mode: Sequence
No. of Images: 500
Start number: 0
dT : 15 us
YAG1 : High
Q-switch1 : 165 us*

YAG 2: High
Q-switch 2 : 175 us
Pulse Delay : 0.3049

Rep Rate: 1 Hz

*: 165 had more choice 1 vectors and lesser SNR fail than any other values. Saturation, BN was almost same for all cases.
Date: 1/02/2009
Flow Rate: 100gpm

Camera:
Distance /Exact Location : 5.5”

[0” of the Ruler was placed at join of black oxidized flange and SS flange towards the outer side. Look at calibration image mark on leftmost bottom side of the image and that will give you distance from the join. The outer side is towards the bottom of the image.]

Location: Downstream
Z-Location: Bottom
Station: 03
F #: 11
Zoom: 1 1/4 ft.
Field of View (from calib): 1.25”

Set-up:
Pump Frequency: 32.35 Hz
Upstream Pressure: 17.9 psig
Downstream Pressure: 9.4 psig
Water Temperature(S/End): 25.5 / 25.97 deg C
Seed: Hollow Glass Spheres
Amount: 2.5 caps.

Insight:
Data Source: Camera
Exposure Mode: Frame Straddle
Capture Mode: Sequence
No. of Images: 500
Start number: 0
dT : 15 us
YAG1 : High
Q-switch1 : 145 us*

YAG 2: High
Q-switch 2 : 175 us
Pulse Delay : 0.3049
Rep Rate: 1 Hz

*: 155: Saturation, BN, Not too much better than 145 in terms of choice vecs, SNR fail
175: More saturation and BN than 165 – almost equal SNR fail and Choice 1 vectors
when compared to 145. Lesser u-vel SDev

165: Saturation, some BN. Almost equal choice 1 vectors to Q = 145
Date: 1/02/2009
Flow Rate: 100gpm

**Camera:**

Distance /Exact Location: 4.25"

[0" of the Ruler was placed at join of black oxidized flange and SS flange towards the outer side. Look at calibration image mark on leftmost bottom side of the image and that will give you distance from the join. The outer side is towards the bottom of the image.]

Location: Downstream

Z-Location: Top

Station: 04

F #: 11

Zoom: 1 1/4 ft.

Field of View (from calib): 1.25"

**Set-up:**

Pump Frequency: 32.35 Hz

Upstream Pressure: 17.9 psig

Downstream Pressure: 09.2 psig

Water Temperature(S/End): 28.06 / 28. 57 deg C

Seed: Hollow Glass Spheres

Amount: 2.5 caps.

**Insight:**

Data Source: Camera

Exposure Mode: Frame Straddle

Capture Mode: Sequence

No. of Images: 500

Start number: 0

dT : 15 us
YAG1 : High
Q-switch1 : 145 us*

YAG 2: High
Q-switch 2 : 175 us
Pulse Delay : 0.3049
Rep Rate: 1 Hz

*: 145 had more choice 1 vectors and lesser SNR fail than any other values. Saturation, BN was almost same for all cases.
Date: 1/02/2009
Flow Rate: 100gpm

**Camera:**
Distance /Exact Location : 4.25”
[0” of the Ruler was placed at join of black oxidized flange and SS flange towards the outer side. Look at calibration image mark on leftmost bottom side of the image and that will give you distance from the join .The outer side is towards the bottom of the image.]

Location: Downstream
Z-Location: Middle
Station: 04
F # : 11
Zoom: 1$\frac{1}{4}$ ft.
Field of View (from calib): 1.25”

**Set-up:**
Pump Frequency: 32.35 Hz
Upstream Pressure: 17.9 psig
Downstream Pressure: 09.2 psig
Water Temperature(S/End): 28.69 / 29.14 deg C
Seed: Hollow Glass Spheres
Amount: 2.5 caps.

**Insight:**
Data Source: Camera
Exposure Mode: Frame Straddle
Capture Mode: Sequence
No. of Images: 500
Start number: 0
dT : 15 us
YAG1 : High
Q-switch1 : 145 us*

YAG 2: High
Q-switch 2 : 175 us
Pulse Delay : 0.3049
Rep Rate: 1 Hz

*: 145 had same amt of particles in A and B. Increasing Q-switch value only increased background noise.
Date: 1/02/2009
Flow Rate: 100gpm

**Camera:**
Distance /Exact Location : 4.25"

[0” of the Ruler was placed at join of black oxidized flange and SS flange towards the outer side. Look at calibration image mark on leftmost bottom side of the image and that will give you distance from the join. The outer side is towards the bottom of the image.]

Location: Downstream
Z-Location: Bottom
Station: 04
F # : 11
Zoom: 1 1/4 ft.
Field of View (from calib): 1.25"

**Set-up:**
Pump Frequency: 32.35 Hz
Upstream Pressure: 17.9 psig
Downstream Pressure: 09.2 psig
Water Temperature(S/End): 29.79 / 30.23 deg C
Seed: Hollow Glass Spheres
Amount: 2.5 caps.

**Insight:**
Data Source: Camera
Exposure Mode: Frame Straddle
Capture Mode: Sequence
No. of Images: 500
Start number: 0
dT : 15 us
YAG1: High
Q-switch1: 175 us*

YAG 2: High
Q-switch 2: 175 us
Pulse Delay: 0.3049
Rep Rate: 1 Hz

*: 175 gave the best values of Choice 1 and SNR fail.
Date: 1/04/2009
Flow Rate: 100gpm

**Camera:**
Distance/Exact Location: 3”

> [0” of the Ruler was placed at join of black oxidized flange and SS flange towards the outer side. Look at calibration image mark on leftmost bottom side of the image and that will give you distance from the join. The outer side is towards the bottom of the image.]

Location: Downstream
Z-Location: Top
Station: 05
F #: 11
Zoom: 1 1/4 ft.
Field of View (from calib): 1.219”

**Set-up:**
Pump Frequency: 32.35 Hz
Upstream Pressure: 17.5 psig
Downstream Pressure: 09.2 psig
Water Temperature(S/End): 20. 70 / 21.12 deg C
Seed: Hollow Glass Spheres
Amount: 2.5 caps.

**Insight:**
Data Source: Camera
Exposure Mode: Frame Straddle
Capture Mode: Sequence
No. of Images: 500
Start number: 0
dT : 15 us
YAG1: High
Q-switch1: 175 us*

YAG 2: High
Q-switch 2: 175 us
Pulse Delay: 0.3049
Rep Rate: 1 Hz

*: 175 gave the best values of Choice 1 and SNR fail and least u-vel SD
Date: 1/04/2009
Flow Rate: 100gpm

**Camera:**
Distance /Exact Location : 3"

[0” of the Ruler was placed at join of black oxidized flange and SS flange towards the outer side. Look at calibration image mark on leftmost bottom side of the image and that will give you distance from the join .The outer side is towards the bottom of the image.]

Location: Downstream
Z-Location: Middle
Station: 05
F # : 11
Zoom: 1 1/4 ft.
Field of View (from calib): 1.219"

**Set-up:**
Pump Frequency: 32.35 Hz
Upstream Pressure: 17.5 psig
Downstream Pressure: 09.2 psig
Water Temperature(S/End): 19. 83 / 20.32 deg C
Seed: Hollow Glass Spheres
Amount: 2.5 caps.

**Insight:**
Data Source: Camera
Exposure Mode: Frame Straddle
Capture Mode: Sequence
No. of Images: 500
Start number: 0
dT : 15 us
YAG1: High
Q-switch1: 175 us*

YAG 2: High
Q-switch 2: 175 us
Pulse Delay: 0.3049
Rep Rate: 1 Hz

*: 175 gave the best values of Choice 1 and SNR fail and least u-vel SD
Date: 1/04/2009
Flow Rate: 100gpm

**Camera:**
Distance /Exact Location : 3"
[0” of the Ruler was placed at join of black oxidized flange and SS flange towards the outer side. Look at calibration image mark on leftmost bottom side of the image and that will give you distance from the join. The outer side is towards the bottom of the image.]

Location: Downstream
Z-Location: Bottom
Station: 05
F # : 11
Zoom: 1\(\frac{1}{4}\) ft.
Field of View (from calib): 1.219"

**Set-up:**
Pump Frequency: 32.35 Hz
Upstream Pressure: 17.5 psig
Downstream Pressure: 09.2 psig
Water Temperature(S/End): 19.00 / 19.58 deg C
Seed: Hollow Glass Spheres
Amount: 2.5 caps.

**Insight:**
Data Source: Camera
Exposure Mode: Frame Straddle
Capture Mode: Sequence
No. of Images: 500
Start number: 0
dT : 15 us
YAG1 : High
Q-switch1 : 175 us*

YAG 2: High
Q-switch 2 : 175 us
Pulse Delay : 0.3049
Rep Rate: 1 Hz

*: 175 gave the best values of Choice 1 and SNR fail and least u-vel SD
A.4  133 gpm

Date: 07/02/2009
Flow Rate: 133gpm

Camera:
Distance /Exact Location : 3.25"
[Ruler (8”mark) was placed at face of black oxidized flange towards test section. Look at calibration image mark on rightmost top side of the image and that will give you distance from the flange. Add the flange thickness to it.]

Location: Upstream
Z-Location: Middle
Station: 01
F #: 11
Zoom: 1 \(\frac{1}{4}\) ft.
Field of View (from calib): 1.25"

Set-up:
Pump Frequency: 41.9Hz
Upstream Pressure: 30.5 psig
Downstream Pressure: 14.38 psig
Water Temperature(S/End): 22.87/ 23.3deg C
Seed: Hollow Glass Spheres
Amount: 3 caps.

Insight:
Data Source: Camera
Exposure Mode: Frame Straddle
Capture Mode: Sequence
No. of Images: 500
Start number: 0

dT: 20 us

YAG1: High

Q-switch1: 160 us

YAG 2: High

Q-switch 2: 175 us

Pulse Delay: 0.3048

Rep Rate: 1 Hz
Date: 07/02/2009
Flow Rate: 133gpm

**Camera:**
Distance /Exact Location: 0 to 15

*[The calibration image “a” will give the exact demarcations of the 0 degree and 15 lines since it is focused on the metal strips. Calibration image “b” serves as a check since it is focused on the channel boundaries]*

Location: Bend
Z-Location: Middle
Station: 01
F #: 11
Zoom: $1 \frac{1}{4}$ ft.
Field of View (from calib): 1.25"

**Set-up:**
Pump Frequency: 41.9Hz
Upstream Pressure: 30.96 psig
Downstream Pressure: 14.63 psig
Water Temperature(S/End): 24.11 / 24.7 deg C
Seed: Hollow Glass Spheres
Amount: 3 caps.

**Insight:**
Data Source: Camera
Exposure Mode: Frame Straddle
Capture Mode: Sequence
No. of Images: 500
Start number: 0
dT: 10 us
YAG1: High
Q-switch1: 175us
YAG 2: High
Q-switch 2: 175us
Pulse Delay: 0.3048
Rep Rate: 1 Hz
Date: 07/05/2009
Flow Rate: 133gpm

**Camera:**
Distance /Exact Location : 75 to 90 deg window

*The calibration image “a” will give the exact demarcations of the 75 degree and 90 lines since it is focused on the metal strips. Calibration image “b” serves as a check since it is focused on the channel boundaries*

Location: Bend
Z-Location: Middle
Station: 06
F # : 11
Zoom: 1\(\frac{1}{4}\) ft.
Field of View (from calib): 1 ”

**Set-up:**
Pump Frequency: 41.9 Hz
Upstream Pressure: 31.1 psig
Downstream Pressure: 14.72 psig
Water Temperature(S/End): 23.23 /23.99 deg C
Seed: Hollow Glass Spheres
Amount: 3 caps.

**Insight:**
Data Source: Camera
Exposure Mode: Frame Straddle
Capture Mode: Sequence
No. of Images: 500
Start number: 0
dT : 10 us
YAG1 : High
Q-switch1 : 175 us

YAG 2: High
Q-switch 2 : 175 us
Pulse Delay : 0.3049

Rep Rate: 1 Hz
Date: 07/05/2009

Flow Rate: 133gpm

**Camera:**

Distance /Exact Location : 5.5”

“0” of the Ruler was placed at join of black oxidized flange and SS flange towards the outer side. Look at calibration image mark on leftmost bottom side of the image and that will give you distance from the join. The outer side is towards the bottom of the image.

Location: Downstream
Z-Location: Middle
Station: 03
F #: 11
Zoom: 1 1/4 ft.
Field of View (from calib): 1.25”

**Set-up:**
Pump Frequency: 41.9 Hz
Upstream Pressure: 30.44 psig
Downstream Pressure: 14.8 psig
Water Temperature(S/End): 24.28 / 24.76deg C
Seed: Hollow Glass Spheres
Amount: 3 caps.

**Insight:**
Data Source: Camera
Exposure Mode: Frame Straddle
Capture Mode: Sequence
No. of Images: 500
Start number: 0
dT : 10 us
YAG1: High
Q-switch 1: 175 us*

YAG 2: High
Q-switch 2: 175 us
Pulse Delay: 0.3049
Rep Rate: 1 Hz
% CHANGE FILENAMES TO BE COMPATIBLE FOR INSIGHT 3G FORMAT

% This code takes the files from the original folder containing them and
% uses DOS’s COPY command to copy them in the same folder with the new name
% allotted.

%Written by Preyank Sheth 02/10/2009 with selected parts borrowed/edited from
%copyab.am* and remove_bad_data.m by Andrew Knisely

% NOMENCLATURE:
% Pathname is directory path
% d = structure containing file information.
% i = Counter for number of original files
% k = Counter for Capturenumber (eg Capture0000k.T000....)

clear
clc
Enter folder where files to be modified are stored.

`[filename, pathname] = uigetfile('*.*', 'Navigate to folder and select any file');`

Chooses all the tif files from the folder.

```matlab
d = dir(strcat(pathname, '*.tif'));
```

Chooses all the tif files from the folder.

```matlab
fprintf('%d', length(d))
k = 0;
```

% put waitbar

Change directory to that from where files are obtained for DOS cmd to work.

```matlab
cd (pathname)
i = 1
while (i <= length(d))
    k = k + 1;
    dos(["ren ", d(i).name, ' ",...
         sprintf('Capture%06d.T000.D000.P000.H001.LA.tif', k)];
    fprintf('%s', d(i).name)
    i = i + 1
    dos(["ren ", d(i).name, ' ",...
         sprintf('Capture%06d.T000.D000.P000.H001.LB.tif', k)];
    fprintf('%s', d(i).name)
    i = i + 1
end
```

% END OF CODE

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% POSSIBILITY OF SUCH DAMAGE.
B.2 Vector Processing GUI

```matlab
% GUI
% This is a GUI used to clean, average and perform other statistical analysis on the fluid data collected. It first displays a menu asking % user for which action they would like to perform.
%
% It is necessary to complete the first 3 steps in order in order to get % the data in the right format which is read by the statistics functions. % The user can stop at any time and the program will ask for needed paths % if they should want to resume calculations later.
%
% The statistics menu will display a series of buttons to perform % statistical calculations on the data. It is important to have this data % in the required format shown here:
%
% x pixel, y pixel, u instantaneous, v instantaneous, CHC, row index, u % deviation, v deviation, U mean, V mean
%
% Created: Andrew Knisely 04−01−09
% Edited: Preyank Sheth 06−19−09
%
% Concepts relating to coding structure derived from codes by D. Hill and % G. Walters

clc
clear

% Initialize variables needed during GUI.m
run.main = 1;
processed.path = 0;
```
while run_main == 1
    main_menu = menu('What would you like to perform?',...
    'Initial data processing','Average Velocities',...
    'Velocity Deviation Calculations','Statistics Calculations',...
    'End Program');
    switch main_menu

    case 1
        processed_path = identifier;
    end

    % Convert path name into proper form
    processed_path = [processed_path,'\'];

    case 2
    % This case finds the average velocity values of the data and
    % creates two new vec files
        if processed_path == 0
            processed_path = uigetdir('',...
            'Please choose the path of processed files');
        end
    end

    % Convert path name into proper form
    processed_path = [processed_path,'\'];
end
stat_path = average_velocity_field_c(processed_path);

case 3
% Run calculations of deviances from the mean.
if stat_path == 0
    stat_path = uigetdir('', 'Please choose the path of statistic files');

% Convert path name into proper form
    stat_path = [stat_path, '\'];
end
    if processed_path == 0
        processed_path = uigetdir('', 'Please choose the path of processed files');

% Convert path name into proper form
    processed_path = [processed_path, '\'];
end
average_extra = u_calc(stat_path, processed_path);

case 4
% Toggle for running statistics menu
    run_stat = 1;

while run_stat == 1
    % creation of statistics menu
    stat_menu = menu('What calculation would you like to perform?', ...
            'RMS', 'Variance', 'Standard Deviation', 'Turbulence Intensity', ...
            'Re Stresses', 'Skewness', 'Kurtosis', 'Return to main menu', ...
            'End program');

% Check to make sure the needed paths have non-zero values and if not then ...
% they present a dialog box for the user to select the needed file
if (stat_menu ≠ 5) && (stat_menu ≠ 8) && (stat_menu ≠ 9)
    if average_extra == 0
        [average_extra, stat_path] = uigetfile('*.*',...
            'Navigate to statistics folder and',...
            'select the "extra" mean velocity file');
    end
    if stat_path == 0
        [average_extra, stat_path] = uigetfile('*.*',...
            'Navigate to statistics folder and select the "extra" mean velocity file');
    end
    if processed_path == 0
        [first_clean_file, processed_path] = uigetfile('*.*',...
            'Select first processed velocity data file');
    end
end

if (stat_menu == 5)
    if processed_path == 0
        [first_clean_file, processed_path] = uigetfile('*.*',...
            'Select first processed velocity data file');
    end
end

if (stat_menu == 6) || (stat_menu == 7)
    if stddev == 0
        [stddev, SD_path] = uigetfile('*.*',...
            'Select the Std Dev file from the statistics folder');
    end
end

switch stat_menu
    case 1
        rms_calc(stat_path,...
average_extra, processed_path)
% variance calculation
case 2
    variance_calc(stat_path, ...
    average_extra, processed_path)
% Standard deviation calculation
    std_dev_calc(stat_path, ...
    average_extra, processed_path)
% turbulence intensity calculation
    turb_intensity_calc(stat_path, ...
    average_extra, processed_path)
% uvbar
    uvfluctuations_average(processed_path)
% Skewness calculation
    skewness_calc(stat_path, average_extra, ...
    processed_path, stddev)
% Skewness calculation
    kurtosis_calc(stat_path, average_extra, ...
    processed_path, stddev)
% return to main menu
    case 8
    run_stat = 0;
% exit the program
    case 9
    run_stat = 0;
    run_main = 0;
    end
    end
if run_main ≠ 0
run_main = 1;
end

% exit the program from the main menu
case 5
    run_main = 0;
end
end
B.3 Generating Velocity Data from PIV Information

function directory_name = identifier

% This processes the raw data, copies it and adds line index values. First
% the program asks for the locations of the raw data and the folder in
% which you would like to save the processed data. It then opens up all
% the files in order, checks and saves the x,y position data and then saves
% the data as a new file with add row indexes which are used in later
% functions.

% Created by: Andrew Knisely 04−07−09
% Edited: Preyank Sheth 06−15−09
%
% Concepts relating to coding structure derived from codes by D. Hill and
% G. Walters

% Input the files. (Taken from meanfield.m)
[filename_raw,pathname_raw]=uigetfile('*.','...

    'Navigate to folder and select any raw data file (*.vec'));
D=dir(strcat(pathname_raw,'*.vec'));
umfiles=length(D);

% Add pathname of folder for the new files.
directory_name = uigetdir(pathname_raw,...

    'Please choose parent folder of the raw data folder');

% Create folder if none exists
if ~exist([directory_name, '\Processed_data\statistics']) %#ok<EXIST>
    mkdir(directory_name,'Processed_data\statistics');
end
directory_name = ['directory_name, 'Processed_data'];

info_num = zeros(numfiles,4);

% Temporarily open up the 1st raw file, to grab the header line and determine "numx" which is used later in code.
origfile=D(1).name;
fid=fopen(strcat(pathname_raw,origfile),'r');
headerline=fgetl(fid);
equal=find(headerline=='=');
numx=str2double(cellstr(headerline(equal(6)+1:equal(7)-4)));
% numy=str2double(cellstr(headerline(equal(7)+1:F-2)));
info = strvcat('delx, x0, dely, y0'); %#ok<VCAT>
fclose(fid);

% User input to determine local velocities and global velocities and
% positions
loc = input('Specify region of interest(enter 0 for upstream, 1 for bend or 2 for downstream): ');
dt = input('Please enter dT value in microseconds: ');
mag = input('Please enter the magnification of the photo in pixels/mm: ');

xofmm = input('Please enter the x offset in inches: ');

xofmm = xofmm * 25.4; % conversion between inches and mm
yofmm = input('Please enter the y offset in inches: ');

yofmm = yofmm * 25.4; % conversion between inches and mm
theta = input('Please enter the rotation (anticlockwise) in degrees: ');
% how much you would have to rotate the local X for it to be // to global x
theta = theta * pi/180;

% Loop to go through all the files found within the folder
h=waitbar(0,'Please wait while files are processed...');
for k = 1:numfiles

    % Opens the file
    filename_raw = D(k).name;
    fid=fopen(strcat(pathname_raw, filename_raw), 'r');

    % Reads the data
    headerline=fgetl(fid);
    data=textscan(fid, '%f %f %f %f %f', 'delimiter', ',');
    fclose(fid);

    J=(1:length(data{1}));'

    % Finds corresponding x,y positions and U,V velocity values
    x_pos = data{1};
    y_pos = data{2};
    u_tilde = data{3};
    v_tilde = data{4};
    type = data{5};
    line_value = J;

    % find valid data
    good = find(type>0);

    % Test for delx, x0, dely, y0
    info_num(k,1) = data{1}(2)−data{1}(1);
    info_num(k,2) = min(data{1});
    info_num(k,3) = data{2}(1)−data{2}(numx+1);
    info_num(k,4) = max(data{2});

    % initialize local velocities and global velocities vectors
    ulms = u_tilde;
    vlms = v_tilde;
ugms = u_tilde;
vgms = v_tilde;

%PS
usms = ugms;
unms = vgms;

% Solve for local velocities
ulms(good,1) = u_tilde(good,1)*1000/(dt*mag);
vlms(good,1) = v_tilde(good,1)*1000/(dt*mag);

% solve for global velocities
% CHANGE
ugms(good,1) = (ulms(good,1)*cos(theta))+(vlms(good,1)*sin(theta));
% CHANGE
vgms(good,1) = (-ulms(good,1)*sin(theta))+(vlms(good,1)*cos(theta));

% solve for global coordinates
% added error adjustments on 6/8/09
xgmm = xofmm + (x_pos*cos(theta)+y_pos*sin(theta))/mag;
% CHANGE
ygmm = yofmm + (-x_pos*sin(theta)+y_pos*cos(theta))/mag;

% Rmean = 4" = 101.6 mm ; 2" = 50.8 mm
if loc == 0 %Upstream
    theta2 = pi/2*ones(size(ygmm));
    smm = xgmm;
    nmm = ygmm-101.6;
elseif loc == 1 %in the bend
    for i = 1:length(xgmm)
        if xgmm(i,1) == 0
            theta2(i,1) = pi/2;
        end
    end
end
else
    theta2(i,1) = atan(ygmm(i,1)./xgmm(i,1));
end

smm = 101.6*(pi/2)-theta2;
nmm = (sqrt(xgmm.^2+ygmm.^2))-101.6;

elseif loc == 2 % downstream
    theta2 = (0*pi/180)*ones(size(ygmm));
    smm = 50.8*pi-ygmm;
nmm = xgmm-101.6;
end

usms(good,1) = (ugms(good,1).*sin(theta2(good,1)))... - (vgms(good,1).*cos(theta2(good,1)));
unms(good,1) = (ugms(good,1).*cos(theta2(good,1)))... + (vgms(good,1).*sin(theta2(good,1)));

% Create new file name and new headerline
temp_name = filename_raw(1:end-4);
new_outname = [temp_name '_processed.vec'];
temp_header = [headerline(1:equal(2)+23),...
    '"U lms", "V lms", "CHC", "Line Index", ...
    '"X global", "Y global", "U gms", "V gms", "Smm", ...
    '"Nmm", "U sms", "U nms" ',headerline(equal(3)-6:end)];

% Save processed file in processed data folder;
fid=fopen([directory_name,'\',new_outname,'wt']);
fprintf(fid,'%s\n', temp_header);
fprintf(fid,'%f, %f, %f, %f, %d, %d, %f, %f, %f, %f, %f, %f\n', ...
    [x_pos y_pos ulms vlms type line_value xgmm ygmm...
     ugms vgms smm nmm usms unms ]);
fclose(fid);
waitbar(k/numfiles,h);
end
close(h)

% Create and save a statistic text file that contains the delx, x0, dely, % and y0 values.
fid=fopen(strcat(directory_name, 'statistics\'),'wt');
fprintf(fid,'%s
', headerline);
fprintf(fid,'%s
', info);
fprintf(fid,'%d, %d, %d, %d
', info num);
fclose(fid);
B.4 Average Velocity

```matlab
function average_path = average_velocity_field_c(pathname)

% Average velocity field generator This program opens up all the cleaned
% captured files in a folder and averages the velocities at a specific
% point. After getting input from the user it then initializes the average
% matrices and then performs a loop to sum the values at a specific point.
% After summing at every point the average for each individual point is
% taken, bad data is removed and a matrix containing the original x,y
% positions is made. This is all then saved in a new file with the name
% average file

% Written by Andrew Knisely with selected parts taken from D. Hill and G.
% Walters
% Edited by Preyank Sheth on 5/28/09 to allow S,N velocities when calculating
% global u-v velocities.

% Inputs: processed path

% Created: 2-19-09

D = dir(strcat(pathname,'*.vec'));
numfiles = length(D);

% From meanfield.m !!!
%%%%%%%%%%%%%%%%%%%%%%%

% temporarily open 1st file to grab the header line and then close file
origfile=D(1).name;
fid=fopen(strcat(pathname,origfile),'r');
headerline=fgetl(fid);
```

fclose(fid);

equal=find(headerline=='=');
F=find(headerline=='F');

numx=str2double(cellstr(headerline(equal(6)+1:equal(7)-4)));
% <= should this be -3 or -4
numy=str2double(cellstr(headerline(equal(7)+1:F-2)));

% Code to get delx, dely from header - not used anymore.
% x0=str2double(cellstr(headerline(equal(10)+1:equal(10)+2)));
% y0=str2double(cellstr(headerline(equal(12)+1:equal(12)+4)));
% delx=str2double(cellstr(headerline(equal(9)+1:equal(9)+2)));
% dely=str2double(cellstr(headerline(equal(11)+1:equal(11)+2)));

% Modified from meanfield.m create a vector of the size of the raw data in
% its original form
data_size=zeros(numx*numy,1);

% Initializing output data matrices
Uave = data_size;
Vave = data_size;
Usave = data_size;
Vnave = data_size;
CHCave = -1*ones(size(data_size));
ave_count = data_size;
% xloc = data_size;
% yloc = data_size;
% global_values = -1;
% while global_values!=1 | global_values 0
global_values = input...('Would you like to use the local(UxL,UyL) or global velocities (Uxg,Vyg,Us,Un)
(Enter 0 for local, 1 for global):');
% Summation loop for velocities at specific points

% end
s = data_size;
n = data_size;
\n% Summation loop for velocities at specific points

g=waitbar(0,'Please wait while average velocities are calculated...');

for j = 1:numfiles;

waitbar(j/numfiles,g);

% Opens the next file for each iteration of the loop and reads the data
% into variable 'data'
filename = D(j).name;
 fid=fopen(strcat(pathname,filename),'r');

% Opens the next file for each iteration of the loop and reads the data
% into variable 'data'

    data=textscan(fid,...
    '%f %f %f %f %f %f %f %f %f %f %f %f %f %f','headerlines',1,'delimiter',',');
    fclose(fid);

% Input local or global locations
if j==1;
    if global_values == 0
        x = data{1};
        y = data{2};
    elseif global_values == 1
        x = data{7};
        y = data{8};
        s = data{11};
        n = data{12};
    end
end

% Input the data from the opened file of velocities and line index
if global_values == 0
    U = data{3};
V = data{4};

elseif global_values == 1
    U = data{9};
    V = data{10};
    Us = data{13};
    Vn = data{14};

    Usave(avg_line_index,1) = Us(avg_line_index) + ...
    Vnave(avg_line_index,1) = Vn(avg_line_index) + ...
    CHCave(avg_line_index,1) = 1;
    line_count = line_count + 1;
end

CHC = data{5};
J = find(CHC>0);
data_index = data{6}(J);

% Loop to compare each line to the index that was given to each piece of
% data during the cleaning of the file.
line_count = 1;
for avg_line_index = min(J):max(J)
    if data_index(line_count,1)==avg_line_index
        Uave(avg_line_index,1) = U(avg_line_index) + ...
        Vave(avg_line_index,1) = V(avg_line_index) + ...
        Usave(avg_line_index,1) = Us(avg_line_index) + ...
        Vnave(avg_line_index,1) = Vn(avg_line_index) + ...
        ave_count(avg_line_index,1) = ave_count(avg_line_index,1) + 1;
        CHCave(avg_line_index,1) = 1;
        line_count = line_count + 1;
    end
   end
   end
   136  close(g);
   137
   138  % Averaging the values
   139  Uave = Uave./ave_count;
   140  Vave = Vave./ave_count;
   141  Usave = Usave./ave_count;
   142  Vnave = Vnave./ave_count;
   143  % Assign large value to locations with no valid data
   144  J = data_size;
   145  for K = 1:length(data_size);
   146      if CHC_ave(K,1) == -1
   147          Uave(K,1) = 9900000256;
   148          Vave(K,1) = 9900000256;
   149          Usave(K,1) = 9900000256;
   150          Vnave(K,1) = 9900000256;
   151      end
   152      J(K,1) = K;
   153  end
   154
   155  % Save two new average velocity files, first one in original raw data
   156  % format, second file with added row index and data count information.
   157  158  % New header line and average file containing only original data
   159  % information
   160  temp_head = [headerline(1:equal(2)+23),'"Uavg", "Vavg", "CHC", ',...
   161  headline(equal(3)-6:end)];
   162  if global_values == 1
   163      temp_head = [headerline(1:equal(2)+1),'"X global",'
   164          '"Y global", "Ugxavg", "Vgyavg", "CHC", ',...
   165          headline(equal(3)-6:end)];
   166
fid=fopen(strcat(pathname,'statistics\average.data.vec'),'wt');
fprintf(fid,'%s
', temp.head);
fprintf(fid,'%f, %f, %f, %f, %d
', [x y Uave Vave CHC_ave]);
fclose(fid);

% New header line and average file containing expanded data information

% Define path for statistical information to be returned by function
average_path = [pathname,'statistics\'];
B.5 Turbulent Fluctuations

```matlab
function avg_ext_file = u_calc(statistics_pathname, processed_pathname)
% Calculate u
% This m-file compares each cleaned file with the mean file and appends the
% cleaned file with the difference between the instantaneous velocity and
% the mean velocity
%
% Written by Andrew Knisely with selected parts taken borrowed from D. Hill
% and G. Walters
%
% Created: 3-15-09
% Edited: 4-13-09

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Requests the "extra" average velocity vec file in order to save the path
% correctly as well as get the mean data
[avg_ext_file, statistics_pathname] = uigetfile('*./*', ...
'Navigate to folder and select the "extra" mean velocity file', ...
statistics_pathname);
fid = fopen(strcat(statistics_pathname, avg_ext_file), 'r');

% Read the data and save the needed mean velocities and data index values
mean_data = textscan(fid, '%f %f %f %f %f %f %f %f %f %f %f', ...
'headerlines', 1, 'delimiter', ',');

U_mean = mean_data{3};
V_mean = mean_data{4};
Us_mean = mean_data{10};
Vn_mean = mean_data{11};
data_index_mean = mean_data{6};
```
fclose(fid);

% Intialize coordinate system to local or global as determined by the
% information in the mean data file.
global_values = input('Would you like to use local or global velocities to calculate fluctuations?
(enter 0 for local, 1 for global):
');

D = dir(strcat(processed_pathname,'*.vec'));
numfiles = length(D);

h=waitbar(0,'Please wait while velocity fluctuations are being calculated');
for j=1:numfiles

  % Opens the next file for each iteration of the loop and reads the data
  % into variable 'data'
  filename = D(j).name;
  fid=fopen(strcat(processed_pathname,filename),'r');
  headerline=fgetl(fid);
  equal=find(headerline=='=');
  data=textscan(fid,'%f %f %f %f %f %f %f %f %f %f %f %f %f %f %f %f %f %f %f %f %f %f %f','
    'delimiter','
');
  fclose(fid);

  % Input the data from the opened file of velocities and line index
  x_pos = data{1};
  y_pos = data{2};
  u_lms = data{3};
  v_lms = data{4};
  CHC = data{5};
  data_index = data{6};
xgmm = data[7];
ygmm = data[8];
ugms = data[9];
v_gms = data[10];
smm = data[11];
nmm = data[12];
usms = data[13];
unms = data[14];

% Initialize the matrix that will contain the velocity deviations
u_fluctuation = zeros(size(u_lms));
v_fluctuation = zeros(size(u_lms));
us_fluctuation = zeros(size(u_lms));
v_n_fluctuation = zeros(size(u_lms));

% Calculate the variations by comparing the instantaneous velocity to
% the mean velocity
for k = 1:length(data_index_mean)
    if global_values == 0
        u_fluctuation(k,1) = u_lms(k,1) - U_mean(k,1);
        v_fluctuation(k,1) = v_lms(k,1) - V_mean(k,1);
    elseif global_values == 1
        u_fluctuation(k,1) = u_gms(k,1) - U_mean(k,1);
        v_fluctuation(k,1) = v_gms(k,1) - V_mean(k,1);
        us_fluctuation(k,1) = u_sms(k,1) - Us_mean(k,1);
        v_n_fluctuation(k,1) = u_nms(k,1) - Vn_mean(k,1);
    else
        us_fluctuation(k,1) = u_sms(k,1) - Us_mean(k,1);
        % vs_fluctuation(k,1) = u_nms(k,1) - Vn_mean(k,1);
    % else
    %     vs_fluctuation(k,1) = u_nms(k,1) - Vn_mean(k,1);
    end
end
% Locate points in which there is no valid data and reset its value to
% the overly large value.
bad = find(CHC<1);
u_fluctuation(bad,1) = 9900000256;
v_fluctuation(bad,1) = 9900000256;
us_fluctuation(bad,1) = 9900000256;
vn_fluctuation(bad,1) = 9900000256;

% Create a temporary header name to include fluctuations in the title
if global_values == 0
    temp_head = [headerline(1:equal(3)-7),
                 '"U lms fluctuation",
                 '"V lms fluctuation",
                 '"U lms mean",
                 '"V lms mean",
                 headerline(equal(3)-7:end)];
elseif global_values == 1
    temp_head = [headerline(1:equal(3)-7),
                 '"U gms fluctuation",
                 '"V gms fluctuation",
                 '"U mean",
                 '"V mean",
                 '"U sms fluctuation",
                 '"U nms fluctuation",
                 '"U sms mean",
                 '"U nms mean",
                 headerline(equal(3)-7:end)];
end

% Update the processed data file with the u,v fluctuations
fid=fopen(strcat(processed_pathname,filename),'wt');
fprintf(fid,'%s
', temp_head);
fprintf(fid,...
'/gif, %f, %f, %f, %d, %d, %f, %f, %f, %f, %f, %f, %f, %f, %f, %f, %f, %f, %f, %f, %f
[x_pos y_pos u_lms v_lms CHC data_index xgmm ygmm u_gms v_gms...
  smm nmm u_sms u_nms u_fluctuation v_fluctuation U_mean V_mean...
  us_fluctuation vn_fluctuation Us_mean Vn_mean']);
close(fid);
waitbar(j/(numfiles),h);
end

close(h)
B.6 Turbulence Statistics

B.6.1 RMS

```matlab
function rms_calc(pathname_stat,average_data_extra,process_path)

% Calculation of RMS
% This m-file calculates RMS.
% It first inputs the path data from the GUI.
% The function then performs a loop to read all the data available.
% Lastly, any points which there is no valid data will are set to value
% of 9900000256


% Written: Andrew Knisely
% Edited: Preyank Sheth
% Created: 3-16-09
% Edited: 05-05-09

% Opens open the average data velocity file and gets the header line and mean data
fid=fopen(strcat(pathname_stat,average_data_extra),'r');
headerline_mean=fgetl(fid);
equal=find(headerline_mean=='=');
F=find(headerline_mean=='F');
mean_data=textscan(fid,'%f %f %f %f %f %f %f %f %f %f %f','delimiter',',');

% user input of which coordinate system to display the statistics in
vel_sys = input('Would you like to use local or global velocities\n(enter 0 for local, 1 for global): ');

if vel_sys == 1
    s_pos_m = mean_data{8};
n_pos_m = mean_data{9};
x_pos_m = mean_data{1};
```

y.pos_m = mean_data{2};
end
CHC.mean = mean_data{5};
data_count = mean_data{7};
fclose(fid);

% create a vector of the size of the raw data in its original form for
% storing the rms values
rms_u = zeros(size(x.pos_m));
rms_v = zeros(size(x.pos_m));
rms_us = zeros(size(x.pos_m));
rms_vn = zeros(size(x.pos_m));

h=waitbar(0,'Please wait while RMS is calculated...');

D = dir(strcat(process_path,'*.vec'));
numfiles = length(D);

% open the processed data files and store velocity information
for j=1:numfiles

% Opens the next file for each iteration of the loop and reads the data
% into variable 'data'
filename = D(j).name;
 fid=fopen(strcat(process_path,filename),'r');
 data=textscan(fid,...
'f%f%f%f%f%f%f%f%f%f%f%f%f%f%f%f%f%f%f%f%f%',...'
'headerlines',1,'delimiter',',');
 fclose(fid);

% Save relevant data from file into the workspace
% if cord.sys == 0
 % x.pos_m = data{1};
% y_pos_m = data[2];
% end

if vel_sys == 0
    x_pos_m = data[1];
    y_pos_m = data[2];
    u_fluc = data[3];
    v_fluc = data[4];
    us_fluc = zeros(size(x_pos_m));
    vn_fluc = zeros(size(x_pos_m));
elseif vel_sys == 1
    u_fluc = data[15];
    v_fluc = data[16];
else
    us_fluc = data[19];
    vn_fluc = data[20];
end

CHC = data[5];
data_index = data[6];

% Loop to sum velocity values for specific points
for count = 1:length(data_index);
    if CHC(count,1)>0
        rms_u(count,1) = rms_u(count,1) + u_fluc(count,1)^2;
        rms_v(count,1) = rms_v(count,1) + v_fluc(count,1)^2;
        rms_us(count,1) = rms_us(count,1) + us_fluc(count,1)^2;
        rms_vn(count,1) = rms_vn(count,1) + vn_fluc(count,1)^2;
    end
end

waitbar(j/(numfiles),h);
end

close(h)
% Calculate RMS velocity
rms_u = sqrt(rms_u./data_count);
rms_v = sqrt(rms_v./data_count);
rms_us = sqrt(rms_us./data_count);
rms_vn = sqrt(rms_vn./data_count);

% find rows in which bad data is found using the CHC code and then set
% the rms value to large value
bad = find(CHC_mean<1);
rms_u(bad,1) = 9900000256;
rms_v(bad,1) = 9900000256;
rms_us(bad,1) = 9900000256;
rms_vn(bad,1) = 9900000256;

% create the temporary header that will replace the header from average file
if vel_sys == 0
    temp_header = [headerline_mean(1:equal(2)+1),...
        '"X pixel", "Y pixel", "u RMS", "v RMS", "CHC", "Average Count","...'
        headerline_mean(equal(3)−6:end)];
    fid=fopen(strcat(pathname_stat,'rms.vec'),'wt');
    fprintf(fid,'%s\n', temp_header);
    fprintf(fid,'%f, %f, %f, %f, %d, %d
',...
        [x_pos_m y_pos_m rms_u rms_v CHC_mean data_count]);
    fclose(fid);
elseif vel_sys == 1
    temp_header = [headerline_mean(1:equal(2)+23),...
        ', "ug RMS", "vg RMS", "CHC", "Average Count", "Smm",'
        '"Nmm", "usms RMS", "unms RMS", ",...'
        headerline_mean(equal(3)−6:end)];
    fid=fopen(strcat(pathname_stat,'rms.vec'),'wt');
    fprintf(fid,'%s\n', temp_header);
    fprintf(fid,'%f, %f, %f, %f, %d, %d
',...
        [x_pos_m y_pos_m rms_u rms_v CHC_mean data_count]);
    fclose(fid);
[x_pos_m y_pos_m rms_u rms_v CHC mean data count s_pos_m... 
  n_pos_m rms_us rms_vn ];
  fclose(fid);
end

% save the data in the statistics folder
B.6.2 Turbulence Intensities

function turb_intensity_calc(pathname_stat,average_data_extra,process_path)

% Calculate Turbulence Intensity (I)
% This m-file calculates Turbulence Intensity.
% It first inputs the path data from the GUI.
% The function then performs a loop to read all the data available.
% Lastly, any points which there is no valid data will be set to value
% of 9900000256

% Written: Andrew Knisel
% Edited: Preyank Sheth
% Created: 3−27−09
% Edited: 05−05−09

% Opens open the average data velocity file and gets the headerline and mean data
fid=fopen(strcat(pathname_stat,average_data_extra),'r');
headerline_mean=fgetl(fid);
equal=find(headerline_mean=='=');
F=find(headerline_mean=='F');
mean_data=textscan(fid,'%f %f %f %f %f %f %f %f %f %f %f','delimiter',',');

x_pos_m = mean_data{1};
y_pos_m = mean_data{2};
s_pos_m = mean_data{8};
n_pos_m = mean_data{9};
U_mean = mean_data{3};
V_mean = mean_data{4};
Us_mean = mean_data{10};
Vn\_mean = mean\_data[11];
CHC\_mean = mean\_data[5];
data\_count = mean\_data[7];
fclose(fid);

% create a vector of the size of the raw data in its original form
% to store turbulence intensity values
TI\_u = zeros(size(x\_pos\_m));
TI\_v = zeros(size(x\_pos\_m));
TI\_us = zeros(size(x\_pos\_m));
TI\_vn = zeros(size(x\_pos\_m));

% set variables used to open processed files
D = dir(strcat(process\_path,'*.vec'));
numfiles = length(D);

h=waitbar(0,'Please wait while Turbulence Intensity is calculated...');

% open the processed data files and store velocity information
\text{for}\ j=1:\text{numfiles}

% Opens the next file for each iteration of the loop and reads the data
% into variable 'data'
filename = D(j).name;
fid=fopen(strcat(process\_path,filename),'r');
data=textscan(fid,...
'labellines',1,'delimiter','
fclose(fid);

% Save relevant data from file
CHC = data[5];
data\_index = data[6];
% save data in turbulence intensity matrix
for count = 1:length(data_index);
    if CHC(count,1)>0
        TI_u(count,1) = TI_u(count,1) + u_fluctuations(count,1)^2;
        TI_v(count,1) = TI_v(count,1) + v_fluctuations(count,1)^2;
        TI_us(count,1) = TI_us(count,1) + us_fluctuations(count,1)^2;
        TI_vn(count,1) = TI_vn(count,1) + vn_fluctuations(count,1)^2;
    end
end
waitbar(j/(numfiles),h);
end
close(h)

% Calculation of Turbulence Intensity Numerator
TI_u = TI_u./data_count;
TI_v = TI_v./data_count;
TI_us = TI_us./data_count;
TI_vn = TI_vn./data_count;
TI_num = sqrt(0.5*(TI_u + TI_v));
TI_numcurv = sqrt(0.5*(TI_us + TI_vn));

% Calculation of Turbulence Intensity Denominator
vel_mean = sqrt(U_mean.^2 + V_mean.^2);
vel_meancurv = sqrt(Us_mean.^2 + Vn_mean.^2);
Combining Numerator and Denominator and Save Information

\[ T_\text{I} = \frac{T_\text{I}_{\text{num}}}{\text{vel}_{\text{mean}}}; \]

\[ T_{\text{Icurv}} = \frac{T_\text{I}_{\text{numcurv}}}{\text{vel}_{\text{meancurv}}}; \]

% find rows in which bad data is found using the CHC code and then set
% the turbulence intensity value to large value

bad = find(CHC_{\text{mean}} < 1);

\[ T_{\text{I}}(\text{bad},1) = 9900000256; \]

\[ T_{\text{Icurv}}(\text{bad},1) = 9900000256; \]

% create the temporary header that will replace the header from average

temp_header = ['headerline_{\text{mean}}(1:equal(2)+23),'
', 'Turbulence Intensity', 'CHC', 'Average Count', 'Smm', 'Nmm',',
''Curvilinear Turbulence Intensity',',headerline_{\text{mean}}(equal(3)-6:end)];

% save the data in the statistics folder

fid=fopen(strcat(pathname_{\text{stat}},'TI.vec'),'wt');
fprintf(fid,'%s
', temp_header);
fprintf(fid,'%f, %f, %f, %d, %d, %f, %f, %f
',
[x_{\text{pos}} \text{m} y_{\text{pos}} \text{m} T_{\text{I}} \text{CHC}_{\text{mean}} \text{data}_{\text{count}} s_{\text{pos}} \text{m} n_{\text{pos}} \text{m} T_{\text{Icurv}}]);
fclose(fid);
B.6.3 Reynolds Shear Stress

```matlab
function uvfluctuations_average(pathname)
% uvbar generator. This program opens up all the cleaned
% captured files in a folder and averages the product of the uv fluctuations
% at each point. After getting input from the user it then initializes the
% average matrices and then performs a loop to sum the values at a specific
% point. After summing at every point the average for each individual point
% is taken, bad data is removed and a matrix containing the original x,y
% positions is made. This is all then saved in a new file with the name
% uvfluctuations file

% Written by Preyank Sheth with selected parts taken from A. Knisely

% Inputs: processed path

% Created: 6-19-09

% % From meanfield.m !!!
%%%%%%

% temporarily open 1st file to grab the header line and then close file
origfile=D(1).name;
fid=fopen(strcat(pathname,origfile),'r');
headline=fgetl(fid);
fclose(fid);
equal=find(headline=='=');
```
F = find(headerline == 'F');

numx = str2double(cellstr(headerline(equal(6)+1:equal(7)-4)));
numy = str2double(cellstr(headerline(equal(7)+1:F-2)));

% Modified from meanfield.m create a vector of the size of the raw data in
% its original form
data_size = zeros(numx*numy,1);

% Initializing output data matrices
%Uave = data_size;
uvave = data_size;
%Usave = data_size;
usvnave = data_size;
CHC_ave = -1*ones(size(data_size));
ave_count = data_size;
% xloc = data_size;
% yloc = data_size;
% global_values = -1;
% while global_values
% global_values = input...
% ('Would you like to use the local(uxL,vyL) or global fluctuations (uxg,vyg,us,un)
% (Enter 0 for local, 1 for global):
%
% s = data_size;
n = data_size;
% Summation loop for velocities at specific points
g = waitbar(0,'Please wait while uvbar is calculated...');
for j = 1:numfiles;
waitbar(j/numfiles,g);
% Opens the next file for each iteration of the loop and reads the data
% into variable 'data'
filename = D(j).name;
fid = fopen(strcat(pathname, filename), 'r');
data=textscan(fid,...
'\%f \%f \%f \%f \%f \%f \%f \%f \%f \%f \%f \%f \%f \%f \%f \%f \%f \%f \%f \%f \%f \%f',...
'headerlines',1,'delimiter','\',');
fclose(fid);

% Input local or global locations
if j==1;
    if global_values == 0
        x = data{1};
        y = data{2};
    elseif global_values == 1
        x = data{7};
        y = data{8};
        s = data{11};
        n = data{12};
    end
end

% Input the data from the opened file of velocities and line index
if global_values == 0
    u = data{3};
    v = data{4};
elseif global_values == 1
    u = data{15};
    v = data{16};
    us = data{19};
    vn = data{20};
else
    Us = data {13};
    Vn = data {14};
end
CHC = data{5};
J = find(CHC>0);
data_index = data{6}{J};

% Loop to compare each line to the index that was given to each piece of
% data during the cleaning of the file.
line_count = 1;
for avg_line_index = min(J):max(J)

    if data_index(line_count,1)==avg_line_index

        uvave(avg_line_index,1) = u(avg_line_index).*...
        \( v(avg_line_index) + uvave(avg_line_index,1); \\
    usvave(avg_line_index,1) = us(avg_line_index).*...
        \( vn(avg_line_index) + usvave(avg_line_index,1); \\
    ave_count(avg_line_index,1) = ave_count(avg_line_index,1)... \\
        + 1;
    CHC_ave(avg_line_index,1) = 1;
    line_count = line_count + 1;

    end
end
end

close(g);

% Averaging the values
uvave = uvave./ave_count;
usvave = usvave./ave_count;

% Assign large value to locations with no valid data
J = data_size;
for K = 1:length(data_size);
    if CHC_ave(K,1) == -1
        uvave(K,1) = 9900000256;
usvnave(K,1) = 9900000256;
end
J(K,1) = K;
end

% Save two new average velocity files, first one in original raw data
% format, second file with added row index and data count information.

% New header line and average file containing only original data
% information
temp

head = [headerline(1:equal(2)+23),'"Uavg", "Vavg", "CHC", ',... headerline(equal(3)-6:end)];
if global_values == 1
  temp
  head = [headerline(1:equal(2)+1),'"X global", "Y global",',... 
    
    '"Ugxavg", "Vgyavg", "CHC", ',headerline(equal(3)-6:end)];
end
de

% New header line and average file containing expanded data information
% New header line and average file containing expanded data information
  temp

head = [headerline(1:equal(2)+23),'"Uavg", "Vavg", "CHC",',... "Line Index", "Average Count", "Smm (empty)", "Nmm (empty)", ',... headerline(equal(3)-6:end)];
if global_values == 1
  temp
  head = [headerline(1:equal(2)+1),'"X global", "Y global",',... "uvbar", "CHC", "Line Index", "Average Count", "Smm", "Nmm",',... "usvnbar'",headerline(equal(3)-6:end)];
end
de

fid=fopen(strcat(pathname,'statistics\uvfluctuationsmean.vec'),'wt');
fprintf(fid,'%s
', temp

head);
fprintf(fid,'%f, %f, %f, %d, %d, %d, %f, %f, %f,
',

[x y uvave CHC_ave J_ave_count s n usvnave']);
fclose(fid);
function std_dev_calc(pathname_stat, average_data_extra, process_path)
% Calculation of Standard Deviation
% This m-file calculates standard deviation.
% It first inputs the path data from the GUI.
% The function then performs a loop to read all the data available.
% Lastly, any points which there is no valid data will are set to value
% of 9900000256

% Written: Andrew Knisely
% Edited: Preyank Sheth
% Created: 3-16-09
% Edited: 05-05-09

% Opens open the average data velocity file and gets the headerline and mean data
fid=fopen(strcat(pathname_stat,average_data_extra),'r');
headerline_mean=fgetl(fid);
equal=find(headerline_mean=='=');
F=find(headerline_mean=='F');
mean_data=textscan(fid,'%f %f %f %f %f %f %f %f %f %f %f','delimiter',','');
x_pos_m = mean_data{1};
y_pos_m = mean_data{2};
s_pos_m = mean_data{8};
n_pos_m = mean_data{9};
CHC_mean = mean_data{5};
data_count = mean_data{7};
fclose(fid);

% create a vector of the size of the raw data in its original form
% to store calculated standard deviation values
std_dev_u = zeros(size(x.pos_m));
std_dev_v = zeros(size(x.pos_m));
std_dev_us = zeros(size(x.pos_m));
std_dev_vn = zeros(size(x.pos_m));

h=waitbar(0,'Please wait while standard deviation is calculated...');
D = dir(strcat(process_path,'*.vec'));
numfiles = length(D);

% open the processed data files and store velocity information
for j=1:numfiles
  % Opens the next file for each iteration of the loop and reads the data
  % into variable 'data'
  filename = D(j).name;
  fid=fopen(strcat(process_path,filename),'r');
  data=textscan(fid,...
    '%f %f %f %f %f %f %f %f %f %f %f %f %f %f %f %f %f %f %f %f %f %f %f %f %f %f %f %f %f %f %f %f',...
    'headerlines',1,'delimiter',',');
  fclose(fid);

  % Save relevant data from file
  CHC = data{5};
  data_index = data{6};
  u_fluctuations = data{15};
  v_fluctuations = data{16};
  us_fluctuations = data{19};
  vn_fluctuations = data{20};
  for count = 1:length(data_index);
    if CHC(count,1)>0
      std_dev_u(count,1) = std_dev_u(count,1) +...
u_fluctuations(count,1)^2;
std_dev_v(count,1) = std_dev_v(count,1) +... 
v_fluctuations(count,1)^2;
std_dev_us(count,1) = std_dev_us(count,1) +... 
us_fluctuations(count,1)^2;
std_dev_vn(count,1) = std_dev_vn(count,1) +... 
vn_fluctuations(count,1)^2;
end
end

waitbar(j/(numfiles),h);
end
close(h)

% calculate the standard deviation
std_dev_u = sqrt(std_dev_u./data_count);
std_dev_v = sqrt(std_dev_v./data_count);
std_dev_us = sqrt(std_dev_us./data_count);
std_dev_vn = sqrt(std_dev_vn./data_count);

% find rows in which bad data is found using the CHC code and then set
% the standard deviation value to large value
bad = find(CHC_mean<1);
std_dev_u(bad,1) = 9900000256;
std_dev_v(bad,1) = 9900000256;
std_dev_us(bad,1) = 9900000256;
std_dev_vn(bad,1) = 9900000256;

% create the temporary header that will replace the header from average file
temp_header = [headerline_mean(1:equal(2)+23),...'
    ', "u Standard Deviation", "v Standard Deviation", "CHC", "Average Count","'
    "Smm", "Nmm", "usms Standard Deviation", "unms Standard Deviation", ',...
headerline_mean(equal(3)-6:end)];
% end
% save the data in the statistics folder
fid=fopen(strcat(pathname_stat,'std_dev.vec'),'wt');
fprintf(fid,'%s
', temp_header);
fprintf(fid,'%f, %f, %f, %f, %d, %d %f, %f, %f, %f
', ... 
[x.pos_m y.pos_m std_dev_u std_dev_v CHC_mean data_count s_pos_m...
  n.pos_m std_dev_us std_dev_vn']);
fclose(fid);
B.6.5 Variance

function variance_calc(pathname_stat,average_data_extra,process_path)
% Calculation of Variance
% This m-file calculates variance. It first inputs the path data from the GUI.
% The function then performs a loop to read all the data available.
% Lastly, any points which there is no valid data will are set to value
% of 9900000256

% Written: Andrew Knisely
% Edited: Preyank Sheth
% Created: 3–16–09
% Edited: 05–05–09

fid=fopen(strcat(pathname_stat,average_data_extra),'r');
headerline_mean=fgetl(fid);
equal=find(headerline_mean=='=');
F=find(headerline_mean=='F');
mean_data=textscan(fid,'%f %f %f %f %f %f %f %f %f %f %f','delimiter',',');
mean_data_count = mean_data{7};
fclose(fid);
% create a vector of the size of the raw data in its original % form to store calculated variance values
var_u = zeros(size(x_pos_m));
var_v = zeros(size(x_pos_m));
var_us = zeros(size(x_pos_m));
var_vn = zeros(size(x_pos_m));

h=waitbar(0,'Please wait while variance is calculated...');
D = dir(strcat(process_path,'*.vec'));
numfiles = length(D);
for j=1:numfiles
    % Opens the next file for each iteration of the loop and reads the data % into variable 'data'
    filename = D(j).name;
    fid=fopen(strcat(process_path,filename),'r');
    data=textscan(fid,...
        '%f %f %f %f %f %f %f %f %f %f %f %f %f %f %f %f %f %f %f %f %f %f',...
        'headerlines',1,'delimiter',',');
    fclose(fid);
    % Save relevant data from file
    CHC = data{5};
data_index = data{6};
    u_fluctuation = data{15};
v_fluctuation = data{16};
us_fluctuation = data{19};
vn_fluctuation = data{20};
    for count = 1:length(data_index);
        if CHC(count,1)>0
            var_u(count,1) = var_u(count,1) + u_fluctuation(count,1)^2;
            var_v(count,1) = var_v(count,1) + v_fluctuation(count,1)^2;
\begin{verbatim}
    var.us(count,1) = var.us(count,1) + us_fluctuation(count,1)^2;
    var.vn(count,1) = var.vn(count,1) + vn_fluctuation(count,1)^2;
    end
    end
    waitbar(j/(numfiles),h);
    end
    close(h)
    
    % calculate the variance
    var_u = var_u./data_count;
    var_v = var_v./data_count;
    var_us = var_us./data_count;
    var_vn = var_vn./data_count;
    
    % find rows in which bad data is found using the CHC code and
    % then set the variance value to large value
    bad = find(CHC_mean<1);
    var_u(bad,1) = 9900000256;
    var_v(bad,1) = 9900000256;
    var_us(bad,1) = 9900000256;
    var_vn(bad,1) = 9900000256;
    temp_header = [headerline_mean(1:equal(2)+23),'
        , "u Variance", "v Variance", "CHC", "Average Count", "Smm", "Nmm",'
        ,"usms Variance", "unms Variance", ',headerline_mean(equal(3)-6:end)];
    
    % save the data in the statistics folder
    fid=fopen(strcat(pathname_stat,'variance_dev.vec'),'wt');
    fprintf(fid,'%s
    ', temp_header);
    fprintf(fid,'%f, %f, %f, %d, %d %f, %f, %f, %f, %f, %f
    ',
        x_pos_m y_pos_m var_u var_v CHC_mean data_count s_pos_m n_pos_m...)
    var_us var_vn');
    fclose(fid);
\end{verbatim}
B.6.6 Skewness

```matlab
function skewness_calc(pathname_stat,average_data_extra,process_path,sd_file)
    % Calculation of Skewness
    % This m-file calculates skewness. It first inputs the path data from the GUI.
    % The function then performs a loop to read all the data available. Then it
    % calculates the numerator for the skewness. It goes on to open the Sd dev file
    % and cubes the respective std dev to get the correct skewness. Lastly, any points
    % which there is no valid data will are set to value of 9900000256

    % Written: Preyank Sheth
    % Created: 6–19–09

    % Opens open the average data velocity file and gets the headerline and mean data
    fid=fopen(strcat(pathname_stat,average_data_extra),'r');
    headerline_mean=fgetl(fid);
    equal=find(headerline_mean=='=');
    F=find(headerline_mean=='F');

    mean_data=textscan(fid,'%f %f %f %f %f %f %f %f %f %f %f','delimiter',',');

    x_pos_m = mean_data{1};
    y_pos_m = mean_data{2};
    s_pos_m = mean_data{8};
    n_pos_m = mean_data{9};
    CHC_mean = mean_data{5};
    data_count = mean_data{7};

    fclose(fid);

    % create a vector of the size of the raw data in its original form to
% store calculated standard deviation values
skew_u = zeros(size(x_pos_m));
skew_v = zeros(size(x_pos_m));
skew_us = zeros(size(x_pos_m));
skew_vn = zeros(size(x_pos_m));
u_sd = zeros(size(x_pos_m));
v_sd = zeros(size(x_pos_m));
us_sd = zeros(size(x_pos_m));
vn_sd = zeros(size(x_pos_m));

h=waitbar(0,'Please wait while skewness is calculated...');

% [filename,pathname]=uigetfile('*.*','Select any cleaned velocity data file');
D = dir(strcat(process_path,'*.vec'));
numfiles = length(D);

% open the processed data files and store velocity information
for j=1:numfiles
    % Opens the next file for each iteration of the loop and reads the data
    % into variable 'data'
    filename = D(j).name;
    fid=fopen(strcat(process_path,filename),'r');
data=textscan(fid,...
    '%f %f %f %f %f %f %f %f %f %f %f %f %f %f %f %f %f %f %f %f %f %f %f %f',...
    'headerlines',1,'delimiter','\',');
fclose(fid);

    % Save relevant data from file
    CHC = data{5};
data_index = data{6};
u_fluctuations = data(15);
v_fluctuations = data{16};
us_fluctuations = data{19};
vn_fluctuations = data{20};

for count = 1:length(data_index);
    if CHC(count,1)>0
        skew_u(count,1) = skew_u(count,1) + u_fluctuations(count,1)^3;
        skew_v(count,1) = skew_v(count,1) + v_fluctuations(count,1)^3;
        skew_us(count,1) = skew_us(count,1) + us_fluctuations(count,1)^3;
        skew_vn(count,1) = skew_vn(count,1) + vn_fluctuations(count,1)^3;
    end
end

waitbar(j/(numfiles),h);
end

close(h)

% calculate the standard deviation
skew_u = sqrt(skew_u./data_count);
skew_v = sqrt(skew_v./data_count);
skew_us = sqrt(skew_us./data_count);
skew_vn = sqrt(skew_vn./data_count);

% find rows in which bad data is found using the CHC code
% and then set the standard deviation value to large value
bad = find(CHC_mean<1);
skew_u(bad,1) = 9900000256;
skew_v(bad,1) = 9900000256;
skew_us(bad,1) = 9900000256;
skew_vn(bad,1) = 9900000256;

% % % Dividing by the sigma^3 denominator % %
% Opens the stddev file and gets the headerline and mean data
fid=fopen(strcat(pathname_stat, sd_file), 'r');
headerline_stddev=fgetl(fid);
equalsd=find(headerline_stddev=='=');
F=find(headerline_stddev=='F');

stddev_data=textscan(fid, '%f %f %f %f %f %f %f %f %f %f ', 'delimiter', ',');

u_sd = stddev_data{3};
v_sd = stddev_data{4};
us_sd = stddev_data{9};
vn_sd = stddev_data{10};
CHC_sd = stddev_data{5};

fclose(fid);

skew_u = skew_u./(u_sd.^3);
skew_v = skew_v./(v_sd.^3);
skew_us = skew_us./(us_sd.^3);
skew_vn = skew_vn./(vn_sd.^3);

bad = find(CHC_sd<1);
skew_u(bad, 1) = 9900000256;
skew_v(bad, 1) = 9900000256;
skew_us(bad, 1) = 9900000256;
skew_vn(bad, 1) = 9900000256;

% create the temporary header that will replace the header from average file
temp_header = [headerline_mean(1:equalsd+23),...
', 'u Skew', 'v Skew', 'CHC', 'Average Count', 'Smm', 'Nmm', ']

% end
% save the data in the statistics folder
fid=fopen(strcat(pathname_stat, 'skew.vec'), 'wt');
fprintf(fid, '%s
', temp_header);
fprintf(fid, '%f, %f, %f, %f, %d, %d %f, %f, %f, %f
',...[x_pos_m y_pos_m skew_u skew_v CHC_mean data_count s_pos_m...
  n_pos_m skew_us skew_vn']);
fclose(fid);
B.6.7 Kurtosis

function kurtosis_calc(pathname_stat, average_data_extra, process_path, sd_file)
% Calculation of kurtosis
% This m-file calculates kurtosis. It first inputs the path data from the GUI.
% The function then performs a loop to read all the data available. Then it
% calculates the numerator for the kurtosis. It goes on to open the Sd dev file
% and raises to power 4 the respective std dev to get the correct kurtosis. Lastly,
% any points which there is no valid data will are set to value of 9900000256

% Written: Preyank Sheth
% Created: 6–19–09

% Opens open the average data velocity file and gets the headerline and mean data
fid=fopen(strcat(pathname_stat, average_data_extra),'r');
headerline_mean=fgetl(fid);
equal=find(headerline_mean=='=');
F=find(headerline_mean=='F');
mean_data=textscan(fid,'%f %f %f %f %f %f %f %f %f %f %f','delimiter',',');

x_pos_m = mean_data{1};
y_pos_m = mean_data{2};
s_pos_m = mean_data{8};
n_pos_m = mean_data{9};
CHC_mean = mean_data{5};
data_count = mean_data{7};

fclose(fid);

% create a vector of the size of the raw data in its original form to
% store calculated standard deviation values
kurt_u = zeros(size(x_pos_m));
kurt_v = zeros(size(x_pos_m));
kurt_us = zeros(size(x_pos_m));
kurt_vn = zeros(size(x_pos_m));
us_sd = zeros(size(x_pos_m));
v_sd = zeros(size(x_pos_m));
us_sd = zeros(size(x_pos_m));
vn_sd = zeros(size(x_pos_m));

h=waitbar(0,'Please wait while kurtosis is calculated...');
D = dir(strcat(process_path,'*.vec'));
numfiles = length(D);

% open the processed data files and store velocity information
for j=1:numfiles

% Opens the next file for each iteration of the loop and reads the data
% into variable 'data'

filename = D(j).name;
 fid=fopen(strcat(process_path,filename),'r');
data=textscan(fid,...
'HEADER',1,'delimiter',',');
fclose(fid);

% Save relevant data from file
CHC = data{5};
data_index = data{6};

u_fluctuations = data{15};
v_fluctuations = data{16};
us_fluctuations = data{19};
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vn_fluctuations = data[20];
for count = 1:length(data_index);

    if CHC(count,1)>0
        kurt_u(count,1) = kurt_u(count,1) + u_fluctuations(count,1)^4;
        kurt_v(count,1) = kurt_v(count,1) + v_fluctuations(count,1)^4;
        kurt_us(count,1) = kurt_us(count,1) + us_fluctuations(count,1)^4;
        kurt_vn(count,1) = kurt_vn(count,1) + vn_fluctuations(count,1)^4;
    end
end

waitbar(j/(numfiles),h);
end

close(h)

% calculate the numerator
kurt_u = sqrt(kurt_u./data_count);
kurt_v = sqrt(kurt_v./data_count);
kurt_us = sqrt(kurt_us./data_count);
kurt_vn = sqrt(kurt_vn./data_count);

% find rows in which bad data is found using the CHC code and then set
% the standard deviation value to large value
bad = find(CHC_mean<1);
kurt_u(bad,1) = 9900000256;
kurt_v(bad,1) = 9900000256;
kurt_us(bad,1) = 9900000256;
kurt_vn(bad,1) = 9900000256;

% Dividing by the sigma^4 denominator
% Opens the stddev file and gets the headerline and mean data
fid=fopen(strcat(pathname_stat,sd_file),'r');
headerline_stddev=fgetl(fid);
equalsd=find(headerline_stddev=='=');
F=find(headerline_stddev=='F');

stddev_data=textscan(fid,'%f %f %f %f %f %f %f %f %f ','delimiter',',');

u_sd = stddev_data{3};
v_sd = stddev_data{4};
us_sd = stddev_data{9};
vn_sd = stddev_data{10};
CHC_sd = stddev_data{5};

close(fid);

kurt_u = kurt_u./(u_sd.^4);
kurt_v = kurt_v./(v_sd.^4);
kurt_us = kurt_us./(us_sd.^4);
kurt_vn = kurt_vn./(vn_sd.^4);

bad = find(CHC_sd<1);
kurt_u(bad,1) = 9900000256;
kurt_v(bad,1) = 9900000256;
kurt_us(bad,1) = 9900000256;
kurt_vn(bad,1) = 9900000256;

% create the temporary header that will replace the header from average file
 temp_header = [headerline_mean(1:equal(2)+23),...;
', "u kurt", "v kurt", "CHC", "Average Count", "Smm", "Nmm",',...;
"us kurt", "un kurt", ',headerline_mean(equal(3)-6:end)];

% end

% save the data in the statistics folder
fid=fopen(strcat(pathname_stat,'kurt.vec'),'wt');
fprintf(fid, '%s
', temp_header);
fprintf(fid, '%f, %f, %f, %f, %d, %d %f, %f, %f, %f
',
[x_pos_m y_pos_m kurt_u kurt_v CHC_mean data_count s_pos_m n_pos_m...
kurt_us kurt_vn]);
fclose(fid);
Appendix C

Design of Fully Developed Section

This custom-built section was designed to obtain a fully-developed flow condition into the test section. It is fit between the shape changer and the test section inlet. The entrance length required for turbulent flow to reach a fully-developed condition is calculated using Equation C.1

\[ EL = 4.4 \times Re^{1/6} \]  

(C.1)

The design Reynolds number was chosen to be \(5 \times 10^5\) which is the maximum possible in the current set-up. An additional 50\% length was added to the value obtained from Equation C.1 to ensure the development of the flow. Thus, the steel tube had a total length of 54”.

The fully-developed section was made of two parts. A stainless steel cover was welded onto a U-channel to form a tube with a 1” square cross-section through its length. Flanges were were carefully aligned and welded onto either side of the tube. SS-304 was the material used for all the parts. The inside surfaces of the U-channel were thoroughly polished and it was ensured that the corners were perpendicular. O-rings prevented leakage at the locations where the flanges were bolted to the shape changer and the test section respectively. Figure C.1 shows an exploded view of the 4 major components of
Figure C.1. Fully-developed flow section assembly - Exploded view

the fully-developed section.

Figures C.2 to C.5 are detailed shop drawings used to manufacture the parts of the fully-developed section.
Figure C.2. Part design drawing: U-channel
Figure C.3. Part design drawing: Top cover
Figure C.4. Part design drawing: Flange towards test section
Figure C.5. Part design drawing: Flange towards shape changer section.
Bibliography


