Team 3

Determining Mass Flow Rate of an Electronic Axial Computer fan from 0.083 to 0.275 slugs/min over 3.466 to 12.59 V Input Voltage

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Abstract

Knowing the mass flow rate of air through an axial PC fan is ideal to know for cooling system design to ensure the proper cooling is being provided. This project aims to determine the mass flow rate through an electronic axial computer fan over a range of 0.083 to 0.275 slugs/min with a target uncertainty of ±15%. This is justified by the 10% uncertainty in the Wathai 12V fan's volumetric flowrate claimed on the Amazon webpage as well as prior art on mean flow with an uncertainty of ±9.3% [1] [2]. Goals for this experiment include creating a design that minimizes flow losses, achieving a relative uncertainty less than or equal to 15% in the mass flow, as well as to plot the mass flow rate of the fan over the operating voltage range of the fan using the provided voltage controller.

The mass flow rate measurements were accomplished with an apparatus designed for creating a controlled measurement system. The apparatus includes a measuring grid for placing a thermal anemometer into the flow field in certain locations for repeatability of the measurements. This ensured that the anemometer was placed in the same locations for each grid square measured across all trials. The measuring grid also allowed for the use of the equal area integration method outlined in "Equal Area vs. Log-Tchebycheff" with a six-by-six square grid, giving 36 total data points across the measuring area [3]. Along with this, the design also includes a diffuser of one effective duct length long to contain all the air that is pushed through the fan blades. It was determined experimentally with pitot tubes that the pressure drop across the diffuser was negligible, allowing for the assumption that there are no significant losses in the flow while the air is traveling through the diffuser to the measuring grid.

The average relative uncertainty of all the trials conducted turned out to be 4.05%. This was much better than expected and can be contributed to an apparatus that allowed repeatable and stable measurements. The team did find that the measured values generally were a 2% to 26% difference from the datasheet on the Amazon page [1]. The final range of mass flow measured through the fan was 0.083 to 0.275 slugs/min with uncertainties ranging from 2.442% to 3.725% uncertainty in the final measurements.

Introduction

A large portion of electronics use convective cooling (fans that blow cool air onto hot computer parts) to keep the parts at a safe temperature and ensure they do not overheat [4]. When an electronic device like a computer overheats, it can lead to significant damage of the internal components. Convective cooling relies on a fan drawing power and blowing cooler air onto the internal components. This blowing motion takes heat energy from the hot components, causing them to remain cool [4] .

If an engineer has a complete understanding of the fan performance, they can efficiently implement the fan in their project using variable power to give just enough cooling to the system. The benefits of using variable speed control on fans include reduced noise, reduced power consumption, and increased fan lifetime [5]. To model the system accurately, the engineer will need to know the relationship between the input voltage and the mass flow rate of the fan. From an experimental design perspective, the motivation can be expanded to include an experiment that can be modified to successfully measure the mass flow rate at varied input voltages on other, different sized fans.

The goal of this project is to determine the mass flow rate through an electronic axial computer fan over a range of 0.0940 to 0.2350 slugs/min with a target uncertainty of ±15%. The Amazon page for the Wathai fan used in testing has a relative uncertainty of 10% on the maximum volumetric flow rate value [1]. This 10% margin on maximum volumetric flow rate has been seen on similar sized fans made by Cooler Master [6]. However, with further research into measurement techniques, the target uncertainty for the experiment outlined in this report is ±15%. This value was reached after consulting a research paper regarding the uncertainty analysis of mean flow, which concluded with a ±9.3% uncertainty in mean flow [2]. Considering the 9.3% uncertainty from the paper and the 10% uncertainty in the fan's claimed performance metrics, it is reasonable to have a goal uncertainty of 15%.

Literature Review

To calculate the mass flow rate of the fan, the definition of mass flow rate is used. This definition depends on a non-uniform velocity profile that varies with position in the cross section in the flow region:

$$\dot{m} = \oint \rho(\overrightarrow{V_{rel}} \cdot \hat{n})dA \tag{1}$$

This velocity at specific points in the cross section can be measured using various devices such as ultrasonic flow measurement, particle image velocimetry, pitot tube arrays, and temperature anemometry.

Ultrasonic flow measurement uses time difference to calculate how to measure air flow. A sound wave is sent in the direction against the flow and then returned to the sensor. The difference in the transit time across the air is proportional to the flow rate of the medium [7].The benefits of ultrasonic measurement are that it has few moving parts, is portable, and is accurate [7].

Particle image velocimetry (PIV) is a method that can be used to measure the velocity profile of a fluid. PIV is often used to validate computational fluid dynamics (CFD) models since it is unobtrusive to the flow [8]. A laser and cameras are used to track marker particles that are placed in the flow. The research paper “Accuracy of volumetric flow rate inflow/outflow measurements by integrating PIV velocity fields,” used two cameras and was able to reach a final highest uncertainty of 4% [8]. PIV experiments tend to always have biases in data since the particles being tracked are extremely small and are tracked over very short distances and periods of time [8].

Another possible method of measuring velocity is by using a “Wilson flow grid”. This method consists of creating a grid of pressure sensors across the area of the pipe. Each sensor has a static and a stagnation port- essentially functioning as a pitot tube. The sensors measure the difference in these pressures, which is then used to find flow speed at each point. From there the average speed can be calculated throughout the entire area. It is important to note that the presence of the sensors in the pipe obstructs the fluid flow causing the air to speed up around the sensors, which, in turn lowers the static pressure more than it would be without the sensor there [9]. Airflow, a company that produces sensors and Wilson flow grids, reports the accuracy of these systems to be as low as 2% [10].

Temperature anemometry can be used to measure an entire velocity profile at any instant instead of having to traverse a probe to different locations into a flow field. Temperature anemometry uses an array of resistors that vary in resistance depending on the temperature. The temperature change is measured by either the voltage or current passing through the resistor [11]. The research paper “Thermal Anemometry Grid Sensor,” lists different methods for doing this. The voltage or current output is then used with the fluid temperature and convection heat transfer principles to determine the speed of the fluid passing over the resistor. This is then extrapolated to a grid format where multiple measurements of the entire flow field can be taken at once [11].

Once the velocity profile has been gathered using experimental data, an integration scheme can be used to solve for the mass flow rate. Integration schemes include equal area method, Log-Tchebycheff method, and diameter bisection method.

The equal area method and the Tchebycheff method are two similar ways to characterize the velocity profile of an air stream through a rectangular duct. According to the journal article “Equal Area vs. Log-Tchebycheff,” both methods divide the cross-section of the duct into parts and a pitot-static tube or other type of pressure probe is then used to measure the pressure of the stream of air at that point [3]. The key difference is how these two methods place the points within the cross-sectional area. In the equal area method, the entire cross section is divided into equal sized rectangles and the measurement point is the center of the rectangles. Depending on the size of the duct, there must be a certain number of rectangles to ensure accurate results. The Tchebycheff method uses percentages of the dimensions of the duct to create a grid. The intersections of the grid are the points where the measurements are taken. Between these two methods, the Tchebycheff method has a higher density of readings towards the middle of the duct and near the walls of the duct, which, makes the velocity profile more accurate [3]. Using one of these schemes allows you to create a two-dimension velocity field which can be used in the integral definition of mass flow. A research paper stated that depending on the pipe/duct size there is no preference of equal area method or Tchebycheff method since there is only a 3% difference in the velocity profiles made by each method at small duct/pipe sizes [12]. The same research paper stated that the equal area method overestimated the flowrate in a circular pipe by 3.5% to 4.7% while Tchebycheff method was able to reach 0.4% to 0.8% of the actual values [12].

The motivation behind the bisection method is that the Log-Tchebycheff method and the equal area method are too cumbersome to calculate where to place the pitot tube [13]. This becomes apparent when the experiment calls for a change in pipe diameter, which causes a large calculation overhead [13]. The bisection method uses pitot tube measurement points that are positioned at $2^{-1,2,\ldots,n}$ from the radius and center of the pipe as shown in Figure 1.

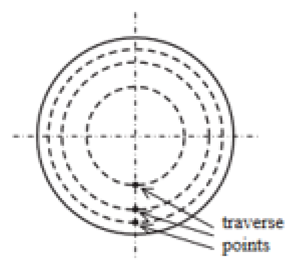

Figure 1: Diameter Bisection method example.

This allows for the measurement scheme to scale well with the varying diameter of the pipe. This scheme does, however, introduce a correction factor because the average velocity is not represented by the velocity at a traverse point. However, the benefits of the bisection method offer more flexibility with the pitot tube points, and there is a smoother error curve [13].

Modeling

To create the equations needed to model the system, consider the following schematic in

System
boundary

Figure 2.

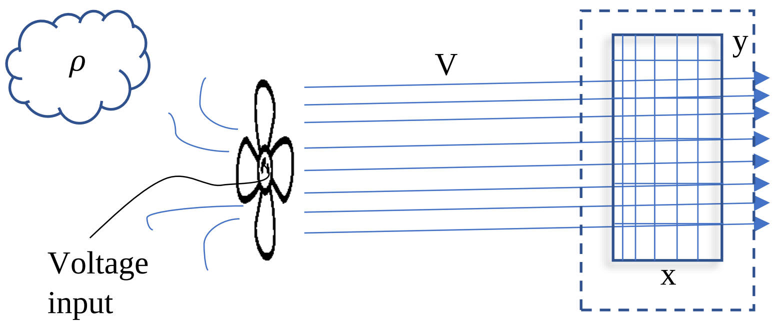

Figure 2: Schematic to analyze mass flow through the system

Using the definition of mass flow rate stated in Equation 1, the integration area can be expanded into x and y coordinates (with flow moving in the z-direction) found in Equation 2.

$$\dot{m} = \oint \oint \rho(\vec{V}_{rel} \cdot \hat{n})dxdy \tag{2}$$

Where ρ is density of the fluid (air), $\vec{V}_{rel}$ is velocity, $\hat{n}$ is the unit vector normal to the integration area, x is the width of the fan testing area, and y is the height of the fan testing area. To better clarify Equation 1, dx and dy are small segments making up dA. Under the assumption that the flow of air is normal to the fan face the dot product can be evaluated, which leads to Equation 3.

$$\dot{m} = \iint \rho V dxdy \tag{3}$$

Given the flow speeds are at relatively low speeds compared to when flow becomes compressible, it is reasonable to assume that the flow is incompressible, so the density stays constant. This leads to the simplified integral in Equation 4.

$$\dot{m} = \rho \iint V dxdy \tag{4}$$

The rectangular fan can be viewed and subdivided into small dx and dy, or rather Δx and Δy, segments using the equal area method as shown in Figure 3.

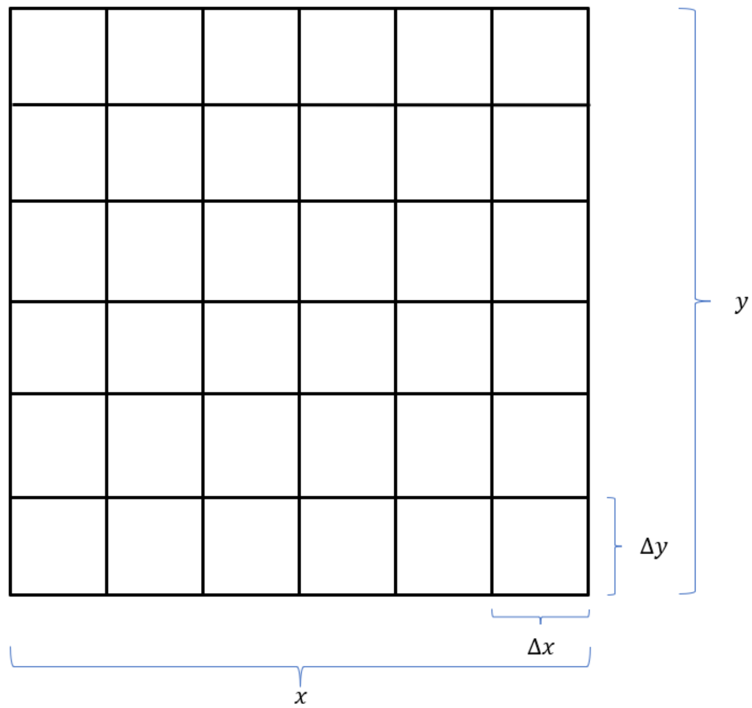

Figure 3: Example of grid view of some testing area of size x by y for an axial computer fan

Since the exact equation for the velocity profile is unknown, the integral can be approximated by taking the sum of velocities in each small equally sized Δx and Δy segment as represented in Equation 5.

$$\dot{m} = \rho \sum_{i=1}^{n} V_i \Delta x \Delta y \quad (5)$$

Using the assumption of incompressible flow and the ideal gas law shown in Equation 6, the density of air can be represented in terms of atmospheric pressure, P_{atm}, atmospheric temperature, T_{atm}, and the gas constant for air, *R*.

$$\rho = \frac{P_{atm}}{RT_{atm}} \quad (6)$$

Substituting Equation 6 into Equation 5, the result is Equation 7 below.

$$\dot{m} = \frac{P_{atm}}{RT_{atm}} \sum_{i=1}^{n} V_i \, \Delta x \Delta y \quad (7)$$

Since the area being evaluated inside of the summation is equal to the total area of the grid, it can be factored out of the summation as the total test area. The inverse of the number of smaller areas (n) can also be pulled out of the summation since it ends up being one over a constant value. The summation then becomes the sum of all the velocities at the different test points.

Performing these simplifications, the final data reduction equation (DRE) is shown in Equation 8.

$$\dot{m} = \frac{P_{atm}}{RT_{atm}} xy \frac{1}{n} \sum_{i=1}^{n} V_i \tag{8}$$

Determining the uncertainty equation for the DRE

The uncertainty equation for mass flowrate for the derived DRE is shown in Equation 9 below.

$$w_{\dot{m}}^2 = \left(\frac{\partial \dot{m}}{\partial P_{atm}}\right)^2 w_{Patm,sys}^2 + \left(\frac{\partial \dot{m}}{\partial T_{atm}}\right)^2 w_{Tatm,sys}^2 + \left(\frac{\partial \dot{m}}{\partial V_1}\right)^2 w_{V_1,sys}^2 + \cdots + \left(\frac{\partial \dot{m}}{\partial V_n}\right)^2 w_{V_n,sys}^2 + \left(\frac{\partial \dot{m}}{\partial x}\right)^2 w_{x,sys}^2 + \left(\frac{\partial \dot{m}}{\partial y}\right)^2 w_{y,sys}^2 + w_{integration}^2 + w_{\dot{m}_{rand}}^2 \tag{9}$$

Here, $w_{\dot{m}}^2$ is the uncertainty in mass flow rate, $w_{P_{atm},sys}^2$ is the systematic uncertainty in atmospheric pressure, $w_{Tatm,sys}^2$ is the systematic uncertainty of the temperature, $w_{V_n,sys}^2$ is the systematic uncertainty in the velocity measured in the n^{th} section, $w_{x,sys}^2$ and $w_{y,sys}^2$ are the systematic uncertainties in the width and height, $w_{integration}^2$ is the uncertainty in the integration method, and $w_{\dot{m}_{rand}}^2$ is the random uncertainty in the mass flow rate measurements.

The last step is to combine all the simplifications used in Appendix A. So, the complete uncertainty equation in uncertainty magnification factor (UMF) form can be seen in Equation 10.

$$\left(\frac{w_{\dot{m}}}{\dot{m}}\right)^2 = (1)^2 \left(\frac{w_{P_{atm},sys}}{P_{atm}}\right)^2 + (-1)^2 \left(\frac{w_{Tatm,sys}}{T_{atm}}\right)^2 + \left(\frac{V_1^2}{(\sum_{i=1}^{n} V_i)^2}\right)\left(\frac{w_{V_1,sys}}{V_1}\right)^2 + \cdots + \left(\frac{V_n^2}{(\sum_{i=1}^{n} V_i)^2}\right)\left(\frac{w_{V_n,sys}}{V_n}\right)^2 + (1)^2 \left(\frac{w_{x,sys}}{x}\right)^2 + (1)^2 \left(\frac{w_{y,sys}}{y}\right)^2 + (1)^2 \left(\frac{w_{integration}}{\dot{m}}\right)^2 + (1)^2 \left(\frac{w_{\dot{m}_{rand}}}{\dot{m}}\right)^2 \tag{10}$$

This form of the uncertainty equation is much nicer- before each parameter's relative uncertainty is the UMF, which shows how much each parameter's relative uncertainty impacts the resultant's relative uncertainty.

Creating a preliminary uncertainty budget

The target uncertainty for this project is 15%, so to get an idea of how much uncertainty should be allotted per parameter, the team looked at the uncertainty for some different sensors that are likely to be used for the apparatus.

To measure atmospheric pressure, a pocket weather meter will be used. This sensor has an uncertainty of 3.133 psf, given that the average pressure at sea level on a standard day is 2117 psf, the relative uncertainty is about 0.148%. Since the experiment may not be operating under these exact conditions, the allotted uncertainty for pressure is rounded up to be 0.2%. Since the pocket meter can measure values within the range expected with a small uncertainty, it is a reasonable sensor to use.

The pocket weather meter will also be used to measure temperature. This is partly for convenience as the same instrument can measure multiple measurands. The uncertainty in the temperature reading is 1.8 ˚R, and with the average room temperature being about 531.67 ˚R, this results in a relative uncertainty of 0.34%. To be safe, the uncertainty will be rounded up to 0.4%.

To measure the height and width of the test area, calipers will be used as they can accurately measure distances in the range the grid measurands are in. The calipers used have an uncertainty of 0.001116 inches, and for a measurement of about 5.664 inches (which is the proposed height and width of the testing area) this gives a relative uncertainty of 0.0197%. Again, the uncertainty is rounded up to 0.2% to be safe.

To determine how much uncertainty should be allotted for velocity, a bit more math is needed along with a few assumptions. First, the velocity sensor to be used has 2 different operating ranges, a low velocity range between 0–394 ft/min, and a high velocity range between 394–2953 ft/min. The systematic uncertainty of the tool changes when operating in the two different regions due to the accuracy of tool changing. These values are summarized in Table 1.

Table 1: Uncertainty table where V is the measured velocity in units of ft/min by the hot wire anemometer

Velocity Range	Systematic Uncertainty	Readability Uncertainty
0-394 ft/min	$(20\ ft/\min + 0.05V)^2$	$(0.985)^2\ ft/min$
394-2953 ft/min	$(59.1\ ft/\min + 0.05V)^2$	$(0.985)^2\ ft/min$

For the budget, the team considered two different cases: the case where all the velocities measured are in the low range, and the case where there is a mix of low and high velocities. The reason behind including two different cases is at low voltages the axial fan is expected to produce an average velocity in the lower velocity range. For higher voltages, the average velocity may be in the higher range, but due to the use of a duct there will also be low range velocities – more on this later in the section.

The uncertainty in the integration term can be calculated by Equation 11.

$$w_{integration} = C(\Delta A)^2 \tag{11}$$

In each mass flow rate trial conducted, there will be 36 test points or 36 equal-sized areas. Comparing the error in integration for using 1 velocity measurement to 36 velocity measurements yields that the error in 36 measurements is 0.077% to that of the 1 measurement case. This was deemed small enough that there was not a need to increase the number of measurements any further. Since the value of the constant C is unknown, for the budget it is assumed that C does not cause the integration relative uncertainty to go above 4%.

The reason behind allotting 6% uncertainty to randomness is that it is a significant portion of the budget (see the UPC charts on page 14). So, providing a lot of room within the unpredictable section of air flow (as fluids often are) is a safe route to follow. This large uncertainty also considers the fact that there will only be a few trials conducted for each voltage, which will give a larger random uncertainty than if there were many trials at that voltage.

For the first case for velocity uncertainty: it is assumed that all speeds are in the lower region. It is also assumed the measured velocities are equal in each of the smaller areas. Substituting the relative uncertainties for the other parameters to see how much uncertainty can be allotted to velocity results in Equation 12,

$$(15\%)^2 = (1)^2(0.2\%)^2 + (-1)^2(0.4\%)^2 + \left(\frac{V}{36V}\right)^2 (w_{rel})^2 + \cdots + \left(\frac{V}{36V}\right)^2 (w_{rel})^2 + (1)^2(0.2\%)^2 + (1)^2(0.2\%)^2 + (1)^2(4\%)^2 + (1)^2(6\%)^2 \quad (12)$$

This can be simplified to Equation 13 below.

$$(15\%)^2 = (0.2\%)^2 + (0.4\%)^2 + (0.2\%)^2 + (0.2\%)^2 + 36\left(\frac{1}{36}\right)^2 (w_{rel})^2 + (4\%)^2 + (6\%)^2 \quad (13)$$

Solving this gives the initial relative uncertainty for velocity to be 78.9%. To give a little extra room with the uncertainty budget, the relative uncertainty is rounded down to 78%. This value is quite high and intuitively seems like it would not be valid; however, since the UMF of the velocity terms is so small the relative uncertainty in velocity can be quite large while keeping a small uncertainty in the resultant mass flow rate.

The next step is to determine the range of acceptable velocities for the low velocity range. Relative uncertainty for any parameter (k) is defined in Equation 14.

$$\frac{w_k}{k} = w_{rel} \quad (14)$$

Plugging in the equation for systematic uncertainty for low range velocities and the 78% for relative uncertainty into Equation 14 yields Equation 15.

$$\frac{\sqrt{(20 + 0.05V)^2 + (0.985)^2}}{V} \leq 78\% \quad (15)$$

Which gives a minimum velocity of 27.4 ft/min for the 'all lower speeds' case. The maximum velocity for the all low-speed condition is 394 ft/min which is induced by the limitation of the sensor.

The second case to consider is if there is a mix of low- and high-end velocities. Given the geometry of the fan, it is expected that there will be slower flow in the shaded areas of Figure 4.

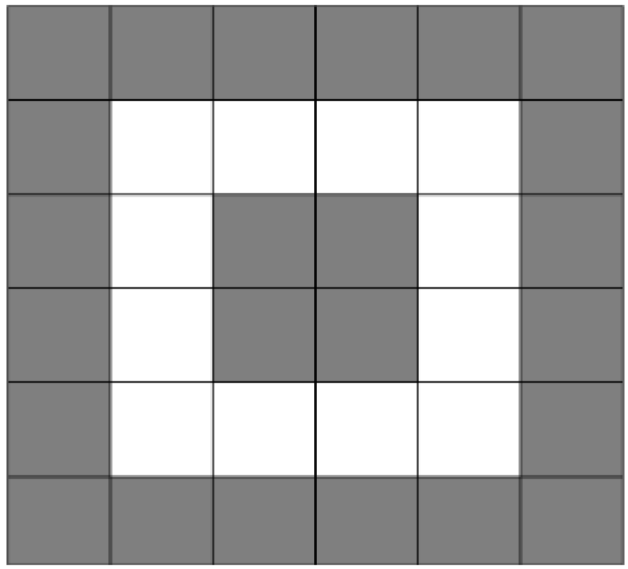

Figure 4:A 6x6 testing area divided up into equal area slices with low velocity sections in dark gray and high velocity sections in white.

This leads to 24 slower speed and 12 higher speed sections. The reasoning behind these locations of slower speeds is due to a couple different reasons. First, the fan is forcibly moving air causing the flow to be turbulent, which causes vortices within the flow. Secondly, due to the use of a duct there is an induced ‘no-slip condition’ which means that the flow along the surface of the duct will have 0 velocity.

With the introduction of two different ranges of speeds the uncertainty equation becomes a bit more complex. Within these two ranges, it is assumed that all low-speed sections will have the same relative uncertainty, while the high-speed sections will have the same relative uncertainty but different from the low-speed sections. This assumption allows Equation 10 to simplify down to Equation 16.

$$(15\%)^2 = (0.2\%)^2 + (0.4\%)^2 + (0.2\%)^2 + (0.2\%)^2 + \frac{1}{24}\left(w_{rel,low}\right)^2 + \frac{1}{12}\left(w_{rel,high}\right)^2 + (4\%)^2 + (6\%)^2 \quad (16)$$

Since the minimum velocity for the higher range is 394 ft/min, that value can be used to solve for the higher range’s maximum relative uncertainty using Equation 17 and the systematic uncertainty for high range velocities.

$$\frac{\sqrt{(59.1 + 0.05(394))^2 + (0.985)^2}}{394} \leq w_{rel,high} \quad (17)$$

This gives a higher speed relative uncertainty of 20%. Plugging this back into Equation 16 results in Equation 18.

$$(15\%)^2 = (0.2\%)^2 + (0.4\%)^2 + (0.2\%)^2 + (0.2\%)^2 + \frac{1}{24}\left(w_{rel,low}\right)^2 + \frac{1}{12}(20\%)^2 + (4\%)^2 + (6\%)^2 \qquad (18)$$

Solving Equation 18 yields a relative uncertainty for the lower speeds of 57.8%, where again this will be rounded down to 57%.

Similar to how it was done for the low velocity case, by using Equation 19, the minimum low-end velocity can be solved for below.

$$\frac{\sqrt{(20 + 0.05V)^2 + (0.985)^2}}{V} \leq 57\% \qquad (19)$$

This equation yields a minimum velocity for the low-speed velocities of 38.5 ft/min.

To summarize, if the measured velocities are all within the low-speed range it must be above 27.4 ft/min, and if the measured velocities are a mix between high and low-speed ranges it must be above 38.5 ft/min to meet the uncertainty goal.

All relative uncertainty values for each parameter can be found in Table 2 below. As a reminder, there are two different velocity profiles: the low speed only profile and the mix of high and low speed profiles. The uncertainties are labeled accordingly in the below table.

Table 2: Relative uncertainty allocated for each parameter

Parameter	***Relative Uncertainty***
Pressure	0.2%
Temperature	0.4%
Length	0.2%
Width	0.2%
Velocity (low speeds case)	78%
Velocity (mixed speeds case)	*Low velocities*: 57% *High velocities*: 20%
Integration scheme	4%
Random	6%

In terms of the uncertainty budget, each parameters contribution for each case can be seen below in the following charts through their uncertainty percent contribution (UPC). Figure 5 shows the UPC pie-chart for the condition of just low speeds for velocity (0–394 ft/min range). Figure 6 shows the UPC pie-chart for the condition of mixed speeds for velocity (0–394 ft/min for low speeds and 394–2953 ft/min for high speeds). Random uncertainty takes up most of the chart followed by the integration uncertainty in both cases. This is due to the UMF terms for both integration and random uncertainty terms being 1 so there is no reduction in the scaling on the these uncertainties for the mass flow rate.

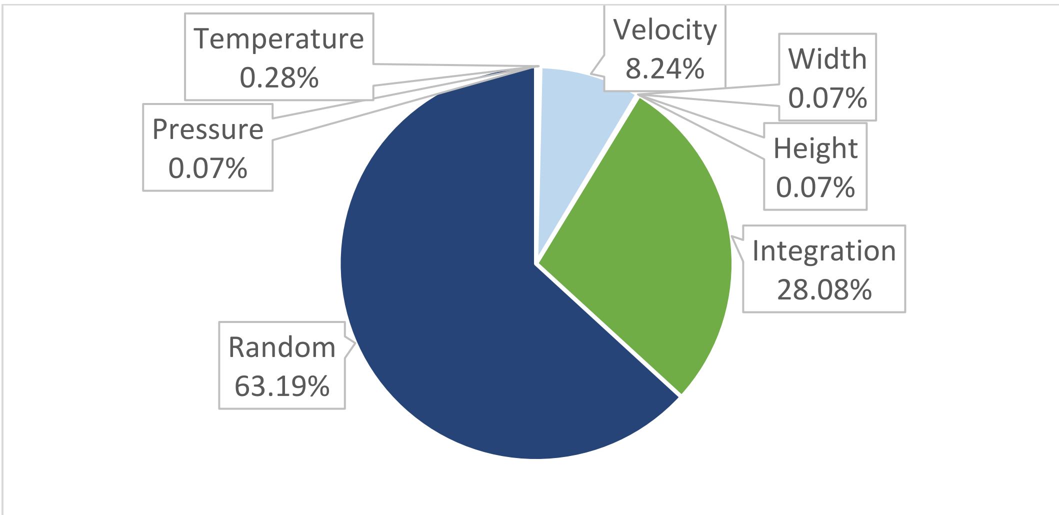

Figure 5: UPC chart for each parameter in the low-speed range condition

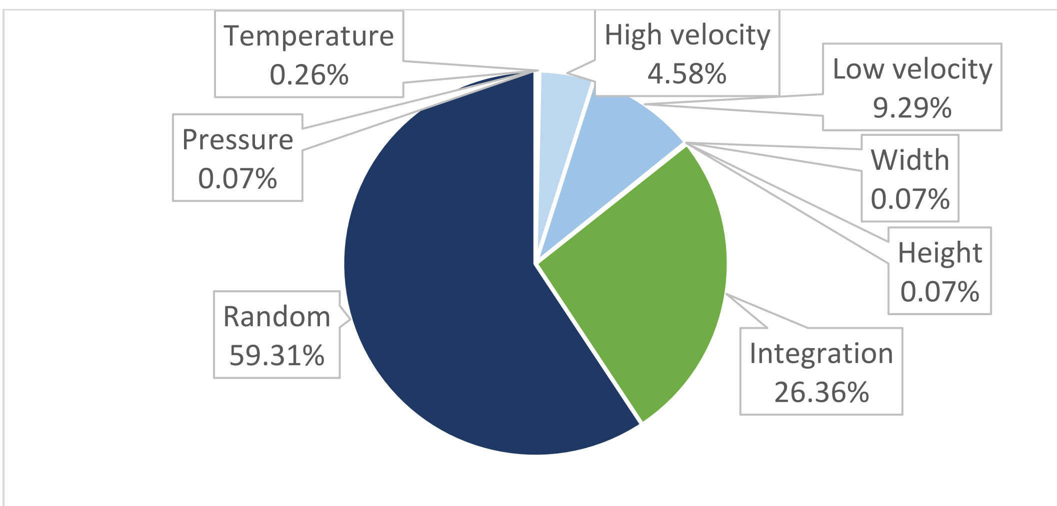

Figure 6: UPC chart for each parameter in the mixed speed range condition

Apparatus, Procedure, and Design Space Plot

One goal in the overall experiment is to maximize the accuracy and precision with which the anemometer can be placed in each square measurement grid. The motivation for this is to minimize the relative uncertainty allocated to random uncertainty and make it easier to gather multiple trials worth of data. An infographic for the proposed apparatus can be found in Figure 7.

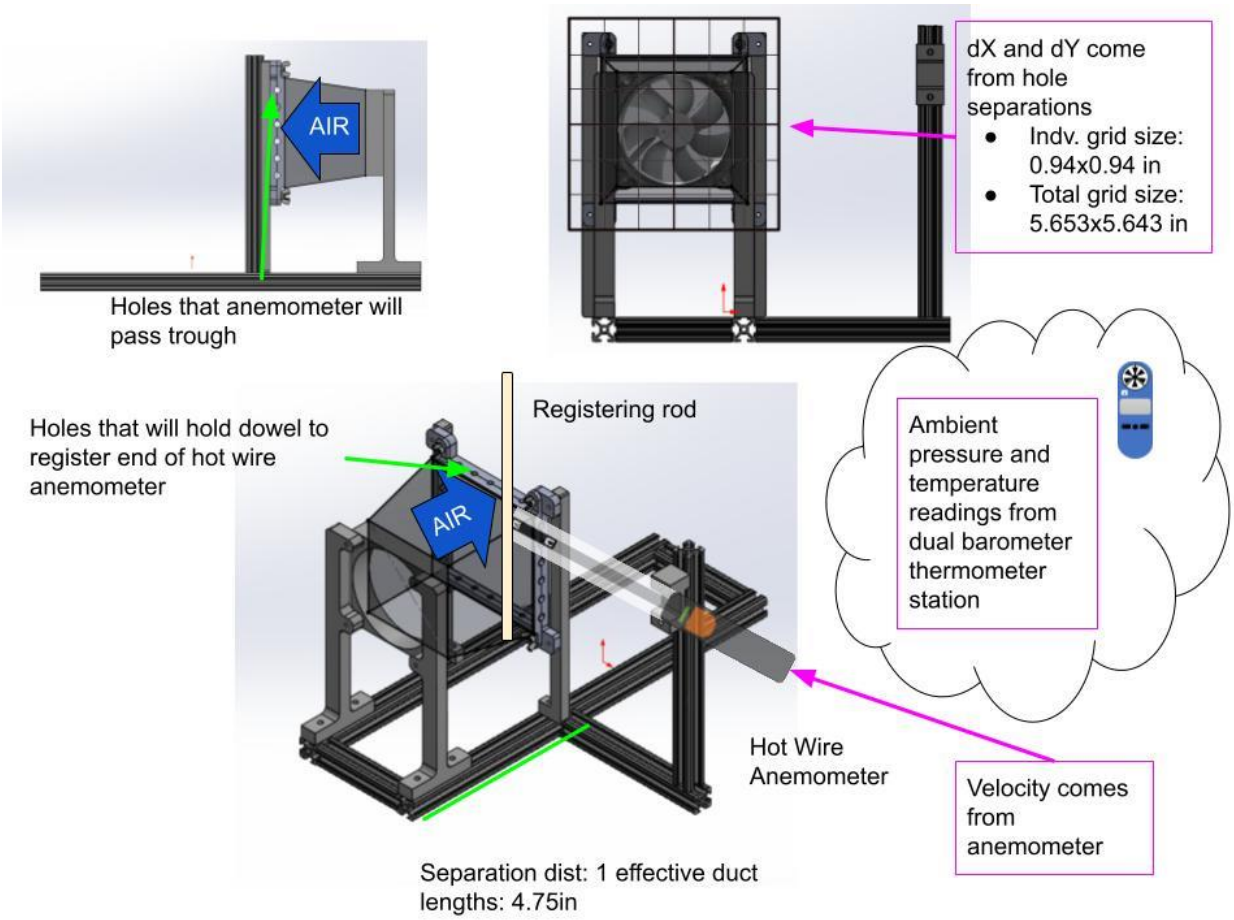

Figure 7: Proposed testing apparatus for mass flowrate experiment

The experimental apparatus has a jig that has two sets of holes perpendicular to each other. The purpose of one set of holes is to allow a registering rod through, while the other set guides the anemometer through. Where these holes intersect is where the measurement will take place. An 80/20 (extruded aluminum slot/rail system) frame is used to keep all devices level and make the data gathering process more efficient. A duct contains the flow and is attached to the fan and the alignment jig. A dual thermometer barometer is used to measure the atmospheric temperature and pressure in the room. These values are needed to calculate the local density of the atmosphere. A set of calipers will be used to measure the distances between each grid measurement to ensure that the experiment remains properly aligned. Finally, although it is not used in the DRE, a digital multimeter will be used to measure the voltage being supplied to the fan. This voltage value is needed when generating the final plot showing the mass flow rates at different voltage inputs.

The specifications for each sensor are tabulated in Table 3. Dial calipers do not have a specified accuracy, so the value assigned to resolution was used for the readability uncertainty and the accuracy uncertainty. Table 3 also contains the resolution and readability for the digital multimeter that will be used as a voltmeter in the apparatus. The voltage measurand does not appear in the DRE nor the uncertainty calculations, but when finding the uncertainty in the fan curve these values will be needed.

Table 3: Measurand Table with measuring tool name and uncertainty values for resolution and accuracy

Measurand	Symbol	Readout Units	Tool	Resolution	Accuracy
$Atmospheric\ Pressure$	P_{atm}	hPa	$Kestral\ 3500\ NV$	± 0.1 hPa	± 1.5 hPa
$Atmospheric\ Temperature$	T_{atm}	°F	$Kestral\ 3500\ NV$	± 0.1°F	± 1.8°F
$Height$	y	$Inches$	$Dial\ Calipers$	$\pm 0.001\ in$	$----$
$Width$	x	$Inches$	$Dial\ Calipers$	$\pm 0.001\ in$	$----$
$Velocity$	V	$Feet\ per\ Minute$	$Testo\ 405i$	$\pm 1\ fpm$	$\pm(20 + 5\%\ m.v.)$ $\pm(59 + 5\%\ m.v.)$
$Voltage$	V_{elec}	$Volts$	$Milwaukee\ DMM$	$\pm(0.001V)$ $\pm(0.01V)$	$\pm(0.5\%\ m.v. + 2\ dgt)$

A summary of the minimum and maximum sensor specifications are shown in Table 4. To simplify things a bit, the measurands of width and height were combined into one term: distance. Using the definition of relative uncertainty, and the relative uncertainties that were calculated for each measurand in Table 2, absolute minimums were then calculated. Given the tools specified operating range and laboratory conditions, practical maximums and minimums were selected.

Table 4: Minimum and maximum values for each type of measurand

Measurand	Uncertainty Calculated Minimum	Measurand Maximum	Practical Minimum	Practical Maximum
$\boldsymbol{Temperature}\ [\boldsymbol{R}]$	450	720	527.67	537.67
$\boldsymbol{Pressure}\ [\boldsymbol{psf}]$	1570	2297	2050	2150
$\boldsymbol{Distance}\ [\boldsymbol{in}]$	2.5	6	4.72	6
$\boldsymbol{Velocity}\ [\boldsymbol{fpm}]$ $(\boldsymbol{Low\ flow\ speeds})$	27.4	394	27.4	394
$\boldsymbol{Velocity}\ [\boldsymbol{fpm}]$ $(\boldsymbol{Low\ flow\ speeds\ with\ high\ speeds})$	38.5	394	38.5	394
$\boldsymbol{Velocity}\ [\boldsymbol{fpm}]$ $(\boldsymbol{High\ flow\ speeds})$	394	2953	394	2953

The apparatus was designed with input from existing experimental setups like the one shown in Figure 8. Some of the setups use ducts, flow straighteners, or a combination of both. The use of a duct is common, as air conditioning ducts are a major commercial use of volumetric flow measurement. The flow straighteners are used to minimize the amounts of points needed to measure as they produce a uniform velocity profile. A flow straightener would block too much of the flow and contribute excessive losses; however, a duct can be employed if the losses in mass flow are negligible. With a duct length of one effective fan diameter the best of both worlds is achieved. The flow is contained inside a duct, allowing for a complete velocity profile to be gathered. Without a duct, some ambient air is drawn through and past the grid, increasing the mass flow measured. The duct is also short enough to prevent excessive losses. To validate this claim that the duct is short enough to prevent noticeable losses, two tests at 5V were run on the refined apparatus. The first trial was run with no duct and produced a mass flow rate of 0.1497 $\frac{slug}{min}$. The second trial was run with a duct and produced a mass flow rate of 0.1455 $\frac{slug}{min}$. The percentage difference between the results of both trials was approximately 3%. With this small difference, the team was confident that the duct would only positively impact the experiment by reducing the large influx of ambient air at the higher fan voltages. For more information on this testing please see Appendix B.

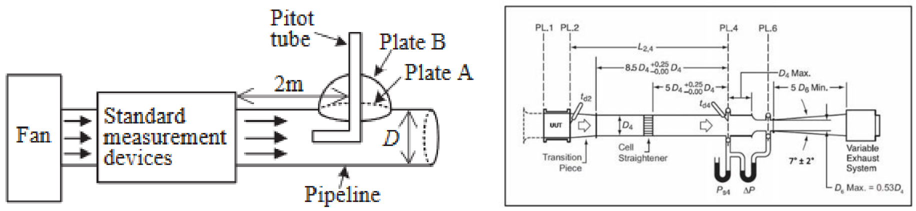

Figure 8: Other test apparatuses suggested by standards and research papers

To accommodate the duct and larger flow grid, the apparatus is raised off the ground. To ensure that the velocity profile is captured as accurately as possible, 36 points are used for the grid. This ensures that any irregularities in the flow are accounted for.

The remaining challenge is dimensioning the distances in the apparatus. For the distance from the outlet of the fan to the measurement jig, the effective duct length equation is used. The effective duct length states that for low RPM flows, which this fan is, the distance is 2.5 times the diameter. This will allow no negative flow velocities to be present and a slightly more uniform velocity profile to integrate. Figure 9 details how the flow transforms over the effective duct length. However, to mitigate mass flow losses, a duct with a length of the fan diameter, 120mm, is used. As a result, the velocity profile is not entirely uniform, however with the density of the grid, the flow irregularities can be accurately captured.

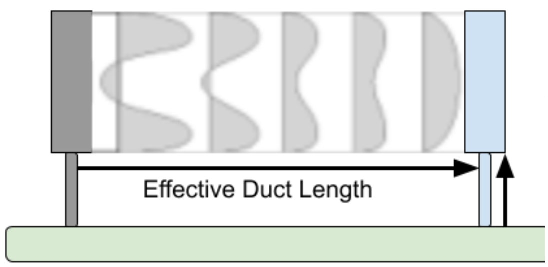

Figure 9:Effective duct length diagram

The height off the ground of the apparatus was determined once the apparatus was constructed. The requirement is that the fan and the grid are aligned at their centers. The grid being swept by the anemometer is larger than the fan area. This is to take more data points, and capture more of the velocity field. This large area allows the flow blockage caused by the apparatus and anemometer to be of less concern.

The procedure of gathering the measurements will follow a grid column-row approach. A visual representation of this can be found in Figure 10. Each grid in a column will have its center flow velocity measured 10 times and then the process will shift down a row and the process will repeat until the entire area of the grid has been measured.

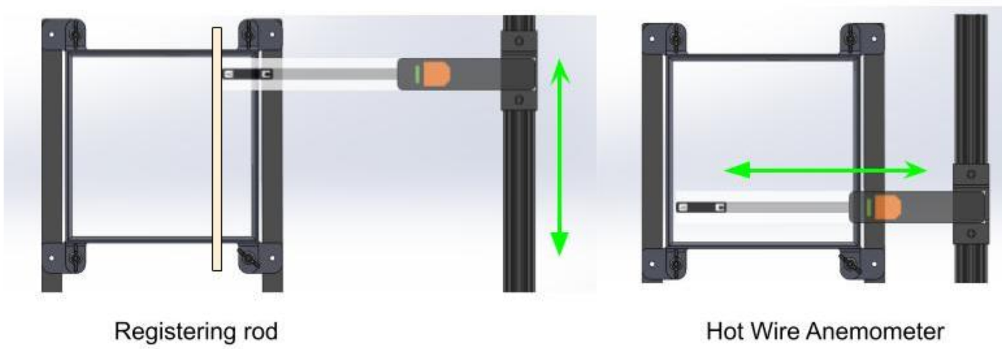

Figure 10: Experimental procedure visualization

The apparatus ensures that the fan always remains centered in the flow grid, and that the anemometer remains aligned in the flow grid. The anemometer is simple to use with the downloadable app. The experiment developed by the team uses 10 values from the anemometer that are then averaged to form 1 data point with the readability as the standard deviation.

The measurement scheme depicted in Figure 10 above is repeated a total of 3 trials at each voltage level to reduce random uncertainty. The voltage levels used during this experiment were 3V, 5V, 10V and 12V.

After all data has been recorded the values are read into the MATLAB post-processing script where the values for mass flow rate and total uncertainty are calculated.

To visualize that the uncertainty is allocated properly, and the proper tools were selected to perform the experiment to within the goal of 15% uncertainty in mass flowrate, a design space plot was created. The design space plot for the experiment is in Figure 11. Using the main DRE found in Equation 8, the x-axis and y-axis were separated into variables that could be controlled on the x-axis, and variables that could not be controlled on the y-axis. These broken-down equations are shown by Equation 20 and Equation 21 respectively. Using these equations for the axis results in the slope of a line on the plot is equal to the mass flowrate.

$$X_{axis} = \frac{n}{(x)(y)} \tag{20}$$

$$Y_{axis} = \frac{P_{atm} \sum_{i=1}^{n} V_i}{R\, T_{atm}} \tag{21}$$

Assuming the use of 36 points of measurements, the red vertical line is created by taking n, the number of measurement points, divided by the overall test area of 5.664 inches by 5.664 inches. The red vertical line will intercept the sloped blue lines which are an estimate of the low and high mass flow rate of the fan. These values were calculated by multiplying the lowest and highest average volumetric flow rates, given by the specification sheet of the fan, by the density of air. Density of air is estimated using a temperature of 72 °F and a pressure of 992.4 hPa, which was recorded in the proposed lab space. The minimum expected mass flow rate is 0.0940 slugs/min and the maximum expected mass flow rate is 0.2305 slugs/min

To prove that the intersection points are reasonable, and the experiment can be performed, lower and upper bounds for the y-axis need to be implemented. Using Equation 21, the equations to find the minimum and maximum allowable y-values are found in Equation 22 and 23 respectively.

$$Y_{axis,min} = \frac{P_{atm,min} V_{sum,min}}{R\ T_{atm,max}} \tag{22}$$

$$Y_{axis,max} = \frac{P_{atm,max} V_{sum,max}}{R\ T_{atm,min}} \tag{23}$$

The summation of velocity can be estimated by using Equation 24. Using this estimation, Equations 22 and 23 can be simplified so only one value for velocity is needed to calculate the lower bound and another to calculate the upper bound.

$$\sum_{i=1}^{n} V_i \approx (V_{avg})(n) \tag{24}$$

The larger allowed average low velocity was calculated to be 38.5 fpm in the mixed velocity condition. This value will be used to calculate the lower y-axis bound because it is higher than the other calculated value of 27.4 fpm. If the experiment can work with 38.5 fpm, then it will work for the lower average velocity. An estimated value for the y-axis lower bound can be found with Equation 25.

$$Y_{axis,min} = \frac{P_{atm,min}(V_{avg,min} n)}{R\ T_{atm,max}} = 3.0777 \frac{slug}{ft^2\ min} \tag{25}$$

The upper y-axis bound is governed by an average velocity is 2953 fpm, which is the maximum velocity the sensor can measure. The fan is not expected to reach this speed, but it is set as the practical maximum for the experiment due to the sensor. The y-axis upper bound can be estimated using Equation 26 below.

$$Y_{axis,max} = \frac{P_{atm,max}(V_{avg,max} n)}{R\ T_{atm,min}} = 252.2735 \frac{slug}{ft^2\ min} \tag{26}$$

These horizontal bounds are represented on Figure 11 by black lines, with the minimum being a solid black line and the maximum being a dashed black line. The upper y-axis bound is outside of the view of the plot and does not play a roll in analyzing if the experiment if possible since it is so high up.

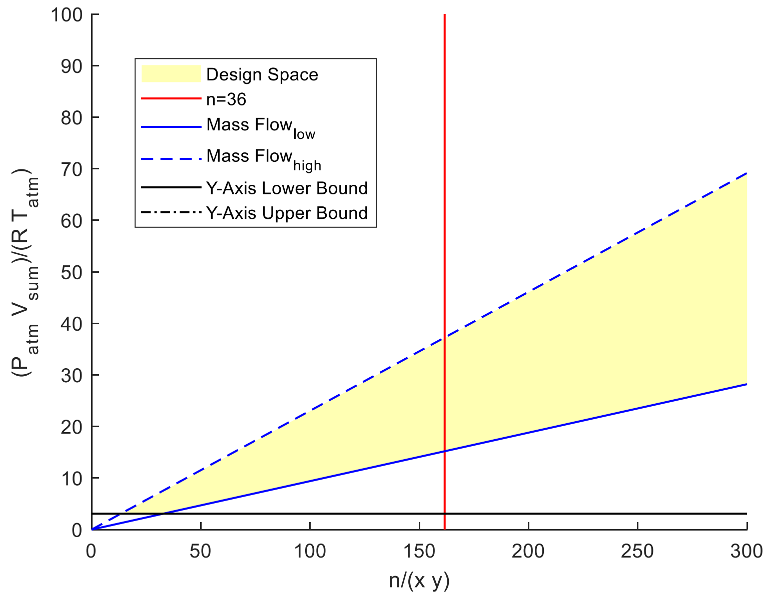

Figure 11: Mass flowrate design space plot with inverse equal area on the x-axis and density of air multiplied by the sum of velocity on the y-axis.

It is easy to see that the intersections of the red vertical line with the sloped blue lines are within the black horizontal lines, proving that the experiment is possible and a goal of 15% uncertainty in mass flowrate is attainable under these assumptions.

Data and Analysis

Using the procedure outlined in the Apparatus, Procedure, and Design Space Plot section of the report, data for individual trials were collected. Representative data for the first trial of the 5V testing is shown below as the post processing procedure is outlined. The representative values for the voltage (V_{elec}), atmospheric pressure (P_{atm}) and temperature (T_{atm}), overall width of the flow grid (x), and overall height of the flow grid (y) are shown in Table 5.

Table 5: Representative Environment Values for 5.258V Trial

Parameter	Representative Value	Units
Voltage	5.258	V
Atmospheric Temperature	534.3	°R
Atmospheric Pressure	2103.8	psf
Width	0.471	ft
Height	0.470	ft

Representative values for velocity as the different flow grid measurement locations are represented in Figure 12 which is a 3D plot of the flow field. To get a velocity for one point, ten velocities were taken at a single location and an average was taken to represent the velocity for that location. Standard deviation of the ten velocity values was also calculated for the purpose of uncertainty calculations for velocity. This process was repeated for all 36 data collection points.

Calibration of the Testo hotwire anemometer was required and a correction factor of 1.046 was found and used to correct the values of velocities by multiplying the average velocity and the standard deviation by the correction factor. Information on how the correction factor was calculated can be found in Appendix D. The adjusted velocity values are the velocity values present in Figure 12, to see the unprocessed data tables please see Appendix E.

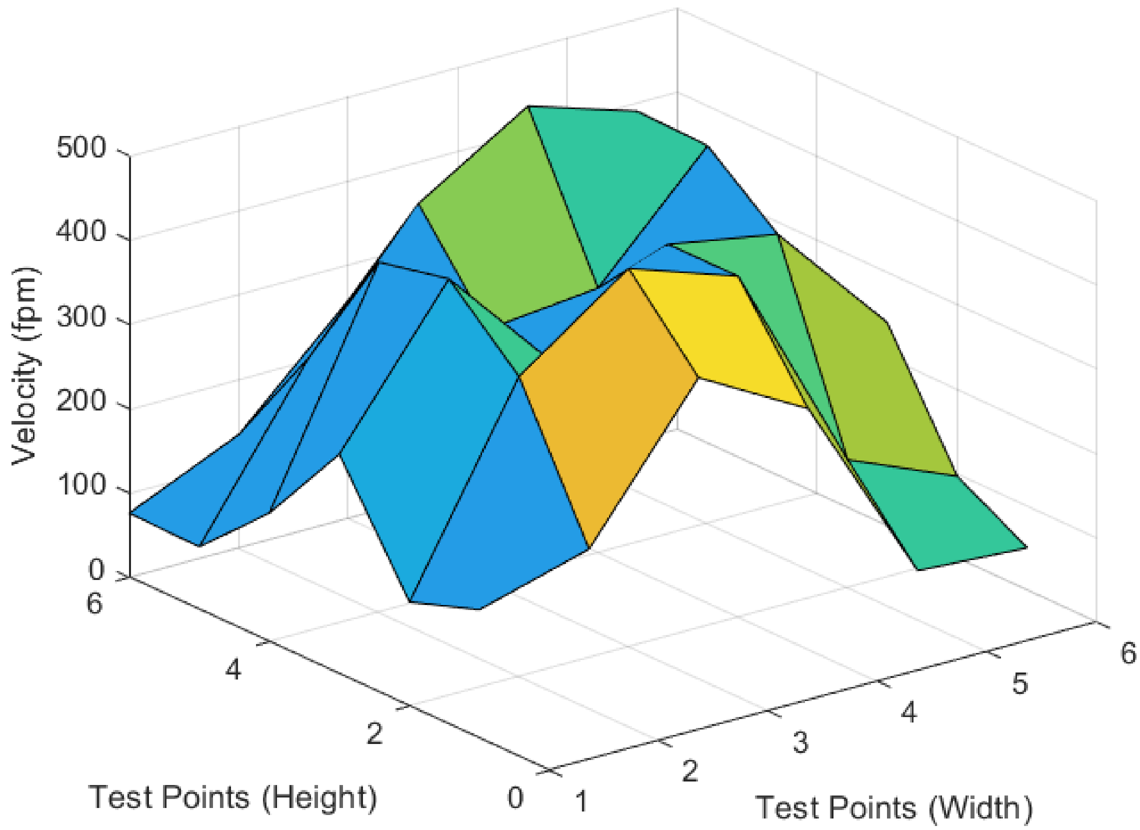

Figure 12: Representation of corrected velocity measurements for 5.258V Trial at all 36 measurement points

Using the DRE equation from Equation 8 the mass flow rate for this trial was calculated to be 0.134 slugs/min. The error for the individual mass flow trial is composed of the systematic errors of the measurands and the uncertainty due to the integration error. The equations for calculating systematic error are outlined in Appendix A and the process of how to calculate the integration error is outlined in Appendix C.

Table 6 is an Uncertainty Table for one complete 5V trial, specifically the 5.258V trial, of the experiment to determine the mass flow rate of an axial fan. The first two rows represent the environmental data, Atmospheric Pressure (P_{atm}) and Temperature (T_{atm}) used to calculate the density of air. The third and fourth rows are the width (x) and height (y) of the flow grid respectively. The remaining rows in the table are the corrected velocity measurement in each sub grid, uncertainty due to integration, and the resulting mass flow rate for the trial. Values in the columns from **Error! Not a valid bookmark self-reference.** were calculated using the uncertainty equations discussed in the Modeling section of the report. The resultant mass flow rate for this 5-volt trial was calculated using Equation 8. For more details on the equations used to calculate the systematic uncertainties for all parameters and the UMF terms for velocity refer to Appendix A.

Table 6: Uncertainty Table for 5.258V Trial for the 5V setting group

Parameter	Representative Value	Syst. Uncertainty	Units	Relative Uncertainty (%)	UMF	RSSC (%)	UPC (%)
Atmospheric Temperature	534.3	1.801	R	0.337	1.000	0.337	0.506
Atmospheric Pressure	2103.8	3.135	psf	0.149	1.000	0.149	0.099
Width	0.471	9.317E-05	ft	0.020	1.000	0.020	0.002
Height	0.470	9.317E-05	ft	0.020	1.000	0.020	0.002
Velocity 1	153	48.056	fpm	31.487	0.016	0.508	1.150
Velocity 2	189	50.136	fpm	26.481	0.020	0.530	1.251
Velocity 3	357	59.490	fpm	16.648	0.038	0.629	1.762
Velocity 4	286	53.843	fpm	18.855	0.030	0.569	1.443
Velocity 5	58	23.481	fpm	40.283	0.006	0.248	0.274
Velocity 6	50	22.853	fpm	45.516	0.005	0.242	0.260
Velocity 7	124	91.329	fpm	73.937	0.013	0.965	4.152
Velocity 8	356	67.933	fpm	19.097	0.038	0.718	2.297
Velocity 9	449	85.423	fpm	19.032	0.047	0.903	3.632
Velocity 10	404	104.900	fpm	25.944	0.043	1.109	5.478
Velocity 11	152	51.616	fpm	34.053	0.016	0.546	1.326
Velocity 12	97	38.175	fpm	39.359	0.010	0.404	0.725
Velocity 13	261	91.552	fpm	35.125	0.028	0.968	4.172
Velocity 14	433	105.653	fpm	24.382	0.046	1.117	5.557
Velocity 15	294	51.250	fpm	17.448	0.031	0.542	1.308
Velocity 16	404	90.213	fpm	22.323	0.043	0.954	4.051
Velocity 17	381	83.306	fpm	21.874	0.040	0.881	3.455
Velocity 18	241	85.880	fpm	35.613	0.025	0.908	3.671
Velocity 19	153	64.462	fpm	42.237	0.016	0.681	2.069
Velocity 20	415	90.830	fpm	21.883	0.044	0.960	4.107
Velocity 21	301	65.291	fpm	21.715	0.032	0.690	2.122
Velocity 22	314	73.633	fpm	23.458	0.033	0.778	2.699
Velocity 23	448	140.854	fpm	31.469	0.047	1.489	9.876
Velocity 24	232	86.892	fpm	37.389	0.025	0.918	3.759
Velocity 25	74	27.391	fpm	36.788	0.008	0.290	0.373
Velocity 26	264	74.163	fpm	28.135	0.028	0.784	2.738
Velocity 27	411	91.859	fpm	22.346	0.043	0.971	4.200
Velocity 28	492	84.518	fpm	17.192	0.052	0.893	3.556
Velocity 29	450	95.655	fpm	21.245	0.048	1.011	4.555
Velocity 30	194	61.092	fpm	31.462	0.021	0.646	1.858
Velocity 31	76	28.515	fpm	37.391	0.008	0.301	0.405
Velocity 32	134	68.641	fpm	51.122	0.014	0.726	2.345
Velocity 33	258	55.131	fpm	21.347	0.027	0.583	1.513
Velocity 34	214	77.615	fpm	36.293	0.023	0.820	2.999
Velocity 35	168	64.263	fpm	38.203	0.018	0.679	2.056
Velocity 36	174	63.624	fpm	36.542	0.018	0.673	2.015
Integration	-	2.699E-04	slugs/min	0.202	1.000	0.202	0.182
Mass Flowrate	0.134	0.006	slugs/min	-	-	4.738	100

This process is repeated two more times to calculate an average mass flow rate for a specified setting of the axial fan. The equation to find the average mass flow rate and the uncertainty are presented below in Equation 27 and Equation 28 respectively.

$$\dot{m}_{avg} = \frac{1}{n}\sum_{i=1}^{n} \dot{m}_i \tag{27}$$

$$w_{\dot{m}_{avg}}^2 = \left(\frac{\dot{m}_1}{\sum_{i=1}^{n} \dot{m}_i}\right)^2 \left(w_{\dot{m}_1}\right)^2 + \left(\frac{\dot{m}_2}{\sum_{i=1}^{n} \dot{m}_i}\right)^2 \left(w_{\dot{m}_2}\right)^2 + \left(\frac{\dot{m}_3}{\sum_{i=1}^{n} \dot{m}_i}\right)^2 \left(w_{\dot{m}_3}\right)^2 + w_{rand}^2 \tag{28}$$

The random uncertainty is calculated using Equation 29 below.

$$w_{rand} = \frac{(t)(S_{\dot{m}})}{\sqrt{n}} \tag{29}$$

Where n is the number of trials being averaged, $S_{\dot{m}}$ is the standard deviation of the different trials, and t is a value selected from the T-Statistic Table with 95% confidence. For the purposes of this experiment, the t value will be 4.303 since there were only three trials performed for each voltage group, which allows for two degrees of freedom.

A sample Uncertainty Table for the 5V group of measurements is shown in Table 7. Random uncertainty contributed the most to the uncertainty of the average- making up over 50% of the overall uncertainty.

Table 7: Uncertainty Table for the 5V group of mass flow measurements resulting in an average of 0.129 slugs/min for 5V setting

Parameter	Representative Value	Syst. Uncertainty	Units	Relative Uncertainty (%)	UMF	RSSC (%)	UPC (%)
Mass Flow 1	0.134	0.006	slugs/min	4.738	0.346	1.637	19.287
Mass Flow 2	0.125	0.005	slugs/min	4.004	0.325	1.300	12.157
Mass Flow 3	0.127	0.006	slugs/min	4.513	0.330	1.489	15.952
Random	-	0.010	slugs/min	2.703	1.000	2.703	52.603
Avg. Mass Flowrate	0.129	0.005	slugs/min	-	-	3.727	100

The process of collecting and processing the data and uncertainty was repeated for the 3V, 10V, and 12V groups, and the mass flow data can be found in Appendix F. Figure 13 shows all the data collected from the different trials on a mass flow rate versus voltage graph.

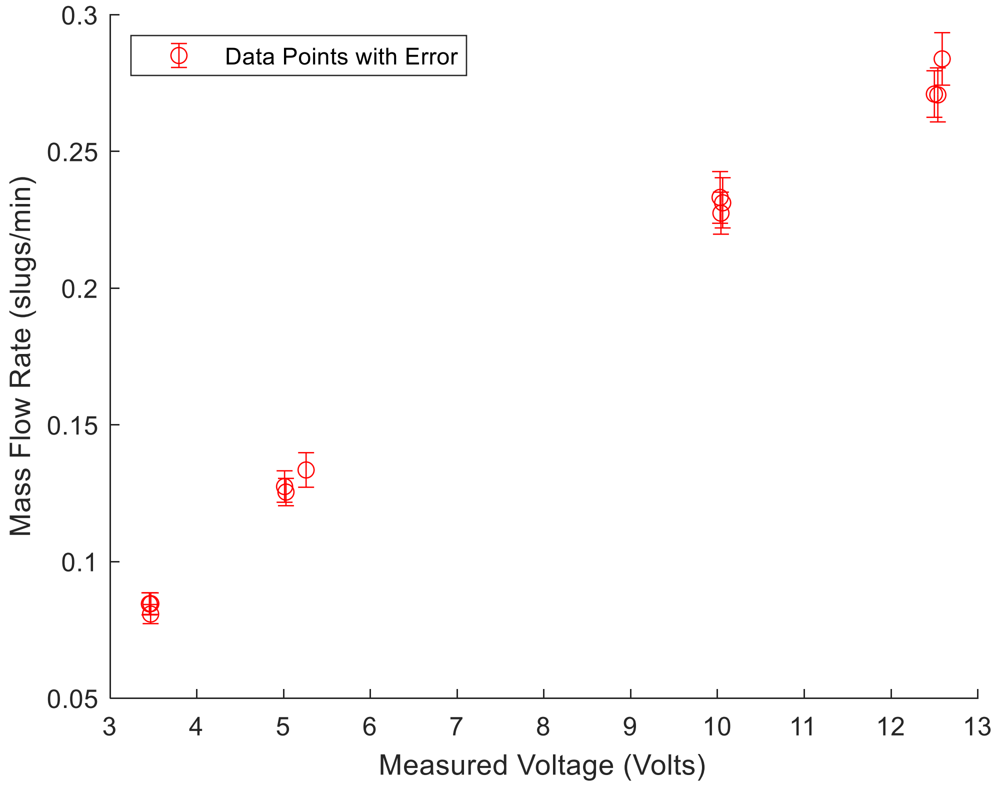

Figure 13: Plot of calculated mass flow rate against measured voltage

The data shows a relatively linear trend, so linear regression will be used to analyze the relationship between mass flow rate of the fan and the voltage input to the fan. A linear regression can be made using the least squares method with matrices and vectors as shown in Equation 30.

$$[A]\{\vec{x}\} = \{\vec{b}\} \tag{30}$$

Where $[A]$ is the coefficient matrix made of regressors, $\{\vec{x}\}$ is the parameter vector, and $\{\vec{b}\}$ is the regressand vector filled with the values the linear fit is being made for. To get an estimate for the slope and intercept of a sloped line the normal equation is used as shown in Equation 31.

$$\{\vec{x}\} = ([A]^T[A])^{-1}\left([A]^T\{\vec{b}\}\right) \tag{31}$$

The linear regression will still have some uncertainty associated with the slope and intercept values it produces. Uncertainty for the slope of the linear regression is calculated using Equation 32.

$$w_m^2 = \frac{\sum(y_i - \bar{y})^2}{\left(\sum(x_i - \bar{x})^2\right)^2} w_x^2 + \frac{1}{\sum(x_i - \bar{x})^2} w_y^2 \tag{32}$$

Where $\bar{x}$ and $\bar{y}$ are the averages of the data values for the horizontal axis (voltage) and vertical axis (mass flow rate) respectively, w_x is the average systematic uncertainty for the horizontal axis variable (voltage), and w_y is characterized by Equation 33 below.

$$w_y^2 = w_{y,sys}^2 + \left(2\left(\frac{\sum(y_i - (mx_i + b)^2)}{n-2}\right)^{\frac{1}{2}}\right)^2 \tag{33}$$

Where n is the number of data points, and $w_{y,sys}$ is the average systematic uncertainty for the vertical axis variable.

All the post processing mentioned in this section is completed by the MATLAB script shown in Appendix G for reference.

Results and Discussion

The overall results of the experiment are shown in Table 8 with the average mass flow rate for the 3V, 5V, 10V, and 12V averaged voltage settings. All calculated mass flows have a relative uncertainty below 4% which is well below the target of 15%. While the fan specifies 3V as the minimum voltage, the fan drew 3.45V at the minimum setting. The same behavior was found at the opposite end with the fan drawing a maximum of 12.54V for the 12V expected setting.

Table 8: Average mass flowrates for average voltages of the different trial groups

Average Voltage of Trials (V)	Average Mass Flow Rate (slugs/min)	Uncertainty (slugs/min)	Relative Uncertainty (%)
3.462	0.083	0.003	3.424%
5.098	0.129	0.005	3.727%
10.04	0.231	0.006	2.443%
12.54	0.275	0.008	2.991%

All the different mass flow rate trials with their associated voltage setting and uncertainty are shown in Table 9. These are the values that will be used to make a proper linear regression of the data and show the relationship between mass flow rate and voltage. The regression of the experimental data is directly compared to the regression of expected operating volumetric flow rate of the fan. Using the average density of air from all the experimental trials (0.0022855 slug/ft^3), the volumetric flow is converted to a mass flow rate. This conversion is recorded in Table 10.

Table 9: All calculated mass flow rates with corresponding voltage and uncertainty

Measured Voltage (V)	Uncertainty in Voltage (V)	Calculated Mass Flow Rate (slug/min)	Uncertainty in Mass Flow Rate (slug/min)
3.452	0.019	0.085	0.004
3.466	0.019	0.081	0.003
3.468	0.019	0.085	0.004
5.258	0.028	0.134	0.006
5.026	0.027	0.125	0.005
5.010	0.027	0.127	0.006
10.03	0.07	0.233	0.009
10.04	0.07	0.227	0.008
10.06	0.07	0.231	0.009
12.54	0.08	0.271	0.010
12.59	0.08	0.284	0.010
12.5	0.08	0.271	0.009

Table 10: Expected volumetric flow rates for different voltage settings for the Wathai axial fan

Voltage (V)	Expected Volumetric Flow Rate (CFM)	Converted Mass Flow Rate (slugs/min)	10% Uncertainty (slugs/min)
3	46.0	0.105	0.011
5	56.8	0.130	0.013
10	85.0	0.194	0.019
12	92.3	0.211	0.021

The experimental data and expected data are plotted on a mass flow rate versus measured voltage graph as depicted in Figure 14. The vertical error bars for the experimental data are the uncertainty of the mass flow rate for that individual trial, for reference those uncertainty values are in Table 9. The vertical error bars for the expected data are a 10% uncertainty calculated from the converted mass flow value since the fan reports a 10% uncertainty for the volumetric flow rate.

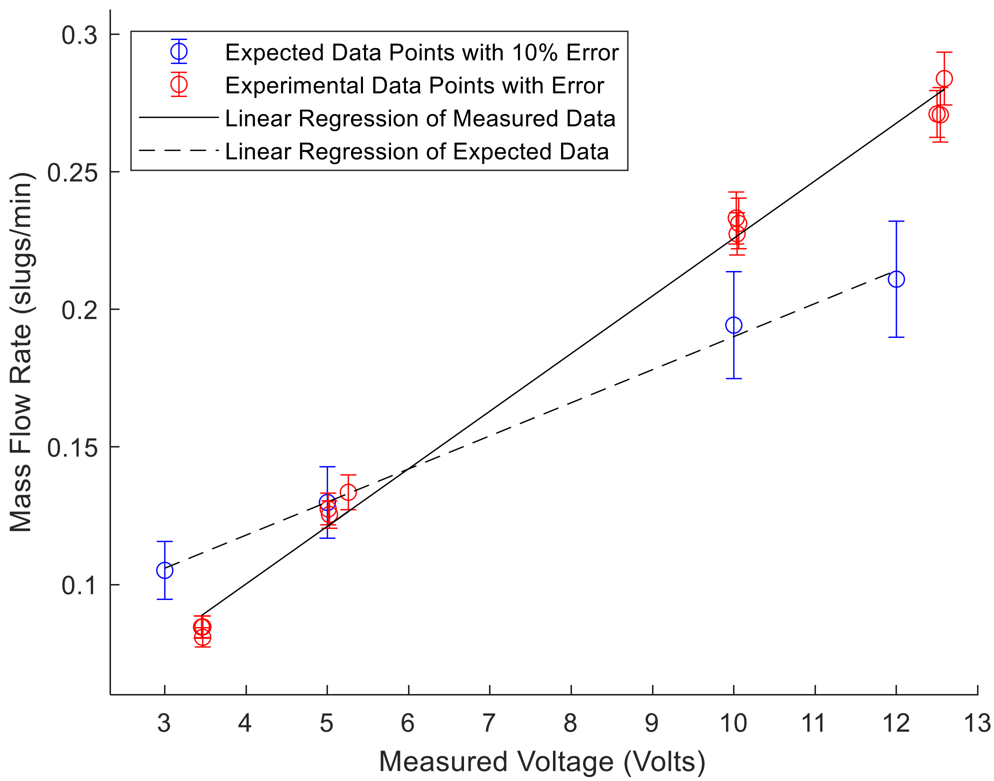

Figure 14: Comparison of linear regression of experimental data and expected data for the mass flow rate of Wathai axial fan at different voltage settings

The experimental data shows that the fan was underperforming compared to expected values in the 3V region and over performing compared to expected values in the 12V region. The linear regression for the experimental data is characterized by Equation 34 and the linear regression for the expected data is characterized by Equation 35.

$$\dot{m}_{experiment} = 0.0209 \pm 0.0012 \frac{slugs}{(\text{min})(Volts)} (V_{elec}) + 0.0164 \frac{slugs}{min} \quad (34)$$

$$\dot{m}_{expected} = 0.0120 \frac{slugs}{(\text{min})(Volts)} (V_{elec}) + 0.0699 \frac{slugs}{min} \quad (35)$$

To draw conclusions from this comparison an additional table was made to compare the expected and experimental data gathered. The results of this are shown in Table 11. The calculated mass flow rate was converted to volumetric flow rate by dividing the mass flow rate for a specific trial by the density of air calculated for that trial. The 5V trials had the smallest percent error and percent difference values of 1.36% and 1.37% respectively. The 12V trials had the largest percent error and percent difference at 35.91% and 30.44% respectively. The values calculated for the 3V and 10V trials and percent errors and percent differences ranging from the upper teens to the mid-twenties.

Table 11: Percent error and percent difference Calculations to compare the expected and experimental data

Measured Voltage (V)	Calculated Mass Flow Rate (slugs/min)	Calculated Volumetric Flow Rate (CFM)	Expected Voltage (V)	Expected Volumetric Flow Rate (CFM)	Percent Error (%)	Percent Difference (%)
3.452	0.085	36.7	3	46	20.12	22.37
3.466	0.081	35.6	3	46	22.52	25.38
3.468	0.085	37.0	3	46	19.63	21.77
5.258	0.134	58.2	5	56.8	2.49	2.46
5.026	0.125	54.9	5	56.8	3.42	3.48
5.01	0.127	56.0	5	56.8	1.36	1.37
10.03	0.233	101.2	10	85	19.03	17.38
10.04	0.227	99.6	10	85	17.21	15.85
10.06	0.231	101.7	10	85	19.61	17.86
12.54	0.271	117.5	12	92.3	27.34	24.05
12.59	0.284	125.4	12	92.3	35.91	30.44
12.5	0.271	118.5	12	92.3	28.37	24.85

Conclusion

In this paper, the mass flow rate through an electronic axial computer fan was studied through the development of an experiment. The mass flow rate of the fan was experimentally determined at the 3V, 5V, 10V, and 12V levels with average mass flow rates of 0.083, 0.1129, 0.231, and 0.275 $\frac{slug}{min}$ respectively. The target uncertainty for the experiment was ±15%. This target was met for each voltage level with uncertainties of 3.425, 3.725, 2.442, and 2.992 percent respectively.

The experiment successfully met the uncertainty target because of the choice of sensors, the number of points sampled during each trial, and the number of trials taken. The grid used in this experiment included 36 points which reduced the integration error substantially and accounted for more variation in the velocity flow field.

The percent difference from the manufacturer's published values cannot be overlooked as some trials had larger deviations. For the 3V, 5V, 10V, and 12V trials the averaged percent difference to the manufacturer-published flow rates were 23.17, 2.44, 17.03, and 26.45 percent. Although some of these percent differences are large, the team is confident in the results and the uncertainty. In the future, further experiments should analyze the power and RPM of the fan to confirm the credibility of the manufacturer spec sheet, as those are the other reported values at each voltage level. Determining the credibility of the manufacturer's specifications will confirm or dispute the accuracy of the fan profile the team generated.

While developing the experiment, the team learned that quick testing while designing an experiment is essential. Sometimes to test a theory simple cardboard and handheld pitot tubes will more than suffice. Spending hours designing a 3D-printed duct or large-scale test rig to test if an assumption is valid is not necessary. The time instead should be spent on refining the main apparatus, where every improvement will be seen in the data, and benefit the accuracy of the experiment.

References

[1] Amazon, Wathai, 20 July 2019. [Online]. Available: https://www.amazon.com/Wathai-Controller-Receiver-Playstation-Component/dp/B07VYGQPCZ?ref_=ast_sto_dp&th=1. [Accessed 5 September 2022].

[2] R. Bryant, O. Sanni, E. Moore, M. Bundy and A. Johnson, "Taylor & Francis Online," 20 May 2014. [Online]. Available: https://www.tandfonline.com/doi/full/10.1080/10962247.2014.881437. [Accessed 20 September 2022].

[3] E. L. M. PE, "Equal Area vs. Log-Tchebycheff," *HPAC Engineering,* pp. 26-31, 1999.

[4] S. Denki, "Training, Fan Basics," [Online]. Available: https://techcompass.sanyodenki.com/en/training/cooling/fan_basic/001/index.html . [Accessed 5 September 2022].

[5] M. Burke, "Analog Dialogue," February 2004. [Online]. Available: https://www.analog.com/en/analog-dialogue/articles/how-to-control-fan-speed.html. [Accessed 8 September 2022].

[6] Cooler Master, [Online]. Available: https://www.coolermaster.com/catalog/coolers/case-fan/silent-fan-120-si1/.

[7] Accutron, "FlowTrax Ultrasonic airflow monitor," [Online]. Available: https://accutroninstruments.com/flowtrax-ultrasonic-airflow-monitor/. [Accessed 11 September 2022].

[8] R. Cressall, R. Schaap, D. R. Neal, A. Mychkovsky, J. Charonko and B. L. Smith, "Accuracy of volumetric flow rate inflow/outflow measurement by integrating PIV velocity fields," 23 September 2020. [Online]. Available: https://iopscience.iop.org/article/10.1088/1361-6501/ab9bb7. [Accessed 8 September 2022].

[9] G. J. Matthews, "How to Determine Air Flow," Airflow Developments Limited.

[10] Airflow Developments Limited, "Airflow Grids," [Online]. Available: http://www.techmark.co.in/pfma/brochures/airflow_grids.pdf. [Accessed 8 September 2020].

[11] M. Arlit, E. Schleicher and U. Hampel, "Thermal Anemometry Grid Sensor," 19 July 2017. [Online]. Available: https://www.mdpi.com/1424-8220/17/7/1663/htm. [Accessed 8 September 2022].

[12] M. R. Ahemad and C. Zhou, "Estimation of volumetric flow rate through a circular duct: Equal area versus Log-Tchebycheff," University of Windsor, Windsor, Ontario, Canada, 2005.

[13] F. Yao, S. Li, Z. Sun, T. Zhou and Z. Dong, "Diameter bisection: An effective traverse method in Pitot tube based flow measurement," in *2016 35th Chinese Control Conference (CCC)*, Chengdu, 2016.

[14] Testo, "Testo 420 flow hood," [Online]. Available: https://static-int.testo.com/media/54/96/f0a8e975911f/Testo-420-Flow-Hood-Data-Sheet-US.pdf. [Accessed 8 September 2022].

[15] Omega, "Air Flow Measurement Instruments: How Precise and Accurate?," [Online]. Available: https://www.omega.co.uk/technical-learning/how-precise-and-accurate-are-air-flow-measurement-instruments.html. [Accessed 8 September 2022].

[16] Dwyer Instruments, "Duct Traversing for Average Air Velocity and Air Volume," 18 October 2017. [Online]. Available: http://blog.dwyer-inst.com/2017/10/18/duct-traversing-for-average-air-velocity-and-air-volume/#sthash.8cx0KtTb.dpbs. [Accessed 17 September 2022].

Appendices

The following section is reserved for additional information the project team deemed useful for understanding the experiment conducted.

Appendix A: Simplifications of the uncertainty equation

The a general equation for the systematic uncertainty for some parameter (k) is a combination of the accuracy and readability of each parameter are show Equation A1.

$$w_{k,sys}^2 = w_{k,acc}^2 + w_{k,read}^2 \quad \text{(A1)}$$

where the accuracy, $w_{k,acc}$, and readability, $w_{k,read}$ of the parameter are defined in Equations A2 and Equation A3.

$$w_{k,acc} = \sqrt{linearity^2 + hysteresis^2 + repeatability^2} \text{ (or is given from spec sheet)} \quad \text{(A2)}$$

$$w_{k,read} = 1/2 \text{ the resolution (last digit shown in the parameter readout)} \quad \text{(A3)}$$

Dividing both sides of Equation 9 by $\dot{m}^2$, gives the following shown in Equation A4.

$$\left(\frac{w_{\dot{m}}}{\dot{m}}\right)^2 = \left(\frac{\left(\frac{\partial \dot{m}}{\partial P_{atm}}\right)}{\dot{m}}\right)^2 w_{Patm,sys}^2 + \left(\frac{\left(\frac{\partial \dot{m}}{\partial T_{atm}}\right)}{\dot{m}}\right)^2 w_{Tatm,sys}^2 + \left(\frac{\left(\frac{\partial \dot{m}}{\partial V_1}\right)}{\dot{m}}\right)^2 w_{V_1,sys}^2 + \cdots + \left(\frac{\left(\frac{\partial \dot{m}}{\partial V_n}\right)}{\dot{m}}\right)^2 w_{V_n,sys}^2 + \left(\frac{\left(\frac{\partial \dot{m}}{\partial x}\right)}{\dot{m}}\right)^2 w_{x,sys}^2 + \left(\frac{\left(\frac{\partial \dot{m}}{\partial y}\right)}{\dot{m}}\right)^2 w_{y,sys}^2 + \left(\frac{w_{integration}}{\dot{m}}\right)^2 + \left(\frac{w_{\dot{m}_{rand}}}{\dot{m}}\right)^2 \quad \text{(A4)}$$

This can be expanded by substituting in the defined equation of $\dot{m}$, resulting in the following equation shown by Equation A5.

$$\left(\frac{w_{\dot{m}}}{\dot{m}}\right)^2 = \left(\frac{\left(\frac{\partial \dot{m}}{\partial P_{atm}}\right)}{\frac{P_{atm}}{RT_{atm}} xy \frac{1}{n}\sum_{i=1}^{n} V_i}\right)^2 w_{Patm,sys}^2 + \left(\frac{\left(\frac{\partial \dot{m}}{\partial T_{atm}}\right)}{\frac{P_{atm}}{RT\_atm} xy \frac{1}{n}\sum_{i=1}^{n} V_i}\right)^2 w_{Tatm,sys}^2$$
$$+ \left(\frac{\left(\frac{\partial \dot{m}}{\partial V_1}\right)}{\frac{P_{atm}}{RT_{atm}} xy \frac{1}{n}\sum_{i=1}^{n} V_i}\right)^2 w_{V_1,sys}^2 + \cdots$$
$$+ \left(\frac{\left(\frac{\partial \dot{m}}{\partial V_n}\right)}{\frac{P_{atm}}{RT_{atm}} xy \frac{1}{n}\sum_{i=1}^{n} V_i}\right)^2 w_{V_n,sys}^2 + \left(\frac{\left(\frac{\partial \dot{m}}{\partial x}\right)}{\frac{P_{atm}}{RT_{atm}} xy \frac{1}{n}\sum_{i=1}^{n} V_i}\right)^2 w_{x,sys}^2$$
$$+ \left(\frac{\left(\frac{\partial \dot{m}}{\partial y}\right)}{\frac{P_{atm}}{RT_{atm}} xy \frac{1}{n}\sum_{i=1}^{n} V_i}\right)^2 w_{y,sys}^2 + \left(\frac{w_{integration}}{\dot{m}}\right)^2 + \left(\frac{w_{\dot{m}_{rand}}}{\dot{m}}\right)^2 \quad \text{(A5)}$$

Now there are a lot of terms and variables here. To make cancelling out terms easier, the partial derivatives are evaluated below in Equation A6 through Equation A10.

$$\frac{\partial \dot{m}}{\partial P_{atm}} = \frac{xy\sum_{i=1}^{n} V_i}{nRT_{atm}} \quad \text{(A6)}$$
$$\frac{\partial \dot{m}}{\partial T_{atm}} = -\frac{P_{atm} xy\sum_{i=1}^{n} V_i}{nRT_{atm}^2} \quad \text{(A7)}$$
$$\frac{\partial \dot{m}}{\partial V_i} = \frac{P_{atm} xy}{nRT_{atm}} \quad \text{(A8)}$$
$$\frac{\partial \dot{m}}{\partial x} = \frac{P_{atm} y\sum_{i=1}^{n} V_i}{nRT_{atm}} \quad \text{(A9)}$$
$$\frac{\partial \dot{m}}{\partial y} = \frac{P_{atm} x\sum_{i=1}^{n} V_i}{nRT_{atm}} \quad \text{(A10)}$$

To put the equation into uncertainty magnification form, the uncertainty magnification factors (UMF) are needed. The UMF’s for each variable are the coefficient multiplied by each variable shown below in Equation A11 through Equation A15.

$$UMF_{P_{atm}} = \frac{\frac{\partial \dot{m}}{\partial P_{atm}}}{\dot{m}} = \frac{\frac{xy\sum_{i=1}^{n} V_i}{nRT_{atm}}}{\frac{P_{atm}}{RT_{atm}} xy \frac{1}{n}\sum_{i=1}^{n} V_i} = 1 * \frac{1}{P_{atm}} \quad \text{(A11)}$$
$$UMF_T = \frac{\frac{\partial \dot{m}}{\partial T_{atm}}}{\dot{m}} = \frac{-\frac{P_{atm} xy\sum_{i=1}^{n} V_i}{nRT_{atm}^2}}{\frac{P_{atm}}{RT_{atm}} xy \frac{1}{n}\sum_{i=1}^{n} V_i} = -1 * \frac{1}{T_{atm}} \quad \text{(A12)}$$

$$UMF_{V_i} = \frac{\frac{\partial \dot{m}}{\partial V_i}}{\dot{m}} = \frac{\frac{P_{atm}xy}{nRT_{atm}}}{\frac{P_{atm}}{RT_{atm}} xy \frac{1}{n} \sum_{i=1}^{n} V_i} = 1 * \frac{1}{\sum_{i=1}^{n} V_i} \tag{A13}$$

$$UMF_x = \frac{\frac{\partial \dot{m}}{\partial x}}{\dot{m}} = \frac{\frac{P_{atm}\Delta y \sum_{i=1}^{36} V_i}{nRT_{atm}}}{\frac{P_{atm}}{RT_{atm}} xy \frac{1}{n} \sum_{i=1}^{n} V_i} = 1 * \frac{1}{x} \tag{A14}$$

$$UMF_y = \frac{\frac{\partial \dot{m}}{\partial y}}{\dot{m}} = \frac{\frac{P_{atm}x \sum_{i=1}^{n} V_i}{nRT_{atm}}}{\frac{P_{atm}}{RT_{atm}} xy \frac{1}{n} \sum_{i=1}^{n} V_i} = 1 * \frac{1}{y} \tag{A15}$$

Rewriting the Equation A4 again in simplified terms can be shown in Equation A16

$$\left(\frac{w_{\dot{m}}}{\dot{m}}\right)^2 = \left(UMF_{P_{atm}}\right)^2 w_{Patm,sys}^2 + \left(UMF_{T_{atm}}\right)^2 w_{Tatm,sys}^2 + \left(UMF_{V_1}\right)^2 w_{V_1,sys}^2 + \cdots + \left(UMF_{V_n}\right)^2 w_{V_n,sys}^2 + (UMF_x)^2 w_{x,sys}^2 + \left(UMF_y\right)^2 w_{y,sys}^2 + (1)^2 \left(\frac{w_{integration}}{\dot{m}}\right)^2 + (1)^2 \left(\frac{w_{\dot{m}_{rand}}}{\dot{m}}\right)^2 \tag{A16}$$

Using the defined UMF's above, the uncertainty equation can be written in terms of relative uncertainties as shown below in Equation A17.

$$\left(\frac{w_{\dot{m}}}{\dot{m}}\right)^2 = (1)^2 \left(\frac{w_{P_{atm},sys}}{P_{atm}}\right)^2 + (-1)^2 \left(\frac{w_{T,sys}}{T_{atm}}\right)^2 + \left(\frac{1}{\sum_{i=1}^{n} V_i}\right)^2 w_{V_1,sys}^2 + \cdots + \left(\frac{1}{\sum_{i=1}^{n} V_i}\right)^2 w_{V_n,sys}^2 + (1)^2 \left(\frac{w_{x,sys}}{x}\right)^2 + (1)^2 \left(\frac{w_{y,sys}}{y}\right)^2 + (1)^2 \left(\frac{w_{integration}}{\dot{m}}\right)^2 + (1)^2 \left(\frac{w_{\dot{m}_{rand}}}{\dot{m}}\right)^2 \tag{A17}$$

To get the velocity terms to be in terms of relative uncertainty like the other terms, the velocity portions can be multiplied by "1" as shown below in Equation A18

$$\left(\frac{w_{\dot{m}}}{\dot{m}}\right)^2 = \cdots + \left(\frac{1}{\sum_{i=1}^{n} V_i}\right)^2 (w_{V_1,sys}^2) \left(\frac{V_1}{V_1}\right)^2 + \cdots \tag{A18}$$

Repeating this for each velocity term and rewriting gives a string of velocity terms following the same pattern as depicted in Equation A19

$$\left(\frac{w_{\dot{m}}}{\dot{m}}\right)^2 = \cdots + \left(\frac{V_1^2}{(\sum_{i=1}^{n} V_i)^2}\right) \left(\frac{w_{V_1,sys}}{V_1}\right)^2 + \cdots + \left(\frac{V_n^2}{(\sum_{i=1}^{n} V_i)^2}\right) \left(\frac{w_{V_n,sys}}{V_n}\right)^2 + \cdots \tag{A19}$$

The last step is to combine it all together to get the final uncertainty equation in UMF form, resulting in Equation 10 in the Modeling section of the report.

Appendix B: Testing and Refinement

To verify that this experiment can be completed within the goals set, a shakedown was conducted. In this shakedown, a single voltage was selected and at this voltage the velocities were measured at each point within the grid. The ambient pressure and temperature as well as height and width of the grid were also measured just prior to collecting the velocity measurements.

Data collection

The process of collecting data was the same as that discussed within the Apparatus, Procedure, and Design space plots section. The fan was propped up and set a specified distance away from the grid. Then, the voltage was set to 5V and the measurands were recorded. The measurands for atmospheric pressure, temperature, and the total height and width of the measurement grid are recorded in Table 12.

Table 12: Testing and Refinement experimental data collection

Measurand	Value
P_{atm} [psf]	2061.2
T_{atm} [R]	531.7
x [in]	5.664
y [in]	5.640

Within the grid, the anemometer recorded ten velocity measurements, which were then averaged. The standard deviation was also calculated and will be discussed in the shakedown uncertainty section. The average velocity at each testing location is shown in Table 13.

Table 13: Average velocity measurement [fpm] at each grid location

Height	167	197	463	388	297	155
	140	355	452	463	411	148
	319	398	299	345	485	318
	503	499	491	445	356	333
	112	405	465	302	120	120
	55	78	109	68	116	79
	Width					

A graphical representation of the velocity profile is shown below in Figure 15. The 3D plot shows the measured velocity from Table 13 plotted on the z-axis, versus the x and y locations in the measuring grid on the x and y axes respectively. This shows that the flow field is slightly like what was expected earlier in the report. The areas surrounding the center hub of the fan seem to have higher velocities than in the center where the fan hub is. The edges of the grid maintain high velocities as the flow is sealed inside the duct. A graph of the non-ducted apparatus is shown in Figure 16.

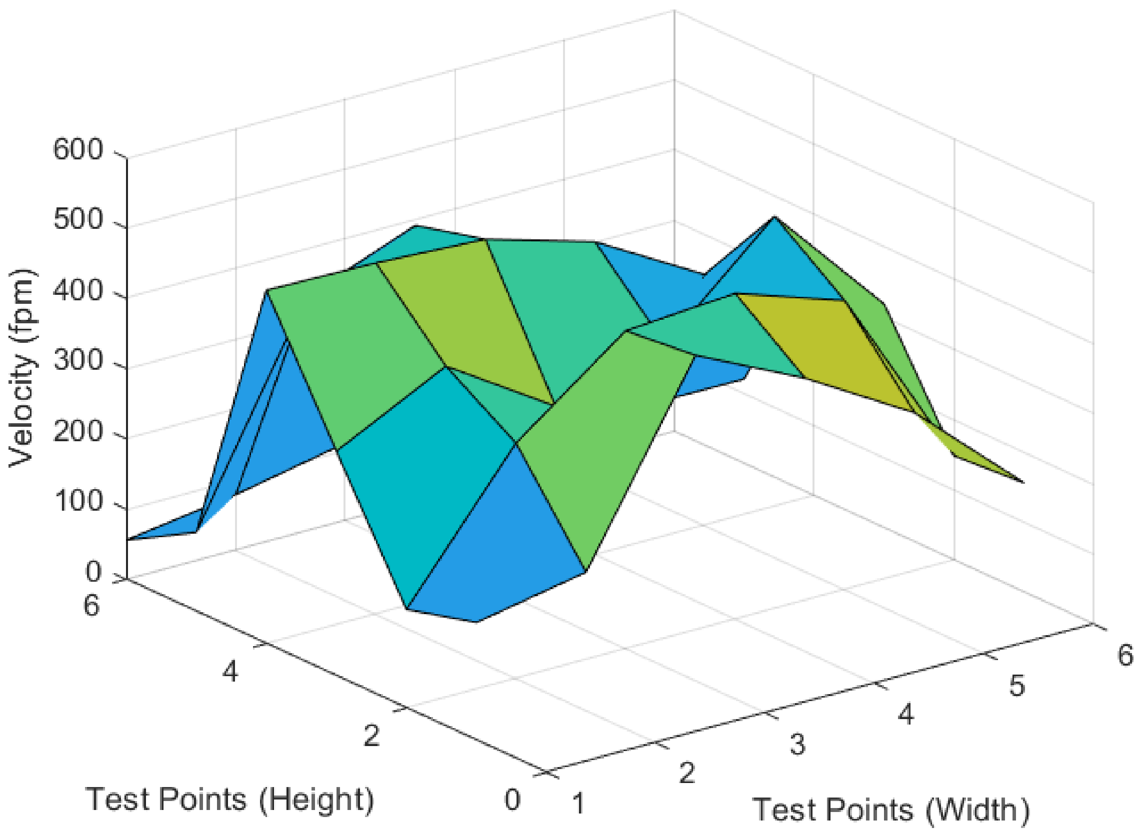

Figure 15: The 3D plot of the velocity profile of the ducted apparatus

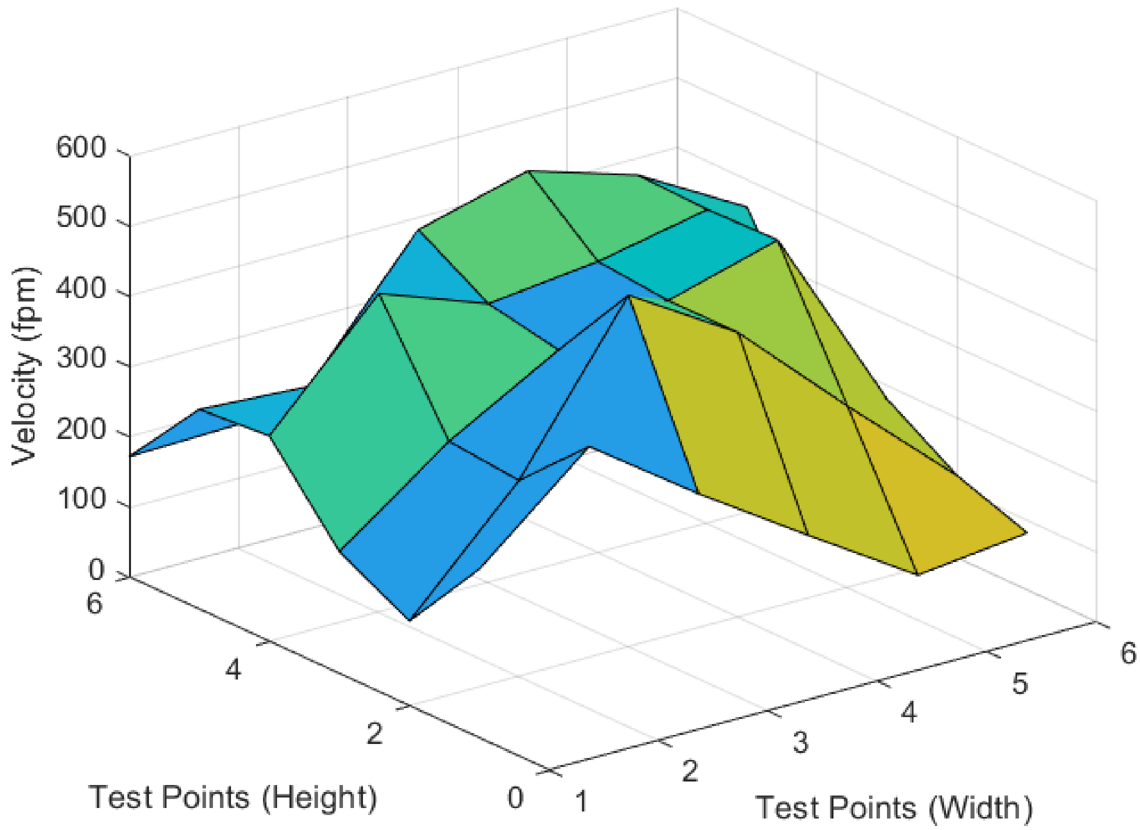

Figure 16: The 3D plot of the velocity profile of the non-ducted apparatus

By using the recorded data and inputting the measurands into the DRE the resultant mass flow rate was determined to be 0.146 slug/min. The data sheet on the Amazon website rated the volumetric flow rate to be 56.8 ft^3/min. By multiplying the expected volumetric flow rate by the density of air from Equation 6, the expected mass flow rate is 0.131 slug/min, only a 11.79% difference. To also show that the shakedown is within the set uncertainties as well as the practical minimums and maximums the point is shown plotted on the design space plot as a pink circle in Figure 17.

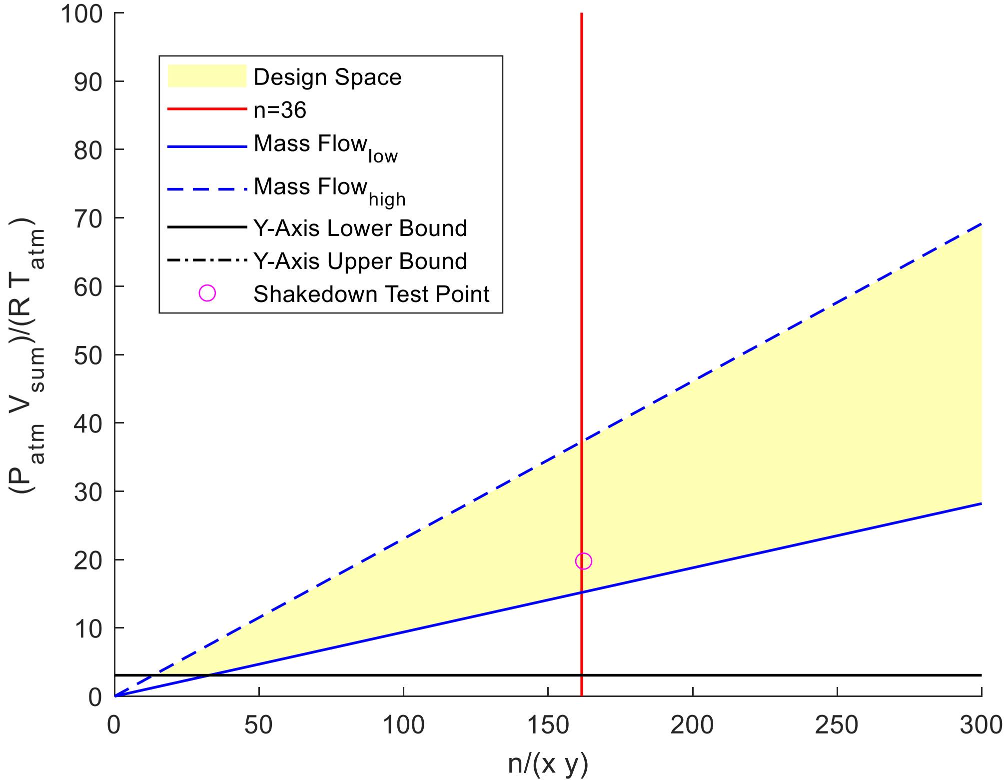

Figure 17: Design Space Plot with shakedown measurement plotted

Shakedown uncertainty

To evaluate the uncertainty of the shakedown measurements the uncertainty equations developed in the modeling section were used. The main difference to note however, is that to calculate the systematic uncertainty in the velocity terms the readability was changed instead to the standard deviation of the velocity measurements at that point. The uncertainty table for the shakedown test of the testing apparatus can be found in Table 14.

The systematic uncertainty is found by root sum squaring the accuracy and the readability as seen in Equation B1.

$$w_{k,sys}^2 = w_{k,acc}^2 + w_{k,read}^2 \quad \text{(B1)}$$

The standard deviation in velocity is used for the readability term as a series of 10 data points were averaged for each measurement. This substitution is seen in Equation B2.

$$w_{V,sys}^2 = w_{V,acc}^2 + (std.dev)^2 \quad \text{(B2)}$$

The above equation is used to determine the systematic uncertainty in velocity in

Table . The equations below are also used to populate the relative uncertainty and UMF values in

Table to observe how each measurement varies from one another.

The relative uncertainty in velocity is defined as the uncertainty in the velocity divided by the velocity measurement, as seen in Equation B3.

$$\frac{w_V}{V} = w_{rel} \tag{B3}$$

The UMF term for the velocity can be found by taking the individual velocity measurement and dividing it by the sum of all velocity measurements, as shown in Equation B4.

$$\frac{V_i}{\sum_{i=1}^{n} V_i} \tag{B4}$$

Table 14: The overall uncertainty calculated for the resultant mass flow rate is 3.700%

Parameter	Representative Value	Syst. Uncertainty	Units	Relative Uncertainty (%)	UMF	RSSC (%)	UPC (%)
Atmospheric Temperature	531.3	1.801	R	0.339	1.000	0.339	0.839
Atmospheric Pressure	2061.2	3.135	psf	0.152	1.000	0.152	0.169
Width	0.472	9.317E-05	ft	0.020	1.000	0.020	0.003
Height	0.470	9.317E-05	ft	0.020	1.000	0.020	0.003
Velocity 1	168	36.291	fpm	21.635	0.016	0.347	0.880
Velocity 2	197	62.808	fpm	31.847	0.019	0.601	2.636
Velocity 3	464	93.325	fpm	20.132	0.044	0.893	5.820
Velocity 4	389	80.655	fpm	20.743	0.037	0.771	4.347
Velocity 5	297	49.571	fpm	16.666	0.028	0.474	1.642
Velocity 6	155	44.037	fpm	28.342	0.015	0.421	1.296
Velocity 7	141	44.877	fpm	31.931	0.013	0.429	1.346
Velocity 8	335	55.845	fpm	16.670	0.032	0.534	2.084
Velocity 9	453	84.126	fpm	18.586	0.043	0.805	4.729
Velocity 10	464	84.038	fpm	18.121	0.044	0.804	4.719
Velocity 11	411	91.949	fpm	22.347	0.039	0.880	5.650
Velocity 12	148	55.712	fpm	37.605	0.014	0.533	2.074
Velocity 13	320	71.615	fpm	22.388	0.031	0.685	3.427
Velocity 14	399	83.774	fpm	21.016	0.038	0.801	4.690
Velocity 15	300	36.720	fpm	12.259	0.029	0.351	0.901
Velocity 16	345	49.002	fpm	14.188	0.033	0.469	1.605
Velocity 17	485	84.294	fpm	17.365	0.046	0.806	4.748
Velocity 18	318	67.071	fpm	21.061	0.030	0.642	3.006
Velocity 19	503	89.434	fpm	17.772	0.048	0.855	5.345
Velocity 20	500	92.959	fpm	18.599	0.048	0.889	5.774
Velocity 21	491	85.088	fpm	17.318	0.047	0.814	4.838
Velocity 22	445	82.443	fpm	18.510	0.043	0.789	4.542
Velocity 23	357	52.583	fpm	14.738	0.034	0.503	1.848
Velocity 24	334	39.484	fpm	11.823	0.032	0.378	1.042
Velocity 25	113	38.003	fpm	33.697	0.011	0.364	0.965
Velocity 26	405	93.360	fpm	23.047	0.039	0.893	5.824
Velocity 27	465	92.731	fpm	19.934	0.044	0.887	5.746
Velocity 28	302	44.733	fpm	14.807	0.029	0.428	1.337
Velocity 29	121	43.069	fpm	35.607	0.012	0.412	1.240
Velocity 30	120	38.437	fpm	32.029	0.011	0.368	0.987
Velocity 31	56	23.445	fpm	42.003	0.005	0.224	0.367
Velocity 32	79	24.787	fpm	31.558	0.008	0.237	0.411
Velocity 33	110	37.316	fpm	34.064	0.010	0.357	0.930
Velocity 34	68	25.786	fpm	37.663	0.007	0.247	0.444
Velocity 35	117	44.583	fpm	38.148	0.011	0.426	1.328
Velocity 36	80	24.921	fpm	31.312	0.008	0.238	0.415
Integration	-	3.817E-05	slugs/min	0.026	1.000	0.026	0.005
Mass Flowrate	0.146	0.005	slugs/min	-	-	3.700	100

Apparatus Refinements

The initial apparatus proved difficult to take measurements in a timely fashion. Expediting the data collection process made it easier to conduct more runs of the experiment over the 36 data points. The refinement of the apparatus focused mainly on improving stability, rigidity and repeatability of the anemometer placement and apparatus. The first iteration of the apparatus was the following as shown in Figure 18. Along with this, the team found that the original use of this apparatus without some sort of flow-containing duct was affecting the velocity measurements. This was because the edges of the flow from the fan were allowed to mix into ambient air and either bring in ambient air through the jig or cause the flow to not go through the jig at all. A diffuser was added to contain the flow and ensure that the flow was moved through the measuring jig. This diffuser was determined to have negligible losses via visually observing the stagnation pressure difference at the fan and at the end of the diffuser. This pressure difference was negligible, allowing the team to use a diffuser without having to account for losses in the flow. This diffuser was carried over from the first iteration into the second iteration of the apparatus as well.

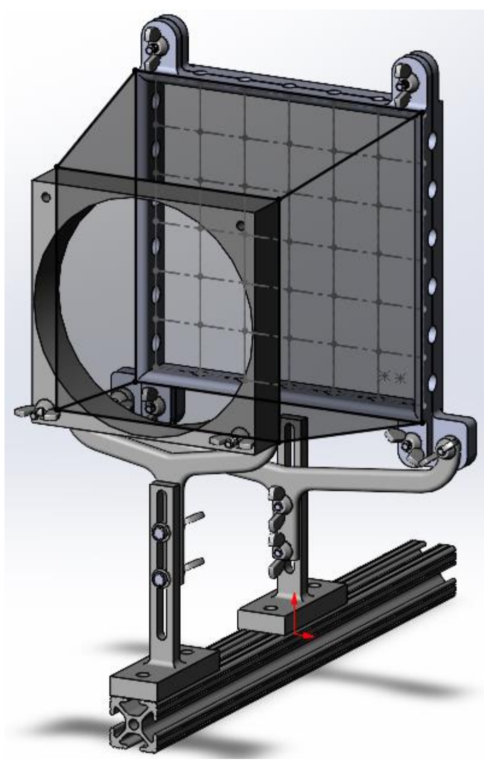

Figure 18: First Apparatus iteration

The apparatus was clamped to the table with a c-clamp to hold it down. The pain points with this design were that the 3D printed stands were flimsy. This introduced a lot of wobble in the entire measuring setup and moved the measuring grid away from being centered with the fan. Along with this, there was no surefire way to trust that the anemometer was always being replaced in the same spot of the grid, or that the anemometer was staying completely still. Having the anemometer stay completely stationary is important to prevent the anemometer from giving false measurements from it being moved around in the flow field. A second iteration was developed as shown in Figure 19.

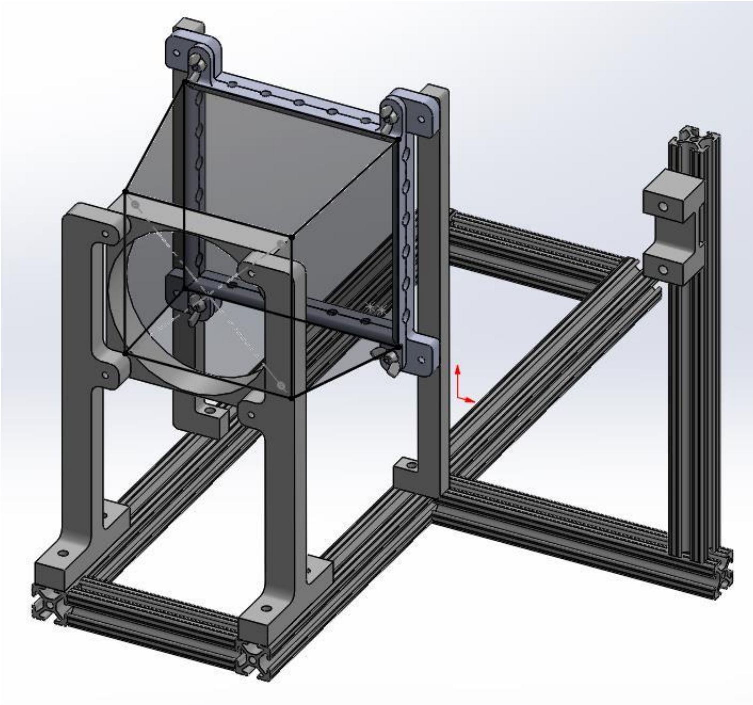

Figure 19: Refined second iteration of the measuring apparatus

The second iteration of the apparatus was given a base that needed no clamping as well as the opportunity to create two-legged mounting solutions for the fan and measuring grid. This helped reduce flexion when trying to insert the registering rod and anemometer into their positions. The holes on the measuring block where the registering rod and anemometer slide into were also made slightly larger to make it easier to insert them into position. A sliding gantry section of aluminum extrusion was also added to allow for a repeatable placement of the anemometer without having to manually hold it. This will allow for the anemometer to be held in place and traversed to the measuring points by moving the aluminum sections as needed to reach the desired data point. Overall, these improvements should allow for heightened user experience as well as higher repeatability of measurements. Not only does this make it easier for the user to collect data, but it also allows for less wobble when adjusting the anemometer. This also provided a very stable position for the anemometer to stay in a single place and eliminated human error from holding the anemometer by hand. This is a big improvement from beforehand where the anemometer was never squarely aligned in any direction with the measuring jig. With this design the anemometer is held in the same repeatable position, and square to the measuring jig with no wobble. As data is collected for the proposed experiment, more refinements were made to expedite the data collection process.

Appendix C: Uncertainty in the Integration Method

To determine the uncertainty due to the equal area method, the definition of Richardson's extrapolation error will be used. The definition stated in Equation C1 is a second order approximation.

$$error_{\Delta A_1} = exact - approx_{\Delta A_1} = C(\Delta A_1)^2 \qquad \text{(C1)}$$

where $error_{\Delta A_1}$ is the error in mass flow rate at a given voltage, $exact$ is the true mass flow rate at that voltage, $approx_{\Delta A_1}$ is the approximate mass flow rate at that voltage and area division, and ΔA_1 is the subdivided area. To determine what the value of the constant C is, another approximation can be taken and simplified in Equation C2.

$$error_{\Delta A_2} = exact - approx_{\Delta A_2} = C(\Delta A_2)^2 \qquad \text{(C2)}$$

Since a 6x6 grid was used, a 2x2 grid can be used within the 6x6 grid to provide the second approximation. The 2x2 within the 6x6 will use the data measured in the trial at the following dark shaded locations shown in Figure 20.

1	2	3	4	5	6
7	8	9	10	11	12
13	14	15	16	17	18
19	20	21	22	23	24
25	26	27	28	29	30
31	32	33	34	35	36

Figure 20: Numbered flow grid to show location of different measurement points

Using Equation C3, taking ΔA_1 to be the individual grid areas of the 6x6, the value for ΔA_1 can be calculated.

$$\Delta A_1 = \frac{A}{36} = 0.00615\ ft^2 \qquad \text{(C3)}$$

Using Equation C4, taking ΔA_2 to be the individual grid areas of the 2x2, the value for ΔA_2 can be calculated.

$$\Delta A_2 = \frac{A}{4} = 0.05538\ ft^2 \qquad \text{(C4)}$$

These values will be constant for all integration uncertainty calculations.

The constant, C, then relies on the difference of the calculated mass flow divided by the difference of the different sized area slices. This relationship is described by Equation C5. The value of C will be different for each mass flow trial. For 5V trial #1, specifically 5.258V, the value for C is $7.127 \frac{slug}{ft^2\ min}$.

$$C = \left| \frac{approx_{\Delta A_2} - approx_{\Delta A_1}}{\Delta A_1^2 - \Delta A_2^2} \right| \tag{C5}$$

Using the relationship established by Equation C6, the error (or uncertainty) in the integration method can be calculated. For 5V trial #1, specifically 5.258V, the integration error is $0.000267\ \frac{slug}{min}$.

$$w_{integration} = C(\Delta A_1)^2 \tag{C6}$$

Appendix D: Hotwire Anemometer Calibration and Correction Factor

Calibration for the Testo anemometer was done to double check the reliability of the device. Using a wind tunnel equipped with a pitot static tube and a supplied excel file, the team was able take pressure measurements in inches of gauge oil and convert the pressure measurements to a velocity measurement. The anemometer probed the approximate same location and the results from this study are shown in Table 15.

Table 15: Wind tunnel velocity measurements compared to anemometer measurements via percent error calculations

Wind Tunnel Velocity (fpm)	Anemometer Velocity (fpm)	Percent Error (%)
1636.707	1500	8.35
1829.894	1760	3.82
1157.326	1050	9.27
2004.548	1830	8.71
2165.159	2003	7.49

Since the percent error gets up to 9.27%, the team speculated that a correction factor for the velocity measurements of the anemometer was needed. A plot of the wind tunnel velocity measurements against the anemometer measurements was created and a linear regression was made to characterize the relationship. The results of this study are shown in Figure 21

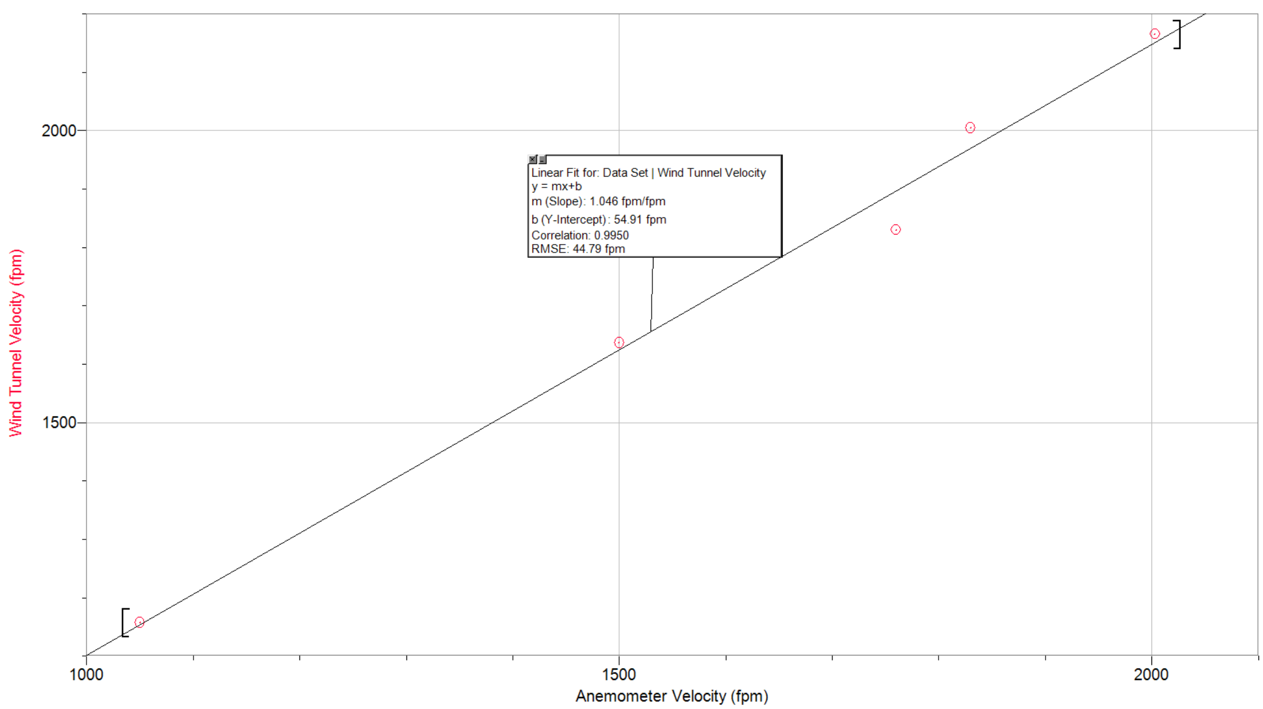

Figure 21:Linear regression of wind tunnel velocity measurements versus anemometer measurements plot resulting in a slope of 1.046

The slope of the linear regression, 1.046, was taken to be the correction factor and used to increase the anemometer velocity measurements by 4.6% to correct for any calibration uncertainty. The team neglected the y-intercept of about 55 fpm because the testo anemometer has an accuracy offset of $\pm 20fpm$ for low velocities and $\pm 59.1fpm$ for high velocities added to the 5% of the measured value to calculate the uncertainty due to accuracy. The velocity values used to calculate the correction factor were outside of the operating range of the fan. The fan produces velocity values on the range of $30fpm$ to $1100fpm$. This range is not fully captured by the collected data, so the team did not fully trust the intercept value to be added to low ranged velocities measured by the anemometer (it could increase the measured value by over 100%). When only using a 4.6% increase to the anemometer value, the percent error between the velocity of the wind tunnel and the anemometer device was decreased by half.

Appendix E: Unprocessed Velocity Data

The following appendix is a collection of all the recorded velocity data for the different experimental trials performed. The tables specify which trial each table is for as well as showing the use of the correction factor of 1.046 being applied to the average velocities.

Table 16: 3V Trial #1 (3.452V)

Test Point Location	Velocity (fpm)	Velocity (fpm)	Velocity (fpm)	Velocity (fpm)	Velocity (fpm)	Velocity (fpm)	Velocity (fpm)	Velocity (fpm)	Velocity (fpm)	Velocity (fpm)	Velocity (fpm)	Average Velocity (fpm)	Standard Deviation	Corrected Average Velocity (fpm)	Corrected Standard Deviation
Point 1	75	133	148	108	112	126	115	126	80	71	88	107	26	112	27
Point 2	90	116	212	201	167	194	156	154	121	227	192	166	44	174	46
Point 3	189	202	184	238	230	212	230	209	252	207	140	208	31	218	32
Point 4	187	196	102	198	159	167	138	217	245	249	198	187	44	196	46
Point 5	39	36	42	46	83	140	83	76	34	62	63	64	31	67	33
Point 6	36	37	31	37	38	41	32	35	42	33	33	36	4	38	4
Point 7	118	45	39	37	144	89	40	46	84	69	41	68	36	72	38
Point 8	124	120	87	102	87	151	71	117	78	103	119	105	24	110	25
Point 9	274	290	293	260	258	302	281	313	302	278	296	286	18	299	18
Point 10	215	246	178	238	264	239	256	263	241	253	261	241	25	252	27
Point 11	109	81	229	226	239	182	223	192	220	156	91	177	59	185	62
Point 12	32	41	38	51	58	112	101	71	86	144	89	75	35	78	37
Point 13	64	178	173	191	97	150	112	152	76	61	165	129	48	135	51
Point 14	276	225	191	167	271	254	186	188	185	179	189	210	39	220	41
Point 15	244	245	269	235	252	268	267	248	251	244	209	248	17	260	18
Point 16	137	155	195	156	146	191	201	199	213	138	165	172	28	180	29
Point 17	239	243	275	256	246	268	250	256	198	140	142	228	48	239	50
Point 18	121	187	185	101	107	109	87	223	159	128	78	135	47	141	49
Point 19	92	78	76	43	60	47	53	42	49	51	62	59	16	62	17
Point 20	176	160	141	183	215	117	112	192	197	235	227	178	42	186	44
Point 21	258	222	201	225	248	238	242	237	247	263	220	236	18	247	19
Point 22	244	253	223	221	132	155	223	200	193	201	172	202	37	211	39
Point 23	310	307	308	319	297	317	293	269	301	299	309	303	14	317	14
Point 24	282	241	121	82	99	129	130	216	119	175	248	167	68	175	72
Point 25	34	40	35	24	31	39	34	32	29	33	36	33	4	35	5
Point 26	53	156	188	178	127	114	88	131	149	101	144	130	40	136	41
Point 27	276	254	281	270	265	253	256	278	279	269	240	266	13	278	14
Point 28	274	298	292	291	288	292	285	309	290	298	277	290	10	304	10
Point 29	261	284	252	220	199	146	196	135	87	169	134	189	62	198	64
Point 30	50	54	43	53	51	53	77	79	76	88	72	63	15	66	16
Point 31	51	46	37	42	29	41	69	56	60	53	46	48	11	50	12
Point 32	55	87	73	54	64	88	104	103	87	65	67	77	18	81	19
Point 33	55	75	86	183	193	263	217	169	104	135	167	150	65	157	68
Point 34	226	256	267	263	224	240	212	214	214	196	171	226	29	236	31
Point 35	164	148	119	144	206	167	135	77	123	218	226	157	46	164	48
Point 36	84	67	45	57	103	167	98	128	104	83	42	89	37	93	39

Table 17: 5V Trial #1 (5.258V)

Test Point Location	Velocity (fpm)	Velocity (fpm)	Velocity (fpm)	Velocity (fpm)	Velocity (fpm)	Velocity (fpm)	Velocity (fpm)	Velocity (fpm)	Velocity (fpm)	Velocity (fpm)	Velocity (fpm)	Average Velocity (fpm)	Standard Deviation	Corrected Average Velocity (fpm)	Corrected Standard Deviation
Point 1	69	149	166	154	191	173	131	113	143	117	199	146	38	153	39
Point 2	252	184	217	154	201	197	210	147	160	118	151	181	39	189	41
Point 3	383	395	315	369	348	328	370	390	271	280	309	342	44	357	46
Point 4	295	326	296	234	246	271	199	254	295	258	329	273	40	286	42
Point 5	63	56	49	54	49	58	51	58	54	63	58	56	5	58	5
Point 6	51	51	46	44	45	50	48	53	44	43	53	48	4	50	4
Point 7	280	144	59	46	57	55	74	87	109	272	116	118	84	124	87
Point 8	393	425	323	215	383	343	313	333	341	320	352	340	54	356	56
Point 9	402	454	441	451	443	392	442	402	443	450	400	429	24	449	25
Point 10	427	404	424	422	419	432	403	244	269	391	417	387	66	404	69
Point 11	120	127	118	184	74	131	150	138	218	203	131	145	42	152	44
Point 12	142	129	88	72	61	72	63	123	101	89	80	93	28	97	29
Point 13	209	316	324	142	227	285	202	126	306	214	390	249	82	261	85
Point 14	459	461	465	500	459	280	331	396	421	391	394	414	65	433	68
Point 15	312	340	294	293	281	237	262	295	277	206	292	281	36	294	38
Point 16	289	354	392	358	392	425	441	404	402	408	385	386	41	404	43
Point 17	410	387	420	276	373	210	299	401	416	418	395	364	70	381	74
Point 18	187	121	164	226	245	279	285	263	329	326	111	231	76	241	80
Point 19	169	167	257	200	150	181	90	105	114	102	70	146	56	153	58
Point 20	384	388	392	338	404	419	415	412	463	434	316	397	41	415	43
Point 21	337	337	329	339	334	239	251	179	262	278	277	287	53	301	55
Point 22	313	332	291	196	286	182	304	319	368	337	373	300	62	314	64
Point 23	529	493	511	438	451	427	468	489	471	235	195	428	110	448	115
Point 24	178	266	194	193	199	201	129	123	322	265	374	222	77	232	81
Point 25	53	67	64	76	68	57	93	80	60	74	91	71	13	74	14
Point 26	104	212	288	248	226	233	254	279	290	279	359	252	63	264	66
Point 27	407	476	397	311	355	391	400	389	430	417	350	393	44	411	46
Point 28	485	469	464	476	452	453	486	471	467	467	480	470	11	492	12
Point 29	477	437	495	414	455	453	437	365	341	394	467	430	48	450	50
Point 30	264	98	111	153	212	181	233	189	236	188	177	186	51	194	53
Point 31	66	71	60	63	70	86	108	88	66	60	64	73	15	76	16
Point 32	73	71	64	128	92	107	105	237	230	138	167	128	60	134	63
Point 33	241	286	285	227	211	273	277	263	265	142	246	247	42	258	44
Point 34	214	166	151	139	111	269	253	192	299	306	149	204	68	214	71
Point 35	199	288	205	166	101	129	110	161	109	132	169	161	55	168	58
Point 36	235	105	121	134	196	271	137	145	107	183	197	166	54	174	57

Table 18: 10V Trial #1 (10.03V)

Test Point Location	Velocity (fpm)	Velocity (fpm)	Velocity (fpm)	Velocity (fpm)	Velocity (fpm)	Velocity (fpm)	Velocity (fpm)	Velocity (fpm)	Velocity (fpm)	Velocity (fpm)	Velocity (fpm)	Average Velocity (fpm)	Standard Deviation	Corrected Average Velocity (fpm)	Corrected Standard Deviation
Point 1	257	214	265	266	244	194	348	275	267	375	277	271	52	284	54
Point 2	472	502	471	471	438	468	278	277	390	472	487	430	81	449	84
Point 3	597	692	598	430	622	719	706	708	643	658	638	637	81	667	85
Point 4	600	264	437	531	283	365	327	458	232	164	156	347	146	363	153
Point 5	105	98	99	97	92	100	121	106	96	96	99	101	8	105	8
Point 6	85	91	101	93	92	96	92	95	85	82	104	92	7	97	7
Point 7	240	294	401	196	239	256	183	183	238	224	216	243	62	254	65
Point 8	596	771	685	812	739	815	833	746	791	752	744	753	67	788	70
Point 9	776	757	717	755	687	715	767	666	627	686	663	711	49	743	51
Point 10	680	642	685	725	726	716	681	646	661	696	690	686	29	718	30
Point 11	290	382	326	248	305	288	222	345	361	394	309	315	53	330	56
Point 12	143	124	110	129	167	133	125	128	113	102	111	126	18	132	19
Point 13	639	597	663	626	666	557	517	449	510	661	708	599	81	627	85
Point 14	703	727	697	717	751	654	798	750	779	744	750	734	40	767	42
Point 15	545	542	571	493	509	577	596	484	407	453	348	502	76	525	80
Point 16	566	600	587	688	551	492	315	276	343	385	535	485	135	508	141
Point 17	551	638	585	560	564	624	613	590	539	434	589	572	55	598	58
Point 18	206	106	134	162	145	256	280	428	396	310	316	249	108	260	113
Point 19	308	230	207	254	296	182	246	251	225	253	266	247	36	258	38
Point 20	540	613	650	719	632	651	475	359	207	356	376	507	163	530	171
Point 21	622	586	577	458	473	435	568	520	546	533	547	533	58	558	60
Point 22	521	557	405	392	584	574	499	480	391	483	415	482	73	504	76
Point 23	442	581	601	591	643	715	685	629	619	704	671	626	76	654	79
Point 24	408	298	578	403	313	315	576	476	514	534	614	457	116	478	121
Point 25	172	141	160	115	97	135	245	295	167	130	158	165	58	173	60
Point 26	92	166	128	257	425	285	458	364	471	364	366	307	132	321	138
Point 27	597	571	558	666	745	634	519	457	692	660	500	600	88	628	93
Point 28	791	782	821	712	713	791	714	717	785	817	824	770	46	805	49
Point 29	779	770	791	786	782	779	653	702	766	669	771	750	50	784	52
Point 30	545	663	547	589	380	593	341	581	668	504	500	537	103	562	108
Point 31	114	86	95	105	100	84	112	104	121	142	134	109	18	114	19
Point 32	111	176	132	122	127	126	122	128	131	111	132	129	17	135	18
Point 33	370	217	163	341	211	441	587	279	379	248	328	324	121	339	126
Point 34	484	611	542	575	588	712	720	619	691	735	683	633	82	662	85
Point 35	248	462	444	452	483	403	325	475	578	469	426	433	86	453	90
Point 36	233	195	228	185	292	310	367	323	221	270	211	258	59	270	61

Table 19: 12V Trial #1 (12.54V)

Test Point Location	Velocity (fpm)	Velocity (fpm)	Velocity (fpm)	Velocity (fpm)	Velocity (fpm)	Velocity (fpm)	Velocity (fpm)	Velocity (fpm)	Velocity (fpm)	Velocity (fpm)	Velocity (fpm)	Average Velocity (fpm)	Standard Deviation	Corrected Average Velocity (fpm)	Corrected Standard Deviation
Point 1	294	313	450	476	308	318	380	251	336	243	171	322	89	337	93
Point 2	759	758	767	706	666	679	652	660	708	595	649	691	54	723	57
Point 3	561	731	738	807	752	779	662	723	719	726	701	718	64	751	67
Point 4	245	500	279	270	292	197	291	494	327	207	260	306	102	320	106
Point 5	119	112	117	118	117	116	119	121	129	119	145	121	9	127	9
Point 6	107	119	120	115	115	116	116	96	114	98	97	110	9	115	10
Point 7	260	291	183	164	127	111	134	236	161	168	245	189	60	198	62
Point 8	654	413	408	602	573	634	596	413	534	658	590	552	97	578	102
Point 9	854	876	888	855	866	899	895	890	885	876	898	880	16	921	17
Point 10	808	779	627	752	709	763	824	784	793	813	811	769	58	805	60
Point 11	323	208	280	467	289	300	324	196	292	411	289	307	78	321	82
Point 12	158	126	117	118	121	141	144	132	174	158	155	140	19	147	20
Point 13	571	560	444	530	419	223	173	388	480	454	522	433	130	453	136
Point 14	931	950	836	884	917	892	926	851	898	893	920	900	34	941	36
Point 15	644	621	539	640	582	633	652	700	755	593	640	636	57	666	60
Point 16	685	566	719	612	693	576	565	671	660	720	741	655	65	685	68
Point 17	425	643	637	692	775	695	634	658	625	708	783	661	95	692	100
Point 18	347	200	169	134	192	240	291	174	199	220	281	222	62	233	65
Point 19	310	274	297	296	437	460	443	452	495	444	296	382	86	400	89
Point 20	826	886	824	813	771	772	764	799	829	722	675	789	57	825	60
Point 21	703	737	654	422	413	636	763	659	700	609	598	627	115	656	120
Point 22	592	747	806	684	776	744	766	700	761	630	600	710	74	742	78
Point 23	824	627	687	861	889	880	836	814	912	948	829	828	95	866	99
Point 24	282	428	419	434	345	398	487	466	407	381	339	399	59	417	62
Point 25	121	108	146	165	215	213	162	123	102	109	129	145	40	151	42
Point 26	384	615	280	284	346	240	229	323	241	346	292	325	108	340	113
Point 27	726	811	789	808	801	826	788	718	682	537	768	750	84	785	88
Point 28	875	991	1005	973	976	976	1013	1018	1007	1000	985	984	39	1029	41
Point 29	595	842	601	833	496	665	575	609	536	882	793	675	137	706	143
Point 30	705	710	500	488	480	313	235	286	431	444	434	457	151	478	158
Point 31	162	143	175	126	144	147	154	125	143	99	135	141	20	148	21
Point 32	161	273	300	336	235	197	213	203	228	268	167	235	55	245	57
Point 33	771	754	745	742	744	815	877	779	767	539	706	749	83	783	87
Point 34	865	827	901	830	842	850	803	770	846	791	634	814	70	852	73
Point 35	524	620	661	457	571	255	221	272	283	308	370	413	160	432	167
Point 36	118	214	322	344	242	296	193	165	133	149	271	222	78	233	82

Table 20: 3V Trial #2 (3.466)

Test Point Location	Velocity (fpm)	Velocity (fpm)	Velocity (fpm)	Velocity (fpm)	Velocity (fpm)	Velocity (fpm)	Velocity (fpm)	Velocity (fpm)	Velocity (fpm)	Velocity (fpm)	Velocity (fpm)	Average Velocity (fpm)	Standard Deviation	Corrected Average Velocity (fpm)	Corrected Standard Deviation
Point 1	48	63	60	50	52	68	63	53	37	48	43	53	9	56	10
Point 2	128	99	105	100	65	85	98	110	99	106	98	99	15	104	16
Point 3	206	156	114	162	206	191	186	82	108	132	134	152	42	159	44
Point 4	60	71	42	64	72	87	58	47	39	51	74	60	15	63	16
Point 5	55	39	36	34	36	36	30	31	31	32	36	36	7	38	7
Point 6	28	27	24	27	26	26	27	24	25	27	24	26	1	27	2
Point 7	58	81	51	39	43	35	46	43	43	29	29	45	15	47	15
Point 8	125	221	223	129	210	209	167	195	187	184	199	186	34	195	35
Point 9	296	281	292	268	282	248	287	272	273	278	286	278	13	291	14
Point 10	267	249	226	264	272	231	142	165	183	213	248	224	44	234	46
Point 11	146	147	167	116	127	125	95	100	78	59	75	112	34	117	36
Point 12	49	40	50	60	38	40	40	35	52	35	51	45	8	47	9
Point 13	69	81	102	93	67	61	58	36	70	62	70	70	18	73	19
Point 14	249	255	242	220	230	228	237	277	202	260	218	238	21	249	22
Point 15	294	282	270	249	253	258	271	269	206	204	226	253	30	265	31
Point 16	239	253	262	265	245	242	241	245	269	252	243	251	11	262	11
Point 17	134	111	85	89	90	210	169	127	190	188	196	144	48	151	50
Point 18	55	52	51	36	30	34	36	38	41	33	34	40	9	42	9
Point 19	80	44	50	87	73	75	92	112	56	57	55	71	21	74	22
Point 20	274	278	290	291	273	254	272	277	276	269	279	276	10	288	10
Point 21	111	104	122	133	111	93	86	115	119	80	101	107	16	112	17
Point 22	187	222	212	177	205	184	196	209	208	199	161	196	18	205	19
Point 23	286	277	268	279	297	286	261	270	265	214	218	266	27	278	28
Point 24	85	129	115	114	84	76	87	80	98	102	84	96	17	100	18
Point 25	51	37	46	44	48	61	44	50	35	36	39	45	8	47	8
Point 26	280	281	264	276	251	231	244	256	226	191	200	245	31	257	32
Point 27	281	288	311	313	302	302	304	306	326	320	307	305	13	320	13
Point 28	329	328	324	318	332	287	269	284	319	328	312	312	22	326	23
Point 29	149	168	157	129	124	108	184	258	279	166	155	171	53	178	56
Point 30	106	179	101	77	86	80	163	215	226	234	207	152	63	159	66
Point 31	83	81	61	45	66	64	60	67	81	79	98	71	15	75	15
Point 32	270	260	266	255	190	237	179	100	69	67	139	185	80	193	84
Point 33	230	262	208	203	231	252	228	226	244	238	275	236	21	247	22
Point 34	249	235	253	211	243	215	241	221	240	247	247	237	14	247	15
Point 35	125	161	159	178	129	155	165	169	140	170	158	155	17	163	18
Point 36	81	49	74	107	102	128	154	118	92	92	81	98	29	103	30

Table 21: 5V Trial #2 (5.026V)

Test Point Location	Velocity (fpm)	Velocity (fpm)	Velocity (fpm)	Velocity (fpm)	Velocity (fpm)	Velocity (fpm)	Velocity (fpm)	Velocity (fpm)	Velocity (fpm)	Velocity (fpm)	Velocity (fpm)	Average Velocity (fpm)	Standard Deviation	Corrected Average Velocity (fpm)	Corrected Standard Deviation
Point 1	68	77	107	77	61	82	79	61	68	77	78	76	13	79	13
Point 2	213	267	233	111	106	114	118	173	115	132	83	151	61	158	64
Point 3	97	140	172	194	157	139	129	81	89	141	122	133	35	139	36
Point 4	235	278	254	260	247	223	248	299	278	257	261	258	21	270	22
Point 5	64	60	49	78	99	78	101	87	106	119	81	84	21	88	22
Point 6	41	44	41	41	47	52	43	47	51	45	40	45	4	47	4
Point 7	142	227	206	311	284	351	270	321	158	217	250	249	66	260	70
Point 8	315	388	419	450	344	401	367	346	348	258	410	368	54	385	56
Point 9	429	416	414	471	456	442	457	461	442	446	423	442	19	462	20
Point 10	358	345	413	289	343	384	390	383	399	390	401	372	36	389	37
Point 11	273	259	210	293	229	245	286	251	194	146	137	229	53	240	55
Point 12	61	45	50	48	73	54	57	64	65	57	71	59	9	61	10
Point 13	241	184	147	273	241	218	249	299	322	252	295	247	51	259	54
Point 14	341	333	331	365	379	391	399	374	380	330	339	360	26	377	27
Point 15	107	103	94	127	117	122	120	141	135	106	108	116	14	122	15
Point 16	390	386	353	365	328	347	349	371	386	370	383	366	20	383	21
Point 17	282	308	293	320	314	278	276	294	224	322	353	297	33	310	35
Point 18	76	74	77	66	58	59	72	65	63	63	47	65	9	68	9
Point 19	153	117	123	142	141	156	123	136	165	104	109	134	20	140	21
Point 20	415	386	400	398	386	388	407	381	369	312	304	377	36	394	38
Point 21	123	161	123	92	97	106	113	129	112	111	154	120	22	126	23
Point 22	115	104	80	103	88	94	98	98	151	129	100	105	20	110	21
Point 23	323	289	234	313	368	372	384	352	374	368	294	334	47	349	49
Point 24	225	198	165	218	269	295	233	277	232	278	224	238	39	249	41
Point 25	46	56	49	52	59	51	73	86	81	70	79	64	14	67	15
Point 26	304	317	316	266	279	379	307	279	205	284	225	287	47	301	49
Point 27	392	389	391	422	453	457	467	435	413	411	362	417	33	437	35
Point 28	430	442	379	361	438	407	437	434	455	387	395	415	31	434	32
Point 29	439	452	471	397	368	385	413	432	465	420	432	425	32	444	34
Point 30	258	271	321	298	275	216	285	128	151	169	119	226	73	237	76
Point 31	106	84	128	79	85	63	108	84	88	86	130	95	21	99	22
Point 32	367	355	390	316	273	258	338	316	236	254	289	308	51	323	53
Point 33	436	382	384	385	336	311	329	402	410	417	404	381	40	399	42
Point 34	366	386	337	362	315	313	311	325	331	371	364	344	27	360	28
Point 35	267	247	173	213	260	265	136	188	135	201	274	214	52	224	54
Point 36	225	185	147	183	69	49	72	66	64	116	149	120	61	126	63

Table 22: 10V Trial #2 (10.04V)

Test Point Location	Velocity (fpm)	Velocity (fpm)	Velocity (fpm)	Velocity (fpm)	Velocity (fpm)	Velocity (fpm)	Velocity (fpm)	Velocity (fpm)	Velocity (fpm)	Velocity (fpm)	Velocity (fpm)	Average Velocity (fpm)	Standard Deviation	Corrected Average Velocity (fpm)	Corrected Standard Deviation
Point 1	108	137	133	151	191	114	160	153	124	171	165	146	25	153	27
Point 2	390	288	282	382	385	369	302	383	326	287	270	333	49	348	51
Point 3	509	526	577	557	516	537	569	547	561	507	536	540	24	565	25
Point 4	482	507	577	633	672	641	613	660	631	476	558	586	71	613	75
Point 5	304	405	426	454	328	418	396	398	335	314	226	364	68	381	71
Point 6	179	185	96	165	194	180	150	154	165	184	127	162	29	169	30
Point 7	400	447	527	446	397	509	331	477	565	532	521	468	71	490	75
Point 8	615	613	679	680	635	566	661	640	634	653	611	635	33	664	35
Point 9	740	714	737	812	810	802	819	814	785	776	746	778	37	814	39
Point 10	711	696	667	724	605	680	707	719	710	637	606	678	44	710	46
Point 11	336	395	378	367	415	391	460	482	398	457	531	419	57	438	60
Point 12	159	132	131	96	110	198	168	106	96	110	103	128	34	134	35
Point 13	393	359	347	376	477	502	447	463	455	382	481	426	55	445	58
Point 14	531	600	650	619	649	564	649	670	578	628	566	609	45	637	47
Point 15	231	223	254	261	215	264	222	254	278	262	295	251	25	262	26
Point 16	208	211	190	164	205	200	173	184	176	155	208	189	20	197	20
Point 17	369	364	447	441	553	582	421	457	531	483	312	451	83	472	87
Point 18	212	143	160	127	192	150	221	116	154	159	256	172	43	180	45
Point 19	113	160	103	132	132	128	126	195	150	126	125	135	25	142	26
Point 20	516	528	611	560	506	545	496	523	584	538	343	523	69	547	72
Point 21	241	285	313	272	260	321	255	241	200	225	231	259	37	270	39
Point 22	444	392	414	383	412	320	348	436	358	352	397	387	39	405	41
Point 23	510	470	431	447	495	425	494	511	568	609	597	505	63	528	66
Point 24	291	382	392	354	341	443	498	385	398	497	392	398	62	416	65
Point 25	86	84	85	77	88	95	92	92	103	108	92	91	9	95	9
Point 26	574	577	538	475	433	521	567	570	548	547	433	526	54	550	57
Point 27	700	721	735	752	845	798	760	734	734	787	798	760	42	795	44
Point 28	748	788	831	807	809	744	737	773	803	844	820	791	36	828	38
Point 29	778	801	760	713	740	773	730	734	703	693	721	741	34	775	35
Point 30	725	729	662	649	662	530	718	714	600	691	641	666	61	696	64
Point 31	104	101	90	103	103	107	141	140	120	96	94	109	17	114	18
Point 32	167	174	124	125	152	99	119	96	112	149	140	132	26	139	27
Point 33	558	587	496	560	579	658	611	629	591	643	543	587	47	614	49
Point 34	581	610	664	685	677	653	558	536	503	772	766	637	88	666	92
Point 35	696	676	724	766	757	717	677	575	525	563	660	667	80	698	84
Point 36	200	178	255	284	262	232	282	123	130	271	321	231	65	241	68

Table 23: 12V Trial #3 (12.59V)

Test Point Location	Velocity (fpm)	Velocity (fpm)	Velocity (fpm)	Velocity (fpm)	Velocity (fpm)	Velocity (fpm)	Velocity (fpm)	Velocity (fpm)	Velocity (fpm)	Velocity (fpm)	Velocity (fpm)	Average Velocity (fpm)	Standard Deviation	Corrected Average Velocity (fpm)	Corrected Standard Deviation
Point 1	183	165	193	192	178	166	199	189	346	335	198	213	64	223	67
Point 2	136	110	111	106	95	117	103	94	104	111	100	108	12	113	12
Point 3	408	440	533	457	396	538	505	212	382	531	550	450	100	471	105
Point 4	612	448	445	534	595	546	580	429	520	518	581	528	64	552	67
Point 5	180	207	251	282	105	261	248	201	221	245	202	218	49	229	51
Point 6	131	121	125	162	115	250	215	224	205	172	185	173	47	181	49
Point 7	122	135	123	117	123	128	143	167	142	154	244	145	36	152	38
Point 8	399	264	336	585	403	390	291	368	290	429	730	408	138	426	145
Point 9	904	919	796	778	847	885	819	917	952	875	838	866	55	906	58
Point 10	919	917	823	872	857	748	747	786	827	831	803	830	59	868	61
Point 11	295	531	561	514	601	519	515	410	398	345	326	456	104	477	109
Point 12	148	170	195	209	203	253	216	196	206	209	198	200	26	209	28
Point 13	596	707	617	555	761	748	769	687	645	577	621	662	76	693	80
Point 14	814	785	746	821	863	935	941	951	928	898	896	871	70	911	73
Point 15	639	713	839	886	888	796	847	794	711	779	746	785	78	821	82
Point 16	664	720	721	693	586	619	736	755	710	736	766	701	56	733	59
Point 17	351	358	375	281	386	302	389	653	577	385	330	399	114	417	119
Point 18	131	251	140	107	91	110	123	140	170	166	136	142	43	149	45
Point 19	347	263	310	437	258	327	405	363	403	261	275	332	65	347	67
Point 20	745	747	676	756	760	769	711	800	787	794	787	757	38	792	39
Point 21	248	217	360	429	408	319	221	219	251	272	241	290	78	303	81
Point 22	481	510	440	268	302	267	385	513	557	560	528	437	114	457	119
Point 23	746	691	682	710	737	795	672	651	752	626	711	707	49	739	51
Point 24	583	613	607	584	586	618	566	377	423	438	408	528	94	552	99
Point 25	185	258	316	384	352	231	223	273	392	362	327	300	70	314	74
Point 26	822	784	768	702	722	711	738	610	904	866	850	771	86	806	90
Point 27	862	910	848	847	891	951	926	912	945	887	880	896	36	938	38
Point 28	666	690	793	778	925	810	784	732	690	695	778	758	75	793	78
Point 29	889	853	844	865	898	862	843	853	882	862	868	865	18	905	19
Point 30	852	853	797	315	702	835	832	775	701	658	673	727	155	760	162
Point 31	265	345	306	359	381	418	387	384	466	257	272	349	67	365	71
Point 32	634	668	674	875	971	855	900	826	923	943	955	839	124	877	129
Point 33	818	869	867	882	928	914	914	961	871	787	841	877	50	918	53
Point 34	891	855	904	842	794	901	890	763	739	815	791	835	58	873	61
Point 35	534	643	486	460	558	588	652	549	547	636	686	576	72	603	75
Point 36	458	496	531	491	459	492	414	577	521	430	514	489	47	512	49

Table 24: 3V Trial #3 (3.468V)

Test Point Location	Velocity (fpm)	Velocity (fpm)	Velocity (fpm)	Velocity (fpm)	Velocity (fpm)	Velocity (fpm)	Velocity (fpm)	Velocity (fpm)	Velocity (fpm)	Velocity (fpm)	Velocity (fpm)	Average Velocity (fpm)	Standard Deviation	Corrected Average Velocity (fpm)	Corrected Standard Deviation
Point 1	160	165	118	120	142	168	181	230	213	216	228	176	41	185	43
Point 2	256	271	272	264	254	235	195	232	230	248	259	247	23	258	24
Point 3	259	266	254	243	264	260	258	248	248	262	225	253	12	265	12
Point 4	168	129	206	205	180	220	161	77	75	164	206	163	50	170	53
Point 5	65	49	42	49	46	47	51	41	72	47	45	50	10	53	10
Point 6	50	38	38	35	40	35	30	30	29	31	31	35	6	37	6
Point 7	128	120	106	152	124	80	71	72	68	98	91	101	28	106	29
Point 8	218	229	235	233	268	288	313	321	205	229	243	253	39	265	41
Point 9	220	244	236	225	227	266	255	257	275	244	243	245	17	256	18
Point 10	211	256	266	289	291	291	293	282	284	258	243	269	26	282	27
Point 11	221	203	211	187	182	202	214	170	97	108	86	171	50	179	52
Point 12	52	42	41	52	41	71	43	58	60	94	128	62	27	65	28
Point 13	107	92	98	134	118	126	157	166	151	176	163	135	29	141	31
Point 14	223	236	239	249	233	245	232	254	264	182	240	236	21	247	22
Point 15	178	207	192	166	128	101	124	140	104	84	120	140	40	147	42
Point 16	139	183	149	138	185	153	155	147	151	158	198	160	20	167	21
Point 17	225	218	210	222	214	136	124	181	202	150	211	190	37	199	38
Point 18	78	103	87	86	101	153	117	157	101	102	72	105	28	110	29
Point 19	44	54	113	141	66	79	74	58	63	87	90	79	28	83	29
Point 20	213	219	239	278	266	282	255	232	259	273	236	250	24	262	25
Point 21	232	208	254	261	277	285	297	286	241	233	254	257	27	269	29
Point 22	91	229	180	165	192	220	253	235	267	277	289	218	58	228	61
Point 23	259	226	214	177	259	269	281	236	254	217	277	243	32	254	33
Point 24	52	40	39	40	45	47	45	37	37	43	41	42	5	44	5
Point 25	74	79	79	64	38	38	63	48	30	36	37	53	19	56	20
Point 26	44	45	52	85	155	125	77	61	50	45	55	72	37	76	38
Point 27	160	193	139	185	157	241	264	270	267	114	164	196	56	205	58
Point 28	323	289	275	263	308	307	321	297	262	276	303	293	22	307	23
Point 29	226	125	162	126	139	128	109	128	136	148	109	140	33	146	34
Point 30	58	70	75	77	77	85	76	77	66	65	73	73	7	76	8
Point 31	31	31	34	37	44	55	67	53	36	47	38	43	11	45	12
Point 32	75	66	61	53	46	48	58	50	44	45	51	54	10	57	10
Point 33	277	293	277	258	95	87	80	75	95	73	69	153	99	160	103
Point 34	238	220	209	223	228	220	195	104	97	119	180	185	53	193	55
Point 35	242	222	225	191	243	266	247	213	254	266	263	239	24	250	25
Point 36	161	156	180	111	159	207	191	195	121	134	153	161	31	168	32

Table 25: 5V Trial #3 (5.010V)

Test Point Location	Velocity (fpm)	Velocity (fpm)	Velocity (fpm)	Velocity (fpm)	Velocity (fpm)	Velocity (fpm)	Velocity (fpm)	Velocity (fpm)	Velocity (fpm)	Velocity (fpm)	Velocity (fpm)	Average Velocity (fpm)	Standard Deviation	Corrected Average Velocity (fpm)	Corrected Standard Deviation
Point 1	128	154	217	258	300	195	65	206	240	276	326	215	77	225	81
Point 2	360	341	335	396	376	389	355	347	317	324	341	353	26	369	27
Point 3	386	416	396	399	382	363	391	395	412	413	394	395	15	413	16
Point 4	222	133	138	248	343	351	356	270	196	264	263	253	78	265	81
Point 5	82	150	86	92	71	71	61	50	67	53	48	76	29	79	30
Point 6	49	60	58	44	41	35	36	59	71	67	69	54	13	56	14
Point 7	252	165	126	181	344	329	180	228	179	235	229	223	67	233	70
Point 8	400	391	389	366	425	413	281	347	409	421	371	383	42	401	44
Point 9	372	371	383	385	396	399	391	378	393	393	402	388	11	405	11
Point 10	271	282	246	320	295	313	253	179	286	308	363	283	48	296	50
Point 11	160	150	178	164	110	76	70	85	91	96	85	115	40	120	42
Point 12	74	58	62	55	66	88	63	50	54	59	47	61	12	64	12
Point 13	290	334	269	228	210	258	306	300	277	270	206	268	40	280	42
Point 14	285	260	268	379	345	392	397	267	385	422	389	344	62	360	65
Point 15	326	330	330	299	296	261	239	263	258	259	227	281	37	294	39
Point 16	386	348	304	277	251	280	283	238	186	219	253	275	57	288	59
Point 17	309	237	251	290	277	185	248	327	259	176	260	256	46	268	48
Point 18	125	142	101	110	109	100	90	87	101	115	74	105	19	110	20
Point 19	119	127	184	270	284	272	267	260	229	262	328	237	66	247	69
Point 20	98	164	135	78	85	113	126	162	296	282	301	167	85	175	89
Point 21	288	347	264	359	359	341	296	285	294	320	353	319	35	333	36
Point 22	415	304	384	362	333	300	326	278	286	293	277	323	46	338	48
Point 23	389	427	411	408	389	423	376	400	393	461	448	411	26	430	28
Point 24	270	218	303	157	154	157	154	334	266	305	303	238	72	249	75
Point 25	72	53	66	61	74	81	72	51	152	187	170	94	50	99	52
Point 26	96	112	82	82	74	71	85	121	90	69	66	86	18	90	18
Point 27	105	111	167	136	144	164	252	256	182	233	225	180	55	188	57
Point 28	441	410	433	429	422	416	433	416	411	413	431	423	11	443	11
Point 29	505	511	481	474	474	491	453	430	493	471	471	478	23	500	24
Point 30	226	207	317	337	125	137	274	346	292	265	339	260	78	272	82
Point 31	65	71	82	87	59	73	70	71	69	70	65	71	8	74	8
Point 32	86	73	69	56	62	60	64	71	64	91	100	72	14	76	15
Point 33	84	81	86	98	81	262	161	100	73	92	82	109	56	114	59
Point 34	445	379	233	205	274	404	409	412	419	416	432	366	86	383	90
Point 35	334	349	334	345	351	315	316	354	302	319	291	328	21	343	22
Point 36	197	291	374	374	236	202	121	166	121	143	117	213	96	223	100

Table 26: 10V Trial #3 (10.06V)

Test Point Location	Velocity (fpm)	Velocity (fpm)	Velocity (fpm)	Velocity (fpm)	Velocity (fpm)	Velocity (fpm)	Velocity (fpm)	Velocity (fpm)	Velocity (fpm)	Velocity (fpm)	Velocity (fpm)	Average Velocity (fpm)	Standard Deviation	Corrected Average Velocity (fpm)	Corrected Standard Deviation
Point 1	293	344	327	191	112	253	289	456	461	425	298	314	108	328	113
Point 2	577	498	414	467	487	674	638	634	647	456	440	539	96	564	100
Point 3	558	310	209	333	452	360	530	704	661	699	711	502	181	526	189
Point 4	432	304	482	608	580	602	534	554	573	536	579	526	90	550	94
Point 5	174	161	201	201	231	287	267	228	148	163	178	204	45	213	47
Point 6	86	92	84	79	76	85	92	92	86	92	86	86	5	90	6
Point 7	196	209	124	137	185	244	195	374	280	366	572	262	131	274	137
Point 8	484	561	537	537	474	538	552	469	562	428	450	508	48	532	50
Point 9	697	722	717	684	641	627	617	653	638	656	677	666	36	697	37
Point 10	641	650	653	629	631	628	607	614	601	628	625	628	16	657	17
Point 11	207	162	234	357	380	348	356	498	430	375	477	348	107	364	112
Point 12	135	215	303	419	390	280	146	183	128	158	130	226	106	236	111
Point 13	529	420	454	397	434	509	368	363	521	400	389	435	61	455	63
Point 14	614	719	672	620	631	690	705	689	709	704	706	678	38	709	40
Point 15	582	570	690	609	602	558	593	638	609	667	661	616	42	645	44
Point 16	340	300	406	362	322	325	429	396	236	322	348	344	54	360	56
Point 17	617	615	594	670	689	669	681	607	683	599	660	644	37	674	39
Point 18	301	342	379	276	240	218	340	297	204	327	455	307	73	321	77
Point 19	425	325	162	202	176	138	137	333	538	617	671	339	198	354	207
Point 20	758	767	723	728	602	593	748	731	580	660	768	696	73	728	77
Point 21	726	717	730	773	693	783	742	798	749	733	798	749	34	784	36
Point 22	579	636	608	653	663	636	543	431	534	527	500	574	73	600	77
Point 23	714	767	774	814	764	882	903	662	771	793	776	784	67	820	71
Point 24	478	442	594	698	730	523	624	651	722	706	694	624	102	653	107
Point 25	114	126	133	122	112	106	116	110	127	110	232	128	36	134	37
Point 26	174	146	148	138	136	136	140	127	139	144	131	142	12	148	13
Point 27	487	442	291	359	285	252	296	316	326	317	267	331	73	346	76
Point 28	783	813	802	795	776	827	786	773	681	717	797	777	43	813	44
Point 29	798	777	738	724	799	751	746	729	738	767	839	764	36	799	38
Point 30	193	411	498	396	439	485	444	475	493	535	510	444	93	464	98
Point 31	131	141	187	163	168	130	181	187	163	149	157	160	21	167	21
Point 32	154	150	160	197	183	197	206	199	134	168	143	172	26	180	27
Point 33	189	176	188	163	171	132	142	162	155	237	183	173	28	180	29
Point 34	286	297	293	479	242	296	296	223	179	174	162	266	89	278	93
Point 35	444	456	393	475	527	574	477	401	452	500	381	462	58	483	61
Point 36	349	373	372	433	477	340	391	364	322	343	399	378	45	396	47

Table 27: 12V Trial #3 (12.50V)

Test Point Location	Velocity (fpm)	Velocity (fpm)	Velocity (fpm)	Velocity (fpm)	Velocity (fpm)	Velocity (fpm)	Velocity (fpm)	Velocity (fpm)	Velocity (fpm)	Velocity (fpm)	Velocity (fpm)	Average Velocity (fpm)	Standard Deviation	Corrected Average Velocity (fpm)	Corrected Standard Deviation
Point 1	501	349	377	321	326	370	371	486	454	473	384	401	65	420	68
Point 2	684	755	768	684	662	659	674	723	735	713	779	712	43	745	45
Point 3	853	867	876	822	829	794	850	822	860	855	853	844	24	883	25
Point 4	384	340	546	591	683	567	484	460	447	379	491	488	103	511	107
Point 5	118	114	127	134	124	153	169	154	130	130	133	135	17	141	18
Point 6	117	98	99	102	114	118	117	118	125	119	108	112	9	117	9
Point 7	252	340	466	219	273	176	139	152	192	296	242	250	94	261	99
Point 8	695	656	524	629	672	775	780	794	608	594	770	682	90	713	94
Point 9	741	762	869	787	787	735	823	798	831	866	859	805	48	842	50
Point 10	857	851	812	840	831	810	822	824	832	799	789	824	21	862	22
Point 11	370	400	377	331	384	387	344	202	244	247	435	338	75	354	78
Point 12	238	218	205	157	183	155	209	177	183	170	155	186	28	195	29
Point 13	183	155	148	137	125	159	146	161	150	160	165	154	15	161	16
Point 14	845	803	833	824	781	690	797	825	755	651	736	776	62	812	65
Point 15	627	661	677	665	663	635	615	576	659	603	698	644	36	673	37
Point 16	551	544	547	541	577	526	516	580	552	593	590	556	26	582	27
Point 17	800	848	847	828	830	847	841	817	800	806	805	824	20	862	21
Point 18	274	369	390	343	375	274	331	425	359	390	406	358	49	374	52
Point 19	276	270	284	256	341	156	117	237	234	164	150	226	70	236	73
Point 20	799	804	681	781	778	738	521	800	866	759	703	748	91	783	95
Point 21	645	737	681	752	753	755	695	702	537	732	797	708	70	740	74
Point 22	659	573	552	565	534	489	628	394	400	516	507	529	82	553	86
Point 23	841	899	908	820	815	852	817	822	851	840	865	848	32	887	33
Point 24	248	294	256	304	556	597	309	297	216	228	322	330	127	345	133
Point 25	112	115	102	104	114	105	105	100	115	116	164	114	18	119	18
Point 26	183	204	201	226	177	206	359	361	319	330	337	264	76	276	79
Point 27	851	804	837	767	854	844	806	781	796	766	827	812	33	849	34
Point 28	972	986	964	976	990	946	1006	985	980	1015	1006	984	20	1029	21
Point 29	899	726	756	759	797	836	814	861	755	970	981	832	87	870	91
Point 30	303	294	327	297	350	295	246	273	274	372	223	296	43	309	45
Point 31	122	125	124	112	111	120	132	138	163	149	145	131	16	137	17
Point 32	172	163	178	151	137	148	137	133	140	120	126	146	19	153	19
Point 33	385	351	480	304	291	270	234	219	197	259	487	316	99	331	104
Point 34	962	886	898	899	903	861	901	929	944	811	861	896	42	937	44
Point 35	738	699	688	599	621	700	765	762	707	768	722	706	56	739	58
Point 36	402	303	377	565	506	447	509	523	376	304	441	432	88	452	92

Appendix F: Average Mass Flow Rate Uncertainty Tables and Individual Calculated Mass Flow Rate Uncertainty Tables

The following appendix is full of the uncertainty tables used to calculate the uncertainties for the different mass flow rates. The first four tables are the uncertainty tables used to calculate the average mass flow rate and the uncertainty for the average mass flow rate. The subsequent tables are the individual trials. Each table is labeled with what trial the data comes from. The last two tables are the data for the shakedown testing comparing the duct and non-duct cases at 5V.

Table 28: Average mass flow rate and uncertainty of average mass flow rate for 3V trials

Parameter	Representative Value	Syst. Uncertainty	Units	Relative Uncertainty (%)	UMF	RSSC (%)	UPC (%)
Mass Flow 1	0.085	0.004	slugs/min	4.770	0.338	1.613	22.200
Mass Flow 2	0.081	0.003	slugs/min	4.319	0.323	1.396	16.629
Mass Flow 3	0.085	0.004	slugs/min	4.656	0.339	1.576	21.196
Random	-	0.005	slugs/min	2.165	1.000	2.165	39.975
Avg. Mass Flowrate	0.083	0.003	slugs/min	-	-	3.424	100

Table 29: Average mass flow rate and uncertainty of average mass flow rate for 5V Trials

Parameter	Representative Value	Syst. Uncertainty	Units	Relative Uncertainty (%)	UMF	RSSC (%)	UPC (%)
Mass Flow 1	0.134	0.006	slugs/min	4.738	0.346	1.637	19.287
Mass Flow 2	0.125	0.005	slugs/min	4.004	0.325	1.300	12.157
Mass Flow 3	0.127	0.006	slugs/min	4.513	0.330	1.489	15.952
Random	-	0.010	slugs/min	2.703	1.000	2.703	52.603
Avg. Mass Flowrate	0.129	0.005	slugs/min	-	-	3.727	100

Table 30: Average mass flow rate and uncertainty of average mass flow rate for 10V Trials

Parameter	Representative Value	Syst. Uncertainty	Units	Relative Uncertainty (%)	UMF	RSSC (%)	UPC (%)
Mass Flow 1	0.233	0.009	slugs/min	4.058	0.337	1.368	31.336
Mass Flow 2	0.227	0.008	slugs/min	3.377	0.329	1.110	20.649
Mass Flow 3	0.231	0.009	slugs/min	3.972	0.334	1.327	29.518
Random	-	0.007	slugs/min	1.051	1.000	1.051	18.497
Avg. Mass Flowrate	0.231	0.006	slugs/min	-	-	2.443	100

Table 31: Average mass flow rate and uncertainty of average mass flow rate for 12V Trials

Parameter	Representative Value	Syst. Uncertainty	Units	Relative Uncertainty (%)	UMF	RSSC (%)	UPC (%)
Mass Flow 1	0.271	0.010	slugs/min	3.651	0.328	1.197	16.020
Mass Flow 2	0.284	0.010	slugs/min	3.374	0.344	1.160	15.039
Mass Flow 3	0.271	0.009	slugs/min	3.139	0.328	1.030	11.865
Random	-	0.019	slugs/min	2.260	1.000	2.260	57.077
Avg. Mass Flowrate	0.275	0.008	slugs/min	-	-	2.991	100

Table 32: Mass flow rate for 3V Trial #1 (V)

Parameter	Representative Value	Syst. Uncertainty	Units	Relative Uncertainty (%)	UMF	RSSC (%)	UPC (%)
Atmospheric Temperature	532.5	1.801	R	0.338	1.000	0.338	0.503
Atmospheric Pressure	2103.4	3.135	psf	0.149	1.000	0.149	0.098
Width	0.471	9.317E-05	ft	0.020	1.000	0.020	0.002
Height	0.470	9.317E-05	ft	0.020	1.000	0.020	0.002
Velocity 1	112	37.094	fpm	33.002	0.019	0.621	1.696
Velocity 2	174	53.943	fpm	30.999	0.029	0.903	3.587
Velocity 3	218	44.556	fpm	20.435	0.037	0.746	2.447
Velocity 4	196	54.697	fpm	27.977	0.033	0.916	3.688
Velocity 5	67	40.167	fpm	60.001	0.011	0.673	1.989
Velocity 6	38	22.193	fpm	59.086	0.006	0.372	0.607
Velocity 7	72	44.845	fpm	62.712	0.012	0.751	2.479
Velocity 8	110	35.525	fpm	32.234	0.018	0.595	1.556
Velocity 9	299	39.515	fpm	13.205	0.050	0.662	1.925
Velocity 10	252	42.086	fpm	16.676	0.042	0.705	2.184
Velocity 11	185	68.325	fpm	36.885	0.031	1.144	5.755
Velocity 12	78	43.887	fpm	56.079	0.013	0.735	2.375
Velocity 13	135	57.250	fpm	42.428	0.023	0.959	4.041
Velocity 14	220	51.575	fpm	23.469	0.037	0.864	3.279
Velocity 15	260	37.574	fpm	14.463	0.044	0.629	1.740
Velocity 16	180	41.161	fpm	22.830	0.030	0.689	2.089
Velocity 17	239	59.076	fpm	24.722	0.040	0.989	4.302
Velocity 18	141	55.969	fpm	39.635	0.024	0.937	3.862
Velocity 19	62	28.676	fpm	46.181	0.010	0.480	1.014
Velocity 20	186	52.528	fpm	28.255	0.031	0.880	3.402
Velocity 21	247	37.554	fpm	15.184	0.041	0.629	1.739
Velocity 22	211	49.313	fpm	23.391	0.035	0.826	2.998
Velocity 23	317	38.604	fpm	12.195	0.053	0.646	1.837
Velocity 24	175	77.125	fpm	44.032	0.029	1.292	7.333
Velocity 25	35	22.244	fpm	63.739	0.006	0.373	0.610
Velocity 26	136	49.354	fpm	36.320	0.023	0.826	3.003
Velocity 27	278	36.605	fpm	13.179	0.047	0.613	1.652
Velocity 28	304	36.634	fpm	12.062	0.051	0.613	1.655
Velocity 29	198	70.985	fpm	35.837	0.033	1.189	6.212
Velocity 30	66	28.234	fpm	42.661	0.011	0.473	0.983
Velocity 31	50	25.392	fpm	50.383	0.008	0.425	0.795
Velocity 32	81	30.396	fpm	37.739	0.013	0.509	1.139
Velocity 33	157	73.229	fpm	46.757	0.026	1.226	6.611
Velocity 34	236	44.136	fpm	18.693	0.040	0.739	2.401
Velocity 35	164	55.389	fpm	33.728	0.028	0.928	3.782
Velocity 36	93	46.041	fpm	49.507	0.016	0.771	2.613
Integration	-	5.430E-05	slugs/min	0.064	1.000	0.064	0.018
Mass Flowrate	0.085	0.004	slugs/min	-	-	4.770	100

Table 33: Mass flow rate for 3V Trial #2 (V)

Parameter	Representative Value	Syst. Uncertainty	Units	Relative Uncertainty (%)	UMF	RSSC (%)	UPC (%)
Atmospheric Temperature	530.8	1.801	R	0.339	1.000	0.339	0.617
Atmospheric Pressure	2066.2	3.135	psf	0.152	1.000	0.152	0.123
Width	0.471	9.317E-05	ft	0.020	1.000	0.020	0.002
Height	0.470	9.317E-05	ft	0.020	1.000	0.020	0.002
Velocity 1	56	24.826	fpm	44.628	0.010	0.429	0.985
Velocity 2	104	29.959	fpm	28.825	0.018	0.517	1.435
Velocity 3	159	52.068	fpm	32.651	0.028	0.899	4.333
Velocity 4	63	27.922	fpm	44.156	0.011	0.482	1.246
Velocity 5	38	23.042	fpm	61.191	0.007	0.398	0.849
Velocity 6	27	21.409	fpm	78.996	0.005	0.370	0.733
Velocity 7	47	27.141	fpm	57.428	0.008	0.469	1.177
Velocity 8	195	46.035	fpm	23.627	0.034	0.795	3.387
Velocity 9	291	37.228	fpm	12.782	0.050	0.643	2.215
Velocity 10	234	55.541	fpm	23.743	0.040	0.959	4.931
Velocity 11	117	44.007	fpm	37.472	0.020	0.760	3.095
Velocity 12	47	23.921	fpm	51.339	0.008	0.413	0.915
Velocity 13	73	30.033	fpm	41.070	0.013	0.519	1.442
Velocity 14	249	39.470	fpm	15.855	0.043	0.681	2.490
Velocity 15	265	45.428	fpm	17.172	0.046	0.784	3.298
Velocity 16	262	34.881	fpm	13.310	0.045	0.602	1.945
Velocity 17	151	56.884	fpm	37.647	0.026	0.982	5.172
Velocity 18	42	23.873	fpm	57.057	0.007	0.412	0.911
Velocity 19	74	32.181	fpm	43.333	0.013	0.556	1.655
Velocity 20	288	35.969	fpm	12.471	0.050	0.621	2.068
Velocity 21	112	30.559	fpm	27.350	0.019	0.528	1.493
Velocity 22	205	35.501	fpm	17.284	0.035	0.613	2.014
Velocity 23	278	43.881	fpm	15.798	0.048	0.758	3.078
Velocity 24	100	30.812	fpm	30.743	0.017	0.532	1.517
Velocity 25	47	23.778	fpm	50.929	0.008	0.411	0.904
Velocity 26	257	46.015	fpm	17.922	0.044	0.794	3.384
Velocity 27	320	38.406	fpm	12.021	0.055	0.663	2.358
Velocity 28	326	42.792	fpm	13.120	0.056	0.739	2.927
Velocity 29	178	62.724	fpm	35.143	0.031	1.083	6.288
Velocity 30	159	71.764	fpm	45.083	0.027	1.239	8.231
Velocity 31	75	28.204	fpm	37.783	0.013	0.487	1.271
Velocity 32	193	88.656	fpm	45.882	0.033	1.531	12.563
Velocity 33	247	39.392	fpm	15.951	0.043	0.680	2.480
Velocity 34	247	35.712	fpm	14.433	0.043	0.617	2.038
Velocity 35	163	33.309	fpm	20.497	0.028	0.575	1.773
Velocity 36	103	39.040	fpm	38.084	0.018	0.674	2.436
Integration	-	1.632E-04	slugs/min	0.202	1.000	0.202	0.219
Mass Flowrate	0.081	0.003	slugs/min	-	-	4.319	100

Table 34: Mass flow rate for 3V Trial #3 (V)

Parameter	Representative Value	Syst. Uncertainty	Units	Relative Uncertainty (%)	UMF	RSSC (%)	UPC (%)
Atmospheric Temperature	531.5	1.801	R	0.339	1.000	0.339	0.529
Atmospheric Pressure	2088.5	3.135	psf	0.150	1.000	0.150	0.104
Width	0.471	9.317E-05	ft	0.020	1.000	0.020	0.002
Height	0.470	9.317E-05	ft	0.020	1.000	0.020	0.002
Velocity 1	185	51.792	fpm	28.061	0.031	0.862	3.428
Velocity 2	258	40.549	fpm	15.701	0.043	0.675	2.101
Velocity 3	265	35.502	fpm	13.396	0.044	0.591	1.611
Velocity 4	170	59.867	fpm	35.152	0.028	0.996	4.580
Velocity 5	53	24.746	fpm	46.974	0.009	0.412	0.783
Velocity 6	37	22.786	fpm	61.917	0.006	0.379	0.663
Velocity 7	106	38.382	fpm	36.364	0.018	0.639	1.883
Velocity 8	265	52.581	fpm	19.876	0.044	0.875	3.533
Velocity 9	256	37.500	fpm	14.649	0.043	0.624	1.797
Velocity 10	282	43.504	fpm	15.435	0.047	0.724	2.419
Velocity 11	179	59.758	fpm	33.409	0.030	0.995	4.563
Velocity 12	65	36.627	fpm	56.478	0.011	0.610	1.714
Velocity 13	141	40.832	fpm	28.857	0.024	0.680	2.131
Velocity 14	247	39.217	fpm	15.880	0.041	0.653	1.965
Velocity 15	147	50.052	fpm	34.091	0.024	0.833	3.201
Velocity 16	167	35.186	fpm	21.072	0.028	0.586	1.582
Velocity 17	199	48.777	fpm	24.508	0.033	0.812	3.040
Velocity 18	110	38.636	fpm	35.117	0.018	0.643	1.908
Velocity 19	83	38.073	fpm	46.074	0.014	0.634	1.852
Velocity 20	262	41.411	fpm	15.825	0.044	0.689	2.191
Velocity 21	269	44.057	fpm	16.383	0.045	0.733	2.480
Velocity 22	228	68.297	fpm	29.951	0.038	1.137	5.961
Velocity 23	254	46.645	fpm	18.379	0.042	0.776	2.780
Velocity 24	44	22.728	fpm	51.291	0.007	0.378	0.660
Velocity 25	56	30.149	fpm	54.105	0.009	0.502	1.162
Velocity 26	76	45.104	fpm	59.739	0.013	0.751	2.600
Velocity 27	205	65.714	fpm	32.083	0.034	1.094	5.518
Velocity 28	307	41.995	fpm	13.698	0.051	0.699	2.254
Velocity 29	146	43.637	fpm	29.876	0.024	0.726	2.433
Velocity 30	76	25.032	fpm	32.947	0.013	0.417	0.801
Velocity 31	45	25.278	fpm	56.202	0.007	0.421	0.817
Velocity 32	57	25.024	fpm	44.081	0.009	0.417	0.800
Velocity 33	160	106.920	fpm	66.968	0.027	1.780	14.609
Velocity 34	193	62.723	fpm	32.445	0.032	1.044	5.027
Velocity 35	250	41.147	fpm	16.440	0.042	0.685	2.164
Velocity 36	168	42.910	fpm	25.524	0.028	0.714	2.353
Integration	-	4.051E-06	slugs/min	0.005	1.000	0.005	0.000
Mass Flowrate	0.085	0.004	slugs/min	-	-	4.656	100

Table 35: Mass flow rate for 5V Trial #1 (V)

Parameter	Representative Value	Syst. Uncertainty	Units	Relative Uncertainty (%)	UMF	RSSC (%)	UPC (%)
Atmospheric Temperature	534.3	1.801	R	0.337	1.000	0.337	0.506
Atmospheric Pressure	2103.8	3.135	psf	0.149	1.000	0.149	0.099
Width	0.471	9.317E-05	ft	0.020	1.000	0.020	0.002
Height	0.470	9.317E-05	ft	0.020	1.000	0.020	0.002
Velocity 1	153	48.056	fpm	31.487	0.016	0.508	1.150
Velocity 2	189	50.136	fpm	26.481	0.020	0.530	1.251
Velocity 3	357	59.490	fpm	16.648	0.038	0.629	1.762
Velocity 4	286	53.843	fpm	18.855	0.030	0.569	1.443
Velocity 5	58	23.481	fpm	40.283	0.006	0.248	0.274
Velocity 6	50	22.853	fpm	45.516	0.005	0.242	0.260
Velocity 7	124	91.329	fpm	73.937	0.013	0.965	4.152
Velocity 8	356	67.933	fpm	19.097	0.038	0.718	2.297
Velocity 9	449	85.423	fpm	19.032	0.047	0.903	3.632
Velocity 10	404	104.900	fpm	25.944	0.043	1.109	5.478
Velocity 11	152	51.616	fpm	34.053	0.016	0.546	1.326
Velocity 12	97	38.175	fpm	39.359	0.010	0.404	0.725
Velocity 13	261	91.552	fpm	35.125	0.028	0.968	4.172
Velocity 14	433	105.653	fpm	24.382	0.046	1.117	5.557
Velocity 15	294	51.250	fpm	17.448	0.031	0.542	1.308
Velocity 16	404	90.213	fpm	22.323	0.043	0.954	4.051
Velocity 17	381	83.306	fpm	21.874	0.040	0.881	3.455
Velocity 18	241	85.880	fpm	35.613	0.025	0.908	3.671
Velocity 19	153	64.462	fpm	42.237	0.016	0.681	2.069
Velocity 20	415	90.830	fpm	21.883	0.044	0.960	4.107
Velocity 21	301	65.291	fpm	21.715	0.032	0.690	2.122
Velocity 22	314	73.633	fpm	23.458	0.033	0.778	2.699
Velocity 23	448	140.854	fpm	31.469	0.047	1.489	9.876
Velocity 24	232	86.892	fpm	37.389	0.025	0.918	3.759
Velocity 25	74	27.391	fpm	36.788	0.008	0.290	0.373
Velocity 26	264	74.163	fpm	28.135	0.028	0.784	2.738
Velocity 27	411	91.859	fpm	22.346	0.043	0.971	4.200
Velocity 28	492	84.518	fpm	17.192	0.052	0.893	3.556
Velocity 29	450	95.655	fpm	21.245	0.048	1.011	4.555
Velocity 30	194	61.092	fpm	31.462	0.021	0.646	1.858
Velocity 31	76	28.515	fpm	37.391	0.008	0.301	0.405
Velocity 32	134	68.641	fpm	51.122	0.014	0.726	2.345
Velocity 33	258	55.131	fpm	21.347	0.027	0.583	1.513
Velocity 34	214	77.615	fpm	36.293	0.023	0.820	2.999
Velocity 35	168	64.263	fpm	38.203	0.018	0.679	2.056
Velocity 36	174	63.624	fpm	36.542	0.018	0.673	2.015
Integration	-	2.699E-04	slugs/min	0.202	1.000	0.202	0.182
Mass Flowrate	0.134	0.006	slugs/min	-	-	4.738	100

Table 36: Mass flow rate for 5V Trial #2 (V)

Parameter	Representative Value	Syst. Uncertainty	Units	Relative Uncertainty (%)	UMF	RSSC (%)	UPC (%)
Atmospheric Temperature	531.5	1.801	R	0.339	1.000	0.339	0.716
Atmospheric Pressure	2086.5	3.135	psf	0.150	1.000	0.150	0.141
Width	0.471	9.317E-05	ft	0.020	1.000	0.020	0.002
Height	0.470	9.317E-05	ft	0.020	1.000	0.020	0.002
Velocity 1	79	27.361	fpm	34.459	0.009	0.307	0.588
Velocity 2	158	69.379	fpm	43.820	0.018	0.778	3.779
Velocity 3	139	45.204	fpm	32.538	0.016	0.507	1.604
Velocity 4	270	40.165	fpm	14.873	0.030	0.451	1.266
Velocity 5	88	32.991	fpm	37.629	0.010	0.370	0.854
Velocity 6	47	22.752	fpm	48.632	0.005	0.255	0.406
Velocity 7	260	76.969	fpm	29.574	0.029	0.863	4.651
Velocity 8	385	68.606	fpm	17.832	0.043	0.770	3.695
Velocity 9	462	84.572	fpm	18.311	0.052	0.949	5.615
Velocity 10	389	54.409	fpm	13.973	0.044	0.610	2.324
Velocity 11	240	63.811	fpm	26.597	0.027	0.716	3.196
Velocity 12	61	24.968	fpm	40.708	0.007	0.280	0.489
Velocity 13	259	62.877	fpm	24.301	0.029	0.705	3.103
Velocity 14	377	47.385	fpm	12.577	0.042	0.532	1.763
Velocity 15	122	30.091	fpm	24.722	0.014	0.338	0.711
Velocity 16	383	44.353	fpm	11.580	0.043	0.498	1.544
Velocity 17	310	49.738	fpm	16.025	0.035	0.558	1.942
Velocity 18	68	25.246	fpm	36.874	0.008	0.283	0.500
Velocity 19	140	34.107	fpm	24.416	0.016	0.383	0.913
Velocity 20	394	87.516	fpm	22.198	0.044	0.982	6.012
Velocity 21	126	34.615	fpm	27.557	0.014	0.388	0.941
Velocity 22	110	32.917	fpm	29.841	0.012	0.369	0.851
Velocity 23	349	62.048	fpm	17.775	0.039	0.696	3.022
Velocity 24	249	51.981	fpm	20.912	0.028	0.583	2.121
Velocity 25	67	27.761	fpm	41.587	0.007	0.311	0.605
Velocity 26	301	60.318	fpm	20.067	0.034	0.677	2.856
Velocity 27	437	87.996	fpm	20.152	0.049	0.987	6.078
Velocity 28	434	86.928	fpm	20.025	0.049	0.975	5.932
Velocity 29	444	88.129	fpm	19.829	0.050	0.989	6.097
Velocity 30	237	82.649	fpm	34.892	0.027	0.927	5.362
Velocity 31	99	33.150	fpm	33.488	0.011	0.372	0.863
Velocity 32	323	64.102	fpm	19.874	0.036	0.719	3.226
Velocity 33	399	89.308	fpm	22.383	0.045	1.002	6.261
Velocity 34	360	47.188	fpm	13.125	0.040	0.529	1.748
Velocity 35	224	62.735	fpm	27.967	0.025	0.704	3.089
Velocity 36	126	68.689	fpm	54.517	0.014	0.770	3.704
Integration	-	6.001E-04	slugs/min	0.478	1.000	0.478	1.428
Mass Flowrate	0.125	0.005	slugs/min	-	-	4.004	100

Table 37: Mass flow rate for 5V Trial #3 (V)

Parameter	Representative Value	Syst. Uncertainty	Units	Relative Uncertainty (%)	UMF	RSSC (%)	UPC (%)
Atmospheric Temperature	531.6	1.801	R	0.339	1.000	0.339	0.563
Atmospheric Pressure	2076.2	3.135	psf	0.151	1.000	0.151	0.112
Width	0.471	9.317E-05	ft	0.020	1.000	0.020	0.002
Height	0.470	9.317E-05	ft	0.020	1.000	0.020	0.002
Velocity 1	225	86.849	fpm	38.618	0.025	0.954	4.467
Velocity 2	369	46.808	fpm	12.684	0.041	0.514	1.298
Velocity 3	413	81.372	fpm	19.685	0.045	0.894	3.921
Velocity 4	265	88.001	fpm	33.241	0.029	0.967	4.586
Velocity 5	79	38.367	fpm	48.553	0.009	0.421	0.872
Velocity 6	56	26.644	fpm	47.571	0.006	0.293	0.420
Velocity 7	233	77.143	fpm	33.140	0.026	0.847	3.524
Velocity 8	401	90.306	fpm	22.542	0.044	0.992	4.829
Velocity 9	405	80.135	fpm	19.768	0.045	0.880	3.803
Velocity 10	296	60.771	fpm	20.510	0.033	0.667	2.187
Velocity 11	120	49.188	fpm	40.891	0.013	0.540	1.433
Velocity 12	64	26.184	fpm	40.733	0.007	0.288	0.406
Velocity 13	280	54.229	fpm	19.345	0.031	0.596	1.742
Velocity 14	360	75.121	fpm	20.850	0.040	0.825	3.342
Velocity 15	294	52.076	fpm	17.735	0.032	0.572	1.606
Velocity 16	288	68.491	fpm	23.811	0.032	0.752	2.778
Velocity 17	268	58.763	fpm	21.921	0.029	0.645	2.045
Velocity 18	110	32.093	fpm	29.246	0.012	0.352	0.610
Velocity 19	247	76.387	fpm	30.873	0.027	0.839	3.455
Velocity 20	175	93.812	fpm	53.617	0.019	1.030	5.212
Velocity 21	333	51.467	fpm	15.438	0.037	0.565	1.569
Velocity 22	338	60.604	fpm	17.912	0.037	0.666	2.175
Velocity 23	430	85.177	fpm	19.796	0.047	0.936	4.296
Velocity 24	249	81.847	fpm	32.840	0.027	0.899	3.967
Velocity 25	99	57.684	fpm	58.385	0.011	0.634	1.970
Velocity 26	90	30.670	fpm	34.022	0.010	0.337	0.557
Velocity 27	188	64.253	fpm	34.213	0.021	0.706	2.445
Velocity 28	443	81.994	fpm	18.523	0.049	0.901	3.981
Velocity 29	500	87.447	fpm	17.503	0.055	0.960	4.529
Velocity 30	272	88.576	fpm	32.513	0.030	0.973	4.646
Velocity 31	74	25.070	fpm	33.714	0.008	0.275	0.372
Velocity 32	76	27.968	fpm	36.949	0.008	0.307	0.463
Velocity 33	114	63.960	fpm	56.052	0.013	0.703	2.423
Velocity 34	383	97.882	fpm	25.555	0.042	1.075	5.674
Velocity 35	343	43.215	fpm	12.589	0.038	0.475	1.106
Velocity 36	223	105.093	fpm	47.190	0.024	1.154	6.540
Integration	-	1.560E-04	slugs/min	0.122	1.000	0.122	0.074
Mass Flowrate	0.127	0.006	slugs/min	-	-	4.513	100

Table 38: Mass flow rate for 10V Trial #1 (V)

Parameter	Representative Value	Syst. Uncertainty	Units	Relative Uncertainty (%)	UMF	RSSC (%)	UPC (%)
Atmospheric Temperature	531.8	1.801	R	0.339	1.000	0.339	0.696
Atmospheric Pressure	2104.4	3.135	psf	0.149	1.000	0.149	0.135
Width	0.471	9.317E-05	ft	0.020	1.000	0.020	0.002
Height	0.470	9.317E-05	ft	0.020	1.000	0.020	0.002
Velocity 1	284	64.185	fpm	22.635	0.017	0.390	0.926
Velocity 2	449	117.299	fpm	26.101	0.027	0.713	3.091
Velocity 3	667	125.657	fpm	18.848	0.041	0.764	3.547
Velocity 4	363	157.419	fpm	43.371	0.022	0.957	5.567
Velocity 5	105	26.551	fpm	25.178	0.006	0.161	0.158
Velocity 6	97	25.800	fpm	26.705	0.006	0.157	0.150
Velocity 7	254	72.508	fpm	28.559	0.015	0.441	1.181
Velocity 8	788	120.968	fpm	15.357	0.048	0.736	3.288
Velocity 9	743	109.076	fpm	14.676	0.045	0.663	2.673
Velocity 10	718	99.686	fpm	13.889	0.044	0.606	2.233
Velocity 11	330	66.705	fpm	20.216	0.020	0.406	1.000
Velocity 12	132	32.615	fpm	24.765	0.008	0.198	0.239
Velocity 13	627	123.906	fpm	19.764	0.038	0.754	3.449
Velocity 14	767	106.116	fpm	13.828	0.047	0.645	2.530
Velocity 15	525	116.888	fpm	22.248	0.032	0.711	3.070
Velocity 16	508	164.151	fpm	32.339	0.031	0.998	6.054
Velocity 17	598	105.995	fpm	17.730	0.036	0.645	2.524
Velocity 18	260	117.760	fpm	45.213	0.016	0.716	3.116
Velocity 19	258	50.262	fpm	19.447	0.016	0.306	0.568
Velocity 20	530	191.156	fpm	36.039	0.032	1.163	8.209
Velocity 21	558	105.853	fpm	18.980	0.034	0.644	2.517
Velocity 22	504	113.656	fpm	22.547	0.031	0.691	2.902
Velocity 23	654	121.371	fpm	18.549	0.040	0.738	3.310
Velocity 24	478	146.987	fpm	30.737	0.029	0.894	4.854
Velocity 25	173	66.767	fpm	38.685	0.010	0.406	1.002
Velocity 26	321	142.889	fpm	44.510	0.020	0.869	4.587
Velocity 27	628	129.401	fpm	20.621	0.038	0.787	3.762
Velocity 28	805	110.580	fpm	13.734	0.049	0.673	2.747
Velocity 29	784	111.387	fpm	14.202	0.048	0.677	2.787
Velocity 30	562	138.769	fpm	24.688	0.034	0.844	4.326
Velocity 31	114	32.063	fpm	28.169	0.007	0.195	0.231
Velocity 32	135	32.286	fpm	23.944	0.008	0.196	0.234
Velocity 33	339	131.779	fpm	38.884	0.021	0.801	3.902
Velocity 34	662	125.655	fpm	18.986	0.040	0.764	3.547
Velocity 35	453	121.910	fpm	26.905	0.028	0.741	3.339
Velocity 36	270	69.976	fpm	25.957	0.016	0.426	1.100
Integration	-	6.320E-04	slugs/min	0.271	1.000	0.271	0.446
Mass Flowrate	0.233	0.009	slugs/min	-	-	4.058	100

Table 39: Mass flow rate for 10V Trial #2 (V)

Parameter	Representative Value	Syst. Uncertainty	Units	Relative Uncertainty(%)	UMF	RSSC (%)	UPC (%)
Atmospheric Temperature	532.5	1.801	R	0.338	1.000	0.338	1.003
Atmospheric Pressure	2087.1	3.135	psf	0.150	1.000	0.150	0.198
Width	0.471	9.317E-05	ft	0.020	1.000	0.020	0.003
Height	0.470	9.317E-05	ft	0.020	1.000	0.020	0.003
Velocity 1	153	38.384	fpm	25.118	0.009	0.237	0.493
Velocity 2	348	63.341	fpm	18.180	0.022	0.391	1.342
Velocity 3	565	90.933	fpm	16.093	0.035	0.562	2.766
Velocity 4	613	116.726	fpm	19.031	0.038	0.721	4.557
Velocity 5	381	80.976	fpm	21.268	0.024	0.500	2.193
Velocity 6	169	41.654	fpm	24.623	0.010	0.257	0.580
Velocity 7	490	112.066	fpm	22.875	0.030	0.692	4.201
Velocity 8	664	98.738	fpm	14.861	0.041	0.610	3.261
Velocity 9	814	107.192	fpm	13.177	0.050	0.662	3.843
Velocity 10	710	105.199	fpm	14.826	0.044	0.650	3.702
Velocity 11	438	100.722	fpm	22.977	0.027	0.622	3.393
Velocity 12	134	44.138	fpm	32.943	0.008	0.273	0.652
Velocity 13	445	99.677	fpm	22.388	0.027	0.616	3.323
Velocity 14	637	102.329	fpm	16.052	0.039	0.632	3.502
Velocity 15	262	42.383	fpm	16.155	0.016	0.262	0.601
Velocity 16	197	36.178	fpm	18.344	0.012	0.223	0.438
Velocity 17	472	120.239	fpm	25.493	0.029	0.743	4.836
Velocity 18	180	53.601	fpm	29.824	0.011	0.331	0.961
Velocity 19	142	37.699	fpm	26.607	0.009	0.233	0.475
Velocity 20	547	112.329	fpm	20.544	0.034	0.694	4.220
Velocity 21	270	51.200	fpm	18.932	0.017	0.316	0.877
Velocity 22	405	89.216	fpm	22.045	0.025	0.551	2.662
Velocity 23	528	108.120	fpm	20.461	0.033	0.668	3.910
Velocity 24	416	103.174	fpm	24.811	0.026	0.637	3.560
Velocity 25	95	26.404	fpm	27.712	0.006	0.163	0.233
Velocity 26	550	103.576	fpm	18.835	0.034	0.640	3.588
Velocity 27	795	108.372	fpm	13.626	0.049	0.669	3.928
Velocity 28	828	107.471	fpm	12.985	0.051	0.664	3.863
Velocity 29	775	104.039	fpm	13.431	0.048	0.643	3.620
Velocity 30	696	113.374	fpm	16.286	0.043	0.700	4.299
Velocity 31	114	31.490	fpm	27.619	0.007	0.194	0.332
Velocity 32	139	38.338	fpm	27.672	0.009	0.237	0.492
Velocity 33	614	102.525	fpm	16.703	0.038	0.633	3.516
Velocity 34	666	130.671	fpm	19.617	0.041	0.807	5.711
Velocity 35	698	125.907	fpm	18.049	0.043	0.778	5.302
Velocity 36	241	75.196	fpm	31.158	0.015	0.464	1.891
Integration	-	9.929E-04	slugs/min	0.437	1.000	0.437	1.671
Mass Flowrate	0.227	0.008	slugs/min	-	-	3.377	100

Table 40: Mass flow rate for 10V Trial #3 (V)

Parameter	Representative Value	Syst. Uncertainty	Units	Relative Uncertainty (%)	UMF	RSSC (%)	UPC (%)
Atmospheric Temperature	531.5	1.801	R	0.339	1.000	0.339	0.728
Atmospheric Pressure	2075.4	3.135	psf	0.151	1.000	0.151	0.145
Width	0.471	9.317E-05	ft	0.020	1.000	0.020	0.002
Height	0.470	9.317E-05	ft	0.020	1.000	0.020	0.002
Velocity 1	328	118.455	fpm	36.118	0.020	0.717	3.259
Velocity 2	564	133.013	fpm	23.581	0.034	0.805	4.109
Velocity 3	526	207.376	fpm	39.458	0.032	1.255	9.987
Velocity 4	550	128.101	fpm	23.291	0.033	0.775	3.811
Velocity 5	213	56.333	fpm	26.459	0.013	0.341	0.737
Velocity 6	90	25.170	fpm	27.862	0.005	0.152	0.147
Velocity 7	274	141.400	fpm	51.596	0.017	0.856	4.643
Velocity 8	532	99.434	fpm	18.699	0.032	0.602	2.296
Velocity 9	697	101.094	fpm	14.506	0.042	0.612	2.373
Velocity 10	657	93.511	fpm	14.238	0.040	0.566	2.031
Velocity 11	364	118.599	fpm	32.616	0.022	0.718	3.266
Velocity 12	236	115.696	fpm	48.922	0.014	0.700	3.109
Velocity 13	455	103.537	fpm	22.760	0.028	0.627	2.489
Velocity 14	709	102.771	fpm	14.489	0.043	0.622	2.453
Velocity 15	645	101.566	fpm	15.756	0.039	0.615	2.396
Velocity 16	360	67.995	fpm	18.887	0.022	0.412	1.074
Velocity 17	674	100.663	fpm	14.944	0.041	0.609	2.353
Velocity 18	321	84.852	fpm	26.408	0.019	0.514	1.672
Velocity 19	354	210.660	fpm	59.488	0.021	1.275	10.306
Velocity 20	728	122.575	fpm	16.833	0.044	0.742	3.489
Velocity 21	784	104.695	fpm	13.358	0.047	0.634	2.545
Velocity 22	600	117.546	fpm	19.590	0.036	0.711	3.209
Velocity 23	820	122.477	fpm	14.942	0.050	0.741	3.484
Velocity 24	653	140.767	fpm	21.573	0.039	0.852	4.602
Velocity 25	134	45.741	fpm	34.164	0.008	0.277	0.486
Velocity 26	148	30.305	fpm	20.443	0.009	0.183	0.213
Velocity 27	346	84.899	fpm	24.542	0.021	0.514	1.674
Velocity 28	813	109.225	fpm	13.434	0.049	0.661	2.771
Velocity 29	799	105.927	fpm	13.252	0.048	0.641	2.606
Velocity 30	464	127.644	fpm	27.513	0.028	0.773	3.784
Velocity 31	167	35.564	fpm	21.286	0.010	0.215	0.294
Velocity 32	180	39.403	fpm	21.913	0.011	0.239	0.361
Velocity 33	180	41.279	fpm	22.872	0.011	0.250	0.396
Velocity 34	278	98.705	fpm	35.463	0.017	0.597	2.263
Velocity 35	483	103.262	fpm	21.377	0.029	0.625	2.476
Velocity 36	396	91.920	fpm	23.220	0.024	0.556	1.962
Integration	-	1.138E-05	slugs/min	0.005	1.000	0.005	0.000
Mass Flowrate	0.231	0.009	slugs/min	-	-	3.972	100

Table 41: Mass flow rate for 12V Trial #1 (V)

Parameter	Representative Value	Syst. Uncertainty	Units	Relative Uncertainty (%)	UMF	RSSC (%)	UPC (%)
Atmospheric Temperature	531.8	1.801	R	0.339	1.000	0.339	0.860
Atmospheric Pressure	2103.0	3.135	psf	0.149	1.000	0.149	0.167
Width	0.471	9.317E-05	ft	0.020	1.000	0.020	0.003
Height	0.470	9.317E-05	ft	0.020	1.000	0.020	0.003
Velocity 1	337	99.902	fpm	29.678	0.018	0.523	2.052
Velocity 2	723	110.955	fpm	15.355	0.038	0.581	2.532
Velocity 3	751	117.841	fpm	15.689	0.039	0.617	2.856
Velocity 4	320	112.278	fpm	35.120	0.017	0.588	2.592
Velocity 5	127	27.944	fpm	22.062	0.007	0.146	0.161
Velocity 6	115	27.485	fpm	23.829	0.006	0.144	0.155
Velocity 7	198	69.221	fpm	34.998	0.010	0.362	0.985
Velocity 8	578	134.418	fpm	23.269	0.030	0.704	3.715
Velocity 9	921	106.492	fpm	11.567	0.048	0.558	2.332
Velocity 10	805	116.208	fpm	14.440	0.042	0.608	2.777
Velocity 11	321	89.139	fpm	27.742	0.017	0.467	1.634
Velocity 12	147	33.912	fpm	23.097	0.008	0.178	0.236
Velocity 13	453	158.730	fpm	35.039	0.024	0.831	5.181
Velocity 14	941	112.025	fpm	11.902	0.049	0.587	2.581
Velocity 15	666	110.208	fpm	16.559	0.035	0.577	2.498
Velocity 16	685	115.598	fpm	16.865	0.036	0.605	2.748
Velocity 17	692	136.807	fpm	19.776	0.036	0.716	3.849
Velocity 18	233	72.551	fpm	31.180	0.012	0.380	1.082
Velocity 19	400	119.435	fpm	29.877	0.021	0.625	2.933
Velocity 20	825	116.986	fpm	14.172	0.043	0.613	2.814
Velocity 21	656	151.462	fpm	23.104	0.034	0.793	4.717
Velocity 22	742	123.606	fpm	16.652	0.039	0.647	3.142
Velocity 23	866	142.412	fpm	16.445	0.045	0.746	4.171
Velocity 24	417	101.262	fpm	24.279	0.022	0.530	2.109
Velocity 25	151	50.157	fpm	33.111	0.008	0.263	0.517
Velocity 26	340	118.933	fpm	34.937	0.018	0.623	2.909
Velocity 27	785	131.787	fpm	16.791	0.041	0.690	3.571
Velocity 28	1029	117.915	fpm	11.462	0.054	0.617	2.859
Velocity 29	706	171.489	fpm	24.282	0.037	0.898	6.047
Velocity 30	478	178.877	fpm	37.428	0.025	0.937	6.580
Velocity 31	148	34.618	fpm	23.442	0.008	0.181	0.246
Velocity 32	245	65.804	fpm	26.812	0.013	0.345	0.890
Velocity 33	783	130.972	fpm	16.717	0.041	0.686	3.527
Velocity 34	852	125.174	fpm	14.693	0.045	0.655	3.222
Velocity 35	432	185.521	fpm	42.954	0.023	0.971	7.078
Velocity 36	233	87.842	fpm	37.751	0.012	0.460	1.587
Integration	-	2.815E-04	slugs/min	0.104	1.000	0.104	0.081
Mass Flowrate	0.271	0.010	slugs/min	-	-	3.651	100

Table 42: Mass flow rate for 12V Trial #2 (V)

Parameter	Representative Value	Syst. Uncertainty	Units	Relative Uncertainty (%)	UMF	RSSC (%)	UPC (%)
Atmospheric Temperature	532.0	1.801	R	0.338	1.000	0.339	1.007
Atmospheric Pressure	2066.8	3.135	psf	0.152	1.000	0.152	0.202
Width	0.471	9.317E-05	ft	0.020	1.000	0.020	0.003
Height	0.470	9.317E-05	ft	0.020	1.000	0.020	0.003
Velocity 1	223	73.900	fpm	33.155	0.011	0.363	1.155
Velocity 2	113	28.399	fpm	25.160	0.006	0.139	0.171
Velocity 3	471	133.438	fpm	28.338	0.023	0.655	3.765
Velocity 4	552	109.405	fpm	19.809	0.027	0.537	2.531
Velocity 5	229	59.700	fpm	26.126	0.011	0.293	0.754
Velocity 6	181	56.751	fpm	31.329	0.009	0.278	0.681
Velocity 7	152	46.790	fpm	30.792	0.007	0.230	0.463
Velocity 8	426	165.431	fpm	38.790	0.021	0.811	5.786
Velocity 9	906	119.412	fpm	13.177	0.044	0.586	3.015
Velocity 10	868	119.428	fpm	13.756	0.043	0.586	3.016
Velocity 11	477	137.178	fpm	28.766	0.023	0.673	3.979
Velocity 12	209	41.059	fpm	19.600	0.010	0.201	0.356
Velocity 13	693	123.150	fpm	17.782	0.034	0.604	3.207
Velocity 14	911	127.641	fpm	14.014	0.045	0.626	3.445
Velocity 15	821	129.388	fpm	15.752	0.040	0.635	3.540
Velocity 16	733	112.457	fpm	15.347	0.036	0.552	2.674
Velocity 17	417	143.326	fpm	34.357	0.020	0.703	4.343
Velocity 18	149	52.819	fpm	35.492	0.007	0.259	0.590
Velocity 19	347	77.125	fpm	22.227	0.017	0.378	1.258
Velocity 20	792	106.237	fpm	13.409	0.039	0.521	2.386
Velocity 21	303	88.393	fpm	29.186	0.015	0.434	1.652
Velocity 22	457	144.434	fpm	31.571	0.022	0.708	4.411
Velocity 23	739	108.879	fpm	14.731	0.036	0.534	2.506
Velocity 24	552	131.291	fpm	23.793	0.027	0.644	3.645
Velocity 25	314	81.770	fpm	26.034	0.015	0.401	1.414
Velocity 26	806	133.879	fpm	16.609	0.040	0.657	3.790
Velocity 27	938	112.486	fpm	11.999	0.046	0.552	2.675
Velocity 28	793	125.864	fpm	15.869	0.039	0.617	3.349
Velocity 29	905	106.019	fpm	11.713	0.044	0.520	2.377
Velocity 30	760	188.945	fpm	24.859	0.037	0.927	7.548
Velocity 31	365	80.300	fpm	21.991	0.018	0.394	1.363
Velocity 32	877	165.243	fpm	18.839	0.043	0.811	5.773
Velocity 33	918	117.527	fpm	12.805	0.045	0.577	2.920
Velocity 34	873	119.572	fpm	13.690	0.043	0.587	3.023
Velocity 35	603	116.528	fpm	19.332	0.030	0.572	2.871
Velocity 36	512	97.981	fpm	19.142	0.025	0.481	2.030
Integration	-	5.475E-04	slugs/min	0.193	1.000	0.193	0.327
Mass Flowrate	0.284	0.010	slugs/min	-	-	3.374	100

Table 43: Mass flow rate for 12V Trial #3 (V)

Parameter	Representative Value	Syst. Uncertainty	Units	Relative Uncertainty (%)	UMF	RSSC (%)	UPC (%)
Atmospheric Temperature	532.1	1.801	R	0.338	1.000	0.338	1.163
Atmospheric Pressure	2089.6	3.135	psf	0.150	1.000	0.150	0.228
Width	0.471	9.317E-05	ft	0.020	1.000	0.020	0.004
Height	0.470	9.317E-05	ft	0.020	1.000	0.020	0.004
Velocity 1	420	105.268	fpm	25.091	0.022	0.547	3.034
Velocity 2	745	106.314	fpm	14.268	0.039	0.552	3.095
Velocity 3	883	106.267	fpm	12.041	0.046	0.552	3.092
Velocity 4	511	136.705	fpm	26.762	0.027	0.710	5.117
Velocity 5	141	32.250	fpm	22.823	0.007	0.167	0.285
Velocity 6	117	27.560	fpm	23.468	0.006	0.143	0.208
Velocity 7	261	104.172	fpm	39.880	0.014	0.541	2.971
Velocity 8	713	133.348	fpm	18.705	0.037	0.693	4.869
Velocity 9	842	113.098	fpm	13.427	0.044	0.587	3.502
Velocity 10	862	104.528	fpm	12.124	0.045	0.543	2.992
Velocity 11	354	86.885	fpm	24.555	0.018	0.451	2.067
Velocity 12	195	41.607	fpm	21.344	0.010	0.216	0.474
Velocity 13	161	32.236	fpm	20.071	0.008	0.167	0.285
Velocity 14	812	119.183	fpm	14.676	0.042	0.619	3.889
Velocity 15	673	100.041	fpm	14.862	0.035	0.520	2.740
Velocity 16	582	92.147	fpm	15.842	0.030	0.479	2.325
Velocity 17	862	104.264	fpm	12.090	0.045	0.541	2.977
Velocity 18	374	64.493	fpm	17.231	0.019	0.335	1.139
Velocity 19	236	79.498	fpm	33.643	0.012	0.413	1.730
Velocity 20	783	136.706	fpm	17.468	0.041	0.710	5.117
Velocity 21	740	121.125	fpm	16.360	0.038	0.629	4.017
Velocity 22	553	122.162	fpm	22.085	0.029	0.634	4.086
Velocity 23	887	108.688	fpm	12.251	0.046	0.564	3.235
Velocity 24	345	138.060	fpm	40.030	0.018	0.717	5.219
Velocity 25	119	31.843	fpm	26.747	0.006	0.165	0.278
Velocity 26	276	86.315	fpm	31.268	0.014	0.448	2.040
Velocity 27	849	107.138	fpm	12.613	0.044	0.556	3.143
Velocity 28	1029	112.553	fpm	10.933	0.053	0.585	3.469
Velocity 29	870	137.447	fpm	15.790	0.045	0.714	5.173
Velocity 30	309	57.339	fpm	18.531	0.016	0.298	0.900
Velocity 31	137	31.781	fpm	23.194	0.007	0.165	0.277
Velocity 32	153	33.796	fpm	22.144	0.008	0.176	0.313
Velocity 33	331	110.078	fpm	33.293	0.017	0.572	3.318
Velocity 34	937	114.689	fpm	12.238	0.049	0.596	3.602
Velocity 35	739	112.231	fpm	15.192	0.038	0.583	3.449
Velocity 36	452	123.220	fpm	27.263	0.023	0.640	4.157
Integration	<missing>	1.169E-04	slugs/min	0.043	1.000	0.043	0.019
Mass Flowrate	0.271	0.009	slugs/min	<missing>	<missing>	3.139	100

Table 44: Mass flow rate using a Duct (Shakedown Data, 5.024V)

Parameter	Representative Value	Syst. Uncertainty	Units	Relative Uncertainty (%)	UMF	RSSC (%)	UPC (%)
Atmospheric Temperature	531.3	1.801	R	0.339	1.000	0.339	0.838
Atmospheric Pressure	2061.2	3.135	psf	0.152	1.000	0.152	0.169
Width	0.472	9.317E-05	ft	0.020	1.000	0.020	0.003
Height	0.470	9.317E-05	ft	0.020	1.000	0.020	0.003
Velocity 1	168	36.291	fpm	21.635	0.016	0.347	0.879
Velocity 2	197	62.808	fpm	31.847	0.019	0.601	2.633
Velocity 3	464	93.325	fpm	20.132	0.044	0.893	5.814
Velocity 4	389	80.655	fpm	20.743	0.037	0.771	4.343
Velocity 5	297	49.571	fpm	16.666	0.028	0.474	1.640
Velocity 6	155	44.037	fpm	28.342	0.015	0.421	1.295
Velocity 7	141	44.877	fpm	31.931	0.013	0.429	1.344
Velocity 8	335	55.845	fpm	16.670	0.032	0.534	2.082
Velocity 9	453	84.126	fpm	18.586	0.043	0.805	4.725
Velocity 10	464	84.038	fpm	18.121	0.044	0.804	4.715
Velocity 11	411	91.949	fpm	22.347	0.039	0.880	5.644
Velocity 12	148	55.712	fpm	37.605	0.014	0.533	2.072
Velocity 13	320	71.615	fpm	22.388	0.031	0.685	3.424
Velocity 14	399	83.774	fpm	21.016	0.038	0.801	4.685
Velocity 15	300	36.720	fpm	12.259	0.029	0.351	0.900
Velocity 16	345	49.002	fpm	14.188	0.033	0.469	1.603
Velocity 17	485	84.294	fpm	17.365	0.046	0.806	4.743
Velocity 18	318	67.071	fpm	21.061	0.030	0.642	3.003
Velocity 19	503	89.434	fpm	17.772	0.048	0.855	5.340
Velocity 20	500	92.959	fpm	18.599	0.048	0.889	5.769
Velocity 21	491	85.088	fpm	17.318	0.047	0.814	4.833
Velocity 22	445	82.443	fpm	18.510	0.043	0.789	4.537
Velocity 23	357	52.583	fpm	14.738	0.034	0.503	1.846
Velocity 24	334	39.484	fpm	11.823	0.032	0.378	1.041
Velocity 25	113	38.003	fpm	33.697	0.011	0.364	0.964
Velocity 26	405	93.360	fpm	23.047	0.039	0.893	5.818
Velocity 27	465	92.731	fpm	19.934	0.044	0.887	5.740
Velocity 28	302	44.733	fpm	14.807	0.029	0.428	1.336
Velocity 29	121	43.069	fpm	35.607	0.012	0.412	1.238
Velocity 30	120	38.437	fpm	32.029	0.011	0.368	0.986
Velocity 31	56	23.445	fpm	42.003	0.005	0.224	0.367
Velocity 32	79	24.787	fpm	31.558	0.008	0.237	0.410
Velocity 33	110	37.316	fpm	34.064	0.010	0.357	0.930
Velocity 34	68	25.786	fpm	37.663	0.007	0.247	0.444
Velocity 35	117	44.583	fpm	38.148	0.011	0.426	1.327
Velocity 36	80	24.921	fpm	31.312	0.008	0.238	0.415
Integration	-	1.737E-04	slugs/min	0.119	1.000	0.119	0.104
Mass Flowrate	0.146	0.005	slugs/min	-	-	3.702	100

Table 45: Mass flow rate no Duct (Shakedown Data, 5V)

Parameter	Representative Value	Syst. Uncertainty	Units	Relative Uncertainty (%)	UMF	RSSC (%)	UPC (%)
Atmospheric Temperature	531.8	1.801	R	0.339	1.000	0.339	0.733
Atmospheric Pressure	2098.6	3.135	psf	0.149	1.000	0.149	0.143
Width	0.470	9.317E-05	ft	0.020	1.000	0.020	0.003
Height	0.470	9.317E-05	ft	0.020	1.000	0.020	0.003
Velocity 1	241	45.867	fpm	19.035	0.023	0.432	1.193
Velocity 2	373	52.190	fpm	13.991	0.035	0.492	1.545
Velocity 3	264	44.770	fpm	16.972	0.025	0.422	1.137
Velocity 4	163	61.387	fpm	37.775	0.015	0.578	2.138
Velocity 5	64	26.493	fpm	41.645	0.006	0.250	0.398
Velocity 6	82	49.609	fpm	60.804	0.008	0.467	1.396
Velocity 7	121	76.651	fpm	63.272	0.011	0.722	3.333
Velocity 8	279	57.514	fpm	20.608	0.026	0.542	1.876
Velocity 9	500	84.702	fpm	16.928	0.047	0.798	4.070
Velocity 10	405	83.128	fpm	20.521	0.038	0.783	3.920
Velocity 11	258	63.280	fpm	24.520	0.024	0.596	2.272
Velocity 12	117	59.252	fpm	50.618	0.011	0.558	1.992
Velocity 13	174	56.536	fpm	32.471	0.016	0.532	1.813
Velocity 14	289	50.527	fpm	17.496	0.027	0.476	1.448
Velocity 15	377	63.970	fpm	16.984	0.035	0.602	2.321
Velocity 16	405	80.550	fpm	19.894	0.038	0.759	3.681
Velocity 17	449	82.971	fpm	18.490	0.042	0.781	3.905
Velocity 18	180	84.809	fpm	47.090	0.017	0.799	4.080
Velocity 19	293	72.105	fpm	24.612	0.028	0.679	2.949
Velocity 20	453	91.468	fpm	20.170	0.043	0.861	4.746
Velocity 21	397	97.114	fpm	24.479	0.037	0.915	5.350
Velocity 22	415	82.937	fpm	20.004	0.039	0.781	3.902
Velocity 23	446	91.419	fpm	20.481	0.042	0.861	4.741
Velocity 24	188	56.612	fpm	30.114	0.018	0.533	1.818
Velocity 25	285	55.569	fpm	19.505	0.027	0.523	1.752
Velocity 26	275	42.989	fpm	15.611	0.026	0.405	1.048
Velocity 27	456	102.367	fpm	22.437	0.043	0.964	5.944
Velocity 28	498	84.536	fpm	16.979	0.047	0.796	4.054
Velocity 29	450	87.760	fpm	19.520	0.042	0.827	4.369
Velocity 30	362	76.903	fpm	21.255	0.034	0.724	3.355
Velocity 31	172	101.224	fpm	58.877	0.016	0.953	5.812
Velocity 32	176	45.708	fpm	25.997	0.017	0.430	1.185
Velocity 33	183	46.058	fpm	25.200	0.017	0.434	1.203
Velocity 34	235	55.704	fpm	23.726	0.022	0.525	1.760
Velocity 35	320	49.456	fpm	15.474	0.030	0.466	1.387
Velocity 36	276	45.560	fpm	16.533	0.026	0.429	1.177
Integration	-	1.307E-04	slugs/min	0.087	1.000	0.087	0.049
Mass Flowrate	0.150	0.006	slugs/min	-	-	3.954	100

Appendix G: MATLAB Script used for Post Processing

This appendix is to supply the code that was used during the post processing steps of the experiments. Without the excel files that are referenced in the code the file cannot run, so this appendix is just for reference.

```
%**************************************************************************
% ME421_Project
%**************************************************************************
clear variables; clc; close all;
%% Conversion Notes:
% 1 mbar = 2.0885472 lbf/ft2
%% Constants
R = 1717;
%% Systematic Errors
fprintf("Systematic Error:\n\n")

% Atmospheric Temperature
wTatm_read = 0.1/2;       % Fahrenheit
wTatm_acc = 1.8;          % Fahrenheit
wTatm_sys = sqrt(wTatm_acc^2 + wTatm_read^2);

fprintf("For atmospheric temperature (R):\n Uncertainty due to readibility: " + ...
    "%f\n Uncertainty due to accuracy: %f\n Systematic Uncertainty: %f\n\n" ...
    ,wTatm_read,wTatm_acc,wTatm_sys)

% Atmospheric Pressure
wPatm_read = (0.1*2.0885472)/2;       %hPa
wPatm_acc = (1.5*2.0885472);          %hPa
wPatm_sys = sqrt(wPatm_acc^2 + wPatm_read^2);

fprintf("For atmospheric pressure (psf):\n Uncertainty due to readibility: " + ...
    "%f\n Uncertainty due to accuracy: %f\n Systematic Uncertainty: %f\n\n" ...
    ,wPatm_read,wPatm_acc,wPatm_sys)

% Displacement
wdist_read = (0.001/12)/2;
wdist_acc = 0.001/12;
wdist_sys = sqrt(wdist_acc^2 + wdist_read^2);

fprintf("For displacement (ft):\n Uncertainty due to readibility: " + ...
    "%f\n Uncertainty due to accuracy: %f\n Systematic Uncertainty: %f\n\n" ...
    ,wdist_read,wdist_acc,wdist_sys)

%% Design Space Plot (Improved)
ii = 300;

Tatm = 72 + 459.67;
Patm = 992.4*2.0885;
R = 1717; %ft*lbs/slug*R
rho = Patm/(Tatm*R);

Tatm_min = 68 + 459.67; %R
Tatm_max = 78 + 459.67; %R

m_dot_low = (46 - 46*0.1)*rho;
m_dot_high = (92.3 + 92.3*0.1)*rho;

Patm_min = 2050; %psf
Patm_max = 2150; %psf

x = 5.664/12; %ft
y = 5.664/12; %ft

vector = linspace(0,ii,ii+1);
Mult_vector = ones(ii+1,1)';
```

```
n = 36;
x_low = n/(x*y);
low = m_dot_low*x_low;
high = m_dot_high*x_low;
V_avg_low = (Tatm*R*low)/(Patm*n);
V_avg_high = (Tatm*R*high)/(Patm*n);

V_avg_min = 38.5;
V_avg_mid = 394;
V_avg_max = 2953;

y_axis_min = (Patm_min*V_avg_min*n)/(Tatm_max*R);
y_axis_mid = (Patm_min*V_avg_mid*n)/(Tatm_max*R);
y_axis_max = (Patm_max*V_avg_max*n)/(Tatm_min*R);

x1 = y_axis_min/m_dot_high;
y1 = y_axis_min;
x2 = y_axis_min/m_dot_low;
y2 = y_axis_min;
x3 = y_axis_max/m_dot_low;
y3 = y_axis_max;
x4 = y_axis_max/m_dot_high;
y4 = y_axis_max;

xfill = [x1 x2 x3 x4];
yfill = [y1 y2 y3 y4];

figure(1)
hold on
p = fill(xfill,yfill,'yellow','FaceAlpha',0.3);
p.EdgeColor = [1 1 1];
plot(x_low*Mult_vector,vector,"r-",'LineWidth', 1)
plot(vector,m_dot_low*vector,'b-','LineWidth',1)
plot(vector,m_dot_high*vector,"b--",'LineWidth',1)
plot(vector,y_axis_min*Mult_vector,'k-','LineWidth',1)
%plot(vector,y_axis_mid*Mult_vector,'k--','LineWidth',1)
plot(vector,y_axis_max*Mult_vector,'k-.','LineWidth',1)
%title("Mass Flow Rate of Axial Fan: Design Space")
xlabel("n/(x y)")
ylabel("(P_a_t_m V_s_u_m)/(R T_a_t_m)")
legend("Design Space","n=36","Mass Flow_l_o_w","Mass Flow_h_i_g_h", ...
    "Y-Axis Lower Bound","Y-Axis Upper Bound",'location','best')
axis([0 300 0 100])

%% Duct Testing:
% 5V with a diffuser:
T_atm = 71.6+459.67;
P_atm = 986.9*2.0885472;
x = 5.664/12;
y = 5.640/12;

data = readmatrix('duct');
[V,unc_V,umf_V] = vel_analysis(data,0);

values = [T_atm;P_atm;x;y;V];
unc = [wTatm_sys;wPatm_sys;wdist_sys;wdist_sys;unc_V];
umf = [1;1;1;1;umf_V;1];

TABLE_diffuser = UNC_function(values,unc,umf);

% 5V without a diffuser:
T_atm = 72.1+459.67;
P_atm = 1004.8*2.0885472;
x = 5.64/12;
y = 5.640/12;

data = readmatrix('One_eff_length_no_duct');
[V,unc_V,umf_V] = vel_analysis(data,0);
```

```
values = [T_atm;P_atm;x;y;V];
unc = [wTatm_sys;wPatm_sys;wdist_sys;wdist_sys;unc_V];
umf = [1;1;1;1;umf_V;1];

TABLE_no_diffuser = UNC_function(values,unc,umf);

%% 3V Trials
data = readmatrix("3V_data");
Trial_1 = data(:,1:2);
Trial_2 = data(:,3:4);
Trial_3 = data(:,5:6);

%Trial #1
Volt_3V_T1 = 3.452;
T_atm = 72.8+459.67;
P_atm = 1007.1*2.0885472;
rho = P_atm/(R*T_atm);
x = 5.653/12;
y = 5.643/12;

[V,unc_V,umf_V] = vel_analysis(Trial_1,0);
values = [T_atm;P_atm;x;y;V];
unc = [wTatm_sys;wPatm_sys;wdist_sys;wdist_sys;unc_V];
umf = [1;1;1;1;umf_V;1];

TABLE_3V_T1_MF = UNC_function(values,unc,umf);

MFT1_3V = str2double(TABLE_3V_T1_MF(43,2));
MFT1_3V_unc = str2double(TABLE_3V_T1_MF(43,3));

%Trial #2
Volt_3V_T2 = 3.466;
T_atm = 71.1+459.67;
P_atm = 989.3*2.0885472;
rho(end+1,1) = P_atm/(R*T_atm);

[V,unc_V,umf_V] = vel_analysis(Trial_2,0);
values = [T_atm;P_atm;x;y;V];
unc = [wTatm_sys;wPatm_sys;wdist_sys;wdist_sys;unc_V];
umf = [1;1;1;1;umf_V;1];

TABLE_3V_T2_MF = UNC_function(values,unc,umf);

MFT2_3V = str2double(TABLE_3V_T2_MF(43,2));
MFT2_3V_unc = str2double(TABLE_3V_T2_MF(43,3));

%Trial #3
Volt_3V_T3 = 3.468;
T_atm = 71.8+459.67;
P_atm = 1000*2.0885472;
rho(end+1,1) = P_atm/(R*T_atm);

[V,unc_V,umf_V] = vel_analysis(Trial_3,0);
values = [T_atm;P_atm;x;y;V];
unc = [wTatm_sys;wPatm_sys;wdist_sys;wdist_sys;unc_V];
umf = [1;1;1;1;umf_V;1];

TABLE_3V_T3_MF = UNC_function(values,unc,umf);

MFT3_3V = str2double(TABLE_3V_T3_MF(43,2));
MFT3_3V_unc = str2double(TABLE_3V_T3_MF(43,3));

values = [MFT1_3V;MFT2_3V;MFT3_3V];
unc = [MFT1_3V_unc;MFT2_3V_unc;MFT3_3V_unc];
umf = [values(1)/sum(values);values(2)/sum(values);values(3)/sum(values)];

TABLE_3V_result = UNC_function_Result(values,unc,umf);

Mass_Flow_Values = values;
```

```
Mass_Flow_Values_unc = unc;
Voltage_values = [Volt_3V_T1;Volt_3V_T2;Volt_3V_T3];

%% 5V
data = readmatrix("5V_data");
Trial_1 = data(:,1:2);
Trial_2 = data(:,3:4);
Trial_3 = data(:,5:6);

%Trial #1
Volt_5V_T1 = 5.258;
T_atm = 74.6+459.67;
P_atm = 1007.3*2.0885472;
rho(end+1,1) = P_atm/(R*T_atm);

[V,unc_V,umf_V] = vel_analysis(Trial_1,0);
values = [T_atm;P_atm;x;y;V];
unc = [wTatm_sys;wPatm_sys;wdist_sys;wdist_sys;unc_V];
umf = [1;1;1;1;umf_V;1];

TABLE_5V_T1_MF = UNC_function(values,unc,umf);

MFT1_5V = str2double(TABLE_5V_T1_MF(43,2));
MFT1_5V_unc = str2double(TABLE_5V_T1_MF(43,3));

%Trial #2
Volt_5V_T2 = 5.026;
T_atm = 71.8+459.67;
P_atm = 999*2.0885472;
rho(end+1,1) = P_atm/(R*T_atm);

[V,unc_V,umf_V] = vel_analysis(Trial_2,0);
values = [T_atm;P_atm;x;y;V];
unc = [wTatm_sys;wPatm_sys;wdist_sys;wdist_sys;unc_V];
umf = [1;1;1;1;umf_V;1];

TABLE_5V_T2_MF = UNC_function(values,unc,umf);

MFT2_5V = str2double(TABLE_5V_T2_MF(43,2));
MFT2_5V_unc = str2double(TABLE_5V_T2_MF(43,3));

%Trial #3
Volt_5V_T3 = 5.01;
T_atm = 71.9+459.67;
P_atm = 994.1*2.0885472;
rho(end+1,1) = P_atm/(R*T_atm);

[V,unc_V,umf_V] = vel_analysis(Trial_3,0);
values = [T_atm;P_atm;x;y;V];
unc = [wTatm_sys;wPatm_sys;wdist_sys;wdist_sys;unc_V];
umf = [1;1;1;1;umf_V;1];

TABLE_5V_T3_MF = UNC_function(values,unc,umf);

MFT3_5V = str2double(TABLE_5V_T3_MF(43,2));
MFT3_5V_unc = str2double(TABLE_5V_T3_MF(43,3));

values = [MFT1_5V;MFT2_5V;MFT3_5V];
unc = [MFT1_5V_unc;MFT2_5V_unc;MFT3_5V_unc];
umf = [values(1)/sum(values);values(2)/sum(values);values(3)/sum(values)];

TABLE_5V_result = UNC_function_Result(values,unc,umf);

Mass_Flow_Values(end+1:end+3,1) = values;
Mass_Flow_Values_unc(end+1:end+3,1) = unc;
Voltage_values(end+1:end+3,1) = [Volt_5V_T1;Volt_5V_T2;Volt_5V_T3];

%% 10V
data = readmatrix("10V_data");
```

```
Trial_1 = data(:,1:2);
Trial_2 = data(:,3:4);
Trial_3 = data(:,5:6);

%Trial #1
Volt_10V_T1 = 10.03;
T_atm = 72.1+459.67;
P_atm = 1007.6*2.0885472;
rho(end+1,1) = P_atm/(R*T_atm);

[V,unc_V,umf_V] = vel_analysis(Trial_1,0);
values = [T_atm;P_atm;x;y;V];
unc = [wTatm_sys;wPatm_sys;wdist_sys;wdist_sys;unc_V];
umf = [1;1;1;1;umf_V;1];

TABLE_10V_T1_MF = UNC_function(values,unc,umf);

MFT1_10V = str2double(TABLE_10V_T1_MF(43,2));
MFT1_10V_unc = str2double(TABLE_10V_T1_MF(43,3));

%Trial #2
Volt_10V_T2 = 10.04;
T_atm = 72.8+459.67;
P_atm = 999.3*2.0885472;
rho(end+1,1) = P_atm/(R*T_atm);

[V,unc_V,umf_V] = vel_analysis(Trial_2,0);
values = [T_atm;P_atm;x;y;V];
unc = [wTatm_sys;wPatm_sys;wdist_sys;wdist_sys;unc_V];
umf = [1;1;1;1;umf_V;1];

TABLE_10V_T2_MF = UNC_function(values,unc,umf);

MFT2_10V = str2double(TABLE_10V_T2_MF(43,2));
MFT2_10V_unc = str2double(TABLE_10V_T2_MF(43,3));

%Trial #3
Volt_10V_T3 = 10.06;
T_atm = 71.8+459.67;
P_atm = 993.7*2.0885472;
rho(end+1,1) = P_atm/(R*T_atm);

[V,unc_V,umf_V] = vel_analysis(Trial_3,0);
values = [T_atm;P_atm;x;y;V];
unc = [wTatm_sys;wPatm_sys;wdist_sys;wdist_sys;unc_V];
umf = [1;1;1;1;umf_V;1];

TABLE_10V_T3_MF = UNC_function(values,unc,umf);

MFT3_10V = str2double(TABLE_10V_T3_MF(43,2));
MFT3_10V_unc = str2double(TABLE_10V_T3_MF(43,3));

values = [MFT1_10V;MFT2_10V;MFT3_10V];
unc = [MFT1_10V_unc;MFT2_10V_unc;MFT3_10V_unc];
umf = [values(1)/sum(values);values(2)/sum(values);values(3)/sum(values)];

TABLE_10V_result = UNC_function_Result(values,unc,umf);

Mass_Flow_Values(end+1:end+3,1) = values;
Mass_Flow_Values_unc(end+1:end+3,1) = unc;
Voltage_values(end+1:end+3,1) = [Volt_10V_T1;Volt_10V_T2;Volt_10V_T3];

%% 12V
data = readmatrix("12V_data");
Trial_1 = data(:,1:2);
Trial_2 = data(:,3:4);
Trial_3 = data(:,5:6);

%Trial #1
```

```
Volt_12V_T1 = 12.54;
T_atm = 72.1+459.67;
P_atm = 1006.9*2.0885472;
rho(end+1,1) = P_atm/(R*T_atm);

[V,unc_V,umf_V] = vel_analysis(Trial_1,0);
values = [T_atm;P_atm;x;y;V];
unc = [wTatm_sys;wPatm_sys;wdist_sys;wdist_sys;unc_V];
umf = [1;1;1;1;umf_V;1];

TABLE_12V_T1_MF = UNC_function(values,unc,umf);

MFT1_12V = str2double(TABLE_12V_T1_MF(43,2));
MFT1_12V_unc = str2double(TABLE_12V_T1_MF(43,3));

%Trial #2
Volt_12V_T2 = 12.59;
T_atm = 72.3+459.67;
P_atm = 989.6*2.0885472;
rho(end+1,1) = P_atm/(R*T_atm);

[V,unc_V,umf_V] = vel_analysis(Trial_2,0);
values = [T_atm;P_atm;x;y;V];
unc = [wTatm_sys;wPatm_sys;wdist_sys;wdist_sys;unc_V];
umf = [1;1;1;1;umf_V;1];

TABLE_12V_T2_MF = UNC_function(values,unc,umf);

MFT2_12V = str2double(TABLE_12V_T2_MF(43,2));
MFT2_12V_unc = str2double(TABLE_12V_T2_MF(43,3));

%Trial #3
Volt_12V_T3 = 12.5;
T_atm = 72.4+459.67;
P_atm = 1000.5*2.0885472;
rho(end+1,1) = P_atm/(R*T_atm);

[V,unc_V,umf_V] = vel_analysis(Trial_3,0);
values = [T_atm;P_atm;x;y;V];
unc = [wTatm_sys;wPatm_sys;wdist_sys;wdist_sys;unc_V];
umf = [1;1;1;1;umf_V;1];

TABLE_12V_T3_MF = UNC_function(values,unc,umf);

MFT3_12V = str2double(TABLE_12V_T3_MF(43,2));
MFT3_12V_unc = str2double(TABLE_12V_T3_MF(43,3));

values = [MFT1_12V;MFT2_12V;MFT3_12V];
unc = [MFT1_12V_unc;MFT2_12V_unc;MFT3_12V_unc];
umf = [values(1)/sum(values);values(2)/sum(values);values(3)/sum(values)];

TABLE_12V_result = UNC_function_Result(values,unc,umf);

Mass_Flow_Values(end+1:end+3,1) = values;
Mass_Flow_Values_unc(end+1:end+3,1) = unc;
Voltage_values(end+1:end+3,1) = [Volt_12V_T1;Volt_12V_T2;Volt_12V_T3];

%% Analysis of Mass Flow v. Voltage
[Table_Percent_Diff] = func_expected(Voltage_values,Mass_Flow_Values,rho);

unc_voltage = unc_of_voltage(Voltage_values);

curve = func_linear(Voltage_values,Mass_Flow_Values);
reg_y = curve(2)*Voltage_values + curve(1);

fprintf('The linear regression of measured data has a slope of %f and an intercept of
%f\n',curve(2),curve(1))
```

```
[unc_slope,Table_of_plot_values] =
func_unc_slope(Voltage_values,unc_voltage,Mass_Flow_Values,Mass_Flow_Values_unc,reg_y);

rho_avg = mean(rho);
Vol = [46 56.8 85 92.3]';
expected_Voltage = [3,5,10,12]';
expected_MF = rho_avg*Vol;
expected_MF_unc = expected_MF*0.1;

exp_curve = func_linear(expected_Voltage,expected_MF);
exp_reg_y = exp_curve(2)*expected_Voltage + exp_curve(1);

fprintf('The linear regression of expected data has a slope of %f and an intercept of
%f\n',exp_curve(2),exp_curve(1))

figure(300)
hold on
errorbar(expected_Voltage,expected_MF,expected_MF_unc,'ob')
errorbar(Voltage_values,Mass_Flow_Values,Mass_Flow_Values_unc,'or')
plot(Voltage_values,reg_y,'-k')
plot(expected_Voltage,exp_reg_y,"--k")
axis('padded')
xlabel('Measured Voltage (Volts)')
ylabel('Mass Flow Rate (slugs/min)')
legend('Expected Data Points with 10% Error', ...
    'Experimental Data Points with Error','Linear Regression of Measured Data', ...
    'Linear Regression of Expected Data', ...
    'location','northwest')

figure(400)
hold on
errorbar(Voltage_values,Mass_Flow_Values,Mass_Flow_Values_unc,'or')
xlabel('Measured Voltage (Volts)')
ylabel('Mass Flow Rate (slugs/min)')
legend('Data Points with Error','location','northwest')

%% Functions
function [Table] = func_expected(Voltage,Mass_Flow,rho)
est_Voltage = [3,5,10,12]';
Vol = [46 56.8 85 92.3]';

[n,m] = size(Voltage);

for i = 1:n
    if Voltage(i) < 4
        Exp_V(i,1) = est_Voltage(1);
        Exp_Vol(i,1) = Vol(1);
        Meas_Vol(i) = Mass_Flow(i)/rho(i);
        Percent_err(i) = (abs(Exp_Vol(i)-Meas_Vol(i))/Exp_Vol(i))*100;
        Percent_diff(i) = (abs(Exp_Vol(i)-Meas_Vol(i))/((Exp_Vol(i)+Meas_Vol(i))/2))*100;

    elseif Voltage(i) < 6
        Exp_V(i,1) = est_Voltage(2);
        Exp_Vol(i,1) = Vol(2);
        Meas_Vol(i) = Mass_Flow(i)/rho(i);
        Percent_err(i) = (abs(Exp_Vol(i)-Meas_Vol(i))/Exp_Vol(i))*100;
        Percent_diff(i) = (abs(Exp_Vol(i)-Meas_Vol(i))/((Exp_Vol(i)+Meas_Vol(i))/2))*100;

    elseif Voltage(i) < 11
        Exp_V(i,1) = est_Voltage(3);
        Exp_Vol(i,1) = Vol(3);
        Meas_Vol(i) = Mass_Flow(i)/rho(i);
        Percent_err(i) = (abs(Exp_Vol(i)-Meas_Vol(i))/Exp_Vol(i))*100;
        Percent_diff(i) = (abs(Exp_Vol(i)-Meas_Vol(i))/((Exp_Vol(i)+Meas_Vol(i))/2))*100;

    else
        Exp_V(i,1) = est_Voltage(4);
        Exp_Vol(i,1) = Vol(4);
        Meas_Vol(i) = Mass_Flow(i)/rho(i);
```

```
        Percent_err(i) = (abs(Exp_Vol(i)-Meas_Vol(i))/Exp_Vol(i))*100;
        Percent_diff(i) = (abs(Exp_Vol(i)-Meas_Vol(i))/((Exp_Vol(i)+Meas_Vol(i))/2))*100;
    end
end

Table(1:n,1) = Voltage;
Table(1:n,2) = Mass_Flow;
Table(1:n,3) = Meas_Vol;
Table(1:n,4) = Exp_V;
Table(1:n,5) = Exp_Vol;
Table(1:n,6) = Percent_err;
Table(1:n,7) = Percent_diff;
end

function [V,unc_V,umf_V] = vel_analysis(data,n)
V = data(:,1);
V_std = data(:,2);

[a,b] = size(V);

    for i = 1:a
        wVel_read = V_std(i);

        if (V(i) < 394)
            wVel_acc = 20+(0.05*V(i)); %fpm
        else
            wVel_acc = 59.1+(0.05*V(i)); %fpm
        end
            wVel_sys = sqrt(wVel_read^2 + wVel_acc^2);
            unc_V(i,:) = wVel_sys;
            umf_V(i,:) = ((V(i)))/((sum(V)));
    end

    if n>1
        profile = [V(1:6)';V(7:12)';V(13:18)';V(19:24)';V(25:30)';V(31:36)'];
        figure (n)
        surfl(profile);
        xlabel("Test Points (Width)")
        ylabel("Test Points (Height)")
        zlabel("Velocity (fpm)")

        figure(n+100)
        stem([1:a],V_std,'k')
        xlabel('Test Index Point')
        ylabel('Standard Deviation of Velocity')
    end

end

function [unc_volt] = unc_of_voltage(Voltage)

[i,j] = size(Voltage);

for i = 1:i
    if Voltage(i) < 6
        res = 0.001;
    else
        res = 0.01;
    end

    unc_read = res/2;
    unc_acc = 0.005*Voltage(i) + 2*res;
    unc_volt(i) = sqrt(unc_read^2 + unc_acc^2);

end
end

function [coef] = func_linear(x,y)
A = [ones(length(x),1),x];
```

```
coef = (A' * A)^-1 *(A' * y);
end

function [unc_slope,TABLE] = func_unc_slope(x,unc_x,y,unc_y,reg_y)

[n,m] = size(x);

wx = mean(unc_x);

y_sys = mean(unc_y);

umf_x = sum((y-mean(y).^2))/((sum((x-mean(x)).^2))^2);

umf_y = 1/(sum((x-mean(x)).^2));

Sy = sqrt((sum((y-reg_y).^2))/(n-2));

wy_rand = 2*Sy;

wy = sqrt(y_sys^2 + wy_rand^2);

unc_slope = sqrt(umf_x*wx^2 + umf_y*wy^2);

TABLE(:,1) = x;
TABLE(:,2) = unc_x;
TABLE(:,3) = y;
TABLE(:,4) = unc_y;


end

function [Unc_Table] = UNC_function(values,unc,umf)
[k,p] = size(values);
k = k+1;
vel_low_res = [values(4+8),values(4+11),values(4+26),values(4+29)];
dA_36 = (values(3)/6)*(values(4)/6);
dA_4 = (values(3)/2)*(values(4)/2);


Unc_Table = ["Parameter";"Atmospheric Temperature";"Atmospheric Pressure";
    "Width";"Height";"Velocity 1";"Velocity 2";"Velocity 3";"Velocity 4";"Velocity 5";
    "Velocity 6";"Velocity 7";"Velocity 8";"Velocity 9";"Velocity 10";"Velocity 11";"Velocity 12";
    "Velocity 13";"Velocity 14";"Velocity 15";"Velocity 16";"Velocity 17";"Velocity 18";"Velocity 19";
    "Velocity 20";"Velocity 21";"Velocity 22";"Velocity 23";"Velocity 24";"Velocity 25";"Velocity 26";
    "Velocity 27";"Velocity 28";"Velocity 29";"Velocity 30";"Velocity 31";"Velocity 32";"Velocity 33";
    "Velocity 34";"Velocity 35";"Velocity 36";"Integration";"Mass Flowrate"];
Unc_Table(1,2) = "Representative Value";
Unc_Table(1,3) = "Syst. Uncertainty";
Unc_Table(1,4) = "Units";
Unc_Table(1,5) = "Relative Uncertainty(%)";
Unc_Table(1,6) = "UMF";
Unc_Table(1,7) = "RSSC (%)";
Unc_Table(1,8) = "UPC (%)";
Unit_vector = ["R";"psf";"ft";"ft";"fpm";"fpm";"fpm";"fpm";"fpm";"fpm";"fpm";
    "fpm";"fpm";"fpm";"fpm";"fpm";"fpm";"fpm";"fpm";"fpm";"fpm";"fpm";"fpm";
    "fpm";"fpm";"fpm";"fpm";"fpm";"fpm";"fpm";"fpm";"fpm";"fpm";"fpm";"fpm";
    "fpm";"fpm";"fpm";"fpm";"fpm";"slugs/min";"slugs/min"];
[l,j] = size (Unit_vector);
ind = k + 2;

col2 = values;
col3 = unc;
col5 = (col3./col2)*100;
result = (col2(2)/(col2(1)*1717))*col2(3)*col2(4)*(1/36)*(sum(col2(5:1:40)));
result_low_res = (col2(2)/(col2(1)*1717))*col2(3)*col2(4)*(1/4)*(sum(vel_low_res));

C = abs((result - result_low_res)/(dA_4^2 - dA_36^2));
unc_int = C*(dA_36^2);
col3(end+1) = unc_int;
```

```
col5(end+1) = (unc_int/result)*100;

col6 = umf;
col7 = col5.*col6;
result = (col2(2)/(col2(1)*1717))*col2(3)*col2(4)*(1/36)*(sum(col2(5:1:40)));
unc_result = sqrt(sum((col7).^2));
col8 = ((col7/unc_result).^2)*100;
total_percent = sum(col8);



Unc_Table(2:l-1,2) = col2;
Unc_Table(2:l,3) = col3;
Unc_Table(2:l+1,4) = Unit_vector;
Unc_Table(2:l,5) = col5;
Unc_Table(2:l,6) = col6;
Unc_Table(2:l,7) = col7;
Unc_Table(ind,2) = result;
Unc_Table(ind,3) = result*(unc_result/100);
Unc_Table(ind,7) = unc_result;
Unc_Table(2:k+1,8) = col8;
Unc_Table(ind,8) = total_percent;

end

function [Unc_Table] = UNC_function_Result(values,unc,umf)
[k,p] = size(values);
k = k+1;

umf(end+1) = 1;

Unc_Table = ["Parameter";"Mass Flow 1";"Mass Flow 2";
    "Mass Flow 3";"Random";"Avg. Mass Flowrate"];
Unc_Table(1,2) = "Representative Value";
Unc_Table(1,3) = "Syst. Uncertainty";
Unc_Table(1,4) = "Units";
Unc_Table(1,5) = "Relative Uncertainty(%)";
Unc_Table(1,6) = "UMF";
Unc_Table(1,7) = "RSSC (%)";
Unc_Table(1,8) = "UPC (%)";
Unit_vector = ["slugs/min";"slugs/min";"slugs/min";"slugs/min";"slugs/min"];
[l,j] = size (Unit_vector);
l = l+1;
ind = k + 2;

col2 = values;
col3 = unc;
col5 = (col3./col2)*100;
col3(end+1) = ((std(values)*4.30265)/sqrt(3));
col5(end+1) = (((std(values)*4.30265)/sqrt(3))/sum(values))*100;
col6 = umf;
col7 = col5.*col6;
result = sum(values)/3;
unc_result = sqrt(sum((col7).^2));
col8 = ((col7/unc_result).^2)*100;
total_percent = sum(col8);

Unc_Table(2:k,2) = col2;
Unc_Table(2:k+1,3) = col3;
Unc_Table(2:l,4) = Unit_vector;
Unc_Table(2:k+1,5) = col5;
Unc_Table(2:k+1,6) = col6;
Unc_Table(2:k+1,7) = col7;
Unc_Table(ind,2) = result;
Unc_Table(ind,3) = result*(unc_result/100);
Unc_Table(ind,7) = unc_result;
Unc_Table(2:k+1,8) = col8;
Unc_Table(ind,8) = total_percent;
```

```
end
```