AE 303 Lab 2 - Test Section Flow Uniformity Characterization

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The purpose of this lab is firstly to characterize the uniformity of the flow field in the wind tunnel by using a total pressure rake located in the test section. Secondly, it is to understand the configuration and process of the low speed wind tunnel. In terms of calculations, it is important to get familiar with the application of the Bernoulli's equation for the dynamic pressure and velocity measurements in the free streams of the wind tunnel, and learn how to present said 2D streamlines as a velocity distribution as a contour map.

The deliverables for the lab are to calculate, for each wind tunnel speed, the dynamic pressure and the unit Reynold's number. Performing data reduction and analysis using the instructions provided by the professor, and conduct convergence tests for a threshold value of 0.005% for the time averaged dynamic pressure calculations, and find how many samples are needed in order to reach this boundary.

I. Nomenclature

$\bar{x}$	=	Sample mean
S_x	=	Sample standard deviation
$S_{\bar{x}}$	=	Sample standard deviation of means
R	=	Universal Gas Constant
M	=	Molar Mass
t	=	Student Uncertainty Value
ρ	=	Density
$p_k(t_i)$	=	Pressure at probe k at time i
$p_s(t_i)$	=	Static pressure at time i
$q_k(t_i)$	=	Dynamic pressure at probe k at time i
$\bar{q_k}$	=	Time-averaged dynamic pressure at probe k
$\hat{q}$	=	Overall mean dynamic pressure
N	=	Number of time measurements
M	=	Number of probes
P	=	Atmospheric pressure
T	=	Temperature
V_k	=	Velocity at probe k
$\bar{V}_k$	=	Time-averaged velocity at probe k
$\hat{V}$	=	Overall mean velocity
μ	=	Dynamic viscosity
Re	=	Reynolds number
L	=	Characteristic length (used for non-dimensionalization)
V_s	=	Theoretical velocity based on set wind tunnel speed
q_s	=	Theoretical dynamic pressure using ideal pitot probes 63 and 64
V_{IAS}	=	Indicated airspeed

II. Introduction

Understanding the uniformity of airflow and the properties that result from it within an airfoil will be a key tool in understanding real life aerodynamic studies, as well as future lab experiments conducted within this apparatus.To

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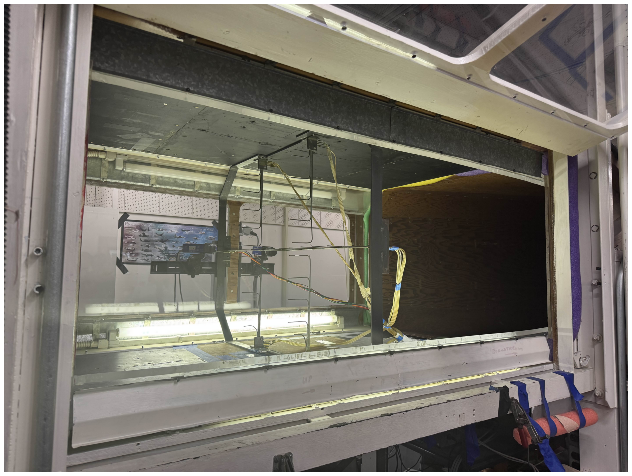

Fig. 1 View of Pitots inside Wind Tunnel.

achieve this understanding, a total pressure pitot tube array will be tested upon with various speeds at a multitude of points in order to develop a velocity distribution within the wind tunnel. The goal is to have a strong understanding of the effects of a wind tunnel.

III. Equipment and Procedure

A. In Lab

The equipment used in this experiment is a wind tunnel, a total pressure pitot tube rake, a ZOC33/64 Px X2 miniature analog pressure scanner, a DSM 4000 analog-to-digital board, and a water manometer. The pitots have tubes attached which connect to the scanning valve, which measures the pressures and sends them to the analog-to-digital board which converts it into digital signals. These signals are sent to the computer which reads and records each pressure. The airspeed of the wind tunnel is controlled by the manometer, which measures the pressure of the airflow within the wind tunnel. This will be recorded at different inches of water to get more results to analyze. An image of the pitots within the wind tunnel is sin in Fig 1, which can be viewed for an example of how the pitots are laid out within the test area.

To begin the experiment, the ambient temperature and pressure are measured in the lab using a digital barometer and thermometer. Analog was avoided in order to have more accurate data. equipment in the wind tunnel are used to gather initial pressure. This is the recordings of the dynamic pressure at 0 inches of water, which is the first run of the test. The data is recorded by the computer and saved for later use, an example of this can be seen in Fig 3 as the recordings are normalized and saved to the computer.. The second run is at 2 inches of water dynamic pressure, and time is given for the speed to become constant before the data is ran. Temperature is also recorded again and is saved along with the pressure. The final run is at 5 inches of water dynamic pressure, and water is measured to be stable before the airflow is recorded. The procedure is the same from here, data is recorded and saved. Once the measurements are concluded, the airflow is brought to a stop and the lab is concluded.

B. Calculations and Analysis

To produce the deliverables for the lab, there are a number of equations we must provide to go from the measured pressures and temperatures to the time-averaged dynamic pressures, velocities, and Reynold's Numbers for each of the runs. To start, all units will be in imperial, since this is what the pressures are measured in. Temperature should be Rankine, density in $\frac{lbs}{ft^3}$, and so on.

Before calculations could be done, the data will need to be organized. In order to properly make use of the pitots, pitots 63 and 64 are separated and used for later use. Pitot 2 will be set to be the row wise average of all the pitots (minus 63 and 64), since it attempts to represent the standard pressure throughout. Pitot 7 is the static pressure in the wind tunnel, and will be used to normalize the rest of the pitots, this requires subtracting the values for pitot 7 with all other pitots in the set, resulting in Pitot 7 being zero. This will be used as standard after the plotting of the measured pressure.

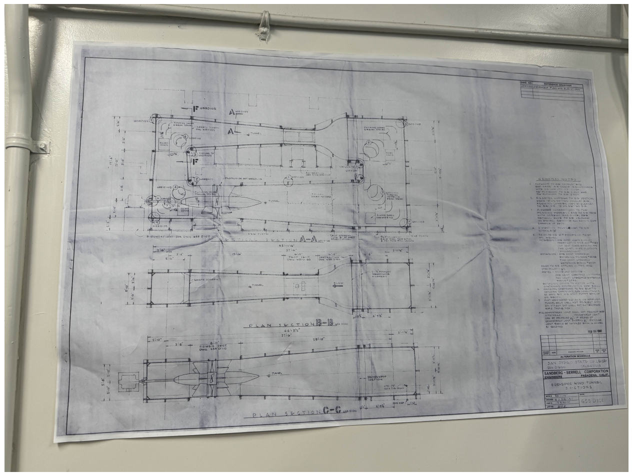

Fig. 2   Original Blue Print of Wind Tunnel.

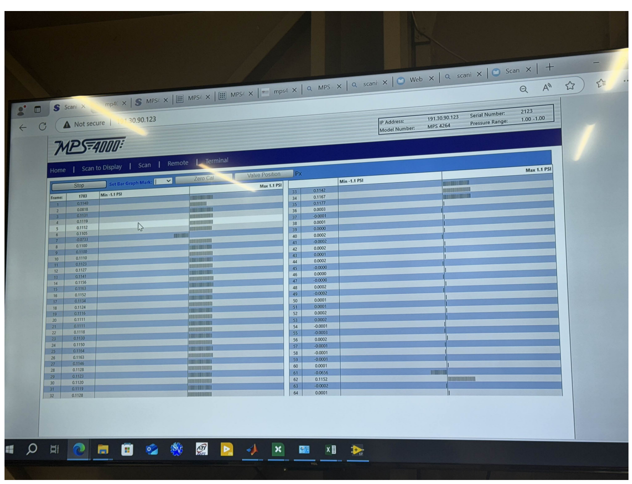

Fig. 3   Screenshot of run 3 measurement readings.

In the initial stages of the data, we will need to find the Dynamic Pressure by subtracting probe 7 from the rest of the probes, zeroing it out and creating a variable free pressure measurement.

$$q_k(t_i) = p_k(t_i) - p_s(t_i) \tag{1}$$

After this equation is used to find the Dynamic Pressure, we can calculate the time averaged, Mean Dynamic Pressure for all probes, following a simple average equation. After, we will also calculate the Overall Mean Dynamic Pressure for each dataset, thereby giving a total average within the system at the given airspeed.

$$\bar{q_k} = \frac{1}{N}\sum_{i=1}^{N} q_k(i) \tag{2}$$

$$\hat{q} = \frac{1}{M}\sum_{k=1}^{M} \bar{q_k} \tag{3}$$

Where N is the number of measurements over time, and M is the number of measured probes. In order to set up further equations, we will need to calculate density, which can be done assuming an ideal gas using the following equation, where we use the atmospheric pressure given in the data tables, the Ideal Gas Constant R in imperial units, and the temperature of the wind tunnel also given in the data table for each speed.

$$\rho = \frac{P}{RT} \tag{4}$$

Using this density, we can calculate the Average Velocity for each probe, as well as for the total time and probe averaged speed in the system. This is given as:

$$\bar{V_k} = \sqrt{\frac{2\bar{q_k}}{\rho}} \tag{5}$$

$$\hat{V} = \sqrt{\frac{2\hat{q}}{\rho}} \tag{6}$$

From here, Reynold's Number will need to be calculated for the whole wind tunnel at each airspeed. This is given as:

$$\frac{Re}{L} = \frac{\rho V}{\mu} \tag{7}$$

Where L = 1 in order to non dimensionalized the system, ρ and V is given in previous equations, and μ is found as a constant at the aforementioned atmospheric pressures and temperatures. The values found for Reynold's Number will be given and reasoned in the Results section. By this point, nearly all values needed have been derived, and the plotting and data reduction is performed. These results will be explained in the next section as well.

The final pieces of theory to explain have to do with the convergence of data sets. The percentage convergence will allow us to decern how close the data is to converging on an accurate enough value to be considered true, and to find how many pieces of data are needed to converge, given a 0.005% Percent Convergence. The Cumulative Mean Calculation is used to calculate the average total value as each probe is included, which is needed to visualize the convergence. These can be found as follows:

$$\text{Percentage Convergence} = \left|\frac{\bar{x}_{i+1} - \bar{x}_i}{\bar{x}_i}\right| \tag{8}$$

$$\bar{x_i} = \frac{1}{i}\sum_{k=1}^{i} x_k \tag{9}$$

The process for finidng convergence uses these equations, and the percentage convergence criterion is applied. The process continues adding new probes to the average until the threshold is met. Once convergence is achieved, the required number of samples is recorded and results of both the Cumulative mean over time, and the percentage convergence trend with a reference line are graphed.

IV. Results

A. Tabular Data

The method for formatting these results sections will be to talk about all data reduction figures in a comprehendible order, and discuss other aspects of the report that are of note. To begin, the calculated Reynold's numbers are the following for each test:

Re (0.0 inH2O)	Re (2.0 inH2O)	Re (5.0 inH2O)
0	4.025×10^5	6.30×10^5

Table 1 Reynolds Number in Different Conditions

This set of Reynold's numbers is similar to expected theoretical values at STP, which is about 33% higher than the experimental values. This gap of values is bridged by the difference in temperature and density in the lab. The temperature especially drives down the density, which in turn changes Re to be lower than what it should be. Because of this change in setting, it is reasonable to call these values appropriate. For some context in the values that brought us to this number, using equation 1 and 2, we can solve for the time-averaged mean dynamic pressure for each of the tests, this is shown in the following table:

Table 2 Pitot pressures at each run (PSI)

0.0 inH2O	2.0 inH2O	5.0 inH2O
3.67×10^{-5}	7.44×10^{-2}	1.88×10^{-1}
-1.09×10^{-4}	7.13×10^{-2}	1.80×10^{-1}
-5.77×10^{-5}	7.40×10^{-2}	1.87×10^{-1}
-3.52×10^{-5}	7.36×10^{-2}	1.86×10^{-1}
3.63×10^{-5}	7.34×10^{-2}	1.85×10^{-1}
-8.57×10^{-5}	7.30×10^{-2}	1.84×10^{-1}
0.00	0.00	0.00
-6.64×10^{-5}	7.29×10^{-2}	1.84×10^{-1}
-3.93×10^{-5}	7.31×10^{-2}	1.85×10^{-1}
-2.43×10^{-4}	7.30×10^{-2}	1.85×10^{-1}
-8.90×10^{-5}	7.37×10^{-2}	1.86×10^{-1}
-2.22×10^{-4}	7.39×10^{-2}	1.87×10^{-1}
-6.26×10^{-5}	7.47×10^{-2}	1.89×10^{-1}
-1.93×10^{-4}	7.49×10^{-2}	1.90×10^{-1}
-3.22×10^{-5}	7.52×10^{-2}	1.90×10^{-1}
-1.41×10^{-4}	7.49×10^{-2}	1.89×10^{-1}
-1.62×10^{-4}	7.42×10^{-2}	1.88×10^{-1}
-1.49×10^{-4}	7.37×10^{-2}	1.87×10^{-1}
-1.39×10^{-4}	7.33×10^{-2}	1.85×10^{-1}
-1.71×10^{-4}	7.32×10^{-2}	1.85×10^{-1}
-2.38×10^{-4}	7.31×10^{-2}	1.85×10^{-1}
-1.42×10^{-4}	7.35×10^{-2}	1.86×10^{-1}
-1.26×10^{-4}	7.41×10^{-2}	1.87×10^{-1}
-1.50×10^{-4}	7.49×10^{-2}	1.89×10^{-1}
-1.69×10^{-4}	7.52×10^{-2}	1.89×10^{-1}
-9.33×10^{-5}	7.52×10^{-2}	1.90×10^{-1}
-3.75×10^{-5}	7.45×10^{-2}	1.89×10^{-1}
-1.16×10^{-4}	7.36×10^{-2}	1.88×10^{-1}
-1.76×10^{-4}	7.37×10^{-2}	1.88×10^{-1}
-1.20×10^{-4}	7.36×10^{-2}	1.88×10^{-1}
-9.58×10^{-5}	7.36×10^{-2}	1.88×10^{-1}
-1.33×10^{-4}	7.40×10^{-2}	1.89×10^{-1}
-1.54×10^{-4}	7.45×10^{-2}	1.90×10^{-1}
-1.06×10^{-4}	7.52×10^{-2}	1.91×10^{-1}
-5.84×10^{-5}	7.58×10^{-2}	1.91×10^{-1}

These values are appropriate for their expected pressures at these speeds. An example of this accuracy is the first column, which would rightly represent the unmoving air of a stopped air tunnel, by being so near to zero. Any negative numbers can be associated with Static pressure misalignment, offset or calibration, or sensor drift. All of these will be expanded upon in the conclusion. This next section of the report covers the data reduction and analysis. Each graph will be explained and analyzed for accuracy using sanity checks.

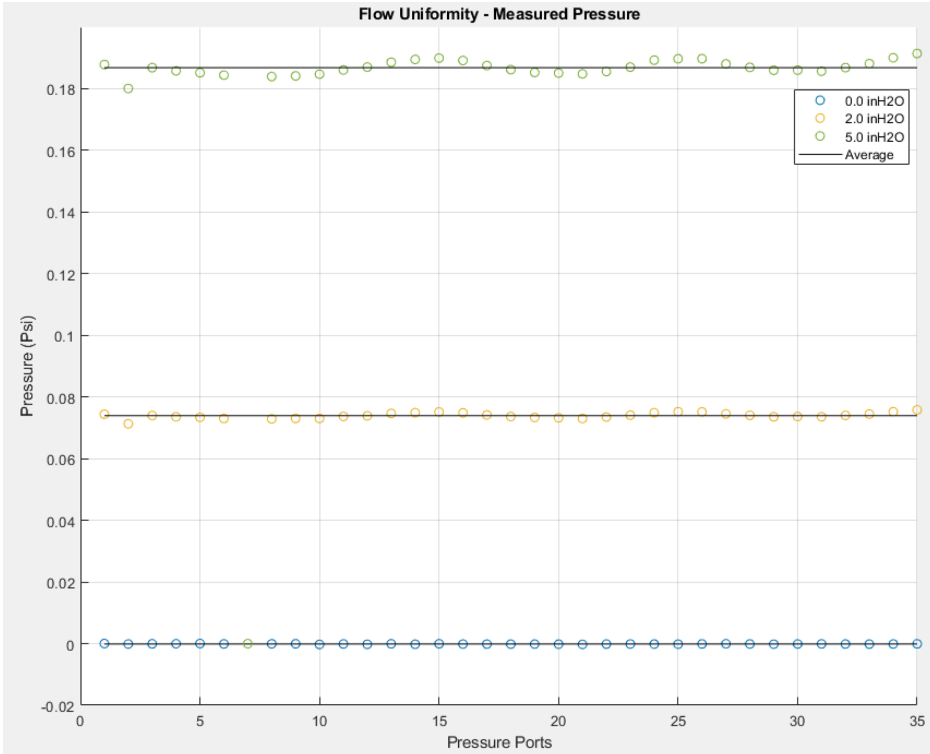

Fig. 4 Averaged measured pressures for each run.

B. Figure Data

To begin, Fig 4 shows the measured pressure for each run, in psi, across the first 35 pitots. This data is simple and will require little explaining. Essentially, the recorded data follows a trend-line very similar to the average, with only two notable points of interest for each run, the second pitot which measures in a slower section of the wind tunnel, and acts as the average after the static adjustment, explaining why it is lower than the average. The second is the 7th pitot, which as explained earlier is the static pitot and sits at or below zero (See discussion for details).

Next, Fig 5 is a very similar plot to Fig 4, except this shows the Dynamic Pressure. the difference between the two being is this one follows calculating with equation 1, which subtracts port 7 from the rest, which is why it is zeroed out. The difference besides that is minimal. One thing to note is q_s makes its first appearance, which is the IAS theoretical data calculated using pitots 63 and 64, which represent the ideal pressures at this speed. One might notices the setting is lower than the average, which can be attributed to many things, but mainly error is the cause of difference between these two lines.

Fig 6 moves us away from pressure, and has the calculations of velocity within the wind tunnel, averaged across time. This also introduces V_s or V setting, which works similarly to q_s, and has theoretical velocity at 0, 95, and 150 ft/s. These are the expected speeds, roughly, with the desired water pressures used for the wind tunnel calibration. Differences seen between this line and the run average will be covered in later sections. Another point to note is the neglecting of velocity during the first run. This is due to small errors in the pitots making larger effects in the calculations. As a result, it will not be majorly referenced in the data, since it can be assumed that the true velocity within the wind tunnel is 0 ft/s.

Moving away from direct observation of data, Fig 7 represents the deviation from the average between each pitot. It is clear there is a waving in the data. The reason for this has to do with the locations of each pitot within the wind tunnel. The velocity of the wind at the sides of the tunnel can be expected to be less from the center, which will be seen as the true velocity within. Because of this, pitots on the outer end of the chamber will be less accurate and have a higher error, It is also possible that the center is not perfectly accurate to the average, since that is the extreme of the data, so somewhere between the center and the ends are the most accurate of all the data.

Figures 8 and 9 are isolated graphs of 7. This is to independently view the two set results. Run 1 will of course not be included, as it is likely to have extremely large error. This is because of the minuscule numbers recorded by the pitots, where readings are so close to 0 that differences are likely to be orders of magnitude larger than those of run 2 and 3.

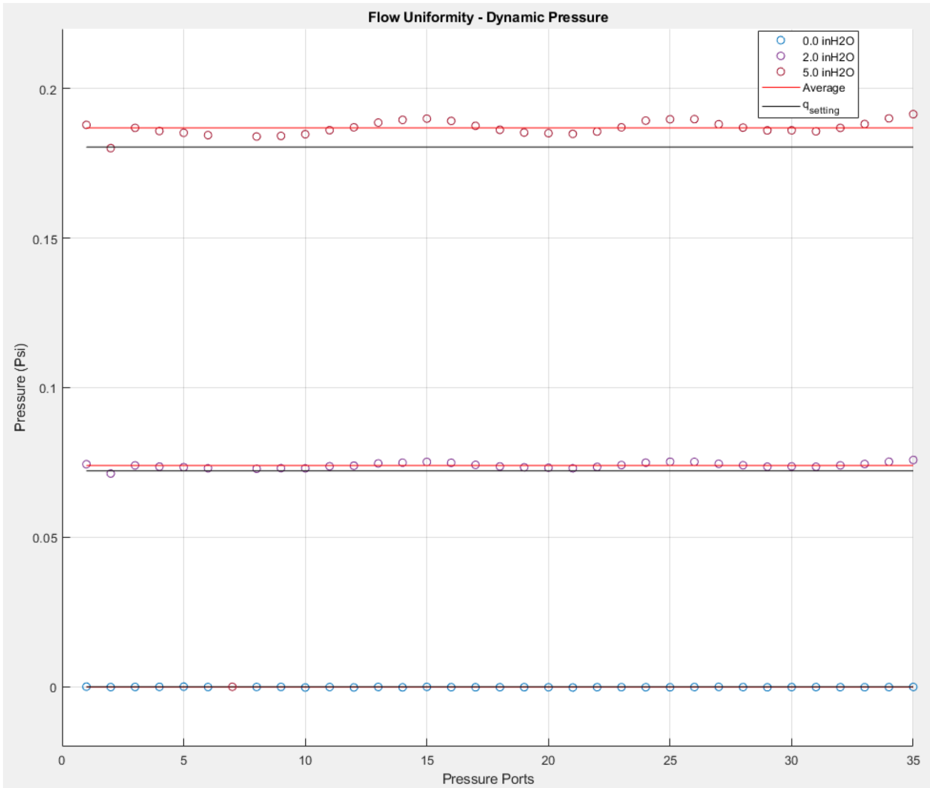

Fig. 5 Averaged dynamic pressures for each run, with averages and q_s

There is little else to talk about with Fig 10 that was not already aptly covered during discussion of fig 7. Just the same, there are points of raised accuracy at the ends and likely center of the wind tunnel. And just the same as with the last three figures, Figures 11 and 12 are run isolated figures to 10. Also matching the previous figures, run 1 will not be included in this data set. It is important to note that between these figures the deviation from the average is extremely small. This is a good sign for future testing.

The following two figures are contour heat maps of the pressure deviation from average displayed in Fig 10. The difference however, is this is displayed with an extra dimension, allowing for the locations in the wind tunnel to be observed, and the deviation can then be observed visually depending on the location of the pitot. As hypothesized in the last group of figures, there is a higher deviation from average the further towards the outside you go. This is clear evidence that the center, or near center, will have the most accurate data.

Fig 15 has many similarities to the last two figures, however it measures total velocity distribution instead of deviation. One piece that is worth noting is the concentration of speed distribution on the middle left of the wind tunnel. I believe this is due to a slight failure to distribute the air flow within the tunnel. This difference is extremely mild but can be observed within this, and the previous two figures. It must be noted that there is a typo in this figure. IAS should equal 45 m/s, or roughly 150 ft/s. This is a minor mistake but leads to a misunderstanding if just the image were to be observed.

The final set of figures, 16, 17, and 18, display the convergence tests for each of the three runs. The upper graph displays the total dynamic pressure average, which gives a line showing the convergence towards the 0.005% threshold. The lower of the two graphs is a more approachable graph, which displays the moving means and how they converge toward the threshold. In the legend of the first is the specific test that delivers the run to the threshold and into a converged state.

The percent change in its final change to the threshold is also derived from the code. For run 1, the percent change is 0.000005, for run 2, 0.000031, for 3, 0.000029. This shows just how close this convergence was before the final run passing it over that line. This is found by subtracting the percent change from n-1 to n, where n is the final run that drops the average below its threshold.

As discussed earlier, the first run will have more dramatic error, and that is why it was excluded from many of the

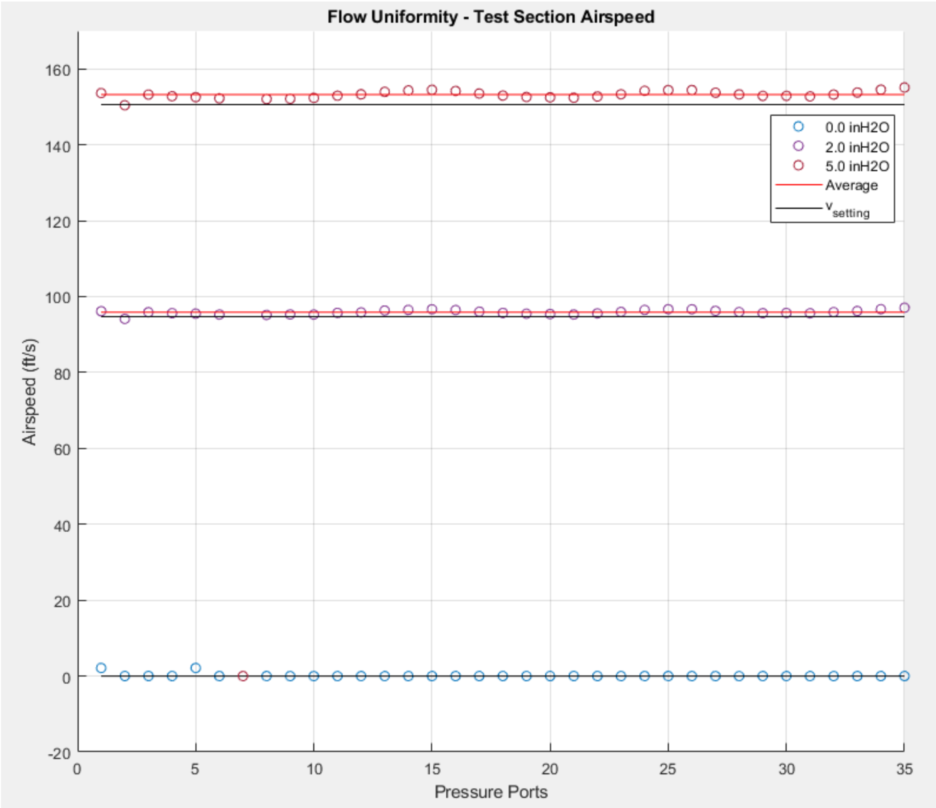

Fig. 6 Averaged measured airspeed for each run, with settings at 0 ft/s, 95 ft/s, and 150 ft/s.

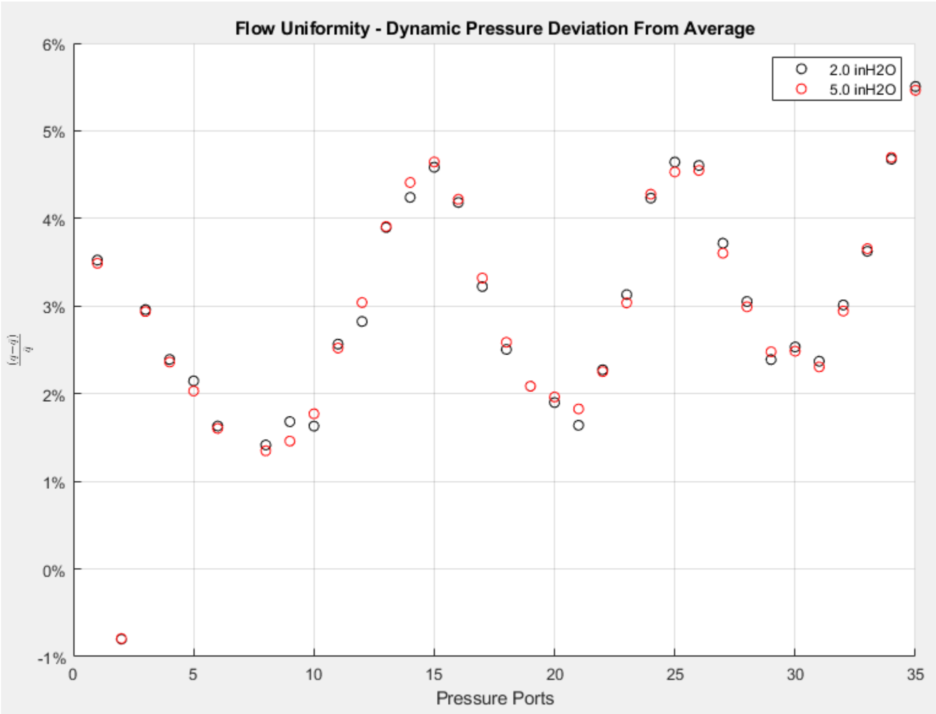

Fig. 7 Flow uniformity for dynamic pressure deviation from average at 2 and 7 inH2O.

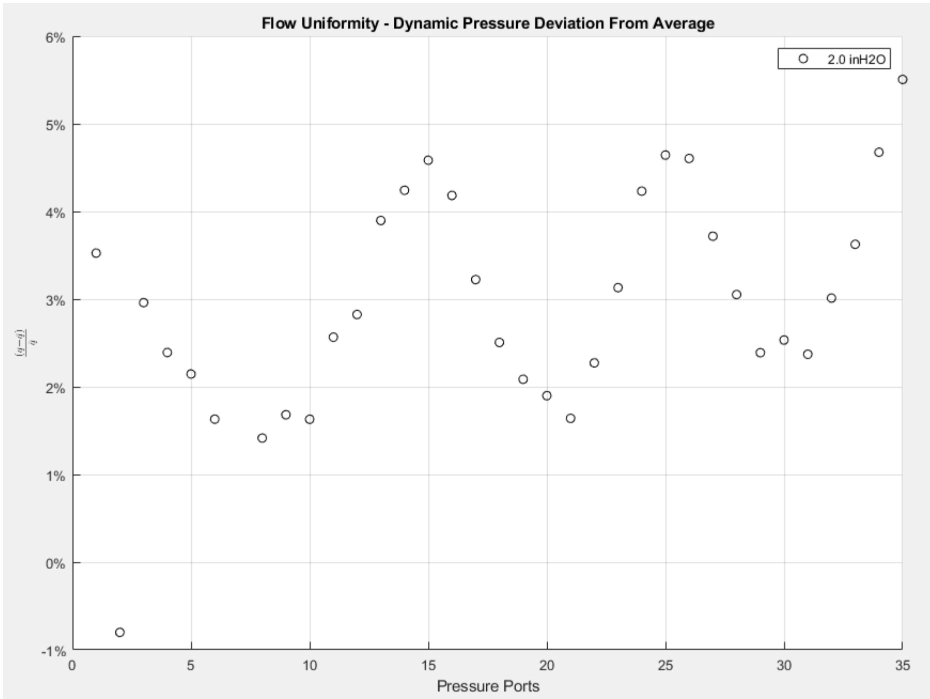

Fig. 8 Flow uniformity for dynamic pressure deviation from average at 2 inH2O.

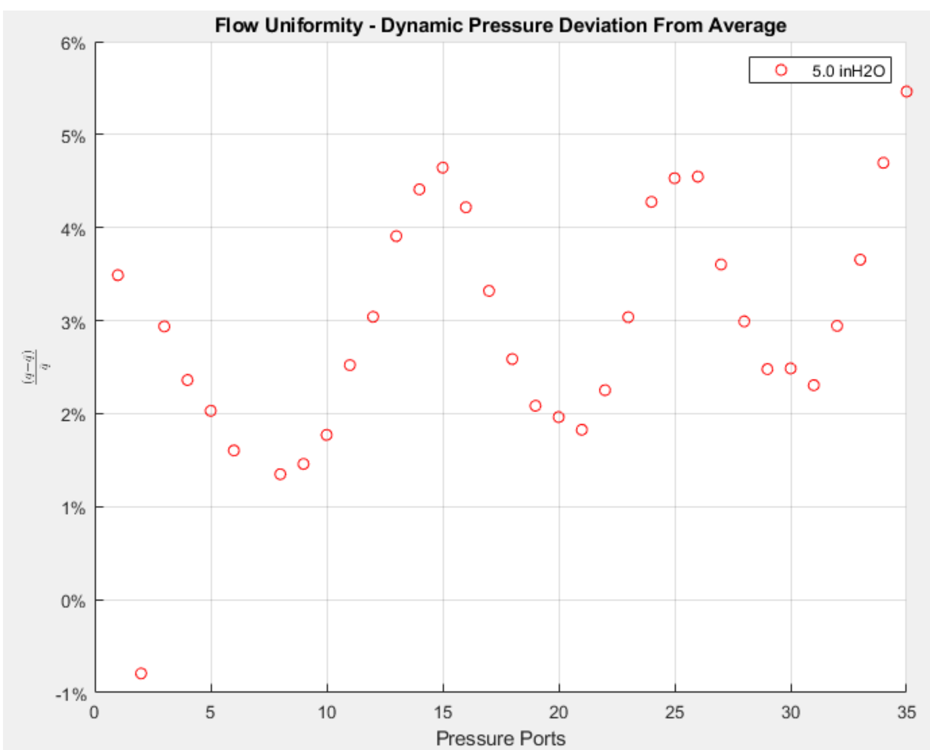

Fig. 9 Flow uniformity for dynamic pressure deviation from average at 7 inH2O.

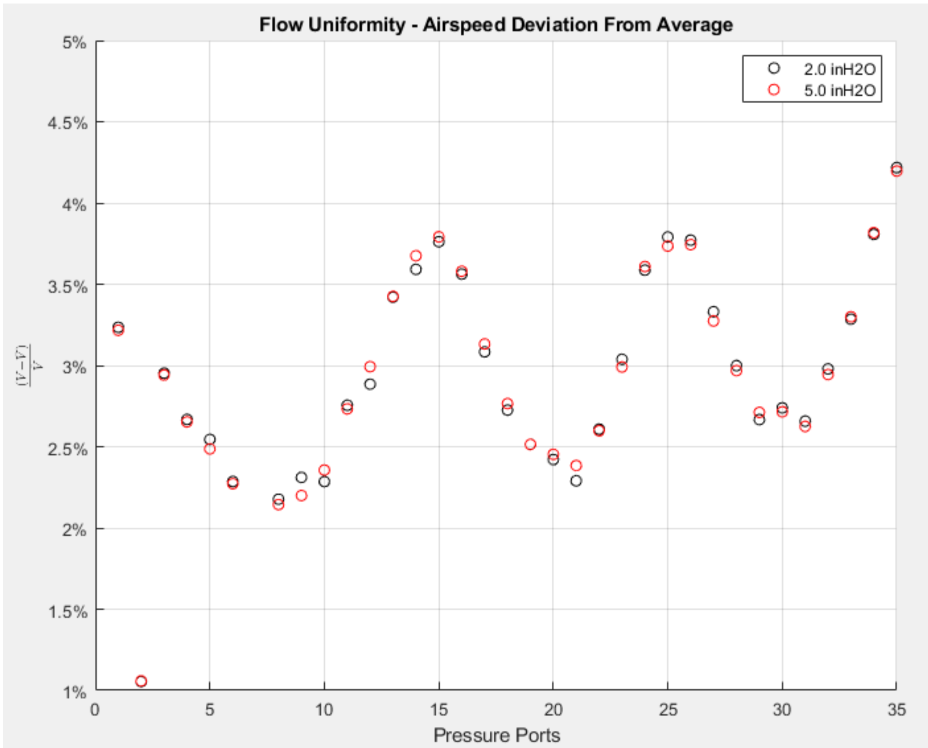

Fig. 10 Flow uniformity for airspeed deviation from average at 2 and 7 inH2O.

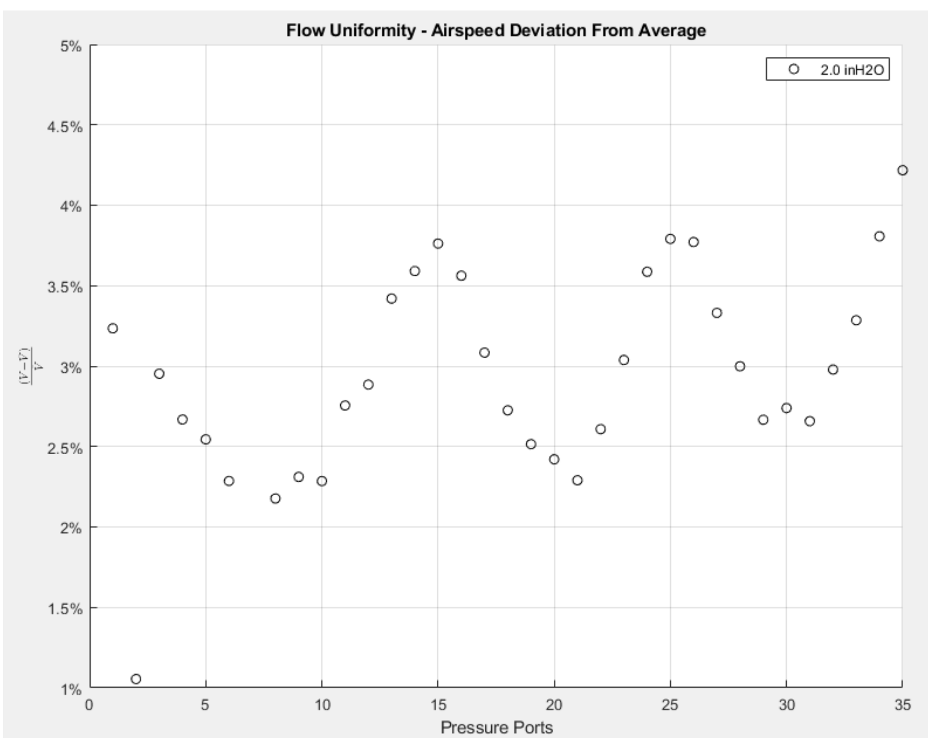

Fig. 11 Flow uniformity for airspeed deviation from average at 2 inH2O.

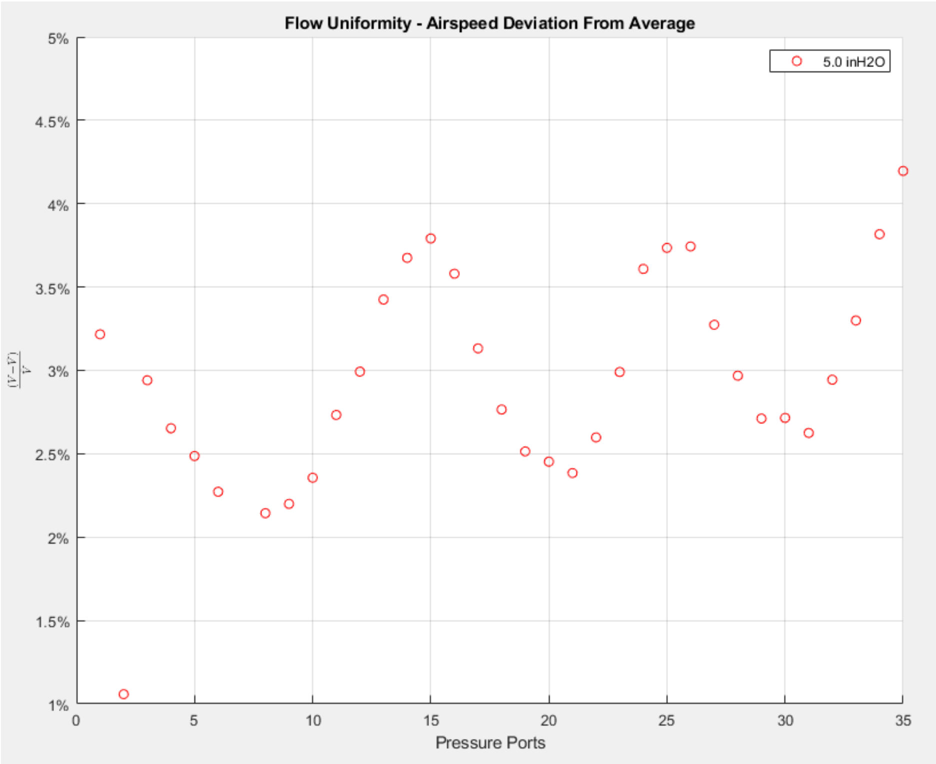

Fig. 12 Flow uniformity for airspeed deviation from average at 7 inH2O.

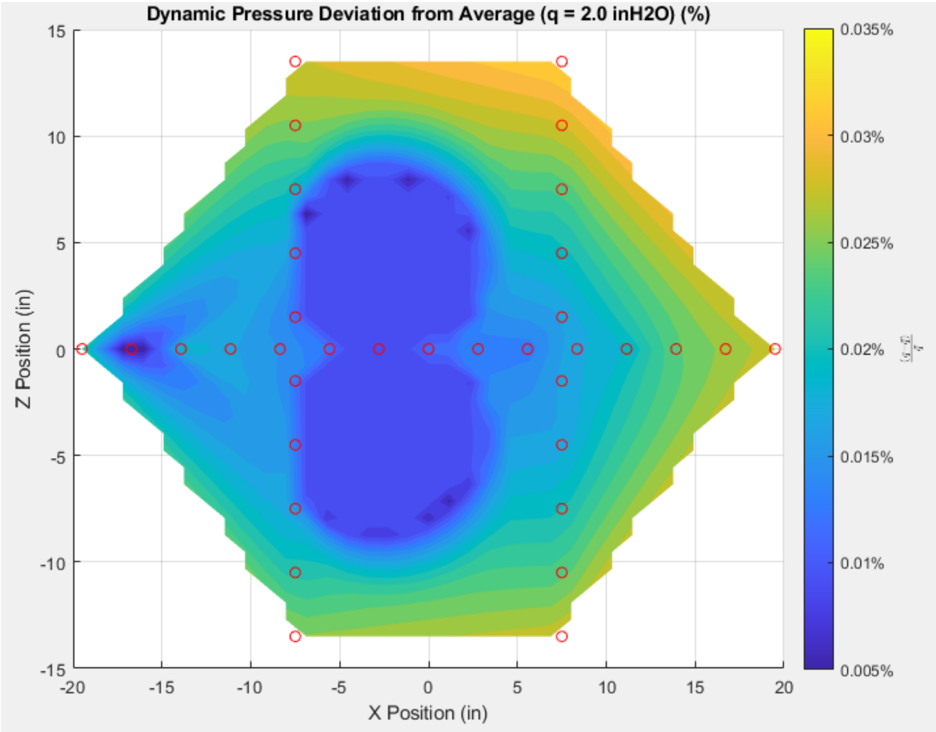

Fig. 13 Enter Caption

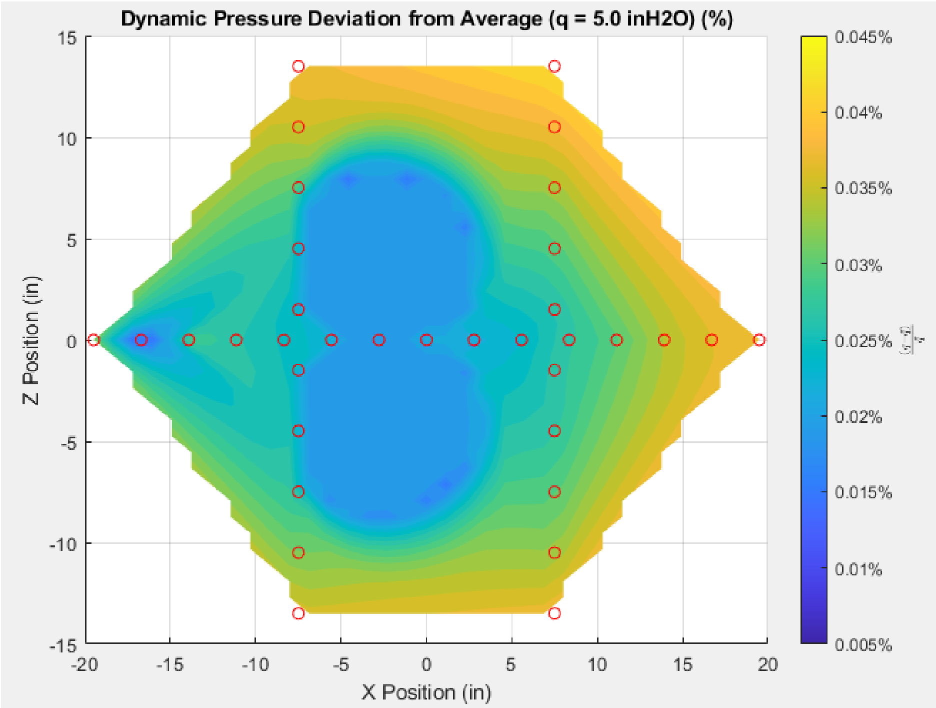

Fig. 14 Dynamic Pressure deviation from average at 7 inH2O.

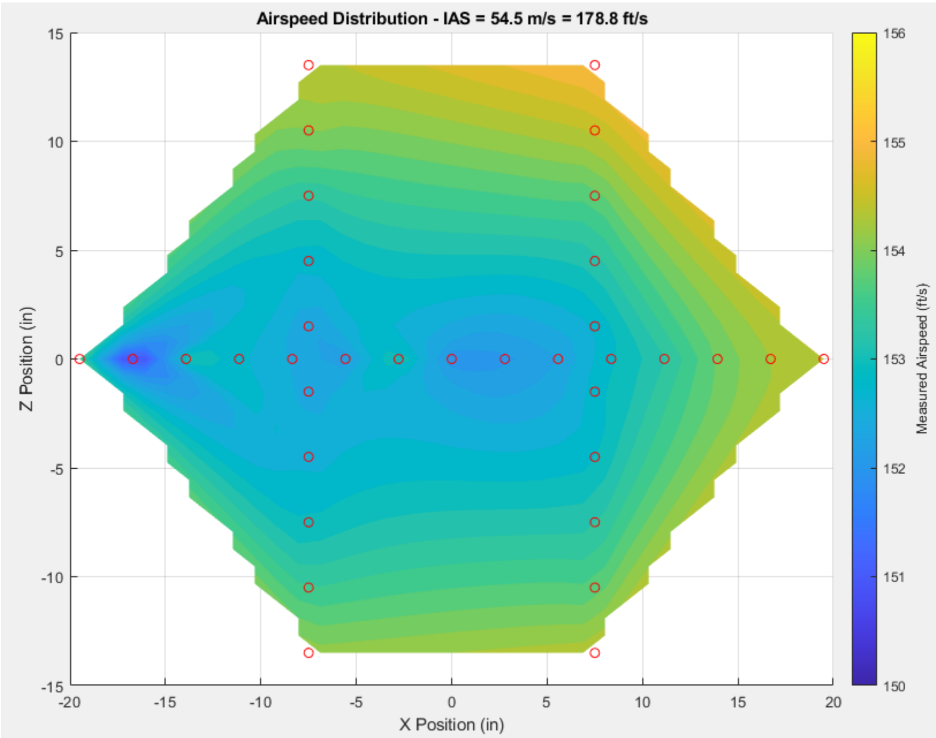

Fig. 15 Velocity distribution for IAS (45 m/s, 150 ft/s).

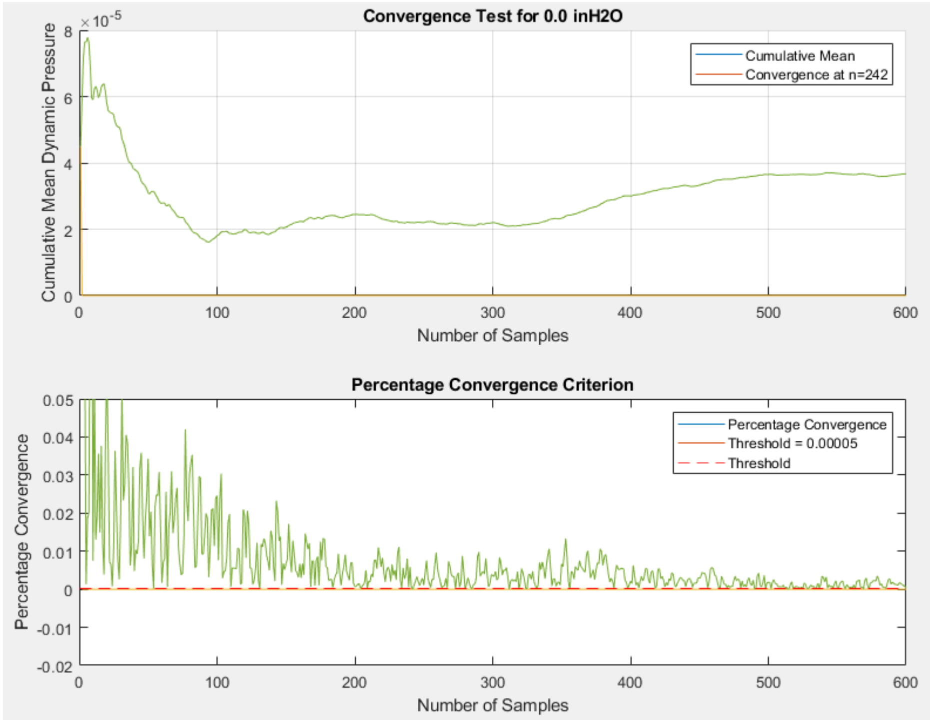

Fig. 16 Convergence test for 0 inH2O.

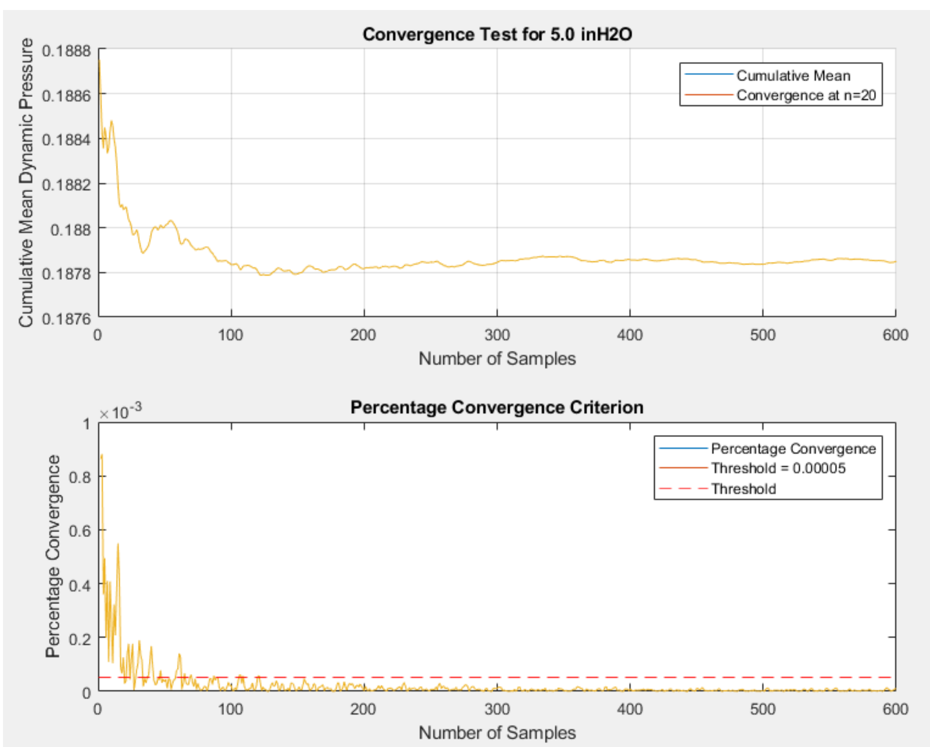

Fig. 17 Convergence test for 2 inH2O.

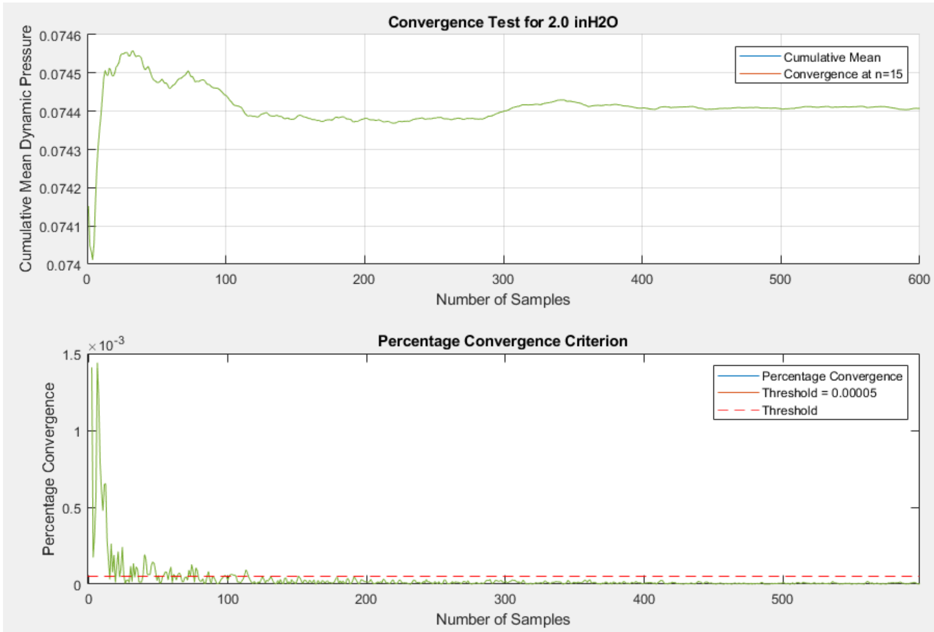

Fig. 18 Convergence test for 7 inH2O.

graphs. This also explains why the number of measurements needed to get to the threshold was so high. Because the numbers are so varied from each other, it becomes extremely difficult to meet an average that is so close to the final result. This is an interesting example of how notice and error becomes far more important to deal with at the micro level, and is a lesson that more precise equipment will need to be used for further, more specific testing.

V. Discussion

In Fig 4, the pressure read in port 7 is negative and becomes more negative as IAS increases. This was the one part in my data I failed to replicate in my code, however I can identify that this would happen due to the difficulty in maintaining a set pressure in the wind tunnel at higher velocities, which affects the static results by being less effective at maintaining a static pressure. This may be expected behavior, but there is little to do to prevent it.

In Figure 4, the average pressure read for IAS = 0 is not shown as per previous instructions, although it should read 0, it would not due to errors in pitots 63 and 64. This can be expected to cause issue in any graph calculating pressure or velocity using the last two pitots (specifically figures 5 and 6.

The deviation in data is found in Pitot 2 rather than 34, which I attribute to mislabeling of the pitots. This deviation occurs from the proximity to the front of the test center, which does not have the space for air to properly unify within the test section. This point does not invalidate the experiment, as it is minimal and will not drastically change the results.

The temperature within the wind tunnel is observed to change as the velocity changes in the wind tunnel. This can be attributed to compressible flow and the conservation of kinetic energy to thermal energy. In adiabatic compression, when airspeed increases, so too does its kinetic energy. As it moves faster, the molecules compress, and hit each other resulting in an increase in temperature. This is similar to how temperature of gas rises in a piston. Furthermore, with Bernoulli's principle, the speed increase of a fluid causes temperature to change assuming other variables are held constant, such as pressure. For this same reasoning, the compression of air from an increase in speed causes an increase in temperature. Viscous heating is also a reason for this, and the friction within the air itself causes heating. Reducing speed, and cooling systems are both simple ways to reduce the temperature in a wind tunnel. Changing the pressure within can balance the Bernoulli's equation and allow for temperatures to remain constant. Also, adding or increasing the ability of the diffuser could fix the issue, since it would negatively accelerate the air and can be used to mitigate excessive heating in specific areas.

This increase in temperature affects the indicated air speed by decreasing the density in the system, which is a result of the conservation of energy, and how kinetic energy is lost through heat. This decrease in density would change the pressure readings, as well as velocity calculations. This can also cause issues in the Constant Dynamic Pressure

Assumption, which assumes a steady state. However, IAS measures the dynamic pressure corrected for airspeed, and with the increase in temperature and decrease in density, the IAS may be higher as a result. The effect can be seen with the Reynolds number, and the lower density would lead to a lower Reynolds number. This would also change the Viscosity, and would also decrease Reynolds number

VI. Conclusion

The work done in this lab was simple, but the calculations and analysis needed to properly understand the wind tunnel was far more complex. Lots of error could be introduced within the wind tunnel, with location, angling, and calibration all being likely sources of error. This can be fixed with more time spent evening the water reading when setting wind speed. Also, more time can be spent waiting for velocity to normalize within the tunnel before taking data measurements. However, I would wager that this is much smaller than one would expect.

I would say the results were good, it is just unfortunate that the IAS did not display as was intended within my figures. I would like to say that there is understanding of it's applications and the theory behind it, but the cause is more due to a lack of ability to display the understanding within the plots. besides that the lab was very strongly displayed, and all required data is shown to be accurate and reliable. Further application of these lessons from this lab will be very useful with future use of the wind tunnel.

VII. Acknowledgments

[1] [2] [3] [4] [5]

References

[1] Liu, X. (ed.), *Convergence Test Sample*, https://sdsu.instructure.com/courses/165529/files/folder/Lab2$_{Test}$

[2] Liu, X. (ed.), *Lab 2 Uniformity Testing Video*, https://sdsu.instructure.com/courses/165529/files/folder/Lab2$_{Test}$

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[5] Liu, X. (ed.), *Lab 2 Instructions*, https://sdsu.instructure.com/courses/165529/files/folder/Lab2$_{Test}$

Appendix

A. MATLAB Code

```matlab
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% AE302 Lab 2 - Wyatt Welch
%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
clc, clear all, load('RawArrays.mat')

S1 = table2array(S1); % PSI
S2 = table2array(S2);
S3 = table2array(S3);

% Remove last 2 columns, zero col 7, replace col 2 with average
A1 = S1(2:end, 1:end-2);
A2 = S2(2:end, 1:end-2);
A3 = S3(2:end, 1:end-2);

B1 = A1 - A1(:,7);
B2 = A2 - A2(:,7);
B3 = A3 - A3(:,7);

C1 = mean(B1, 2);
C2 = mean(B2, 2);
C3 = mean(B3, 2);

B1(:,2) = C1;
B2(:,2) = C2;
B3(:,2) = C3;

S1c = mean(B1, 1);
S2c = mean(B2, 1);
S3c = mean(B3, 1);

% Data
AmT0 = 71.7 + 459.67; % F to R
WtT0 = 78.4 + 459.67;
AmP0 = 30.16 / 2.036; % inHg to PSI

AmT2 = 71.7 + 459.67;
WtT2 = 76.6 + 459.67;
AmP2 = AmP0;

AmT5 = 71.7 + 459.67;
WtT5 = 82.7 + 459.67;
AmP5 = AmP0;

% Time-Averaging Dynamic Pressure for Each Pitot Tube

S1Avg=mean(B1,1);
S2Avg=mean(B2,1);
S3Avg=mean(B3,1);
```

```
q_hat1 = mean(S1Avg);
q_hat2 = mean(S2Avg);
q_hat3 = mean(S3Avg);

% Average pressure at given dynamic pressure setting
S1_total = B1;
S2_total = B2;
S3_total = B3;

P_avg1 = mean(S1_total, 2);  % Average across columns (all pitots)
P_avg2 = mean(S2_total, 2);
P_avg3 = mean(S3_total, 2);

Static1 = S1_total(:,7);
Static2 = S2_total(:,7);
Static3 = S3_total(:,7);

q_avg1 = mean(P_avg1 - Static1);
q_avg2 = mean(P_avg2 - Static2);
q_avg3 = mean(P_avg3 - Static3);

% Calculate free stream velocity, Reynold's Number

den1 = (AmP0) / (1716 * WtT0); % slugs/ft
den2 = (AmP2) / (1716 * WtT2);
den3 = (AmP5) / (1716 * WtT5);

V_avg1 = sqrt((2*S1Avg)/den1);
V_avg2 = sqrt((2*S2Avg)/den2);
V_avg3 = sqrt((2*S3Avg)/den3);

V_hat1 = sqrt((2*mean(S1c([1:6, 8:end]), 2))/den1);
V_hat2 = sqrt((2*mean(S2c([1:6, 8:end]), 2))/den2);
V_hat3 = sqrt((2*mean(S3c([1:6, 8:end]), 2))/den3);

V_theo1 = sqrt((2*0)/den1);
V_theo2 = sqrt((2*0.0721824/den2));
V_theo3 = sqrt((2*0.180456/den3));

mu_ref = 3.737e-7; % Reference dynamic viscosity in slugs/(ft s)
T_ref = 518.67;    % Reference temperature in Rankine
S = 198.72;        % Sutherland's constant in Rankine

mu0 = mu_ref * (WtT0 / T_ref)^(3/2) * ((T_ref + S) / (WtT0 + S));
mu2 = mu_ref * (WtT2 / T_ref)^(3/2) * ((T_ref + S) / (WtT2 + S));
mu5 = mu_ref * (WtT5 / T_ref)^(3/2) * ((T_ref + S) / (WtT5 + S));

Re1 = (den1 * V_hat1) / mu0;
Re2 = (den2 * V_hat2) / mu2;
Re3 = (den3 * V_hat3) / mu5;

% Plots
pitotN = 1:35;
```

```
N = size(pitotN);


figure(1) %Flow uniformity - Measured Pressure

hold on, grid on
ylim([-.02 .2])

scatter(pitotN,S1c)
plot(pitotN, ones(1, length(pitotN)) * mean(S1c(:, [1:6, 8:end]), 2), 'k')
scatter(pitotN,S2c)
plot(pitotN, ones(1, length(pitotN)) * mean(S2c(:, [1:6, 8:end]), 2), 'k')
scatter(pitotN,S3c)
plot(pitotN, ones(1, length(pitotN)) * mean(S3c(:, [1:6, 8:end]), 2), 'k')

xlabel("Pressure Ports")
ylabel("Pressure (Psi)")
title("Flow Uniformity - Measured Pressure")
legend("0.0 inH2O", '', "2.0 inH2O", '', "5.0 inH2O", "Average")


figure(2) %Flow uniformity - Dynamic Pressure
hold on, grid on
ylim([-.02 .22])

scatter(pitotN, S1Avg)
plot(pitotN, ones(N) * mean(S1c(:, [1:6, 8:end]), 2), 'r')
plot(pitotN, ones(N) * 0, 'k')
scatter(pitotN, S2Avg)
plot(pitotN, ones(N) * mean(S2c(:, [1:6, 8:end]), 2), 'r')
plot(pitotN, ones(N) * 0.0721825, 'k')
scatter(pitotN, S3Avg)
plot(pitotN, ones(N) * mean(S3c(:, [1:6, 8:end]), 2), 'r')
plot(pitotN, ones(N) * .180456, 'k')

xlabel("Pressure Ports")
ylabel("Pressure (Psi)")
title("Flow Uniformity - Dynamic Pressure")
legend("0.0 inH2O", '', '', "2.0 inH2O", '', '', "5.0 inH2O", "Average", '
    q_s_e_t_t_i_n_g')


figure(3)
hold on, grid on
ylim([-20 170])

scatter(pitotN,V_avg1)
plot(pitotN, ones(N) * V_hat1,'r')
plot(pitotN, ones(N) * V_theo1, 'k')
scatter(pitotN,V_avg2)
plot(pitotN, ones(N) * V_hat2,'r')
plot(pitotN, ones(N) * V_theo2, 'k')
scatter(pitotN,V_avg3)
plot(pitotN, ones(N) * V_hat3,'r')
```

```
plot(pitotN, ones(N) * V_theo3, 'k')


xlabel("Pressure Ports")
ylabel("Airspeed (ft/s)")
title("Flow Uniformity - Test Section Airspeed")
legend("0.0 inH2O", '', '', "2.0 inH2O", '', '', "5.0 inH2O", "Average", "
    v_s_e_t_t_i_n_g")


figure(4)
hold on, grid on
ylim([-1 6])

scatter(pitotN, 100 * (S2Avg - mean(S2Avg)) / mean(S2Avg),'k');
scatter(pitotN, 100 * (S3Avg - mean(S3Avg)) / mean(S3Avg),'r');

xlabel("Pressure Ports")
ylabel('$\frac{(q - \bar{q})}{\bar{q}}$', 'Interpreter', 'latex');
title("Flow Uniformity - Dynamic Pressure Deviation From Average")
legend("2.0 inH2O", "5.0 inH2O")
ytickformat('percentage')


figure(5)
hold on, grid on
ylim([-1 6])

scatter(pitotN, 100 * (S2Avg - mean(S2Avg)) / mean(S2Avg),'k');

xlabel("Pressure Ports")
ylabel('$\frac{(q - \bar{q})}{\bar{q}}$', 'Interpreter', 'latex');
title("Flow Uniformity - Dynamic Pressure Deviation From Average")
legend("2.0 inH2O")
ytickformat('percentage')


figure(6)
hold on, grid on
ylim([-1 6])

scatter(pitotN, 100 * (S3Avg - mean(S3Avg)) / mean(S3Avg),'r');

xlabel("Pressure Ports")
ylabel('$\frac{(q - \bar{q})}{\bar{q}}$', 'Interpreter', 'latex');
title("Flow Uniformity - Dynamic Pressure Deviation From Average")
legend("5.0 inH2O")
ytickformat('percentage')


figure(7)
hold on, grid on
ylim([1 5])
```

```
scatter(pitotN, 100 * (V_avg2 - mean(V_avg2)) / mean(V_avg2), 'k')
scatter(pitotN, 100 * (V_avg3 - mean(V_avg3)) / mean(V_avg3), 'r')

xlabel("Pressure Ports")
ylabel('$\frac{(V - \bar{V})}{\bar{V}}$', 'Interpreter', 'latex');
title("Flow Uniformity - Airspeed Deviation From Average")
legend("2.0 inH2O", "5.0 inH2O")
ytickformat('percentage')


figure(8)
hold on, grid on
ylim([1 5])

scatter(pitotN, 100 * (V_avg2 - mean(V_avg2)) / mean(V_avg2), 'k')

xlabel("Pressure Ports")
ylabel('$\frac{(V - \bar{V})}{\bar{V}}$', 'Interpreter', 'latex');
title("Flow Uniformity - Airspeed Deviation From Average")
legend("2.0 inH2O")
ytickformat('percentage')


figure(9)
hold on, grid on
ylim([1 5])

scatter(pitotN, 100 * (V_avg3 - mean(V_avg3)) / mean(V_avg3), 'r')

xlabel("Pressure Ports")
ylabel('$\frac{(V - \bar{V})}{\bar{V}}$', 'Interpreter', 'latex');
title("Flow Uniformity - Airspeed Deviation From Average")
legend("5.0 inH2O")
ytickformat('percentage')

%Dynamic Pressure Deviation from Average (q = 2.0 inH2O)
x = [linspace(-19.5, 19.5, 15), repelem(-7.5,10), repelem(7.5,10)]';
z = [repelem(0,15), (-13.5:3:13.5), (-13.5:3:13.5)]';
S2Avg = S2Avg';
[X,Z] = meshgrid(linspace(min(x), max(x), 35), linspace(min(z), max(z),35));
F2 = scatteredInterpolant(x,z, (S2Avg - mean(S2Avg)) / mean(S2Avg), "natural",
    "none");
QD2 = F2(X,Z);
QD2(QD2 < 0) = .01;
figure(10)
hold on, grid on
contourf(X,Z,QD2,20,'LineColor','none')
title('Dynamic Pressure Deviation from Average (q = 2.0 inH2O) (%)')
xlabel("X Position (in)")
ylabel("Z Position (in)")
cb = colorbar;
ylabel(cb, '$\frac{(q - \bar{q})}{\bar{q}}$', 'Interpreter', 'latex');
cb.TickLabels = strcat(cb.TickLabels, '%');
plot(x,z,'ro')
```

```
xlim([-20 20])
ylim([-15 15])
clim([0 .06])

S3Avg = S3Avg';
F3 = scatteredInterpolant(x,z, (S3Avg - mean(S3Avg)) / mean(S3Avg), "natural",
    "none");
QD3 = F3(X,Z);
QD3(QD3 < 0) = .01;
figure(11)
hold on, grid on
contourf(X,Z,QD3,20,'LineColor','none')
title('Dynamic Pressure Deviation from Average (q = 5.0 inH2O) (%)')
xlabel("X Position (in)")
ylabel("Z Position (in)")
cb = colorbar;
ylabel(cb, '$\frac{(q - \bar{q})}{\bar{q}}$', 'Interpreter', 'latex');
cb.TickLabels = strcat(cb.TickLabels, '%');
plot(x,z,'ro')
xlim([-20 20])
ylim([-15 15])
clim([-.02 .06])


IAS = 54.5 * 3.28084;
V_IAS = sqrt((2*S3Avg)/den3);
V_IAS(V_IAS <1) = 153.2294;
F4 = scatteredInterpolant(x,z, V_IAS, "natural", "none");
QD4 = F4(X,Z);
QD3(QD3 < 1) = 153.2294;
figure(12)
hold on, grid on
contourf(X,Z,QD4,20,'LineColor','none')
title('Airspeed Distribution - IAS = 54.5 m/s = 178.8 ft/s')
xlabel("X Position (in)")
ylabel("Z Position (in)")
cb = colorbar;
ylabel(cb, 'Measured Airspeed (ft/s)');
plot(x,z,'ro')
xlim([-20 20])
ylim([-15 15])
clim([150 156])


% Convergence
B17 = B1;
B17(:,7) = [];
N = length(B17);
threshold = 0.00005;
cum_mean = zeros(N,1);
perc_conv = zeros(N,1);

for i = 1:N
    cum_mean(i) = mean(B17(1:i));
```

```
    if i == 1
        perc_conv(1) = NaN;
    else
        perc_conv(i) = abs((cum_mean(i) - cum_mean(i-1)) / cum_mean(i-1));
    end
end

conv_idx = find(perc_conv < threshold, 1);
if isempty(conv_idx)
    conv_idx = N;
    fprintf('not converged')
else
    fprintf('converged at simple %d with %% change = %f\n', conv_idx,perc_conv
       (conv_idx));
end

figure(13)
subplot(2,1,1);
hold on, grid on
plot(1:N, cum_mean)
plot(conv_idx, cum_mean(conv_idx))
xlabel('Number of Samples')
ylabel('Cumulative Mean Dynamic Pressure')
title('Convergence Test for 0.0 inH2O')
legend('Cumulative Mean', sprintf('Convergence at n=%d',conv_idx))

subplot(2,1,2)
plot(2:N, perc_conv(2:end))
hold on
plot(conv_idx, perc_conv(conv_idx))
xlabel('Number of Samples')
ylabel('Percentage Convergence')
title('Percentage Convergence Criterion')
yline(threshold, 'r--')
legend('Percentage Convergence', sprintf('Threshold = %.5f', threshold), "
   Threshold")


B27 = B2;
B27(:,7) = [];
N = length(B27);
threshold = 0.00005;
cum_mean = zeros(N,1);
perc_conv = zeros(N,1);

for i = 1:N
    cum_mean(i) = mean(B27(1:i));
    if i == 1
        perc_conv(1) = NaN;
    else
        perc_conv(i) = abs((cum_mean(i) - cum_mean(i-1)) / cum_mean(i-1));
    end
end
```

```
conv_idx = find(perc_conv < threshold, 1);
if isempty(conv_idx)
    conv_idx = N;
    fprintf('not converged')
else
    fprintf('converged at simple %d with %% change = %f\n', conv_idx,
        perc_conv(conv_idx));
end

figure(14)
subplot(2,1,1);
hold on, grid on
plot(1:N, cum_mean)
plot(conv_idx, cum_mean(conv_idx))
xlabel('Number of Samples')
ylabel('Cumulative Mean Dynamic Pressure')
title('Convergence Test for 2.0 inH2O')
legend('Cumulative Mean', sprintf('Convergence at n=%d', conv_idx))

subplot(2,1,2)
plot(2:N, perc_conv(2:end))
hold on
plot(conv_idx, perc_conv(conv_idx))
xlabel('Number of Samples')
ylabel('Percentage Convergence')
title('Percentage Convergence Criterion')
yline(threshold, 'r--')
legend('Percentage Convergence', sprintf('Threshold = %.5f', threshold), "
   Threshold")
```