Fluid Mechanics Lab Report

MACE31422

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1. Abstract

This report contains methodology, results and discussions from a hands-on experiment, which takes measurements of some important flow quantities such as fluctuating velocities, upstream and downstream pressure or root mean square velocities. The range of effects from the viscous sublayer as well as the streamwise turbulence intensity are discussed.

2. Introduction

The transport of fluid inside a pipe is extremely important in our daily life. The applications range from water pipes in our households to the blood veins in our body. Therefore, investigating the properties of pipe flows becomes is crucial in engineering point of view. In this experiment, fully developed turbulent pipe flows for 3 different fluid inlet velocities along a metal pipe are investigated through a constant temperature hot-wire anemometer and preset Labview codes. The mean velocity profile and the shear wall stress are presented, while the turbulence intensity is presented and compared to the previous work.

3. Methodology

3.1 Apparatus

In the experiment, a variable speed fan is used to drive a flow of air through a 102mm internal diameter metal pipe, the length to diameter ratio of the pipe is sufficient for the flow to be fully developed. The pressure in the pipe is measured at two locations by a 16-channel pressure scanner, where the upstream and downstream pressure are measured 3 meters apart and it is made sure that at upstream pressure the flow is fully developed. The velocity of the air flow is measured via constant temperature hot-wire anemometer, which contains a single sensor hot-wire probe that records the voltage across it. As velocity of air flow changes, the resistance of the probe could also change, resulting in a change in the voltage, and the change in voltage can thus be used to calculate the velocity of the air flow. A set of position meter and traverse gear are used to ensure accurate positioning of the how-wire anemometer. The data from all the above apparatus are collected on PC by a preset LabVIEW code.
Labelled pictures taken from the experiment are shown in figures from Appendix A

3.2 Procedure

At the start of the experiment, the hot-wire anemometer is calibrated using a separate calibration wind tunnel where a low turbulence flow is generated. The voltage measured in the anemometer is recorded to compare with the velocity of the flow in the calibration wind tunnel obtained by measuring the pressure difference from the inlet to the part of least area of the wind tunnel. The data is recorded via preset Labview code so that the calibration is done automatically.
After the hot-wire anemometer is calibrated properly, it is mounted to the set of

position meter and traverse gear. It is then positioned so that the tip of the probe is around 0.5 times of pipe diameters into the pipe. Once the body of the anemometer touches the wall of the pipe, the connected digital voltmeter would read 0V due to short circuit, this is used to set the position meter to 0mm as it touches the wall of the pipe. After this, the variable speed fan is switched on and set to high speed. For convenience reasons, detail Reynold number calculations are not done, and the speed of the flow is set as relatively high at first.
Then 6 students attending the laboratory are divided into 3 groups, for each group one student sets the traverse gear and read on the position meter to ensure accurate positioning, and then the other student manipulates the LabVIEW panel on the PC to store data. This action is repeated for first 10 data points (listed in Appendix B, then the two students swap so that everyone gains experience in doing both tasks. After the operations are done to the 19 datapoints for high speed scenario, the GTA would check the results to see if they are properly collected, and then the variable speed fan is set to give medium and low speed, while same operations are carried out by the other two groups of students. At the end of the experiment, the obtained data are put into 3 .csv files sent to us via email. It should be noted that for the 19^{th} datapoint, at 51mm from the pipe wall, the position of the probe cannot reach 51mm (maximum 49.xxx mm) as the traverse gear is jammed by the wall of room. However, this should have little effect as it is close to the midpoint of the pipe, so that the velocity change should not be considerable, and the results should be fine.

3.3 Postprocessing Data

After the experiment, the data obtained are then processed with care. For each position, 5 fluctuating velocities are taken. A MATLAB code is written to quickly calculate the average velocity of the 5 fluctuating velocities from the 19 datapoints for each speed scenario. This is shown in Appendix C. Then the mean velocity is normalized and plotted with position vector on linear axes and log-log axes for all three different velocities. The slope of the log-log diagram is investigated further to explore the velocity profile in the turbulent region. Then the wall shear stress is estimated via the measured pressure drop in the pipe, and it is subsequently used to investigate the streamwise turbulent velocity by plotting the turbulent intensity against distance from the wall of the pipe normalized with wall-related quantities. This is then compared to previous work by [1].

4. Results

4.1 Average Velocity Profiles

The linear axes and log-log axes average velocity profiles from the 3 speed scenarios are shown below, where two best fit lines are marked with red arrow for each log-log axes graph to help illustrate the clear difference in behavior between the fully turbulent and viscosity-affected regions. The datapoints are denser near wall as the velocity gradient near wall is steeper, so denser data points are needed.

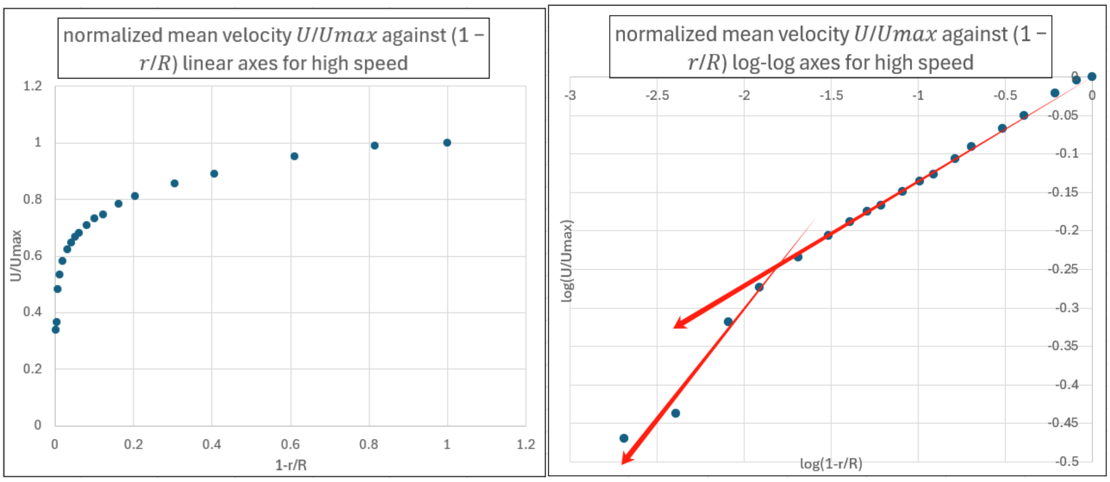


Figure 1 and 2: normalized mean velocity against normalized position for linear and log-log axes for high-speed scenario.

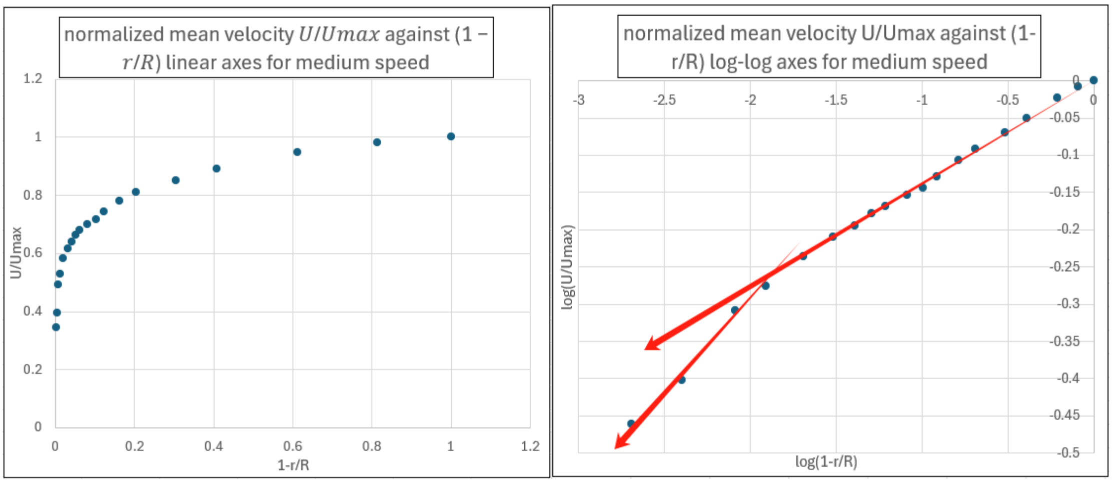


Figure 3 and 4: normalized mean velocity against normalized position for linear and log-log axes for medium-speed scenario.

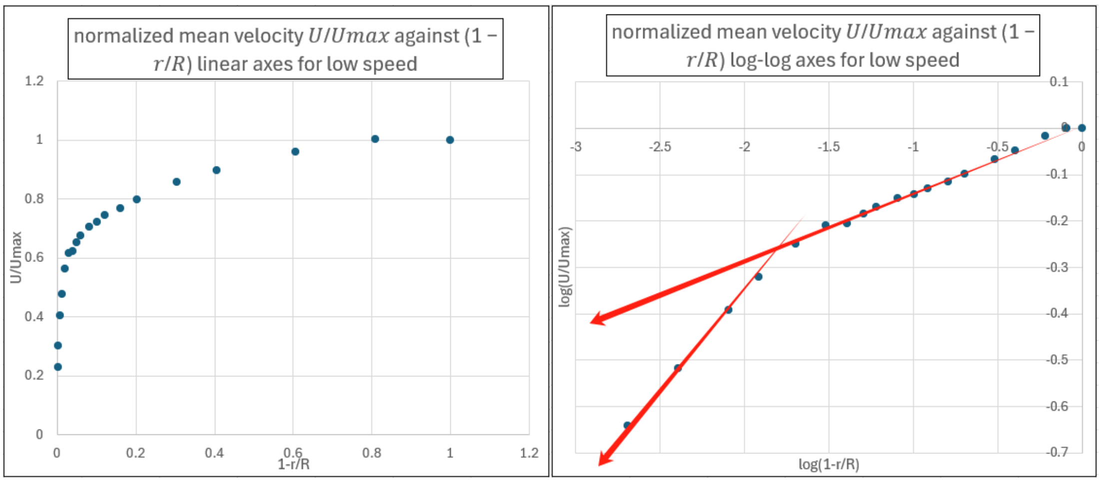


Figure 5 and 6: normalized mean velocity against normalized position for linear and log-log axes for low-speed scenario.

4.2 Wall Shear Stress

Wall shear stress is estimated by considering the force balance between the pressure gap in the pipe and the friction developed by the pipe walls. For a fully developed pipe flow, the velocity of the flow becomes constant and there is no resultant force. This means that the pressure gap in the pipe that drives the flow moving must equal to the friction at the pipe walls that does negative work on the pipe flow. The formula for the force induced by the pressure gap is $\Delta P\pi R^2$, while the formula for the force induced by the wall friction is $\tau_W 2\pi RL$. By equating the two terms and divide both sides by $2\pi RL$ gives $\tau_W = \frac{\Delta PR}{2L}$, which is an estimation of the wall shear stress. For the carried out experiment, $\Delta P = P_2 - P_1$ where P_2 is the upstream pressure tap and P_1 is the downstream pressure tap, the values of P_2 and P_1 are obtained by taking the average of P Ben 1 and P Ben 2 in the extracted data. The R value used in the equation is the average of three measured maximum distance, which is 49.198mm, to ensure consistency of data. L is the distance between the two pressure taps and the value is 3m. Therefore, for high-speed scenario:

$$\tau_W = \frac{\Delta PR}{2L} = \frac{62.5458 \times 49.198 \times 10^{-3}}{2 \times 3} = 0.5128547114 \approx 0.5129Pa$$

For medium-speed scenario:

$$\tau_W = \frac{\Delta PR}{2L} = \frac{46.3044 \times 49.198 \times 10^{-3}}{2 \times 3} = 0.3796806452 \approx 0.3797Pa$$

For low-speed scenario:

$$\tau_W = \frac{\Delta PR}{2L} = \frac{14.6426 \times 49.198 \times 10^{-3}}{2 \times 3} = 0.1200644391 \approx 0.1201Pa$$

4.3 Streamwise Turbulence Intensity

The streamwise turbulence intensity (STI) is a dimensionless quantity defined as $u^{2+} = (\frac{U_{rms}}{U_\tau})^2$, where U_{rms} is the measured root-mean-square velocity and U_τ is the friction velocity, defined as $U_\tau = \sqrt{\frac{\tau_W}{\rho}}$. The streamwise turbulence intensity is normally plotted against the wall distance normalized with wall-related quantities. This is typically denoted y^+, and is defined as: $y^+ = \frac{\rho U_\tau y}{\mu}$, where y is the distance from the wall. The resulting non-dimensional profiles is plotted with u^{2+} on the vertical axis, with a linear scale and y^+ on the horizontal axis, with a logarithmic scale. The profiles from the carried out experiment and the previous work by Hultmark, M. et al. [1] are shown below.

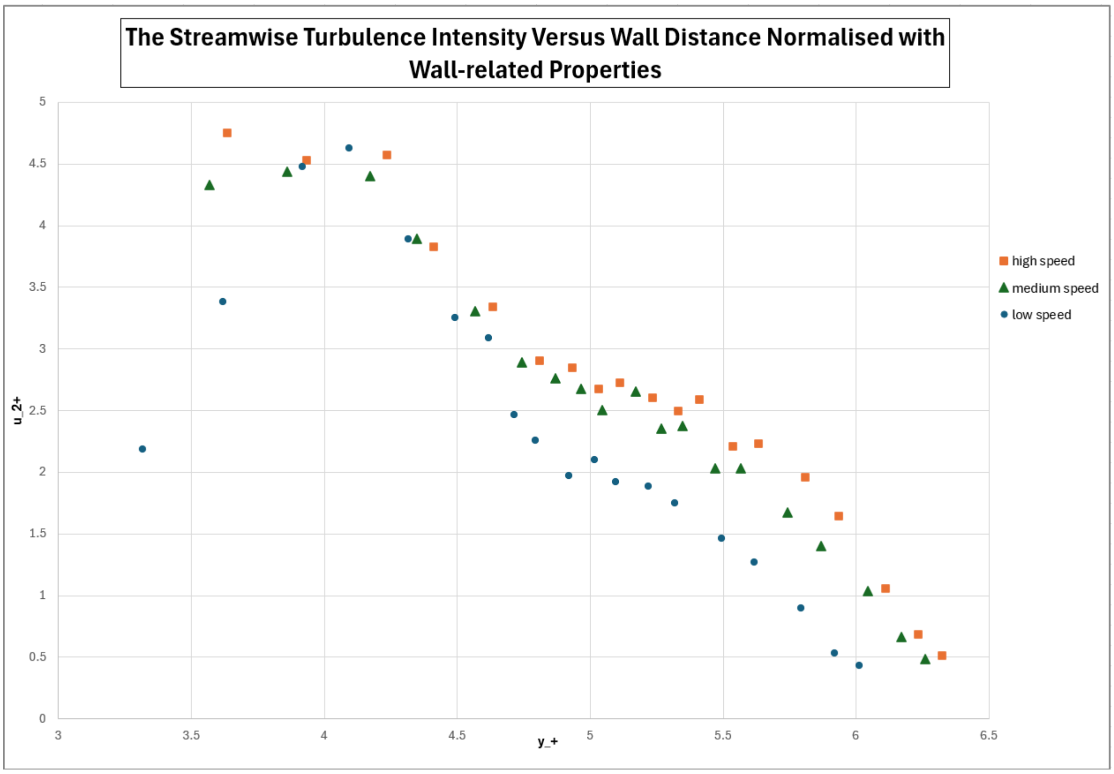


Figure 7: The streamwise turbulence intensity versus wall distance normalised with wall-related properties from carried out experiment.

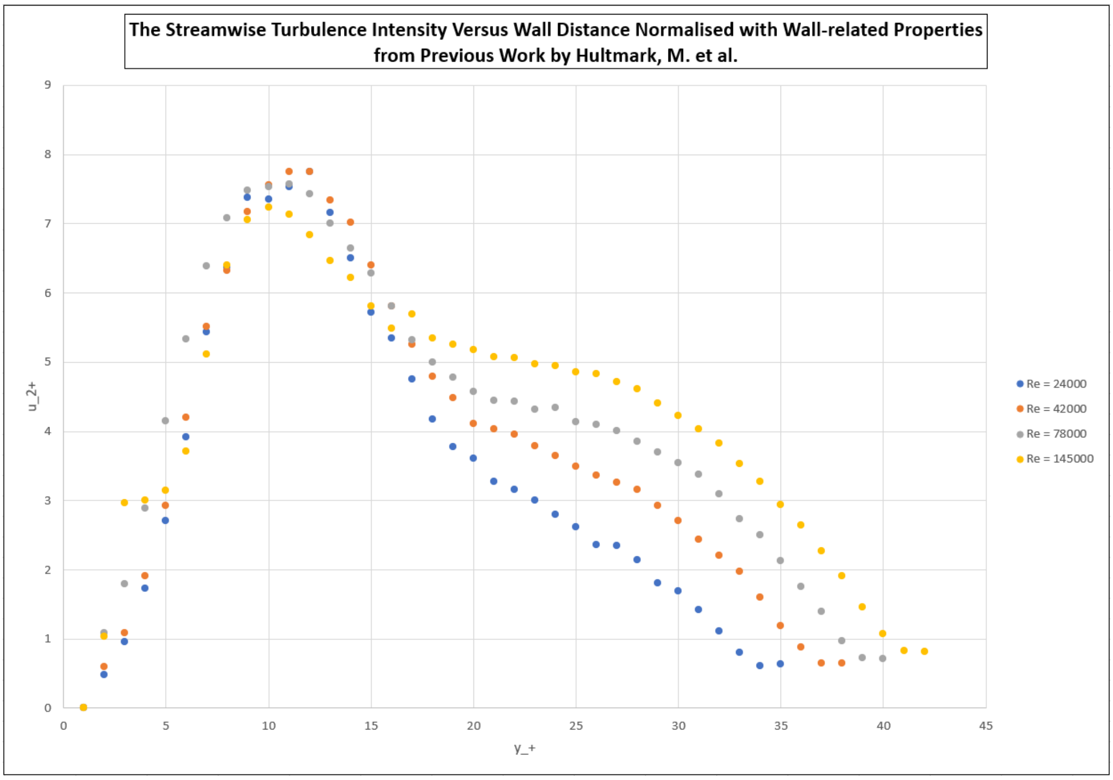


Figure 8: The streamwise turbulence intensity versus wall distance normalised with wall-related properties from previous work by Hultmark, M. et al. [1]

5. Discussion

5.1 Average Velocity Profiles

As shown in Figures 1-6, the normalized velocity profiles from three different speed scenario generally show an agreement on the trend. From the 3 log-log diagrams, the behaviors of fully turbulent regions (the region with the red arrow going through the origin) and the viscosity affected regions (region with the second red arrow not going through origin) shows a clear difference. The intersections of the red arrows denote the location where the viscous effects extend to, and in this case the 3 diagrams read approximately the same at log normalized position of -1.8, which corresponds to about 0.78mm from the wall. From the log-log diagram, the intersections of the arrows lie approximately between the 4th and the 5th data point, referring the midpoint of the 4th and the 5th data point in the linear axes diagram reads approximately 0.55. This means that at the point where the viscosity-affected sublayer intersects with the fully turbulent region, the velocity is approximately 55% of the maximum speed. The change in Reynolds numbers also has impact on the velocity profile. As shown in the linear axes figures, the higher the Reynolds number is, the higher the minimum speed is (the 1st data point) and vice versa. It should be noted that for the 18th data point in the low speed scenario, the relative speed is actually higher than that from 19th data point, which is not reasonable as the 19th data point should give the maximum speed at the middle of the pipe. One possible reason for such phenomenon is potential operational error in performing the extraction of data, for example the student operating the LabVIEW on PC might not wait long enough for the probe to receive stabilize enough data after moving it, leading to a slight error in the 18th data point. If one were to fit a power law to the velocity profile (excluding the viscous sublayer) of the form $\frac{\mathrm{U}}{\mathrm{U_{max}}} = (\frac{\mathrm{y}}{\mathrm{R}})^{\mathrm{n}}$, the optimum value of n could be investigated by checking the slope of the log-log axes diagram in the turbulent region. This is because the power law could be represented in the form $\log\frac{\mathrm{U}}{\mathrm{U_{max}}} = n \times \log\frac{\mathrm{y}}{\mathrm{R}}$, which is essentially the same with the equation of the above log-log axes diagram. The slopes of the turbulent regions are calculated, and average value of the three results is taken. The value of n is about 0.13934.

5.2 Streamwise Turbulence Intensity

As shown in Figure 7 and 8, the maximum values of u^{2+} and y^{+} from previous work by Hultmark, M. et al. exceed that from the carried out experiment. One possible reason is that the inlet velocity from the previous work is greater than the inlet velocity of the carried out experiment, as this will increase the range of the root mean square speed and eventually increase the range of u^{2+}. However, the Reynolds numbers for the carried out experiment are not recorded properly, which makes it impossible to compare the inlet velocities of the two experiments. For the same phenomenon in values in y^{+}, the reason could be regarding to the radius difference in the pipes. The radius of the pipe in previous work is 64.92mm, which is higher than

both the actual (51mm) and the used-for-calculation (49.198) radius of the pipe. As a result, τ_W from previous work should be higher than that from the carried out experiment, which subsequently lead to a greater value of y^+. Furthermore, the greater inlet velocity from previous work could lead to greater drop in pressure, which also contribute to greater τ_W and thus greater y^+.
In terms of trend, both graphs show an agreement that u^{2+} tends to increase for low y^+, but as y^+ continues to increase, u^{2+} would then start to decrease. Furthermore, it is noticeable that inside the decreasing region of high Reynolds number cases, the slope of the diagram decreases for short values of y^+, then returns to original slope. It also should be noted that the increasing region of the high and medium Reynolds number cases from the carried out experiment case seems to be missing in the provided diagram. One suggested reason for the phenomenon is that the density of the samples may not be dense enough. For the previous work done, the number of samples for Re=24000 is 33 data points, while the number of samples for the carried out experiment is only 19. Furthermore, the number of samples increase for 2 or 3 for every increment in Reynolds number for the previous work. This suggests that more data points are needed to fully evaluate the streamwise turbulence intensity from increasing Reynolds numbers.

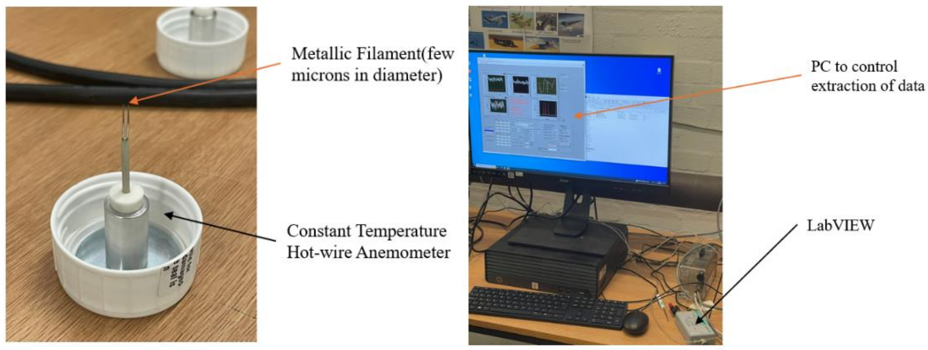
6. Conclusion

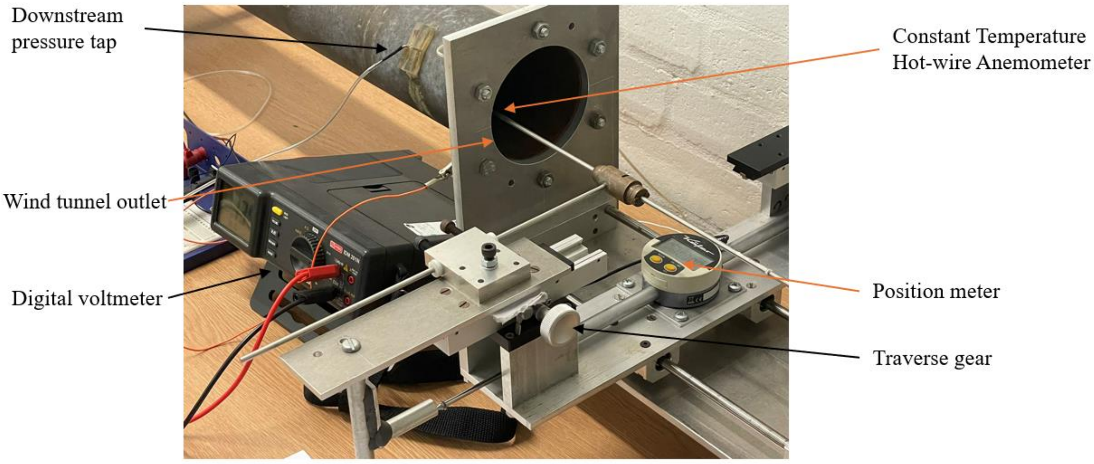
To draw the conclusion, the experiment has successfully carried out despite some negligible errors are presented, the average velocity profiles result from three different cases have shown an agreement on the trend as well as the position of the viscous sublayer. The streamwise turbulence intensity is compared with previous work, but due to unclear selection of inlet speed during the experiment, the difference in maximum value of u^{2+} and y^+ remains unexplained. Also, the density of data extracted is suggested to be higher to fully evaluate the streamwise turbulence intensity.

7. Reference

[1]: HULTMARK M, BAILEY SCC, SMITS AJ. Scaling of near-wall turbulence in pipe flow. *Journal of Fluid Mechanics*. 2010;649:103-113. doi:10.1017/S0022112009994071

Appendix A





Appendix B

Distance from wall, y (mm)	r (mm)
0.1	50.9
0.2	50.8
0.4	50.6
0.6	50.4
1.0	50.0
1.5	49.5
2.0	49.0
2.5	48.5
3.0	48.0
4.0	47.0
5.0	46.0
6.0	45.0
8.0	43.0
10.0	41.0
15.0	36.0
20.0	31.0
30.0	21.0
40.0	11.0
51.0	0.0

Appendix C

As shown in the following figure, a MATLAB code is written to help calculating the average velocity of the flow in three cases and average rms speed of the flow in three cases. Before the code starts, position column, meanvel column and RMS vel column from three different flow inlet speed scenarios are imported into MATLAB workspace as three separate 96x3 tables.

alldatatest01high	96x3 table
alldatatest01low	96x3 table
alldatatest01medium	96x3 table

```matlab

means=ones(19,1);
select=input('type 1 for high, 2 for medium and 3 for low');
selectv = input('For average velocity type 1, for rmsV type 2.');

if select ==1
  if selectv == 1
    for i = 1:19
        vel1=alldatatest01high{(5*i-3),2};
        vel2=alldatatest01high{(5*i-2),2};
        vel3=alldatatest01high{(5*i-1),2};
        vel4=alldatatest01high{(5*i),2};
        vel5=alldatatest01high{(5*i+1),2};
        mean=(vel1+vel2+vel3+vel4+vel5)/5;
        means(i,:)=mean;
    end
  elseif selectv == 2
    for i = 1:19
        vel1=alldatatest01high{(5*i-3),3};
        vel2=alldatatest01high{(5*i-2),3};
        vel3=alldatatest01high{(5*i-1),3};
        vel4=alldatatest01high{(5*i),3};
        vel5=alldatatest01high{(5*i+1),3};
        mean=(vel1+vel2+vel3+vel4+vel5)/5;
        means(i,:)=mean;
    end
  else
      print('error')
  end
elseif select == 2
    if selectv == 1
      for i = 1:19
        vel1=alldatatest01medium{(5*i-3),2};
        vel2=alldatatest01medium{(5*i-2),2};
        vel3=alldatatest01medium{(5*i-1),2};
        vel4=alldatatest01medium{(5*i),2};
        vel5=alldatatest01medium{(5*i+1),2};
        mean=(vel1+vel2+vel3+vel4+vel5)/5;
        means(i,:)=mean;
      end
```

```matlab
    if selectv == 1
      for i = 1:19
        vel1=alldatatest01medium{(5*i-3),2};
        vel2=alldatatest01medium{(5*i-2),2};
        vel3=alldatatest01medium{(5*i-1),2};
        vel4=alldatatest01medium{(5*i),2};
        vel5=alldatatest01medium{(5*i+1),2};
        mean=(vel1+vel2+vel3+vel4+vel5)/5;
        means(i,:)=mean;
      end
    elseif selectv == 2
      for i = 1:19
        vel1=alldatatest01medium{(5*i-3),3};
        vel2=alldatatest01medium{(5*i-2),3};
        vel3=alldatatest01medium{(5*i-1),3};
        vel4=alldatatest01medium{(5*i),3};
        vel5=alldatatest01medium{(5*i+1),3};
        mean=(vel1+vel2+vel3+vel4+vel5)/5;
        means(i,:)=mean;
      end
    else
      print('error')
    end
  elseif select == 3
    if selectv == 1
      for i = 1:19
        vel1=alldatatest01low{(5*i-3),2};
        vel2=alldatatest01low{(5*i-2),2};
        vel3=alldatatest01low{(5*i-1),2};
        vel4=alldatatest01low{(5*i),2};
        vel5=alldatatest01low{(5*i+1),2};
        mean=(vel1+vel2+vel3+vel4+vel5)/5;
        means(i,:)=mean;
      end
    elseif selectv == 2
      for i = 1:19
        vel1=alldatatest01low{(5*i-3),3};
        vel2=alldatatest01low{(5*i-2),3};
        vel3=alldatatest01low{(5*i-1),3};
        vel4=alldatatest01low{(5*i),3};
```

```matlab
        vel1=alldatatest01medium{(5*i-3),3};
        vel2=alldatatest01medium{(5*i-2),3};
        vel3=alldatatest01medium{(5*i-1),3};
        vel4=alldatatest01medium{(5*i),3};
        vel5=alldatatest01medium{(5*i+1),3};
        mean=(vel1+vel2+vel3+vel4+vel5)/5;
        means(i,:)=mean;
      end
    else
      print('error')
    end
elseif select == 3
    if selectv == 1
      for i = 1:19
        vel1=alldatatest01low{(5*i-3),2};
        vel2=alldatatest01low{(5*i-2),2};
        vel3=alldatatest01low{(5*i-1),2};
        vel4=alldatatest01low{(5*i),2};
        vel5=alldatatest01low{(5*i+1),2};
        mean=(vel1+vel2+vel3+vel4+vel5)/5;
        means(i,:)=mean;
      end
    elseif selectv == 2
    for i = 1:19
        vel1=alldatatest01low{(5*i-3),3};
        vel2=alldatatest01low{(5*i-2),3};
        vel3=alldatatest01low{(5*i-1),3};
        vel4=alldatatest01low{(5*i),3};
        vel5=alldatatest01low{(5*i+1),3};
        mean=(vel1+vel2+vel3+vel4+vel5)/5;
        means(i,:)=mean;
    end
    else
      print('error')
    end
else
    print('error')
end
means

```