MAE 4223

Aerospace Engineering Laboratory

Wake Velocity Profile of a Cylinder

Charles O'Neill

2-1-2001

TABLE OF CONTENTS

ABSTRACT

Wind tunnel velocity profile measurements of a cylinder's wake were made in a wind tunnel. Two flow velocities near the turbulent transition Reynolds number were tested. The experimental procedure is reviewed. A method was derived for converting manometer pressures to velocities in an incompressible wind tunnel. Experimental wave velocity profiles are plotted. The experimental results show that the empirical wake deficit equation accurately predicts a cylinder's wake profile. Instrumentation errors and experiment implications are discussed.

INTRODUCTION

The velocity distribution downstream of a cylinder was measured in a wind tunnel. The experiment required the calibration and use of temperature and pressure instrumentation. Local atmospheric properties were determined and the results were used to calibrate a pressure transducer. A method based on the Bernoulli equation is derived to convert between the measured pitot tube pressure and the local wind tunnel velocity. Two velocities were tested and the wake distributions plotted. The velocity profiles were nondimensionalized and compared to an empirical wake profile equation. Errors in the instrumentation are discussed and quantified.

EQUIPMENT

The equipment consisted of a low speed wind tunnel and measurement equipment. The experimental equipment setup is shown in Figure 1.

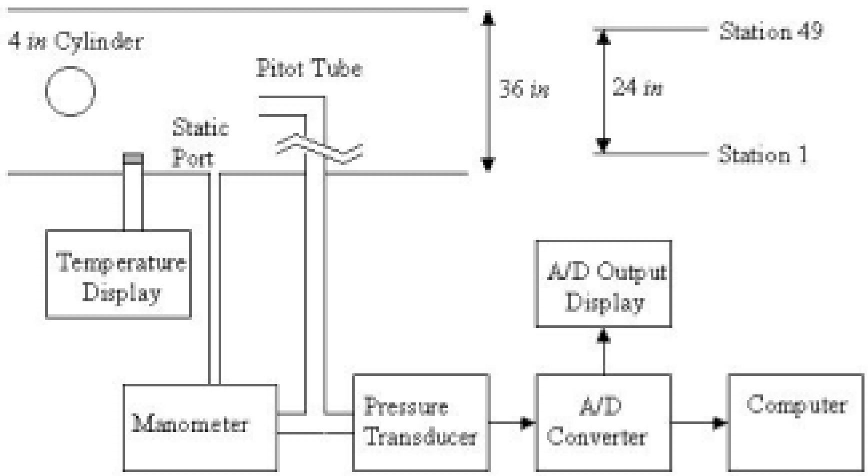

Figure 1. Wind Tunnel and Measurement Equipment

Oklahoma State University's low speed wind tunnel was used. This tunnel has a square 36-inch test chamber. A vertical 4 inch PVC cylindrical pipe was centered upstream of the viewing chamber. The measurement equipment consisted of temperature and pressure measurement systems. The tunnel temperature was measured just downstream of the cylinder. Atmospheric pressure was measured with a mercury barometer. The tunnel pressure measurement system consisted of a pitot-static tube connected to a pressure transducer and a manometer. The pressure transducer was connected to an A/D converter, which fed both a digital display and a computer recording system.

PROCEDURE

The experimental procedure consisted of three steps. First, the local atmospheric pressure was determined. Next, the pressure transducer was calibrated. Finally, data was taken.

Atmospheric pressure was measured using a mercury barometer. The barometer was calibrated for mercury level and a measurement was made. Then, local temperature and gravity corrections were made to the pressure measurement.

The pressure transducer was calibrated with correlate the transducer voltage output with the corresponding pitot-static pressure differential. This calibration data allowed for the conversion between transducer voltages and pitot tube pressures. Ten pressures were input into the pitot-static system and the corresponding transducer voltages and manometer readings were recorded.

Finally, the wind tunnel was started and velocity profile measurements began. Two wind tunnel settings were tested, 0.8 *in.* H_2O and 1.4 *in.* H_2O. The pitot tube was started 6 inches off the wind tunnel wall, station 1, and moved in half-inch horizontal increments to 6 inches off the opposite wall, station 49. Pressure measurements were made at each station.

THEORY

A simple relationship between water height and pressure for manometers is derived from Bernoulli's equation.

$$\Delta P = \tfrac{1}{2}\rho V^2$$

Rearranging yields,

$$V = \sqrt{\frac{2\Delta P}{\rho}}$$

Adding the pressure due to height, $\Delta P = \rho_{H_2O} g h$, yields,

$$V = \sqrt{\frac{2\rho_{H_2O} g h}{\rho}}$$

As seen above, only the ratio between the densities of the manometer fluid and air are important in the velocity measurement. From Kuethe [1] the density of water is 1000 kg/m^3.

Errors in measurement are introduced by the conversion of analog measurements to digital data. From Beckwith [2], the voltage resolution per bit is,

$$\varepsilon_v = \frac{\Delta V}{2^n}$$

where n is the number of bits used in the A/D converter and ΔV is the voltage range.

RESULTS AND DISCUSSION

Measurements were conducted as described above for two velocities. The raw data is given in Tables 1 through 4 in the Appendix.

The pressure transducer was calibrated as given above. A linear best-fit line was determined to convert voltage data to pressure data. A plot of the calibration points and the best-fit line is given in Figure 2. The best-fit line was defined by $P = 5.299V + 0.0196$ where the pressure is in inches of water and the voltage is in volts. The calibration data points were surprisingly linear.

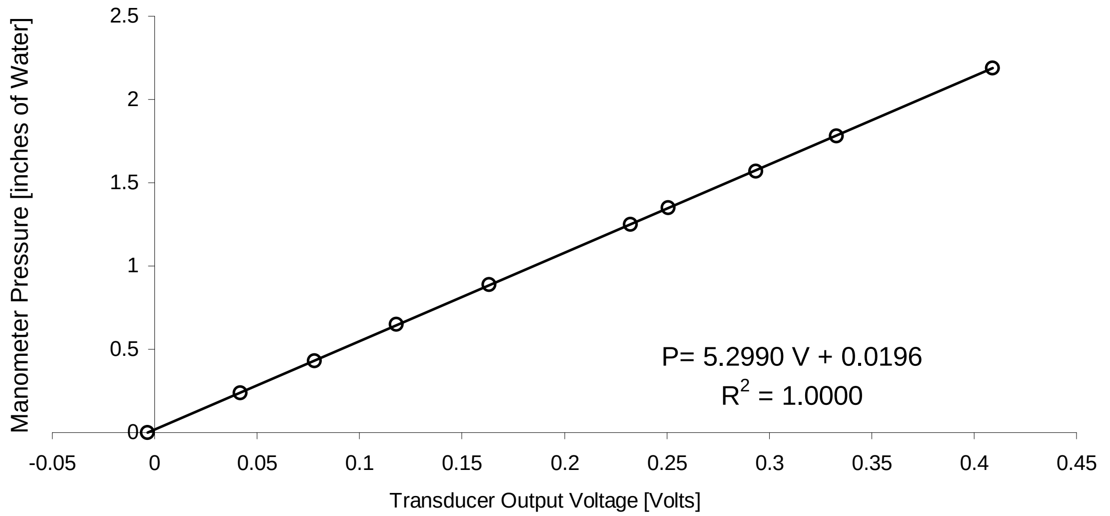

Figure 2. Pressure Transducer Calibration

The measured pressure data was converted to velocity by application of the manometer equation above and Bernoulli's equation. Tables of raw velocity distributions are given in Table 5 in the Appendix and are plotted in Figure 3.

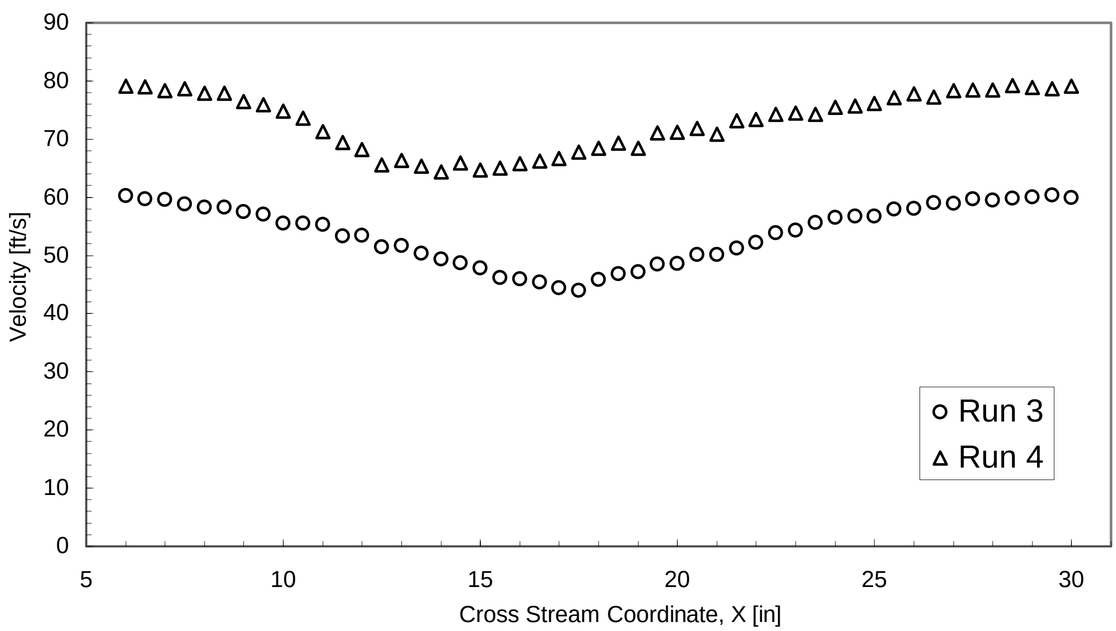

Figure 3. Raw Velocity Distribution

The higher velocity test, Run 4, has a wake centerline skewed off the 18-inch wind tunnel centerline. Also, Run 4 had a more rounded velocity profile than Run 3. The Reynolds numbers for Run 3 is near 120000 while Run 4 is near 170000. At these low Reynolds numbers, the flow is laminar but easily transitioned to turbulent. Run 3 seems to have a different upstream wake distribution than Run 4. The higher velocity Run 4 is rounded and skewed. This suggests that perhaps the cylinder has transitioned to turbulent flow on the right side and is still partially laminar on the left. Different flow regimes would force the wake to become non-centered and would create a different wake profile. Also by inspection, Run 3 has a proportionally larger drop in wake centerline velocities than Run 4. Because laminar flow cylinder flow has more drag than turbulent, the wake profile supports the argument that Run 3 is still turbulent but Run 4 has partially transitioned to turbulent.

Calibration of the pressure transducer introduced errors. The calibration data points were surprisingly linear. Because the calibration points had to be visually read off of a manometer scale and verbally transferred to the data recorder, there was a high probability of a mistake. The manometer readings appeared to be accurate. This was unexpected due to the manometer being crippled with a broken leveling mechanism. At the calibration point 5, a maximum deviation from linearity of was found. This error was 0.2 percent of the observed full scale. From the MKS 223 data sheet [3] at 5 Volts, the manufacture's accuracy specification is 0.3 percent of the full-scale reading.

The raw velocity profiles were converted to nondimensional velocity deficits and coordinates. Both velocities and the empirical profile are plotted in Figure 4.

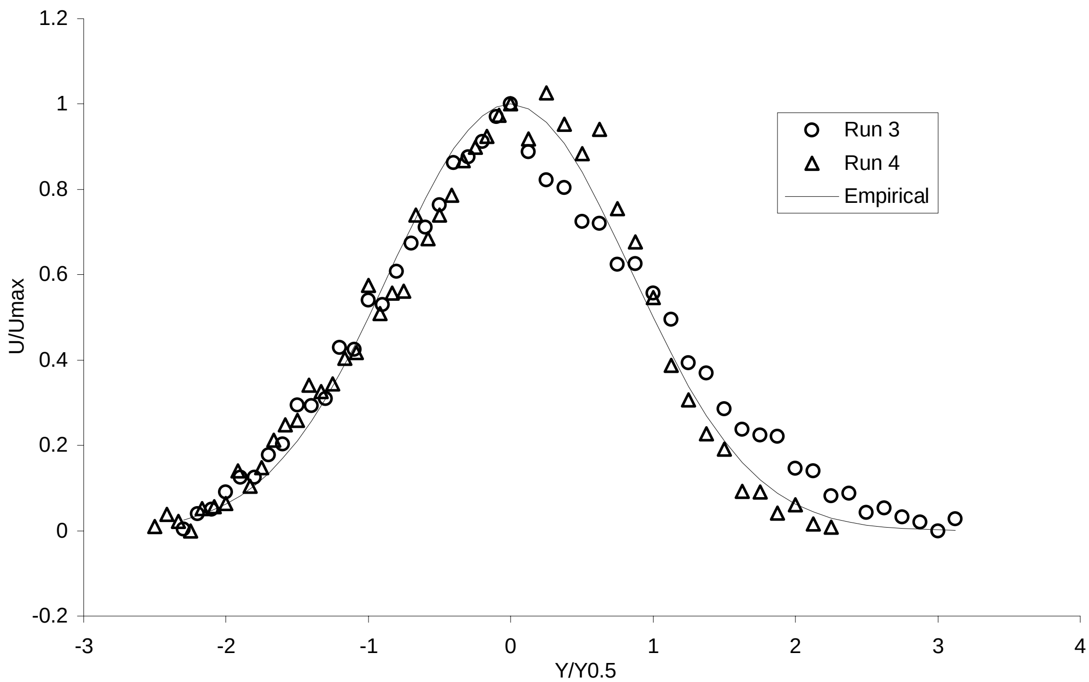

Figure 4. Nondimensional Velocity Deficits

Surprisingly, the experimental data points are predicted by the empirical wake velocity equation. Both runs have considerable scatter with a positive $Y/Y_{0.5}$; however, the empirical equation seems to account for the dominant physical processes occurring in the wake. The empirical equation undershoots the experimental distributions far from the wake centerline and overshoots near the centerline. This difference may be due to the partially laminar flow regime of the cylinder. A flow visualization experiment with smoke or oil drops would help to qualify which type of flow is occurring at the cylinder. Knowledge of the flow type would allow for a better understanding of how the different flow regimes influence the wake profile.

Conversion from analog to digital introduces errors into the data. The A/D converter is using 12 bits at ±10 Volts. From above, the resolution is 0.0049 Volts or 0.0258 *in* H_2O after scaling by the pressure transducer calibration factor or 5.299 *in* H_2O *per Volt*. The lowest pressure reading, 0.439 *in* H_2O has an A/D conversion error of 1 in 17 or 2.58 percent. The scatter of the data points is within this quantification error. The A/D converter creates the largest error due to the pressure transducer's specifications being an order of magnitude better than the A/D converter's.

CONCLUSIONS AND RECOMMENDATIONS

The following conclusions and recommendations are made with respect to measuring the velocity profile of a cylinder's wake.

1. Unsymmetrical separation skewed the wake in Run 4. Partial separation could have been caused by imperfections in the flow or cylinder tripping one side to turbulent flow.

2. A cylinder with 60 to 80 ft/s flow is operating near the transition Reynolds number. Transition could cause problems with repeatability and comparisons.

3. A higher resolution A/D converter would be effective in reducing the quantification errors. The pressure transducer is capable of more precise measurements than the A/D converter.

4. Flow visualization would help to define the flow regime and to show turbulent transition areas.

5. The empirical wake deficit equation predicted the wake profile even with significant differences in the velocity profile shape and relative magnitude.

REFERENCES

1. Kuethe, A. M., and Chow, Chuen-Yen., "Table 2. Properties of Air and Water," *Foundations of Aerodynamics*, 5th ed., Wiley, New York, 1998, p. 532.

2. Beckwith, T. G., Marangoni, R. D., and Lienhard, J. H., "Analog to Digital Conversion Considerations," *Mechanical Measurements*, 5th ed, Addison Wesley, New York, 1993, p. 365.
3. MKS Instruments, http://www.mksinst.com/pdf/223.pdf, 2001.

APPENDIX

SAMPLE CALCULATIONS

1. Conversion from pressure transducer output to pressure.

$$P = 5.2990\,\mathrm{V} + 0.0196$$
$$P = 5.2990\left(0.1522\right) + 0.0196$$
$$\mathrm{P} = 0.8261\ \ in\, H_2O$$

2. Velocity calculated from pitot-static pressure.

$$V = \sqrt{\frac{2\rho_{H_2O}gh}{\rho}}$$
$$V = \sqrt{\frac{(2)\left(1000\,kg/m^3\right)\left(32.174\ ft/s^2\right)\left(0.8261\,in.\,H_2O\right)}{\left(1.2164\,kg/m^3\right)\left(12\,in/\ ft\right)}}$$
$$V = 60.347\ ft/s$$

3. Empirical non-dimensional velocity deficit equation.

$$\frac{\Delta U}{\Delta U_{\max}} = \exp\left(-0.693\left(\frac{Y}{Y_{0.5}}\right)^2\right)$$
$$\frac{\Delta U}{\Delta U_{\max}} = \exp\left(-0.693\left(-2.3000\right)^2\right)$$
$$\frac{\Delta U}{\Delta U_{\max}} = 0.0256$$

TABULAR DATA

Table 1. Calibration Data

10 CALIBRATION POINTS

N	DP (IN H2O)	DPM (mm H2O)	E (VOLTS)
1	0.000E+00	0.000E+00	-3.394E-03
2	2.400E-01	6.096E+00	4.170E-02
3	4.300E-01	1.092E+01	7.810E-02
4	6.500E-01	1.651E+01	1.181E-01
5	8.900E-01	2.261E+01	1.632E-01
6	1.250E+00	3.175E+01	2.323E-01
7	1.350E+00	3.429E+01	2.509E-01
8	1.570E+00	3.988E+01	2.934E-01
9	1.780E+00	4.521E+01	3.328E-01
10	2.190E+00	5.563E+01	4.091E-01

-3.7009E-03 7.4297E-03 :A,B -> E = A + (B *DPM)

Table 2. Laboratory Atmospheric Properties

run2

01-19-2001 08:35:19

99.445	KPA - ATMOSPHERIC PRESSURE
11.70	DEG. C - TEMPERATURE
284.85	DEG. K - ABS. TEMP.
1.2164	KG/M3 - AIR DENSITY
1.773E-05	PA-S - DYNAMIC VISCOSITY
1.458E-05	M2/S - KINEMATIC VISCOSITY
4.011E+00	(M/S)/(mm H2O)

Table 3. Run #3 Measurements

49 CALIBRATION POINTS

N	DP (IN H2O)	DPM (mm H2O)	E (VOLTS)
1	1.000E+00	2.540E+01	1.522E-01
2	2.000E+00	5.080E+01	1.491E-01
3	3.000E+00	7.620E+01	1.483E-01
4	4.000E+00	1.016E+02	1.449E-01
5	5.000E+00	1.270E+02	1.421E-01
6	6.000E+00	1.524E+02	1.421E-01
7	7.000E+00	1.778E+02	1.378E-01
8	8.000E+00	2.032E+02	1.357E-01
9	9.000E+00	2.286E+02	1.285E-01
10	1.000E+01	2.540E+02	1.286E-01
11	1.100E+01	2.794E+02	1.274E-01
12	1.200E+01	3.048E+02	1.182E-01
13	1.300E+01	3.302E+02	1.185E-01
14	1.400E+01	3.556E+02	1.100E-01
15	1.500E+01	3.810E+02	1.108E-01
16	1.600E+01	4.064E+02	1.052E-01
17	1.700E+01	4.318E+02	1.006E-01
18	1.800E+01	4.572E+02	9.805E-02
19	1.900E+01	4.826E+02	9.450E-02
20	2.000E+01	5.080E+02	8.792E-02
21	2.100E+01	5.334E+02	8.704E-02
22	2.200E+01	5.588E+02	8.477E-02
23	2.300E+01	5.842E+02	8.102E-02
24	2.400E+01	6.096E+02	7.923E-02
25	2.500E+01	6.350E+02	8.630E-02
26	2.600E+01	6.604E+02	9.053E-02
27	2.700E+01	6.858E+02	9.173E-02
28	2.800E+01	7.112E+02	9.714E-02
29	2.900E+01	7.366E+02	9.736E-02
30	3.000E+01	7.620E+02	1.041E-01
31	3.100E+01	7.874E+02	1.039E-01
32	3.200E+01	8.128E+02	1.088E-01
33	3.300E+01	8.382E+02	1.133E-01
34	3.400E+01	8.636E+02	1.209E-01
35	3.500E+01	8.890E+02	1.227E-01
36	3.600E+01	9.144E+02	1.292E-01
37	3.700E+01	9.398E+02	1.330E-01
38	3.800E+01	9.652E+02	1.341E-01
39	3.900E+01	9.906E+02	1.343E-01
40	4.000E+01	1.016E+03	1.404E-01
41	4.100E+01	1.041E+03	1.408E-01
42	4.200E+01	1.067E+03	1.457E-01
43	4.300E+01	1.092E+03	1.451E-01
44	4.400E+01	1.118E+03	1.489E-01
45	4.500E+01	1.143E+03	1.480E-01
46	4.600E+01	1.168E+03	1.498E-01
47	4.700E+01	1.194E+03	1.508E-01
48	4.800E+01	1.219E+03	1.525E-01
49	4.900E+01	1.245E+03	1.502E-01

1.1515E-01 9.9640E-06 :A,B -> E = A + (B *DPM)

Table 4. Run #4 Measurements

49 CALIBRATION POINTS

N	DP (IN H2O)	DPM (mm H2O)	E (VOLTS)
1	4.900E+01	1.245E+03	2.643E-01
2	4.800E+01	1.219E+03	2.615E-01
3	4.700E+01	1.194E+03	2.630E-01
4	4.600E+01	1.168E+03	2.652E-01
5	4.500E+01	1.143E+03	2.601E-01
6	4.400E+01	1.118E+03	2.596E-01
7	4.300E+01	1.092E+03	2.589E-01
8	4.200E+01	1.067E+03	2.515E-01
9	4.100E+01	1.041E+03	2.550E-01
10	4.000E+01	1.016E+03	2.508E-01
11	3.900E+01	9.906E+02	2.447E-01
12	3.800E+01	9.652E+02	2.413E-01
13	3.700E+01	9.398E+02	2.402E-01
14	3.600E+01	9.144E+02	2.325E-01
15	3.500E+01	8.890E+02	2.340E-01
16	3.400E+01	8.636E+02	2.323E-01
17	3.300E+01	8.382E+02	2.268E-01
18	3.200E+01	8.128E+02	2.256E-01
19	3.100E+01	7.874E+02	2.114E-01
20	3.000E+01	7.620E+02	2.173E-01
21	2.900E+01	7.366E+02	2.130E-01
22	2.800E+01	7.112E+02	2.126E-01
23	2.700E+01	6.858E+02	1.971E-01
24	2.600E+01	6.604E+02	2.018E-01
25	2.500E+01	6.350E+02	1.971E-01
26	2.400E+01	6.096E+02	1.932E-01
27	2.300E+01	5.842E+02	1.864E-01
28	2.200E+01	5.588E+02	1.838E-01
29	2.100E+01	5.334E+02	1.817E-01
30	2.000E+01	5.080E+02	1.776E-01
31	1.900E+01	4.826E+02	1.755E-01
32	1.800E+01	4.572E+02	1.822E-01
33	1.700E+01	4.318E+02	1.734E-01
34	1.600E+01	4.064E+02	1.793E-01
35	1.500E+01	3.810E+02	1.850E-01
36	1.400E+01	3.556E+02	1.803E-01
37	1.300E+01	3.302E+02	1.958E-01
38	1.200E+01	3.048E+02	2.025E-01
39	1.100E+01	2.794E+02	2.140E-01
40	1.000E+01	2.540E+02	2.283E-01
41	9.000E+00	2.286E+02	2.358E-01
42	8.000E+00	2.032E+02	2.432E-01
43	7.000E+00	1.778E+02	2.466E-01
44	6.000E+00	1.524E+02	2.562E-01
45	5.000E+00	1.270E+02	2.563E-01
46	4.000E+00	1.016E+02	2.612E-01
47	3.000E+00	7.620E+01	2.592E-01
48	2.000E+00	5.080E+01	2.636E-01
49	1.000E+00	2.540E+01	2.644E-01

2.1093E-01 2.2742E-05 :A,B -> E = A + (B *DPM)

Table 5. Position, Voltage, Pressure and Velocity for Runs 3 and 4.

Run 3

X [in]	Transducer Voltage	Pressure [in H2O]	Velocity [ft/s]
6.0	0.152	0.826	60.3
6.5	0.149	0.810	59.7
7.0	0.148	0.805	59.6
7.5	0.145	0.787	58.9
8.0	0.142	0.773	58.4
8.5	0.142	0.773	58.4
9.0	0.138	0.750	57.5
9.5	0.136	0.739	57.1
10.0	0.129	0.701	55.6
10.5	0.129	0.701	55.6
11.0	0.127	0.695	55.3
11.5	0.118	0.646	53.4
12.0	0.119	0.648	53.4
12.5	0.110	0.602	51.5
13.0	0.111	0.607	51.7
13.5	0.105	0.577	50.4
14.0	0.101	0.553	49.4
14.5	0.098	0.539	48.8
15.0	0.095	0.520	47.9
15.5	0.088	0.485	46.3
16.0	0.087	0.481	46.0
16.5	0.085	0.469	45.5
17.0	0.081	0.449	44.5
17.5	0.079	0.439	44.0
18.0	0.086	0.477	45.9
18.5	0.091	0.499	46.9
19.0	0.092	0.506	47.2
19.5	0.097	0.534	48.5
20.0	0.097	0.536	48.6
20.5	0.104	0.571	50.2
21.0	0.104	0.570	50.1
21.5	0.109	0.596	51.3
22.0	0.113	0.620	52.3
22.5	0.121	0.660	54.0
23.0	0.123	0.670	54.3
23.5	0.129	0.704	55.7
24.0	0.133	0.724	56.5
24.5	0.134	0.730	56.7
25.0	0.134	0.731	56.8
25.5	0.140	0.764	58.0
26.0	0.141	0.766	58.1
26.5	0.146	0.792	59.1

Run 4

X [in]	Transducer Voltage	Pressure [in H2O]	Velocity [ft/s]
30.0	0.264	1.420	79.1
29.5	0.262	1.405	78.7
29.0	0.263	1.413	78.9
28.5	0.265	1.425	79.3
28.0	0.260	1.398	78.5
27.5	0.260	1.395	78.4
27.0	0.259	1.392	78.3
26.5	0.252	1.352	77.2
26.0	0.255	1.371	77.7
25.5	0.251	1.349	77.1
25.0	0.245	1.316	76.2
24.5	0.241	1.298	75.7
24.0	0.240	1.292	75.5
23.5	0.233	1.252	74.3
23.0	0.234	1.260	74.5
22.5	0.232	1.251	74.2
22.0	0.227	1.221	73.4
21.5	0.226	1.215	73.2
21.0	0.211	1.140	70.9
20.5	0.217	1.171	71.9
20.0	0.213	1.148	71.1
19.5	0.213	1.146	71.1
19.0	0.197	1.064	68.5
18.5	0.202	1.089	69.3
18.0	0.197	1.064	68.5
17.5	0.193	1.043	67.8
17.0	0.186	1.007	66.6
16.5	0.184	0.994	66.2
16.0	0.182	0.982	65.8
15.5	0.178	0.961	65.1
15.0	0.176	0.950	64.7
14.5	0.182	0.985	65.9
14.0	0.173	0.938	64.3
13.5	0.179	0.970	65.4
13.0	0.185	1.000	66.4
12.5	0.180	0.975	65.6
12.0	0.196	1.057	68.3
11.5	0.203	1.093	69.4
11.0	0.214	1.154	71.3
10.5	0.228	1.229	73.6
10.0	0.236	1.269	74.8
9.5	0.243	1.308	75.9

X [in]	Transducer Voltage	Pressure [in H2O]	Velocity [ft/s]
27.0	0.145	0.788	59.0
27.5	0.149	0.809	59.7
28.0	0.148	0.804	59.5
28.5	0.150	0.813	59.9
29.0	0.151	0.819	60.1
29.5	0.153	0.828	60.4
30.0	0.150	0.816	60.0

X [in]	Transducer Voltage	Pressure [in H2O]	Velocity [ft/s]
9.0	0.247	1.326	76.5
8.5	0.256	1.377	77.9
8.0	0.256	1.378	77.9
7.5	0.261	1.404	78.7
7.0	0.259	1.393	78.4
6.5	0.264	1.416	79.0
6.0	0.264	1.421	79.1

SPREADSHEET OUTPUT