

1 Overview

The purpose of this lab exercise is to use a computer controlled data acquisition system to automate data for flow bench measurements, and to then apply uncertainty analysis in the data reduction. For each steady-state operating condition of the flow bench, the sensors are sampled several times. The recorded measurement is taken to be the average of those readings. The standard deviation of the readings is used to estimate the random uncertainty due to unsteadiness in the flow bench and the device under test. A complete uncertainty analysis is performed during data reduction.

2 Apparatus

The experiment involves the flow bench used in the preceding lab assignment. The primary new feature in the current lab exercise is the use of a data acquisition system to record the voltage and resistance measurements for the sensors on the flow bench.

Figure 1 is a block diagram of the data acquisition system attached to the flow bench. The DMM/Switch is an Agilent 34970A digital multimeter and switch unit manufactured by Agilent (www.agilent.com). The DMM/Switch is connected to a personal computer (PC) via a serial cable. For this lab exercise the data collection is managed via the BenchLink Data Logger application running on the PC.

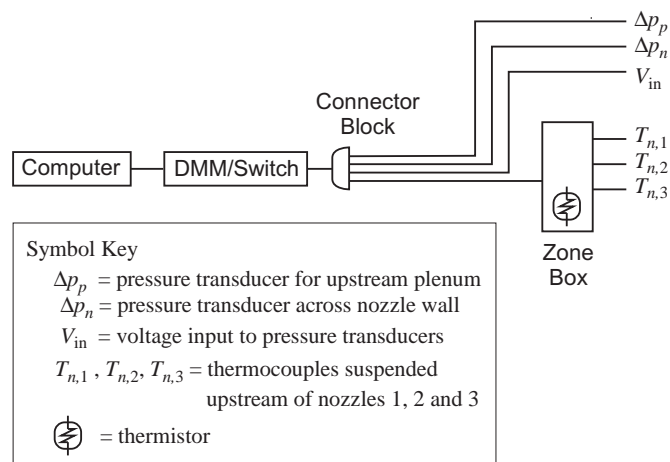


Figure 1: Data acquisition for the flow bench

3 Operating Range of the Flow Bench

The data acquisition system records the output of thermocouples, zone box thermistor, and pressure transducers. It does not check whether the magnitude of these signals are meaningful. The data reduction process happens after the measurements are complete, so it is possible that the data collected by the system might not make good use of the flow bench. For example, if a low flow rate is measured with a large nozzle, there will be a large uncertainty in the flow rate. Another poor use of the flow bench is when a system curve is measured over such a small range of system pressure drops that the loss coefficient deduced from the system curve is not accurate.

To make the best use of time spent in the laboratory, it is wise to anticipate the range of transducer outputs for maximum utility of the flow bench. The goal is to run the experiment over the widest possible range of transducer readings that is consistent with practical operation of the system under test. For a fan test, the experiments should be conducted from the minimum flow condition (no flow, maximum pressure drop) to the the maximum flow condition (free air, no pressure drop). For a system curve, the experiments should be conducted over the maximum range of the plenum pressure transducer.

3.1 Plenum Pressure Transducer Limits

Recall that the voltage output of the pressure transducer output is converted to pressure with

$$\frac{\delta p - \delta p_{\min}}{\delta p_{\max} - \delta p_{\min}} = \frac{V_{\text{out}} - V_{\min}}{V_{\max} - V_{\min}}. \quad (1)$$

The internal circuitry of the transducer provides a linearized output between $V_{\min} = 1$ volt and $V_{\max} = 5$ volts. The maximum flow condition (or *free air* condition) for a fan curve test occurs when $\delta p = \delta p_{\min}$, which corresponds to $V_{\text{out}} = 1$ V. During fan curve measurements, check that the output of the plenum pressure transducer does not fall below one volt.

To make maximum use of the measurement capabilities of the flow bench during a system curve measurement, the flow rate should be adjusted to obtain data over the full range of the plenum pressure transducer. The pressure transducers are designed to withstand a slight overpressure, i.e., they can be exposed to a pressure slightly above the maximum range of the transducer. However, for accurate readings, the pressure transducer should not be exposed to pressures above the rated δp_{\max} . This sets the upper limit of δp for the system curve measurements at $\delta p = \delta p_{\max}$, which corresponds to $V_{\text{out}} = V_{\max} = 5$ V.

3.2 Nozzle Limits

For a given nozzle diameter, the accuracy of the flow rate measurement decreases with the magnitude of the flow rate because the accuracy of the pressure drop reading decreases with the magnitude of the pressure drop across the nozzle. To maximize the accuracy of a flow rate measurement, the pressure drop across the nozzle should be near the high end of the pressure transducer measurement range¹. Thus, the output of the pressure transducer should be closer to V_{\max}

¹The pressure drop should not be so large, however, that compressibility becomes important, i.e, the compressibility factor Y should be close to one.

than V_{\min} . Low nozzle pressure drops should not be avoided. Rather, the tests should be conducted so that large nozzle pressure drops are included.

The usable range of flow rates for each nozzle overlaps the range of operation for other nozzles. Repeating the flow rate measurement with multiple nozzles provides a redundancy check on the experiments. An uncertainty analysis during data reduction will show how the choice of nozzle size affects the accuracy of the measured flow rates.

4 Procedure

To complete the laboratory exercise you will need to perform the following tasks.

1. Attach the device under test (DUT) to the flow bench.
2. Configure the flow bench. Record the atmospheric pressure with the barometer.
3. Start the data acquisition software and configure the data channels.
4. Collect several (say 10 or more) steady data sets at different settings of the blast gate (different flow rates).
5. Export the data collected during the experiment.
6. Obtain average and standard deviations for each sensor at each operating condition.
7. Convert the average and standard deviations of the sensor data to flow rates and uncertainties in flow rates.

Each of these steps is discussed in separate sections, below.

4.1 Attaching the DUT to the Flow Bench

Two separate measurements may be performed: a fan curve measurement, and a loss coefficient measurement. Before attaching the device under test (DUT) to the flow bench, measure the rough opening in the flow bench. The area of this opening is needed in the data reduction for computing loss coefficients for grill materials.

For the fan curve measurement, a fan is bolted to the press-board mounting plate, and the assembly is taped to the opening of the flow bench. Be sure to record the name plate data from the fan. (Manufacturer, model number, nominal operating voltage.) The power leads of the fan are attached to a DC power supply. Before attaching the fan to the the flow bench, turn on the power to the fan and make sure it is oriented to blow air into the flow bench.

For the loss coefficient measurement, the DUT is sealed to the front of the flow bench with duct tape. If the DUT is heavy, e.g. a sheet metal case, it will need to be supported from below. If the DUT is a grill or other vent covering, it can be sealed *and* supported only with duct tape.

Table 1: Configuration of channels on the Agilent 34970A

Channel	Physical Quantity	Reading	Scaling	Digits
101	Thermocouple upstream of nozzle 1	Voltage	± 10 mV	$6\frac{1}{2}$
102	Thermocouple upstream of nozzle 2	Voltage	± 10 mV	$6\frac{1}{2}$
103	Thermocouple upstream of nozzle 3	Voltage	± 10 mV	$6\frac{1}{2}$
104	Zone box thermistor	Four wire resistance	100 k Ω	$6\frac{1}{2}$
105	Pressure transducer between ambient and upstream plenum	Voltage	± 10 V	$6\frac{1}{2}$
106	Pressure transducer across flow nozzles	Voltage	± 10 V	$6\frac{1}{2}$

4.2 Configuration of the DUT and Flow Bench

Make sure that the input selector for the plenum pressure transducer is in the proper position.

For a fan curve measurement, the plenum must be connected to the high side of the pressure transducer.

For a loss coefficient (system curve) measurement, the plenum must be connected to the low side of the pressure transducer.

4.3 Configuration of the Data Acquisition Software

Analog data is converted to digital values by the Agilent DMM/Switch unit. The digital values are sent to the PC, where the data is stored. These operations are controlled by the Agilent BenchLink Data Logger application. The first step in using this software is to configure each channel of the Agilent DMM/Switch so that it records the desired physical quantities. Instructions for configuring the channels are provided in the separate handout titled “Agilent 34970A Data Logger Software”. The appropriate channel settings are summarized in Table 1. Set the scan interval to between 2 and 5 seconds.

If the scan interval is t_s and each measurement involves n_s readings of the sensors, the minimum time to complete the experiment is (of course) $n_s t_s$. Be sure to budget your time accordingly.

4.4 Data Collection

The data acquisition system is used to make multiple readings at each operating condition. Once the flow bench and DMM/Switch have been configured, the primary steps of data collection are

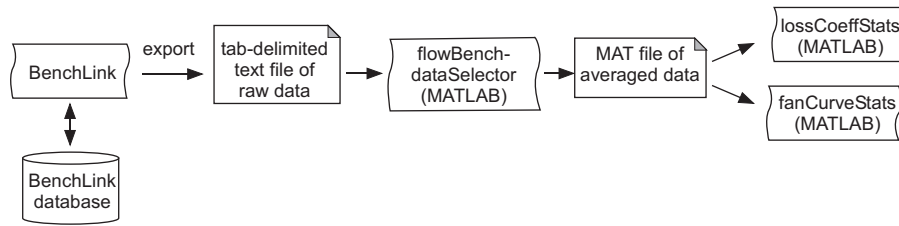


Figure 2: Overview of data reduction process showing the transfer of data between programs.

1. Adjust the blast gate to set the operating condition.
2. Watch the plot created by the data acquisition software to guarantee that the system has achieved steady state.
3. Allow the data acquisition system to record at least forty measurements after the system has achieved steady state.
4. Return to step 1 to set a new operating condition.

Collect data for at least 10 operating points. Be careful to note the nozzle size being used, and the time at which any changes in nozzle diameter are made. You will need to manually associate the nozzle diameter with the data collected by the data acquisition system. Table 3 on page 12 may be helpful in logging changes to the flow bench configuration during data collection.

4.5 Export the Raw Data

The BenchLink Data Logger software saves data in an internal database. To compute the flow rate this data needs to be exported to a plain text file. Instructions for exporting the data are included in the handout titled “Agilent 34970A Data Logger Software”. Figure 2 is a schematic of the entire data reduction process. The left side of the diagram represents the exchange of data between BenchLink, the BenchLink database, and the plain text file exported from BenchLink.

You need to decide whether to save the time stamp for each reading. Including a time stamp, adds a column of time and date values for each reading of each sensor. The time stamp is not used in the data reduction calculations, but it may be useful in figuring out which nozzle was used for each data point. If the time stamp is exported with the sensor measurements, you will need to save a separate copy of the raw data and delete the time stamp columns. The `flowBenchDataSelector` MATLAB function described in § 4.6 does not work if the input data file contains time stamps.

Figure 3 shows the beginning of a raw data file exported from a BenchLink database. You can download this sample file as `sampleRaw.dat` from <http://www.me.pdx.edu/~gerry/class/ME449/data/>. The raw data file displayed in Figure 3 *does not* have a time stamp. The time columns (e.g. “101(Seconds)”, “102(Seconds)”) indicate the time from the beginning of the experiment. These times are used by the `flowBenchDataSelector` function.

101(Seconds)	101(VDC)	102(Seconds)	102(VDC)	103(Seconds)	103(VDC)	...
0.168	+5.579200E-05	0.369	+5.855000E-05	0.571	+6.256200E-05	...
2.002	+5.616800E-05	2.054	+5.829900E-05	2.105	+6.231100E-05	...
4.017	+5.541600E-05	4.069	+5.804900E-05	4.119	+6.306400E-05	...
⋮	⋮	⋮				

Figure 3: Excerpt of a raw data file exported from a BenchLink database. This particular data set is available as `sampleRaw.dat` from <http://www.me.pdx.edu/~gerry/class/ME449/data/>.

Make sure you store the exported data in a location where you can retrieve it later. One obvious place to store the data is in your home directory in the CECS file server. (Also known as your N:\ drive.)

4.6 Obtain Averages of Sensor Measurements

The raw data exported from the BenchLink database contains several readings for each operating condition of the flow bench. Before the data is converted to flow rates and pressure drops across the DUT, the average and standard deviation of the sensor data is computed at each operating condition. The statistical summary of the raw data can be obtained with Excel, or with the `flowBenchDataSelector` MATLAB function available from <http://www.me.pdx.edu/~gerry/class/ME449/codes/>.

4.6.1 Using `flowBenchDataSelector` to Average the Sensor Data

The `flowBenchDataSelector` function greatly simplifies the process of extracting the average and standard deviation of the sensor data at each operating condition. Learning how to use `flowBenchDataSelector` is a bit of a challenge because the user interface is obscure and quirky. However, `flowBenchDataSelector` is designed to perform only one task, and once you learn the steps for selecting data, the program is easy to use. Figure 4 is a screen shot of the `flowBenchDataSelector`.

Launch the GUI by typing

```
>> flowBenchDataSelector
```

at the command prompt. This requires that both `flowBenchDataSelector.m` and `flowBenchDataSelector.fig` are in the current MATLAB path. When the `flowBenchDataSelector` function is running, use the following steps to average the raw data with the `flowBenchDataSelector`. The steps correspond to the numbers in Figure 4.

1. Read the text file exported from BenchLink with “File” → “Open” command from the “File” menu.
2. Pick 105(VDC) channel from the “Monitor Channel” pop-up menu.
3. Enter the nozzle diameters you measured by clicking the “Change Nozzle Diameters” button.
4. Select the nozzle diameter of the first flow bench setting from the “Nozzle Dia” pop-up menu.

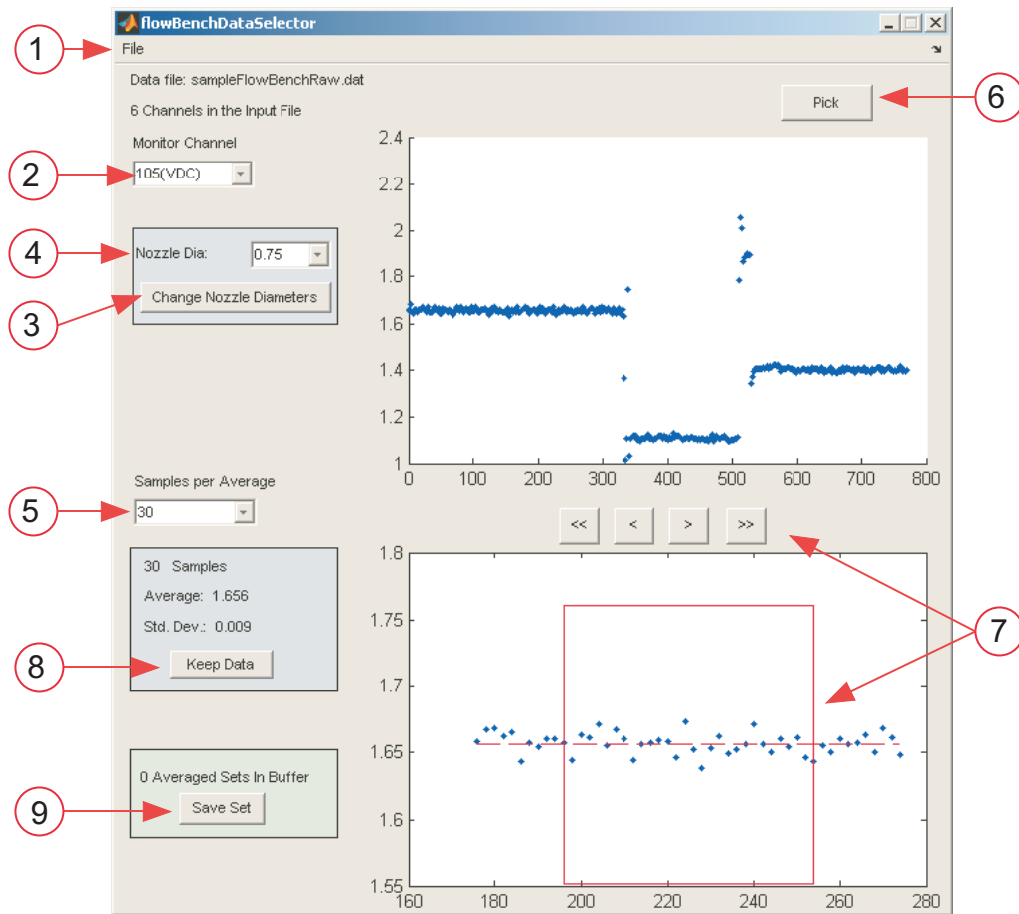


Figure 4: Screen shot of flowBenchDataSelector.

5. Set the number of points to average with the “Samples per Average” pop-up menu.
6. Click on the “Pick” button above the axis in the upper half of the window. The cursor changes to cross hairs. Align the cross hairs at the beginning of the data you want to average and click once with the left mouse button. The vertical position of the cursor does not matter. The horizontal position determines the starting time of the data to be averaged. Once the data is selected, it appears in the lower plot axes.
7. Inspect the data displayed in the lower plot axes. Individual data points are labelled with blue dots. A red box surrounds the data that is selected. The average and standard deviation of the data are displayed to the left of the lower plot axes. If the data is acceptable, proceed to the next step. If the averaging window is not capturing a good region of data you can use the nudge buttons in the space between the two axes. You can also select another part of the data with the “Pick” button above the upper

axis.

8. If the data is acceptable, click the “Keep Data” button at the bottom of the window. Return to step 6 to select more data, or proceed to the next step to save the data.
9. Click the “Save Set” button to save the averaged data to a `.mat` file for further post-processing. See Figure 2.
10. Quit the program by selecting “File” → “Quit” from the “Quit” menu. You do not need to quit the program to load another data set, or to save a different set of averaged values.

5 Loss Coefficients for Perforated Plates

5.1 Set-Up

1. Connect the perforated plate or filter material to the inlet of the flow bench. Record the size of the rough opening for the material. Make sure there are no leaks around the edge where the material is attached to the flow bench inlet.
2. Select proper input to the transducer measuring the difference in pressure between the first plenum and the ambient. For the loss coefficient measurement, connect the plenum pressure to the *low side* of the pressure transducer. Do not disconnect the tubing. Rather, slide the selector to the appropriate position “A” or “B”.
3. Turn on the DMM/Switch and the power supply for the pressure transducers. Adjust the power supply so that it produces 15 Volts DC. Using the rotary knob on the front of the DMM, verify that the output of the pressure transducers is close to 1 Volt when the DUT fan and the flow bench fan are both off.

Hint: In order to get the voltage to display on the DMM, you may need to put the Mon button on the front panel.

5.2 Data Collection

Use the sample data sheet is provided in the appendix as a guide to data collection, but use the Benchlink application to record the data. *Be sure* to record which flow nozzles are used during each setting of the blast gate.

5.3 Share Data with Other Groups

After completing the experiment, and averaging the data with the `flowBenchDataSelector` send your `.mat` file to me (Gerry) via email. I will post your measurement data on the class web site.

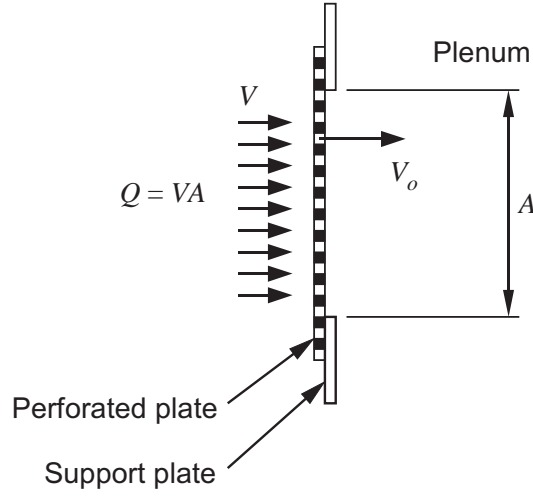


Figure 5: Superficial velocity approaching the plate.

5.4 Analysis of Perforated Plate Data

Figure 5 is a schematic of the perforated plate attached to the inlet of the flow bench. The head loss for the perforated plate is

$$h_L = K_L \frac{V^2}{2g} \quad (2)$$

where K_L is the loss coefficient, and V is the superficial velocity of the air approaching the plate. The flow bench is used to measure the volumetric flow rate Q through the perforated plate. If the gross area of the opening in the support plate is A , and the measured flow rate Q , then the superficial velocity is $V = Q/A$.

Note that $V_o = VA/A_o$ is the nominal velocity through the openings in the plate, where A_o is the aggregate area of the openings in the plate.

5.5 Measuring the Free Area of Perforated Plates

The geometry of the hole pattern for the perforated sheet metal is depicted in Figure 6. The equilateral triangle in Figure 6 is a basic cell that is repeated over the plate. The free area ratio of the plate is the same as the free area ratio of the triangle. The free area of the triangle is

$$A_{ft} = 3A_s$$

where A_s is the area of one of the shaded sectors. In general, $A_s = (\alpha/2)(d^2/4) = \alpha d^2/8$ where α is the angle of a sector and d is the diameter of the hole. For an equilateral triangle, $\alpha = \pi/3$ so $A_s = \pi d^2/24$ and

$$A_{ft} = \frac{\pi d^2}{8}$$

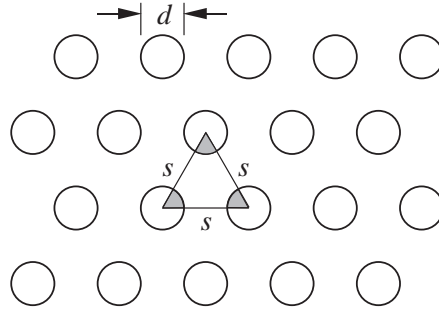


Figure 6: Geometry of hole pattern for perforated sheet metal.

The area of the triangle is $A_t = (\sqrt{3}/4)s^2$. Therefore, the free area ratio of the plate is

$$f = \frac{A_{ft}}{A_t} = \frac{(\pi/8)d^2}{(\sqrt{3}/4)s^2} = \frac{\pi}{2\sqrt{3}} \left(\frac{d}{s}\right)^2 \quad (3)$$

5.6 Conversion of Averaged Flow Bench Data

Once the BenchLink data has been averaged using the procedures described in § 4.6, you will need to convert the averaged data to flow rates. The `lossCoeffStats` and `fanCurveStats` MATLAB functions supplied in the MATLAB archive at <http://www.me.pdx.edu/~gerry/class/ME449/codes/> should make the data reduction process quite easy. Both `lossCoeffStats` and `fanCurveStats` call the `flowBenchStats` function, which does the work of converting the measurements to flow rate and its uncertainty.

The `lossCoeffStats` function computes the loss coefficient for the averaged data saved by `flowBenchDataSelector`. Refer to Figure 2 for a graphical representation of the data flow from the Benchlink program to the `lossCoeffStats` function. The `lossCoeffStats` function can be called in the following ways.

```
lossCoeffStats
lossCoeffStats(fname)
lossCoeffStats(fname, patm)
lossCoeffStats(fname, patm, dpatm)
```

The first input argument is the name of the MAT file containing the averages and standard deviations of the sensor measurements. The second and third inputs, `patm` and `dpatm`, are the nominal atmospheric pressure and the uncertainty in the atmospheric pressure. The value of `patm` is measured with the barometer on the wall of the lab when the experiments are conducted.

6 Loss Coefficient Report

The report should contain complete discussions of the loss coefficient measurements and their results. Guidelines for those discussions are given below. In addition, the report should contain an appendix with the averaged data used as input to the flow rate and uncertainty calculations. Do not include the raw

Table 2: Reduced Data

Plenum Δp (Pa)		Flow Rate (m^3/s)	
Δp	$u_{\Delta p}$	Q	u_Q

data as exported from the BenchLink database. The loss coefficient plot should include error bars on Q and Δp for each point.

1. Use Equation (3) to compute the free area ratio f for your plate.
2. Convert your raw data to pressure drop and flow rate. Use the least squares method to obtain the loss coefficient for the plate. Plot pressure drop versus flow rate and add the curve predicted by the curve fit.
3. From the class web site, download at least one additional data set for loss coefficient of another perforated plate measured by another group. Reduce the raw data and obtain the loss coefficient for their plate.
4. Compare the loss coefficients for the your plate and the plate(s) measured by the other group(s). Is there a relationship between loss coefficient and free area ratio? Compare the measured loss coefficients with the following formula from Idel'chik [1, p. 402].

$$K_L = \frac{1}{f} \left[0.707 \sqrt{1-f} + (1-f) \right]^2 \quad (4)$$

where K_L is the minor loss coefficient and $h_L = K_L(V^2/(2g))$ is the head loss across the perforated plate. For head loss computations in screens and perforated plates, the velocity used in the definition of K_L is the *superficial velocity*, i.e.

$$V = \frac{Q}{A}$$

where Q is the flow rate through the screen or plate, and A is the total area of the screen or plate. The area is *not* the free area of the holes.

References

- [1] I. Idelchik. *Handbook of Hydraulic Resistance*. Hemisphere Publishing Corp., New York, second edition, 1986.

Appendix: Data Sheet/Event Log

The blank data sheet in Table 3 is provided to stimulate your thinking about what to record and how to record it. You should create your own version of these tables in your notebook.

Table 3: Manual data and Event Log.

Start time: _____
 Stop time: _____
 Thermistor reading at start: _____
 Thermistor reading at stop: _____
 Ambient Pressure: _____

Reading	Time	Nozzle Diameter (inch)	Plenum Manometer (inch H ₂ O)	Nozzle Δp (inch H ₂ O)	Comments
1					
2					
3					
4					
5					
6					
7					
8					
9					
10					
11					
12					
13					
14					
15					