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Particle Image Velocimetry Investigation of Flow Around Grooved Cylinders

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PARTICLE IMAGE VELOCIMETRY INVESTIGATION OF FLOW AROUND GROOVED CYLINDERS

A Thesis
presented in partial fulfillment of requirements
for the degree of Master of Science
in the Department of Mechanical Engineering
The University of Mississippi

by
Jhalak Dhakal
December 2023
ABSTRACT

This thesis presents an experimental study of the flow around a grooved cylinder in an internal flow passage with a square cross-section. The effects of groove parameters, such as groove diameter (depth) and orientation (streamwise and longitudinal), on the wake characteristics and the pressure drop across the cylinders are investigated. Three Reynolds numbers of, 1230, 2000, and 2825, are tested. Particle image velocimetry (PIV) and cross-correlation techniques were used to measure the velocity fields and visualize the flow patterns. The results show that streamwise grooved cylinders with larger groove diameters (H2.0, H2.5, and H3.0) have reduced wake length and width and lower pressure differential compared to the baseline cylinder for the Reynolds numbers of 2825 and 2000. Only the H3.0 cylinder exhibits these desirable flow characteristics for all the tested Reynolds numbers. The contour visualization of streamlines and vorticity reveals the flow patterns and the wake structures around the grooved cylinders. The findings of this study suggest that streamwise grooved cylinders with larger groove diameters can be used to delay the flow separation, make the flow more stable, and reduce the pressure drop in an internal flow passage. Additionally, streamwise grooves are found to be more effective than longitudinal grooves, which serve the purpose of making the flow downstream more streamlined with less energy dissipation.
DEDICATION

This thesis is dedicated to my wife Bindu, my family and friends who have supported me during my graduate school journey. Thank you all for putting up with my endless chatter about fluids and PIV.
LIST OF ABBREVIATIONS OR SYMBOLS

ABBREVIATIONS
CCD - Charged Coupled Device
CFD - Computational Fluid Dynamics
CHC - Choice Code
EML - Energy Management Lab
FFT - Fast Fourier Transform
FOV - Field of View
IA - Interrogation Area
LDV - Laser Doppler Velocimetry
Nd:YAG - Neodymium-doped Yttrium Aluminium Garnet
PIV - Particle Image Velocimetry
PTV - Particle Tracking Velocimetry
RMS - Root Mean Square
ROI - Region of Interest
TKE - Turbulence Kinetic Energy

NOMENCLATURE
Ar - Archimedes number
D - Cylinder Outer Diameter (mm)
$d_p$ - Particle Diameter (m)
H0.5 - Cylinder with lateral (horizontal) groove of 0.5 mm diameter
H1.0 - Cylinder with lateral (horizontal) groove of 1.0 mm diameter
H1.5 - Cylinder with lateral (horizontal) groove of 1.5 mm diameter
H2.0 - Cylinder with lateral (horizontal) groove of 2.0 mm diameter
H2.5 - Cylinder with lateral (horizontal) groove of 2.5 mm diameter
H3.0 - Cylinder with lateral (horizontal) groove of 3.0 mm diameter
$L_c$ - Characteristics length of fluid flow (m)
Re - Reynolds number
$S_t$ - Stokes number
$U_\infty$ - Tunnel average velocity (m/s)
$\langle u \rangle$ - Mean streamwise velocity field (m/s)
$V$ - Mean total velocity (m/s)
$\langle v \rangle$ - Mean spanwise velocity field (m/s)
V0.5 - Cylinder with longitudinal (vertical) groove of 0.5 mm diameter
V1.0 - Cylinder with longitudinal (vertical) groove of 1.0 mm diameter
V1.5 - Cylinder with longitudinal (vertical) groove of 1.5 mm diameter
V2.0 - Cylinder with longitudinal (vertical) groove of 2.0 mm diameter
V2.5 - Cylinder with longitudinal (vertical) groove of 2.5 mm diameter
V3.0 - Cylinder with longitudinal (vertical) groove of 3.0 mm diameter
$w$ - Velocity in z-direction

GREEK SYMBOLS
$\Delta P$ - Differential Pressure (Pa)
$\mu_f$ - Fluid viscosity (Pa.s)
$\langle \omega \rangle$ - Mean vorticity vector field (1/s)
$\langle \psi \rangle$ - Streamline field
$\rho_p$ - Particle density ($kg/m^3$)
ACKNOWLEDGEMENTS

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Chapter 1

INTRODUCTION

The study of fluid flow around circular cylinders has been a central focus in fluid engineering for many years. Circular cylinders can be classified as semi-aerodynamic bodies, exhibiting characteristics of both aerodynamic bodies, such as airfoils, and non-aerodynamic bodies with sharp edges, like squares. Aerodynamic structures are designed to prevent separation, while non-aerodynamic structures have predetermined separations at certain corners. On the other hand, semi-aerodynamic structures have separation points that fluctuate based on free-stream velocity, flow profile, free-stream turbulence, geometry, and surface roughness [1]. The flow of an incompressible fluid around a circular cylinder is a remarkably complex issue in aerodynamics, regarding theoretical understanding and physical phenomena [1]. The application of fluid flow past circular cylinders ranges from heat exchangers, chimney stacks, nuclear reactors, and fuel rods [2] to bridges and offshore structures[3], power lines air ventilation, and electronics cooling [4]. Circular pin fins are effective cooling structures that enable large heat transfer in the internal cooling channels of a gas turbine blade. However, they induce significant pressure drop, ultimately degrading the overall operational performance of the cooling channel [5]. In light of this challenge, this study investigates innovative solutions to minimize the pressure drop in the cooling channel by introducing grooves into the cylinders.

The hypothesis is that these grooved cylinders, as shown in Figure 2.2, could potentially reduce the pressure drop while maintaining, or even enhancing, the heat transfer capabilities of the system. To test this hypothesis, a series of experiments using a single cylinder, of various groove configurations are conducted in a low Reynolds number flow contrary to
highly turbulent flow in the cooling channel. This approach allows us to isolate the effects of the grooved cylinder and gain a detailed understanding of its flow characteristics.

To visualize and analyze the flow fields around the grooved cylinder, Particle Image Velocimetry (PIV) is employed. This technique allows for precise, non-intrusive measurements of the flow velocity [6], providing invaluable insights into the behavior of the fluid as it interacts with the grooved cylinder. The grooves designed with their sizing and alignments are discussed in detail in the next chapter.

By bridging the gap between the established practice of using circular pin fins and the concept of grooved cylinders, this study could pave the way for more efficient and effective cooling systems in turbines. The findings could have far-reaching implications, not only for the design of turbine blades but also for a wide range of applications where heat transfer and pressure drop are critical factors.

1.1 LITERATURE REVIEW

As stated in the introductory statements, the point of separation on circular cylinders varies and is influenced by factors such as roughness, incoming velocities, and geometry. The management of flow around cylinders is crucial given its wide range of applications. There are two methods for controlling flow: passive and active. Unlike active control, passive control does not necessitate the use of external energy, is cost-effective, and therefore merits investigation. Passive flow control strategies encompass a variety of methods, including the use of control rods [7], porous media coating [8], and vortex generators [9], as well as the application of a splitter plate [10], groove [11], screen [12], rough surfaces [13], spirals [14] and helical plates [15], and slit passive jets [16].

The study of flow characteristics and control of vortical structures in the cylinder wake by setting up grooves has been done extensively for decades. Kimura and Tsutahara [17] conducted experimental and numerical investigations on three types of grooves with circular
cross-sections. Each cylinder featured a single longitudinal circular groove, with grooves of varying radii positioned at different angles ($\theta$) relative to the direction of the freestream velocity. Their findings indicated that the grooves had no impact when their position was less than $\theta = 75$ degrees. However, they observed that type 2 grooves positioned at $\theta = 83$ degrees demonstrated the highest control efficiency. Their numerical findings confirmed that the presence of cavity flows in a groove on the surface of a circular cylinder effectively shifted the point of laminar separation further downstream. They further deduced that such grooves’ impact is akin to dimples’ influence on a golf ball. Since then, numerous researchers have explored the impact of grooves of various shapes on the cylinder. However, a customary limitation in these studies is that the grooves used are typically very small, often less than 1% of the cylinder’s diameter. This makes them more similar to a rough surface rather than a distinct groove [18]. Huang et al. [19] used a spiral groove on a rough cylinder and a non-grooved rough cylinder in their experiment, comparing the drag reduction between them. They found that, in the rough cylinder cases, the application of grooves can also lead to drag reduction. In our research, we are not limiting ourselves to examining a few types of grooves. Instead, we are conducting an extensive exploration of various sizes of grooves with circular cross-sections. These grooves are oriented in two ways - laterally and longitudinally along the cylinder, providing us with a comprehensive overview.

1.2 MOTIVATION

As reviewed previously, extensive research has been performed to understand the flow past cylinders with various passive control techniques. However, grooved cylinders have not yet been thoroughly studied, and numerous unknowns remain, waiting to be fully uncovered in the uncharted territory of grooved cylinders. This present study aspires not just to uncover the potential of grooved cylinders in redefining cooling systems but also to pave a path toward more efficient, effective, and transformative solutions across a myriad of critical applications.
1.3 OBJECTIVES

The main objectives of this study are listed below.

- To experimentally conduct detailed investigations of the flow fields around grooved cylinders.
- To understand the impacts of grooves on flow separation around a cylinder and pressure drop characteristics in an internal flow passage.
- To have detailed understanding of downstream wake characteristics which includes wake length and width.
- To visualize the time averaged vorticity and streamtraces for each test sample for all the Reynolds numbers.
- To map how groove size and orientation affect the flow fields.

Particle image velocimetry (PIV) and cross-correlation techniques are utilized to achieve the objectives of this study. The review of this experimental technique is done in the upcoming section.

1.4 REVIEW ON PARTICLE IMAGE VELOCIMETRY

This section introduces Particle Image Velocimetry (PIV), a non-intrusive optical measurement technique utilized to measure the velocity fields of fluids. It provides a historical context and explains how PIV has been used in various research studies. Furthermore, this section discusses the technical aspects of PIV, including the algorithms and post-processing methods employed.

1.4.1 Introduction and brief history

The study of fluid mechanics frequently makes use of PIV. Understanding fluid flow phenomena, including turbulence, vortices, mixing, and shear stress, is simplified with PIV. It has
become a critical tool in many engineering research domains, including aerospace, automobile, and bioengineering, due to its capacity to deliver precise velocity information at a high spatial and temporal resolution. Although fluid mechanics experiments and observations date back to Leonardo Da Vinci, Louis Prandtl who made the first use of particle-laden flow analysis in 1904 to study velocity fields in a wind tunnel. In his experiment, he used small particles to visualize the flow fields and measure the velocity distributions around a wing profile [20].

Prandtl conducted pioneering work on flow visualization and developed an experimental apparatus to investigate flow separation, as shown in Figure 1.1. He introduced small particles into a water flow to visualize the separation phenomenon in his water tunnel. He obtained the first PIV images with temporal resolution through photographs of the flow. His work laid the foundation for developing flow visualization techniques, including PIV, LDV (Laser Doppler Velocimetry), and PTV (Particle Tracking Velocimetry). These flow visualization methods involve the introduction of tracer particles into the fluid to track its motion, described in the Hardware Systems and Components subsection. Illuminating these particles with a light source can capture and analyze their movements to determine flow characteristics. Tropea et al. [21] provided a comprehensive review of flow visualization techniques, offering detailed information on these methods. In the current study, the PIV method was utilized to measure fluid flow, and subsequent sections will delve into the specifics of this technique.

Advancements in imaging technology and high-speed computing have enabled researchers to employ modern PIV algorithms for fundamental experimental images, such as the ones captured by Prandtl. This has allowed for the visualization of flow characteristics, such as viscosity, which was challenging to obtain during Prandtl’s era [22].

1.4.2 PIV method for Laminar and Turbulent flows

In this thesis, we’re studying the airflow around a grooved cylinder with various groove ge-
ometries in a wind tunnel. The flow is mostly laminar, even at the highest speed of testing, it begins to transition to turbulent flow. One of our goals is to visualize the streamlined flow fields around the cylinder. Therefore, our proposed experimental setup with PIV is an effective method to achieve this. PIV and HPIV (Holographic Particle Image Velocimetry) are able to compute 2D and 3D flow fields, respectively. It is challenging to obtain the out-of-plane component of the velocity when utilizing a single camera. Hence, Stereo- or Tomographic-PIV with multiple cameras are better suited to obtain all three velocity components in a flow field. In this research, a 2D PIV is used, which restricts the possibilities of capturing 3D data, which is especially relevant in both laminar and turbulent 3D velocity fields. However, Ayegba et al. [24] in their study confirmed that 2D flow measurements could still provide useful information even for turbulent flows. Therefore, in the current study, 2D PIV was used with confidence to capture the flow fields and flow separation characteristics around a grooved cylinder, mostly under laminar conditions.

1.4.3 Hardware Systems and Components

A schematic of a typical 2D PIV setup can be found in Figure 1.2. The hardware of the setup consists of a camera, a light source, and trace particles that can be added to the flow by a particle generator. In the upcoming subsections, the requirements and theory of these
components are explained.

1.4.3.1 Camera and light source

As previously discussed in the introduction, the underlying principle of PIV involves the motion capture of seed particles in a fluid flow. A laser is utilized to visualize these particles, creating a thin laser sheet with appropriate optical settings. The illuminated particles can be recorded using a high-speed camera that is positioned perpendicular to the laser sheet. By capturing two consecutive images of these particles, their movement can be tracked, and the corresponding velocity information can be determined by measuring the distance they traveled between two consecutive frames. This velocity information is then used to characterize the flow field. The methodology and the technique for extracting data from these images are also sequentially described in the subsection of software programs and components.

1.4.3.2 Seed Particles

During PIV measurements, the velocities of the seed particles are determined instead of the velocity of the fluid itself. It is assumed that the seed particles are distributed homogeneously,
and they follow the flow faithfully. It is also assumed that the particle displacements are uniform within an interrogation region. Therefore, the collective motion of the particles represents the motion of the flow. Nonetheless, these assumptions may not hold true in all cases. Therefore, PIV requires a thorough examination of the fluid and particle properties to prevent any unwanted interactions. These properties can be characterized by their respective characteristic times, as outlined in Equation 1.1 for the characteristic time of the carrier fluid and Equation 1.2 for the relaxation time of the particle. In these equations, $L_c$ denotes the characteristic length of the fluid flow, $U_f$ represents the fluid velocity, $d_p$ signifies the particle diameter, $\rho_p$ stands for the particle density, and $\mu_f$ represents the fluid viscosity [6].

$$\tau_f = \frac{L_c}{U_f} \quad (1.1)$$

$$\tau_p = \frac{\rho_p d_p^2}{18 \mu_f} \quad (1.2)$$

Equation 1.3 defines the Stokes number, widely employed as an indicator of particle traceability [25]. This number is the ratio of the characteristic times of the particles and the flow. It provides insight into a particle’s ability to track the flow accurately. By assessing the magnitude of the Stokes number, one can determine whether the selected particle can closely follow the motion of the carrier fluid. When the Stokes number is low, the particle can respond rapidly to changes in the flow. Conversely, when the Stokes number is large, the tracer particle is unable to respond to swift changes in the fluid’s motion. Particles having a Stokes number below 0.1 are deemed accurate enough and can be used as flow tracers [6].

$$S_t = \frac{\tau_p}{\tau_f} = \frac{\rho_p d_p^2 U_f}{18 \mu_f L_c} \quad (1.3)$$

The Archimedes number is the ratio of gravitational and viscous forces acting on a particle in a fluid, which determines the effect of buoyancy.

$$Ar = \frac{g d_p^3 \rho_p (\rho_p - \rho_f)}{\mu_f^2} \quad (1.4)$$
where $\rho_f$ is the density of the fluid and $g$ is the acceleration gravity constant. An appropriate value for the Archimedes number is if $Ar < 5 \times 10^{-2}$ [25].

In addition, capturing tracer particles through the camera requires the consideration of their optical properties. To minimize distortions and refractions at interfaces, the refractive index of tracer particles should closely match that of the surrounding fluid for effective PIV imaging.

Achieving the desired Stokes and Archimedes numbers can be done by selecting a small diameter or neutrally buoyant particles. However, a tradeoff between these options must be made since a particle with a diameter that is too small may result in weak, scattered light. In general, the appropriate mean size of olive oil droplets in airflow is typically around 1-20 $\mu m$ for accurate PIV measurements [26].

According to research, an increase in seeding density results in a decrease in the number of spurious vectors in PIV data [27]. However, a very high seeding density can have a negative impact on PIV measurements and cause difficulty in identifying particles in the region of interest, resulting in a "slurry" flow. It is generally recommended to use 5-15 seed particles per interrogation region of $64 \times 64$ pixels [26].

1.4.4 Software Programs and Components

PIV analysis software measures and analyzes the recorded data from images. This study uses Insight and Tecplot 360 software for PIV analysis. A concise description of the underlying theory of PIV analysis, along with specific settings for our PIV analysis, is presented in this section.

1.4.4.1 Region of Interest and Masking

A Field of View (FOV) is a raw image from a single capture. A region of interest, or ROI, can be defined numerically or by selecting a rectangular region on the FOV that needs to be processed. When this region is chosen, only the section within the ROI is affected by
any processing. Due to certain structures, there may be other areas where no fluid passes within the ROI. To save time and system resources, masks can be applied to these areas manually or through a macro. Two types of masks exist: static and dynamic. A static mask remains in place on the analysis region, while a dynamic mask moves to cover a specific flow feature. Both masks can be used together and assigned a velocity. In this thesis, masks are not employed. The Field of View (FOV) encompasses two components to be masked: the circular cross-section of the cylinder and the resulting shadow beneath it. These areas are both excluded from the data processing in Tecplot 360 later on.

1.4.4.2 Image Pre-processing

The aim of the pre-processing is to minimize the error in PIV data caused by inaccurate velocity vectors, which is achieved by performing data preprocessing. For certain types of images, such as those involving two-phase flow, preprocessing is needed to separate the phases before PIV processing or size analysis can be performed. The image preprocessors available in PIV include the image calculator, image binning, image filter, and image generator. The image calculator performs various arithmetic operations, grayscale inversion, masking, rotation, and flipping[26]. Image binning reduces image size, while image filtering involves linear and non-linear filtering such as Local Mean, Gaussian, Laplacian, Local Median, and Local Range. The image generator produces an image from a list of images using average, minimum, or maximum intensity. In this thesis, the image generator is used in conjunction with the image calculator. The background image is obtained by using the minimum intensity of a sequence of images, and this background image is then subtracted from the raw images.

1.4.4.3 Spatial Calibration

Calibration refers to mapping camera pixels to the world coordinates. This mapping also referred to as spatial calibration, is utilized in measurements to convert image displacement into world coordinates. The calibration factor is entered for 2D calibration, which is then used to calculate the flow velocity in meters per second. If 2D calibration is not selected,
velocity vector magnitudes are in camera pixels per second [26].

\[ Velocity = \frac{\text{pixel displacement} \times (\text{mm/pixel})}{dt} \text{ (in m/s)} \]  

Perspective calibration analyzes the calibration target images that are captured with the software. The image analysis finds the location of each calibration marker point in the sequence of image frames and matches the image (X,Y) location to the target marker (X,Y,Z) location in the fluid. This set of calibration points is used to create a calibration mapping function. Perspective calibration is utilized for stereo PIV system [26].

In our research, a method known as Measured 2D calibration was employed. With this approach, the software automatically computes the value of millimeters per pixel. We positioned a scale with a known dimension within the field of view for measurement and the object’s size in millimeters into the designated ”Object Size in mm” field. Subsequently, we selected ”Measure” and utilized the cursor to indicate the beginning and end points of the object. These steps enable us to determine the calibration factor of 36.36 mm per pixel in our study.

1.4.4.4 PIV algorithm

The pivotal aspect of PIV cross-correlation processing lies in the choice of algorithm. Multiple algorithms are available for various processing steps, including grid generation, spot masking, correlation, and peak location. The optimal selection depends on factors such as flow characteristics, velocity gradients, seeding, and acceptable processing duration. The Insight software is tailored to align these algorithms with our specific flow conditions [26]. These algorithms produce good results for our experiment.

In setting up the PIV Processor, we primarily utilized two algorithms: Classic PIV and Ensemble PIV. The Classic PIV algorithm processes individual pairs of two PIV images, yielding a distinct vector field for each instantaneous pair. On the other hand, the Ensemble PIV calculates the averaged flow from all captures, producing a single time-averaged vector
field for all captures. In this thesis, we employ the Ensemble PIV since our focus is on obtaining the averaged velocity information of flow around a cylinder with various groove geometries. To acquire instantaneous properties, such as velocity fluctuations and Reynolds Stress, the preferable choice would be the Classic PIV.

After choosing one between the Classic PIV and Ensemble PIV algorithms, Insight 4G employs four plugin engines for specific tasks: Grid Engines for grid generation, Spot Mask Engines for masking spots, Correlation Engines for cross-correlation, and Peak Engines for locating correlation peaks [26]. These four engines represent the essential stages in image processing.

The Grid Engine divides the input images into smaller segments for processing, initializing the vector field. For every grid point, the process manager transfers the pixels from the input images into the segments and forwards them to the Spot Mask Engine [26]. In our research, we employed the NyquistGrid plugin, which provides a vector grid with 50% spot overlap, adhering to the Nyquist sampling criteria.

The Spot Mask Engine prepares the segments for processing and transfers them to the Correlation Engine. In our study, we utilized the GaussianMask plugin, which applies a Gaussian weighting function to each pixel in spot A, resulting in a bright center and darker edges. This weighting emphasizes the importance of central pixels over those at the periphery [26].

The Correlation Engine plays a pivotal role in computing the correlation function and produces a correlation map, which is subsequently forwarded to the Peak Engine. In our study, we implemented the FFTCorrelation plugin, which utilizes the Fast Fourier Transform to compute the correlation [26]. It is recommended that the spots have dimensions that are square powers of 2, and both Spot A and Spot B should be of the same size. Specifically, in our case, Spot A and Spot B had initial and final dimensions of $16 \times 8$ pixels, with maximum
displacements set to 1/4 of the size of Spot A.

The Peak Engine is responsible for identifying the location of the peak in the correlation map. The default Peak Engine used in conjunction with the FFTCorrelation Engine is the GaussianPeak plugin. This plugin achieves sub-pixel accuracy by fitting a Gaussian curve to the highest pixel and its four nearest neighbors. Two separate 3-point fits are conducted: one in the x-direction using the peak pixel and the pixels to its left and right, and one in the y-direction using the peak pixel and the pixels above and below. The Gaussian peak equation is given by:

\[ dx = x + \frac{(\log(l) - \log(r))}{2 \cdot (\log(l) + \log(r)) - 2 \log(c)} - x_0 \]  

(1.6)

Where \( l \), \( r \), and \( c \) denote the intensity values for left, right, and peak pixels in the correlation map, \( x \) represents the integer shift, and \( x_0 \) signifies the zero shift location \[26\].

Similarly, \( dy \) is also calculated in the Y direction. By dividing the displacements in the X and Y directions, \( dx \) and \( dy \), by the time interval between two frames, \( dT \), we obtain the velocities in the X and Y directions, \( du \) and \( dv \), respectively. The values are for each Interrogation Area (IA) of ROI.

Figure 1.3: Cross correlation method in PIV \[28\]
After completing these steps in the Processing Tab, further vector validation and conditioning are carried out in the Post Processing Tab for the whole ROI flow field.

1.4.4.5 Data Validation and Conditioning

If the PIV image capture and processing guidelines developed by Keane and Adrian [29] are adhered to, the processing of PIV images can yield accurate velocity measurements in over 95% of cases. Factors such as in-plane and out-of-plane motion or low seeding density that result in a weak correlation signal can lead to lost pairs and erroneous vectors. These erroneous vectors occur when the highest correlation peak is not due to pairs of particles moving with the flow (the velocity peak) but rather a random pairing of particle images that produces a signal with the highest correlation peak. Vector field validation functions are designed to eliminate these erroneous vectors and replace the removed vectors through interpolation. The Insight software carries out vector validation as a part of its post-processing setup.

In our thesis, we utilized the Processing Pipeline Editor, where we implemented Global Validation, followed by Local Validation, and finally, the Vector Conditioning Processor to produce the final validated output. The Global Validation is a range filter that identifies vectors that fall outside a user-specified valid velocity range. This is considered a global filter as the velocity range is applied across the entire velocity field [26]. Within the Global Validation setup, we employed an Absolute Range of valid velocity, defined by velocity magnitude.

Local Vector Validation, on the other hand, uses the vectors surrounding each vector to compute a reference vector for validation. If the discrepancy between the current vector and the reference vector exceeds a user-defined tolerance, the current vector is deemed invalid, and the vector choice code (CHC) is set to -1 [26]. In our study, both $|du|$ and $|dv|$ tolerance were set to 2 pixels.

Following vector validation, Vector Conditioning is used to fill gaps in the vector field or
smooth out the vector field using interpolation; this includes performing low-pass filter smoothing with a Gaussian convolution kernel [26]. The final output vector file displays these conditioned vectors in yellow.

The Insight software generates vector files (.vec) following the processing of the image. In our research, these files contained an averaged vector field derived from a set of 1000 captures. As we utilized Spatial Calibration, the vector files were expressed in units of m/s. The file header line labeled the data columns and indicated the measurement units used, with X/Y positions in mm and u/v velocity in m/s.

These files were then transferred to the separately installed Tecplot software. Within the Insight software, there is a TSI Tecplot Add-On, which allows for the viewing of Insight-2D vector files and the computation of flow properties.
A 2D PIV system is available in the Energy Management Lab (EML) at the University of Mississippi. A low-speed wind tunnel was constructed specifically for the current study. Each of the 13 test cylinder samples was placed in the tunnel one after the other, with the fan generating a constant specified speed. All these samples were tested at three different constant speeds. In addition, the static pressure drop for all these samples was also examined using a micromanometer. The specifics of the test cylinder samples, tunnel assembly, PIV, and micromanometer are elaborated in the following sections.

2.1 TEST CYLINDER SAMPLES

In our study, we used 13 cylindrical samples. All the cylinders have an external diameter of 10 mm and a height of 22 mm. They are designed to fit securely in our test section with a two-step base. Figure 2.1 shows a bare cylinder without grooves incorporated. The remaining 12 cylinders, shown in Figure 2.2, have grooves (threads) cut into them. Six of these had threads cut laterally along the cylinder (termed “horizontal” threads), and the other six had threads cut longitudinally (termed “vertical” threads). The threads were circular and varied in diameter. For horizontal threads, a constant pitch of 1.5 times the groove diameter (D) was maintained. The horizontal grooves were also referred to as "streamwise" in this study, as the grooves align with the streamwise flow direction in the experiments. For the vertical grooves, a series of was grooves selected along the cylinder circumference. The dimensions, pitch, and number of grooves for both horizontal and vertical threads are well illustrated in Table 2.1 and Table 2.2. We denote cylinders as “AX” where A
Figure 2.1: Bare Cylinder

represents the thread direction, and X represents the thread diameter in mm. For instance, H1.0 refers to a cylinder with horizontal threads of 1.0 mm diameter, and V2.5 refers to a cylinder with vertical threads of 2.5 mm diameter.

<table>
<thead>
<tr>
<th>Cylinders</th>
<th>Groove Diameter (mm)</th>
<th>No. of Grooves</th>
<th>Groove Pitch (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H0.5</td>
<td>0.5</td>
<td>29</td>
<td>0.75</td>
</tr>
<tr>
<td>H1.0</td>
<td>1.0</td>
<td>14</td>
<td>1.5</td>
</tr>
<tr>
<td>H1.5</td>
<td>1.5</td>
<td>9</td>
<td>2.25</td>
</tr>
<tr>
<td>H2.0</td>
<td>2.0</td>
<td>7</td>
<td>3.0</td>
</tr>
<tr>
<td>H2.5</td>
<td>2.5</td>
<td>6</td>
<td>3.75</td>
</tr>
<tr>
<td>H3.0</td>
<td>3.0</td>
<td>5</td>
<td>4.5</td>
</tr>
</tbody>
</table>

Table 2.1: Lateral Grooves
Figure 2.2: Threaded Cylinders

<table>
<thead>
<tr>
<th>Cylinders</th>
<th>Groove Diameter (mm)</th>
<th>No. of Grooves</th>
<th>Groove Pitch (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>V0.5</td>
<td>0.5</td>
<td>32</td>
<td>0.933</td>
</tr>
<tr>
<td>V1.0</td>
<td>1.0</td>
<td>16</td>
<td>1.767</td>
</tr>
<tr>
<td>V1.5</td>
<td>1.5</td>
<td>12</td>
<td>2.225</td>
</tr>
<tr>
<td>V2.0</td>
<td>2.0</td>
<td>8</td>
<td>3.142</td>
</tr>
<tr>
<td>V2.5</td>
<td>2.5</td>
<td>7</td>
<td>3.366</td>
</tr>
<tr>
<td>V3.0</td>
<td>3.0</td>
<td>6</td>
<td>3.665</td>
</tr>
</tbody>
</table>

Table 2.2: Longitudinal Grooves
2.2 LOW SPEED WIND TUNNEL

The experiments were carried out in the low-speed wind tunnel at three different tunnel average velocities: 0.84 m/s, 1.38 m/s, and 1.95 m/s. These velocities correspond to the tunnel Reynolds numbers 1230, 2000, and 2825, respectively. The wind tunnel’s test section has a square cross-section measuring 22 mm on each side and a length of 300 mm. To ensure that the airflow becomes fully developed and stable, an entrance length of 300 mm is provided to the test section. The cylinder samples were inserted from the front side of the experimental setup, as depicted in the isometric view of Figure 2.3.

The 9MP high-speed CCD camera was positioned horizontally at the back of the test section, capturing a spatial domain of 100 mm × 22 mm, which was designated as ROI. For statistical analysis, the camera recorded 1000 pairs of images. The test section was designed with transparent glass on the top and back. This allows the laser to penetrate through the top and the camera to capture images from the back. The laser sheet, which eventually enters the test section, is adjusted so that it projects vertically down through the center of the test section from the top. However, one challenge we encountered was the formation of shadows by the laser on the top of our sample, as shown in the Camera View of Figure 2.3. These shadows interfere with our ability to distinguish the flow captures, making it difficult to analyze the flow characteristics in these regions.

To address this issue, we implemented a solution in our data post-processing stage. Specifically, we blanked out the shadow region along with the upper circular section of the sample, which has a diameter of 10 mm. This means that we removed these regions from our data analysis. By doing so, we were able to focus on the regions of interest without the interference of the shadows. This approach allowed us to obtain clear and accurate PIV measurements despite the challenges posed by the laser shadows.

In the current study, we’re examining the cylinders with grooves running horizontally (stream-
wise) and vertically (laterally). For the cylinders with horizontal grooves, their placement within the test section slot isn’t crucial. This is because the samples are symmetrical along both the horizontal and vertical axes, as seen from the camera’s field of view. Furthermore, characteristics like the point of separation and downstream wake remain consistent in these cylinders. However, for cylinders with vertical grooves, the angle of each groove relative to the horizontal axis is vital. This angle influences various factors, including the point of separation, downstream wake characteristics, vorticity, and other turbulent statistics. Our primary goal is to reduce pressure drop and achieve a more streamlined and stable downstream flow through this study by scrutinizing more horizontal grooves. We’re also observing the general characteristics around the cylinder with vertical grooves, considering the position of individual grooves. For our current analysis, we’ve set a single reference groove at a radial 90-degree angle to the incoming freestream direction.
Figure 2.3: Experimental Setup schematics
2.3 DETAILS OF PIV

This current PIV system employs an Nd:YAG laser to illuminate the region being measured. The principle behind determining the flow velocity lies in measuring individual particle displacements within a known time interval between laser pulses and using information from the Charged Coupled Device (CCD) camera to ascertain the two-dimensional location of the particles. One of the key advantages of PIV is its ability to provide measurements at multiple points simultaneously, capturing an entire field of flow at a single instant in time. This results in instantaneous vector fields that offer a comprehensive view of the flow dynamics. Furthermore, time-averaged statistics can be obtained by averaging instantaneous flow fields, providing a robust analysis of the flow characteristics. This combination of instantaneous and time-averaged data makes the PIV a powerful tool for studying complex fluid dynamics.

The Evergreen-Quantel Nd:YAG laser was used. It offers a wide range of pulse energies, from 15 mJ to 400 mJ per pulse, allowing for flexibility in various applications. The pulse duration ranges from 4 ns to 20 ns, which effectively freezes the particle images, providing clear and precise measurements. It is able to measure flow velocities ranging from mm/s to supersonic speeds due to its wide range of deltaT. We operated the laser at a pulse repetition rate of (50-200Hz) “mid-speed” settings. The laser operates at a wavelength of 532 nm. This specific wavelength is often used in PIV systems due to its strong interaction with common seeding particles. The device operates on a 120V, single-phase power supply featuring a closed-loop water cooling system.

The images were captured using a TSI Powerview 630136 high-resolution CCD camera equipped with a Nikon 50mm lens and a fixed aperture of f16. This camera was specifically designed to capture images of particles from the illuminated flow field. The model 630136 has a $3388 \times 2712$ array of light-sensitive square pixels of size 37 $\mu$m. The CCD quantum frame rate for our experiment was 17.077 frames/second. The cameras were pre-aligned to view a 2D domain of 100 mm×22 mm. The distance between the tunnel wall and
the camera was approximately 500 mm.

The Model 610036 synchronizer by TSI was used as an external trigger and connected to the laser and the PIV camera to control the flash lamps and Q-switches. The synchronizer was under software control. The pulse separation time (delta T) between the two frames was set 35 µs for the values of Re tested. The two-frame double exposure was set at a 15 Hz capture rate.

2.3.1 Timing setup

The timing setup is very essential to capture a better image. In this experiment, the frame mode is set to the straddle mode to acquire two consecutive single-exposure images. The pulse repeat rate (Hz) values are 15 Hz. In order to obtain a good 2D result. There is no capture delay between the start of the laser triggering and the start of capture for the camera we used. The schematics to describe the timing are detailed in Figure 2.4.

![Figure 2.4: Timing setup in PIV (Image Credit: TSI)](image)

2.4 MICROMANOMETER

Pressure drop is the difference in static pressure across an element in a closed pipe system. In our experiment, we measured the pressure drop across different samples using a TSI Alnor EBT730 Micromanometer (as shown in Figure 2.5), which has a high-pressure differential accuracy of ±0.025 Pascal. A nylon tube was connected to the Differential Pressure Ports, which connects pressure probes. The differential pressure probes measure the static pressure
upstream and downstream of the samples. The upstream probe was inserted from the front face of the test section, which had a length of 300 mm, and placed at the left extremity of the section. The downstream probe was inserted in the same way and placed at the right extremity of the section. The probes were kept perpendicular to the flow and aligned with the wall at the centerline.

We maintained the same temperature and pressure conditions for each measurement. We repeated each measurement five times and calculated the average. For each measurement, we obtained 300 sets of data per second for five minutes. We changed only the samples while keeping the flow velocity constant. We used a data acquisition module to record the average of the 300 sets of data that were within a 93% confidence interval. We assumed that all the other variables remained the same for a specified flow at all times.

(a) Front view Features
(b) Back view Features

Figure 2.5: Micromanometer (Image Credit: TSI)
In this experiment, we compare a bare cylinder (our baseline sample) with twelve grooved cylinders - six with horizontal grooves and six with vertical grooves. PIV is employed to observe various flow properties around the cylinders in a 2D ROI. These properties include the time-averaged velocity in both streamwise and spanwise directions ($u$ and $v$ respectively), absolute velocity magnitudes ($V$), vorticity ($\omega$), and flow streamlines ($\psi$).

We also thoroughly compare the streamwise velocity distribution at five equidistant vertical locations downstream for all the samples. Additionally, we observe the streamwise velocity along the horizontal centerline of our circular cross-section for all samples. A key part of our analysis is determining the location of the end of the wake for all samples.

The experiment operates on three distinct freestream velocities, and we observe the trends over these flow rates. The cylinder samples are positioned at 38% from the start of our ROI, as we are primarily interested in the zone after the sample, which occupies about 62% of the ROI area.

In our contours, the flow direction is from left to right. The axes are non-dimensionalized by the cylinder’s external diameter (D) of 10 mm, as shown in Figure 2.1. The axes are adjusted such that our sample is at X/D=0. The downstream of the cylinder is positioned at increasing negative X/D when moving to the right past the cylinder until the right end of the ROI. Similarly, the upstream region has increasing positive X/D when moving to the left of the cylinder until the left end of the ROI.
In the Y direction, we have increasing Y/D from Y/D=0 at the bottom left of our ROI. The center of our cylinder sample is precisely located at Y/D=1.0325. Since we are not interested in the regions near the top and bottom walls of our test section, those wall regions are omitted while creating our ROI for contours. This setup allows us to conduct a comprehensive and detailed analysis of the flow properties around the cylinders.

3.1 OPEN TUNNEL VELOCITY PROFILE

Before proceeding with the measurements using any samples, we aim to ensure that our experimental method is valid. To this end, we conducted an experiment in an open channel for the Reynolds number tested. The streamwise velocity profiles corresponding to these Reynolds numbers are illustrated in Figure 3.1.

We obtained the time-averaged streamwise velocity \( u \) along five vertical lines at X/D=-2, X/D=0 (the sample location), X/D=-2, X/D=-4, and X/D=-6 in the open channel. For Re=1230, Re=2000, and Re=2825, the centerline streamwise velocity at X/D=0 reached around 97%-98% of the fully developed centerline velocity measured at X/D = -6. This ensures that the experiments in the current study were performed under the channel flows, very close to the fully developed condition.

The velocity profiles appear to be slightly skewed towards the lower half of the channel. This is consistently observed across all the Reynolds numbers tested. Given that our setup channel may not be perfectly horizontally aligned and may have bends, achieving a perfectly symmetrical distribution is challenging, resulting in a skewed flow. However, this asymmetric aspect is not a critical factor that affects the main fluid dynamics phenomena we want to observe, such as flow separation and wake characteristics, around the cylinder samples with different groove designs. Therefore, the experiments were performed while ignoring this skewness in the velocity profiles.
Figure 3.1: Streamwise velocity distribution for open channel flow (no sample)
3.2 MEAN VELOCITY

The contour plots of time-averaged $u$ are given in Figures 3.3, 3.8 and 3.13 for the corresponding Reynolds numbers of 1230, 2000, and 2825, respectively. Similarly, the contour plots of spanwise (lateral) time-averaged $v$ are given in Figures 3.4, 3.9, and 3.14. The mean velocities are non-dimensionalized by the respective tunnel average velocities ($U_\infty$). The time-averaged normalized absolute $V$ magnitude contours are shown in Figures 3.5, 3.10, and 3.15 for the respective Reynolds numbers of 1230, 2000 and 2825.

3.2.1 Mean streamwise velocity

The time-averaged $u$ contour, depicted in Figures 3.3, 3.8, and 3.13, use a "large rainbow" colormap. The value limit is consistently set from -1.5 to 1.5 across all the contours. The white areas in the upper and lower halves, divided by the horizontal centerline passing through the sample center, represent contour values greater than 1.5. These white layers on both halves indicate the strong shear layers exerted over the cylinder’s downstream wake. A clear visualization of the wake can be obtained from the mean velocity magnitude contours, which are discussed in detail in the respective subsection. The breakdown analysis of the values extracted from the streamwise velocity contours is further done in the wake analysis section. Thus, the mean streamwise velocity contours are the major backbones of our thesis outcomes.

3.2.2 Mean spanwise velocity

The time-averaged spanwise velocity contours, in Figure 3.4, Figure 3.8, and Figure 3.14, use a “large rainbow” colormap to show the vertical component (spanwise or lateral) of resultant velocity, denoted by $v$, normalized by the respective tunnel average velocities ($U_\infty$). The red zones represent areas where the flow direction is moving upwards vertically, while the green zones indicate areas where the flow is moving downwards vertically. The yellow color represents areas with near-zero values, as shown in the legend colormaps. The spanwise velocities are relatively small compared to the streamwise velocities because our inlet flow
is streamwise. The red and green zones appear immediately after the flow hits our sample. In the upper area, the vertical component of the flow moves upwards, while at the bottom of the sample, it moves downwards. Following this, the flow begins to merge downstream. In the downstream upper half, the vertical component of the flow moves downwards, while in the downstream lower half, it moves upwards. This movement tends to reattach and gradually become streamwise. Through the spanwise velocity contours, we can visualize the intensities of these velocities over the ROI, and since our resultant flow is more dominated by streamwise components, we do not dig into the details of these contours.

3.2.3 Mean velocity magnitude

The time-averaged $V$ magnitude contours in Figures 3.5, 3.10, and 3.15 use a “large rainbow” colormap. The dark blue color indicates zero velocity. The zone enveloped by blue lines downstream of the flow represents the cylinder wake. These contours are intuitive for visualizing the wake size for different samples and Reynolds numbers. Since the flow is heavily influenced by the streamwise velocity component, which has both negative and positive values, we use streamwise data to analyze the wake length and width in the following sections. For Re=2825 in Figure 3.15, the wake width at $X/D=-0.5$ shrinks as the H groove size increases, with H3.0 having the narrowest wake. Similar trends are observed for Re=2000 and Re=1230 in Figure 3.10 and Figure 3.5, respectively.

3.3 MEAN VORTICITY

The vorticity serves as a metric for assessing the rotational motion in a fluid. Contrary to circulation, which is a scalar integral quantity offering a macroscopic evaluation of rotation over a specific fluid area, the vorticity is a vector field providing a microscopic evaluation of rotation at any given point within the fluid [30]. The vorticity at a specific point indicates the propensity of fluid elements to "spin" and represents the local rate of fluid rotation at that point. The vorticity vector, normalized by $U_\infty/D$, is computed using Equation 3.1.
\[
\frac{\vec{\omega}}{U_\infty/D} = \begin{bmatrix}
\omega_x \\
\omega_y \\
\omega_z
\end{bmatrix} = \begin{bmatrix}
\frac{\partial w}{\partial y} - \frac{\partial v}{\partial z} \\
\frac{\partial u}{\partial z} - \frac{\partial w}{\partial x} \\
-\frac{\partial u}{\partial y}
\end{bmatrix}
\] (3.1)

where:

- \(\omega_x, \omega_y, \) and \(\omega_z\) are the components of the vorticity vector,
- \(u, v, \) and \(w\) are the components of the velocity vector,
- \(D\) is the cylinder diameter, and \(U_\infty\) is the freestream velocity.

In three-dimensional analysis, we have three components of vorticity. In our analysis, we do not have a third velocity component, which leads to a single out-of-plane Z-vorticity component. The time-averaged vorticity is calculated based on the time-averaged \(u\) and time-averaged \(v\). The positive vorticity flow rotates counterclockwise, while clockwise rotation is the negative vorticity.

The time-averaged vorticity contours in Figures 3.6, 3.11, and 3.16 use a “small rainbow” colormap to show the time-averaged z-vorticity, denoted by \(\omega\), normalized by \(U_\infty/D\). The red indicates the positive counter while the blue represents negative counter vorticity. Since our flow is not turbulent, vorticity quantities are not that strong. However, a value range of -0.018 to 0.018 has been set for all contours.

For \(Re=2835\) in Figure 3.14, the red and blue streaks appear immediately after the flow hits our sample. Developing from the upper area of the samples, a negative counter rotation is observed, while a positive counter rotation exists from the bottom of the sample. Following this, these streaks begin to fade downstream and eventually die. We can observe that the vorticity values, indicated by the color intensity of the streaks, are lower for the H2.5 and H3.0 cylinders, with H3.0 having the least. This pattern is also seen for \(Re=2000\) and \(Re=1230\), respectively, from Figure 3.11 and Figure 3.6. For other horizontal samples, apart from H2.5 and H3.0, we can distinctly identify the vorticity values along vertical lines downstream,
similar to the method used in the wake length analysis section. Also, the vorticity contours of V cylinders are plotted in respective figures.

3.4 STREAMTRACES

Streamtraces serve as a visualization tool to illustrate the flow pattern of a vector field. They represent the trajectory that a particle, without mass, would trace if it were placed within the vector field’s flow. Streamtraces offer crucial insights into the flow’s characteristics and behavior, such as its direction and varying magnitudes at distinct points. In our research, we employed Tecplot 360 software for calculating streamtraces. The software first identifies the velocity gradient within the volume zones. It then interpolates this gradient to the surface zones and computes the dot product with the surface zones’ unit normal. This process results in the components of the velocity gradient in the direction perpendicular to the surface, forming a vector [31]. Our field is 2D itself, so it just calculates velocity gradients over the surface in both directions (x and y) and gets resulting vector for the whole field.

The time-averaged streamtraces plot in Figures 3.7, 3.12, and 3.17 use arrowheads to show the streamtraces in a light yellow flow field, denoted by $\psi$ for the respective Reynolds numbers of 1230, 2000 and 2825. The streamtraces allow us to identify and analyze critical points such as foci and saddle points in the downstream flow. Foci are points in the flow where streamlines converge or diverge, indicating regions of swirling motion. On the other hand, saddle points are locations where the flow diverges along one direction and converges along the orthogonal direction, creating a saddle-like shape in the streamline pattern. We can see two foci where streamtraces form two closed loops. The saddle point, where streamtraces diverge along one axis and converge along the other, is seen for a bare cylinder for Re=2825 in Figure 3.2.

In Figure 3.17, for Re=2835, the foci of the H3.0 cylinder are more compressed and closer to each other than those of the bare cylinder. This is due to the narrower wake width from the start of the downstream development, causing both the upper and lower shear layers
to move closer, pushing the foci towards each other as we transition from the bare cylinder to the H3.0 cylinder. The saddle point, which marks the end of the wake and is discussed in detail in the next section on wake length analysis, shifts further to the left for the H3.0 cylinder compared to the bare cylinder. This pattern of compressed foci for the H3.0 cylinder is also observed for Re=2000, as depicted in Figure 3.12. However, upon close inspection of the H3.0 streamtraces for Re=1230 in Figure 3.7, the foci are nearly absent. This could be due to the limitations of our analysis software’s computational capabilities in detecting such small foci. Alternatively, it could be that the flow reattachment occurred so early for this particular Reynolds number that the foci couldn’t form.
Figure 3.3: Normalized streamwise velocity contours for $Re=1230$
Figure 3.4: Normalized spanwise velocity contours for Re=1230
Figure 3.5: Normalized velocity magnitude contours for $Re=1230$
Figure 3.6: Normalized vorticity contours for Re=1230
Figure 3.7: Streamtraces for Re=1230
Figure 3.8: Normalized streamwise velocity contours for \( \text{Re}=2000 \)
Figure 3.9: Normalized spanwise velocity contours for Re=2000
Figure 3.10: Normalized velocity magnitude contours for Re=2000
Figure 3.11: Normalized vorticity contours for Re=2000
Figure 3.12: Streamtraces for Re=2000
Figure 3.13: Normalized streamwise velocity contours for Re=2825
Figure 3.14: Normalized spanwise velocity contours for Re=2825
Figure 3.15: Normalized velocity magnitude contours for Re=2825
Figure 3.16: Normalized vorticity contours for Re=2825
Figure 3.17: Streamtraces for Re=2825
3.5 WAKE LENGTH ANALYSIS

We extracted the time-averaged $u$ at the horizontal centerline from all samples across three different Reynolds numbers. The extraction range was from $X/D=-0.7$ to $X/D=-5.0$. We chose 50 data points, equally spaced between $X/D=-0.7$ and $X/D=-5.0$. The symmetry of our samples along the centerline made it an ideal choice, as it is where the length of the cylinder wake downstream is the longest. We then plotted this normalized $u$ against $X/D$. This allowed us to identify the points where the curves intersected with zero streamwise velocity. These intersections represent the values of $X/D$ where backflow completely stops, and the flow starts to reattach. These specific $X/D$ locations are of great interest as they determine the end of the wake and, consequently, the wake length. Our primary focus is to isolate the wake length characteristics for different grooves. This is a crucial observation as it can potentially influence the static pressure drop and streamlining of the flow.

For $Re=2825$, as depicted in Figure 3.18, analysis of the streamwise velocity profile shows an early termination of the wake for the largest horizontal groove size, H3.0, in comparison to all other samples. The wake ends notably early at $X/D = -2.5178$. A pattern emerges where the wake position shifts towards the left, transitioning from bare cylinders to increasing horizontal groove sizes—except for H0.5 cylinder. The $X/D$ values for H1.0 remain relatively consistent with that of bare cylinders. However, a significant leftward shift in $X/D$ values is observed in the progression from H1.5, H2.0, H2.5, and culminating in H3.0, as detailed in Table 3.1.

<table>
<thead>
<tr>
<th>Cylinder</th>
<th>Bare</th>
<th>H0.5</th>
<th>H1.0</th>
<th>H1.5</th>
<th>H2.0</th>
<th>H2.5</th>
<th>H3.0</th>
</tr>
</thead>
</table>

Table 3.1: Wake ending locations at $Re=2825$ for H Cylinders

For $Re=2000$, as shown in Figure 3.19, examining the streamwise velocity profile indicates an early end to the wake with the largest horizontal groove size, H3.0, compared to other samples. The wake stops notably sooner at $X/D = -2.6105$. A trend emerges where the wake position moves to the left, shifting from bare cylinders to larger horizontal groove...
sizes—except for H0.5 cylinders. A considerable leftward shift in X/D values is noticeable in the progression from H1.0, H1.5, H2.0, H2.5, and reaching its peak left in H3.0, as outlined in Table 3.2.

<table>
<thead>
<tr>
<th>Cylinder</th>
<th>Bare</th>
<th>H0.5</th>
<th>H1.0</th>
<th>H1.5</th>
<th>H2.0</th>
<th>H2.5</th>
<th>H3.0</th>
</tr>
</thead>
</table>

Table 3.2: Wake ending locations at Re=2000 for H Cylinders

For Re=1230, as shown in Figure 3.20, examining the streamwise velocity profile indicates an early end to the wake with the largest horizontal groove size, H3.0, compared to other samples. The wake stops notably sooner at X/D =- 2.807. However, the pattern observed in Re=2825 and Re=2000 do not match at this flow. We can not say there is any trend in wake lengths respective to horizontal groove size by looking at the values in Table 3.3.

<table>
<thead>
<tr>
<th>Cylinder</th>
<th>Bare</th>
<th>H0.5</th>
<th>H1.0</th>
<th>H1.5</th>
<th>H2.0</th>
<th>H2.5</th>
<th>H3.0</th>
</tr>
</thead>
</table>

Table 3.3: Wake ending locations at Re=1230 for H Cylinders
3.5.1 Vertical Cylinders

Similar to the above subsection on the horizontal cylinders, we analyzed the wake lengths for every vertical cylinders compared with the baseline bare cylinder for all three Reynolds numbers, i.e., Re=2825, Re=2000 and Re=1230. We seek any pattern that could come out from these observations. For Re=2825, the centerline streamwise velocity profile is shown in Figure 3.21, and the corresponding wake length ends are tabulated in Table 3.4. For Re=2000, the centerline streamwise velocity profile is depicted in Figure 3.22, and the respective wake length ends are extracted in Table 3.5. For Re=1230, the centerline streamwise velocity profile is shown in Figure 3.23, and the corresponding wake lengths end where the streamwise component becomes zero are given in Table 3.6. There is no specific pattern of interest in vertical cylinders for wake length characteristics.

<table>
<thead>
<tr>
<th>Cylinder</th>
<th>Bare</th>
<th>V0.5</th>
<th>V1.0</th>
<th>V1.5</th>
<th>V2.0</th>
<th>V2.5</th>
<th>V3.0</th>
</tr>
</thead>
</table>

Table 3.4: Wake ending locations at Re=2825 for V Cylinders
Figure 3.20: Centerline streamwise velocity profile for H cylinders at Re=1230

<table>
<thead>
<tr>
<th>Cylinder</th>
<th>Bare</th>
<th>V0.5</th>
<th>V1.0</th>
<th>V1.5</th>
<th>V2.0</th>
<th>V2.5</th>
<th>V3.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>X/D</td>
<td>-2.8820</td>
<td>-2.7374</td>
<td>-2.73</td>
<td>-2.7262</td>
<td>-2.7344</td>
<td>-2.6624</td>
<td>-2.7389</td>
</tr>
</tbody>
</table>

Table 3.5: Wake ending locations at Re=2000 for V Cylinders

Figure 3.21: Centerline streamwise velocity profile for V cylinders at Re=2825
Figure 3.22: Centerline streamwise velocity profile for V cylinders at Re=2000

Figure 3.23: Centerline streamwise velocity profile for V cylinders at Re=1230

<table>
<thead>
<tr>
<th>Cylinder</th>
<th>Bare</th>
<th>V0.5</th>
<th>V1.0</th>
<th>V1.5</th>
<th>V2.0</th>
<th>V2.5</th>
<th>V3.0</th>
</tr>
</thead>
</table>

Table 3.6: Wake ending locations at Re=1230 for V Cylinders
3.6 WAKE WIDTH ANALYSIS

We selected five vertical lines, evenly spaced, downstream of the cylinder at X/D=-1, X/D=-2, X/D=-3, X/D=-4, and X/D=-5. We then obtained the time-averaged streamwise velocity for each sample at three Reynolds numbers. We plotted the corresponding Y/D values against the streamwise velocity values for each sample. The graphical plots for horizontal cylinders, along with the bare sample for Re=2825, Re=2000 and Re=1230, are presented in Figures 3.24, 3.25, and 3.26, respectively. The corresponding plots for vertical samples in all the flow rates can be accessed in Appendix Figures A.1, A.2, and A.3. The analysis for horizontal samples is further broken down to one specific analysis at a single vertical location immediately after the beginning of wake.

For this specific analysis, we compared a single series of \( (u/U_\infty, Y/D) \) data at X/D=-1 for all samples. The curve intersects \( u/U_\infty = 0 \) at two Y/D locations. The upper location marks the point where the upper shear layer separates from the wake, and the lower location indicates where the lower shear layer separates from the wake. These specific Y/D locations (upper and lower) are of significant interest as they define the lateral expansion of the wake and, consequently, the wake width. Our main objective is to examine the wake width characteristics of different grooves. Since we observed patterns of wake lengths in the previous section for horizontal only, for wake width analysis, we also chose only the horizontal cylinders. This observation is vital as it could potentially affect the static pressure drop and the streamlining of the flow.

For Re=2825, as shown in Figure 3.29a, the streamwise velocity profile along Y/D for bare and horizontal cylinders at X/D=-1 was analyzed. The graphical calculation in Table 3.29b reveals that the horizontal groove size H3.0 has the smallest wake among all the samples. The wake width for H3.0 is 6.136mm, which is 0.6136 of Y/D, while the bare sample has a wake width of 9.222 mm. The wake widths for H2.0 and H2.5 are also smaller than the bare sample, with 8.913mm and 8.276mm, respectively. However, the other horizontal samples
$Re = 2825$

Figure 3.24: Streamwise velocity profile at downstream vertical locations for $Re=2825$
$Re = 2000$

Figure 3.25: Streamwise velocity profile at downstream vertical locations for $Re=2000$
$Re = 1230$

Figure 3.26: Streamwise velocity profile at downstream vertical locations for $Re=1230$
do not exhibit a reduced wake width at this Reynolds number.

For Re=2000, as shown in Figure 3.28a, the streamwise velocity profile along Y/D for bare and horizontal cylinders at X/D=−1 was analyzed. The graphical calculation in Table 3.28b reveals that the horizontal groove size H3.0 has the smallest wake among all the samples. The wake width for H3.0 is 6.052 mm, which is 0.6052 of Y/D, while the bare sample has a wake width of 9.24 mm. The wake widths for H2.0 and H2.5 are also smaller than the bare sample, with 8.758 mm and 8.125 mm, respectively. However, the other horizontal samples do not exhibit a reduced wake width at this Reynolds number. This is similar to what we got for Re=2825.

For Re=1230, as shown in Figure 3.27a, the streamwise velocity profile along Y/D for bare and horizontal cylinders at X/D=−1 was analyzed. The graphical calculation in Table 3.27b reveals that the horizontal groove size H3.0 has the smallest wake among all the samples. The wake width for H3.0 is 8.063 mm, which is 0.8063 of Y/D, while the bare sample has a wake width of 8.719 mm. However, the other horizontal samples (except H3.0) do not exhibit a reduced wake width at this Reynolds number. At this Reynolds number, we do not observe any consistency in the data, and wake width is within a small range as all curves are almost aligned in Figure 3.27a.
(a) Streamwise Velocity profile at X/D=-1

(b) Wake width calculation

<table>
<thead>
<tr>
<th>Cylinder</th>
<th>Bare</th>
<th>H0.5</th>
<th>H1.0</th>
<th>H1.5</th>
<th>H2.0</th>
<th>H2.5</th>
<th>H3.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper at Y/D=</td>
<td>1.4723</td>
<td>1.4552</td>
<td>1.4848</td>
<td>1.4993</td>
<td>1.4821</td>
<td>1.524</td>
<td>1.4423</td>
</tr>
<tr>
<td>Lower at Y/D=</td>
<td>0.6004</td>
<td>0.5721</td>
<td>0.569</td>
<td>0.5657</td>
<td>0.5846</td>
<td>0.5974</td>
<td>0.636</td>
</tr>
<tr>
<td>Width Y/D</td>
<td>0.8719</td>
<td>0.8831</td>
<td>0.9158</td>
<td>0.9366</td>
<td>0.8975</td>
<td>0.9266</td>
<td>0.8063</td>
</tr>
</tbody>
</table>

Figure 3.27: Wake width of H Cylinders at Re=1230
(a) Streamwise Velocity profile at X/D=-1

(b) Wake width calculation

<table>
<thead>
<tr>
<th>Cylinder</th>
<th>Bare</th>
<th>H0.5</th>
<th>H1.0</th>
<th>H1.5</th>
<th>H2.0</th>
<th>H2.5</th>
<th>H3.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper Y/D</td>
<td>1.512</td>
<td>1.4739</td>
<td>1.4995</td>
<td>1.487</td>
<td>1.4747</td>
<td>1.4681</td>
<td>1.3487</td>
</tr>
<tr>
<td>Lower Y/D</td>
<td>0.588</td>
<td>0.546</td>
<td>0.5452</td>
<td>0.5651</td>
<td>0.5989</td>
<td>0.6556</td>
<td>0.7435</td>
</tr>
<tr>
<td>Width Y/D</td>
<td>0.924</td>
<td>0.9279</td>
<td>0.9543</td>
<td>0.9219</td>
<td>0.8758</td>
<td>0.8125</td>
<td>0.6052</td>
</tr>
</tbody>
</table>

Figure 3.28: Wake width of H Cylinders at Re=2000
(a) Streamwise Velocity profile at X/D=-1

(b) Wake width calculation

<table>
<thead>
<tr>
<th>Cylinder</th>
<th>Bare</th>
<th>H0.5</th>
<th>H1.0</th>
<th>H1.5</th>
<th>H2.0</th>
<th>H2.5</th>
<th>H3.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper at Y/D=</td>
<td>1.5395</td>
<td>1.5345</td>
<td>1.5465</td>
<td>1.5289</td>
<td>1.5053</td>
<td>1.4605</td>
<td>1.3465</td>
</tr>
<tr>
<td>Lower at Y/D=</td>
<td>0.6173</td>
<td>0.6073</td>
<td>0.5810</td>
<td>0.6026</td>
<td>0.6143</td>
<td>0.6329</td>
<td>0.7329</td>
</tr>
<tr>
<td>Width Y/D</td>
<td>0.9222</td>
<td>0.9272</td>
<td>0.9655</td>
<td>0.9269</td>
<td>0.8913</td>
<td>0.8276</td>
<td>0.6136</td>
</tr>
</tbody>
</table>

Figure 3.29: Wake width of H Cylinders at Re=2825
3.7 PRESSURE DROP

Table 3.7 shows the micromanometer readings of pressure drop in Pascals, for horizontal samples and bare sample at different Reynolds numbers. Table 3.8 shows the same for vertical samples and bare sample. Figure 3.30 displays the data in a bar chart format.

For horizontal cylinders, H2.0, H2.5 and H3.0 have lower pressure drops than the baseline sample at all Reynolds numbers, with H3.0 being the best sample for minimizing pressure drop. For Re=1230, Re=2000, and Re=2825, H3.0 reduces the pressure drop by 15.5%, 17.2%, and 19.3%, respectively, compared to the bare cylinder.

<table>
<thead>
<tr>
<th>Cylinder</th>
<th>Bare</th>
<th>H0.5</th>
<th>H1.0</th>
<th>H1.5</th>
<th>H2.0</th>
<th>H2.5</th>
<th>H3.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>∆P (Re=1230)</td>
<td>1.2742</td>
<td>1.2746</td>
<td>1.3074</td>
<td>1.2912</td>
<td>1.2336</td>
<td>1.1672</td>
<td>1.0766</td>
</tr>
<tr>
<td>∆P (Re=2000)</td>
<td>2.5316</td>
<td>2.5232</td>
<td>2.6046</td>
<td>2.5208</td>
<td>2.4128</td>
<td>2.2852</td>
<td>2.0964</td>
</tr>
<tr>
<td>∆P (Re=2825)</td>
<td>4.408</td>
<td>4.3724</td>
<td>4.484</td>
<td>4.3162</td>
<td>4.116</td>
<td>3.8858</td>
<td>3.5586</td>
</tr>
</tbody>
</table>

Table 3.7: Pressure Drop (in Pa) for H Cylinders

<table>
<thead>
<tr>
<th>Cylinder</th>
<th>Bare</th>
<th>V0.5</th>
<th>V1.0</th>
<th>V1.5</th>
<th>V2.0</th>
<th>V2.5</th>
<th>V3.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>∆P (Re=1230)</td>
<td>1.2742</td>
<td>1.2886</td>
<td>1.3018</td>
<td>1.2998</td>
<td>1.316</td>
<td>1.3468</td>
<td>1.368</td>
</tr>
<tr>
<td>∆P (Re=2000)</td>
<td>2.5316</td>
<td>2.541</td>
<td>2.5856</td>
<td>2.5884</td>
<td>2.615</td>
<td>2.6568</td>
<td>2.6342</td>
</tr>
<tr>
<td>∆P (Re=2825)</td>
<td>4.408</td>
<td>4.4478</td>
<td>4.502</td>
<td>4.4554</td>
<td>4.5112</td>
<td>4.4936</td>
<td>4.6584</td>
</tr>
</tbody>
</table>

Table 3.8: Pressure Drop (in Pa) for V Cylinders

Figure 3.30: Pressure Drop
In this thesis, we presented the results of our experiments on the flow around a grooved cylinder in an internal flow passage with a square cross-section. We investigated the effects of groove parameters, such as groove diameter (depth) and orientation (streamwise and longitudinal), on the flow characteristics of the downstream. Specifically, the wake length and width were studied extensively, along with the pressure drop across these samples at Reynolds numbers of 1230, 2000, and 2825. We used PIV and cross-correlation techniques to measure the velocity fields specifically. We also visualized the streamlines and the vorticity contours to illustrate the flow patterns and the wake structures. The main conclusions from this study are listed below.

- A consistent reduction in the wake length is observed for the horizontally grooved cylinders H2.0, H2.5, and H3.0 at the Reynolds numbers of 2825 and 2000, compared to the baseline cylinder.

- Only the H3.0 cylinder showed a reduction in wake length at a Reynolds number of 1230 compared to the bare cylinder. The results for other samples at this flow rate are inconsistent.

- A consistent narrowing of the wake in the spanwise direction is evident for the streamwise grooved cylinders H2.0, H2.5, and H3.0 at Reynolds numbers of 2825 and 2000, compared to the baseline sample.

- Only the H3.0 cylinder shows a reduction in wake width at a Reynolds number of
1230 compared to the bare sample. The results for other samples at this flow rate are inconsistent.

- A consistent reduction in pressure drop is observed across samples H2.0, H2.5, and H3.0 for all three tested Reynolds numbers.

- The cylinders H2.0, H2.5, and H3.0 exhibit desirable flow characteristics for the Reynolds numbers of 2000 and 2825.

- Only the H3.0 cylinder exhibits desirable wake characteristics and pressure drop at all flow rates.

- The contour visualization of mean streamwise velocity, mean spanwise velocity, mean velocity magnitude, vorticity, and streamlines all support the above analysis.

- Data related to vertical cylinders have not been analyzed as the streamwise groove orientation aligns with our objectives. Further investigation could involve a breakdown of these longitudinal grooves.

There are various limitations to the experiments performed. They are discussed below and require further attention for future experiments.

- Fan Speeds: Our fan had only three-speed settings, limiting our ability to control the Reynolds number and distinguish the flow regimes. A more precise and robust fan system that can produce laminar, critical, and turbulent flows is essential.

- Tunnel Size and Turbulence: Our tunnel was too small to generate turbulent flow, which is more relevant for turbine internal cooling. A larger test setup that can replicate high-turbulence flows is recommended for future experiments.

- Setup Quality and Accuracy: Our experimental setup consisted of custom-made 3D printed components, which may have caused leveling, bending, and loss issues. These
factors may have affected the symmetry of the velocity profile in the open channel, as discussed in the first section of this chapter.

- Tunnel average Velocity Measurement: Our tunnel average velocity value was based on the 2D flow field from the PIV output, which may have been influenced by the incoming seeded flow. A more reliable velocity measurement system that is not affected by the seeding particles is preferable for future experiments.

- Flow Visualization: Our 2D PIV flow field was a result of the overall 3D flow effect, which may have obscured some details. Volumetric PIV would be more effective in visualizing the flow in depth.

- Instantaneous flow characteristics and turbulent statistics: In this study, we focused solely on the analysis of time-averaged statistics. However, examining instantaneous derived quantities along with turbulent statistics, such as velocity gradients, instantaneous vorticity, normal and shear Reynolds stress, and turbulent kinetic energy calculations, could provide insights into fluctuations in the flow field and associated energy dissipation. These analyses could be the immediate focus of future work, further scrutinizing the outcomes of this study.
BIBLIOGRAPHY
Bibliography


LIST OF APPENDICES
Figure A.1: Streamwise velocity profile at downstream vertical locations for Re=1230
Figure A.2: Streamwise velocity profile at downstream vertical locations for Re=2000
Figure A.3: Streamwise velocity profile at downstream vertical locations for Re=2825
VITA

Jhalak Dhakal

Education

B.S. in Mechanical Engineering, Tribhuvan University (Nepal), Sep 2016
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Undergraduate Thesis: Design Study of Runner for Gravitational Vortex Power Plant

Relevant Coursework

- Aerodynamics
- Finite Element Analysis
- Introduction to Advanced Computational Mechanics
- Introduction to CFD
- Introduction to Turbulence
- Linear Systems and Controls
- Mechatronics
- Thermal Engineering Management

Relevant Professional Experience

- Graduate Mechanical Engineering Intern, Lennox International (May 2022 - July 2022)
- Mechanical Engineer, TATA Motors Nepal (July 2017 - August 2019)

Technical Tools and Skills

- Automotive Systems
- CAD Softwares: Solidworks/AutoCAD
- HVAC Systems
- Computational Softwares: ANSYS/ABAQUS
- LaTex
- MATLAB
- Python

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Nepal Engineers’ Association - Member of Institutional Development Committee (2020-2021)