ME 552: Lab 2
Hot Wire Anemometer Calibration and Jet Flow Experiment

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1 Introduction

Hot Wire Anemometry (HWA) is a turbulent flow measurement technique that can determine mean and fluctuating velocity components, turbulence, and localized temperature. HWA sensors are thin metallic wires that warm with electric current and cool through forced convection in the incident flow. These sensors are typically made of platinum or tungsten and drawn to a diameter of 0.5-5 μm and length of 0.1-1 mm [Comte-Bellot 1976]. The main advantages of HWA over comparable methods, such as laser velocimetry, of which LDV is one type, are a higher sampling frequency, smaller probe volume, and less expense.

Although a hot wire is more common for this technique, a hot film is sometimes used, typically in liquids, and both of these can be used with both constant-current and constant-temperature systems. Constant-temperature systems are composed of a Wheatstone bridge and amplifier circuit that pass temperature changes through a feedback loop to maintain constant temperature. The voltage at the top of the bridge can then be related back to the velocity of the flow [IFA 300 Manual].

For this lab exercise, the IFA 300 Constant Temperature Anemometer System was pared with a single sensor hot wire probe to first calibrate the probe and then to conduct a jet flow experiment. LabVIEW was used to collect the data, and Python was used, in conjunction with the equations below, to process and analyze the data.

2 Assumptions

The change in height is negligible when calculating the velocity from Bernoulli's Equation for low density air. The velocity in the plenum is negligible. The temperature of the gas is constant. The wire temperature is held constant. The ambient temperature is held constant. Radiation is negligible and temperature difference due mainly to forced convection. Energy out at the wire is proportional to the voltage across the bridge which is measured.

3 Design Stage Uncertainty

Design stage uncertainty trees were determined for flow velocity and turbulence intensity. The tree for flow velocity can be found in Appendix D with a brief explanation. The tree for turbulence intensity is not included due to its simplicity. Please refer to the method used for the flow velocity tree and the turbulence intensity equations in Appendix B, if further investigation is desired.

Design stage uncertainty was then calculated using the first order Kline-McClintock method, as automated in Python. These calculated values were then integrated into the error bars calculated on the plots included in the analysis below. These plots were created in Python, and the code for the entirety of this lab exercise, including the uncertainty analysis, can be found in Appendix C.

4 Calibration

4.1 Procedure

For the probe calibration, compressed air was fed through the hot wire calibrator and two nozzles before flowing vertically across the horizontally held probe. This probe was wired to the IFA 300 Anemometer System, which was connected to a USB DAQ and PC equipped with both ThermalPro and LabVIEW software packages.

After aligning the probe with the jet center at about 2mm height and obtaining the cold wire probe resistance, the shorted BNC cable resistance, and the probe holder resistance, the zero flow and ten other data points were recorded for various flow rates at the recommended overheat ratio (1.53 in our case). The pressure transducer and hot wire voltage readings over a 5 second period were also recorded for each flow rate. This was then repeated for overheat ratios of 1.34 and 1.22.

4.2 Analysis

The data obtained during the experiment was analyzed using a Python code that found the average and standard deviation of the 50,000 samples taken for each data point. This Python code is found in Appendix C, and the film temperatures corresponding to the three overheat ratios are in the table below.

Overheat Ratio	T_w (K)
1.22	304.15
1.39	394.15
1.53	478.15

Then, the calibration curves for each of the three overheat ratios were found and plotted in Python. The large degree of uncertainty attributed to the lower voltages in these figures is due to the relatively large tolerance of the pressure transducers used in the experiment. The uncertainty improved greatly at higher voltages as the differential pressure increased to values greater than the tolerance of the pressure transducers. See figures below.

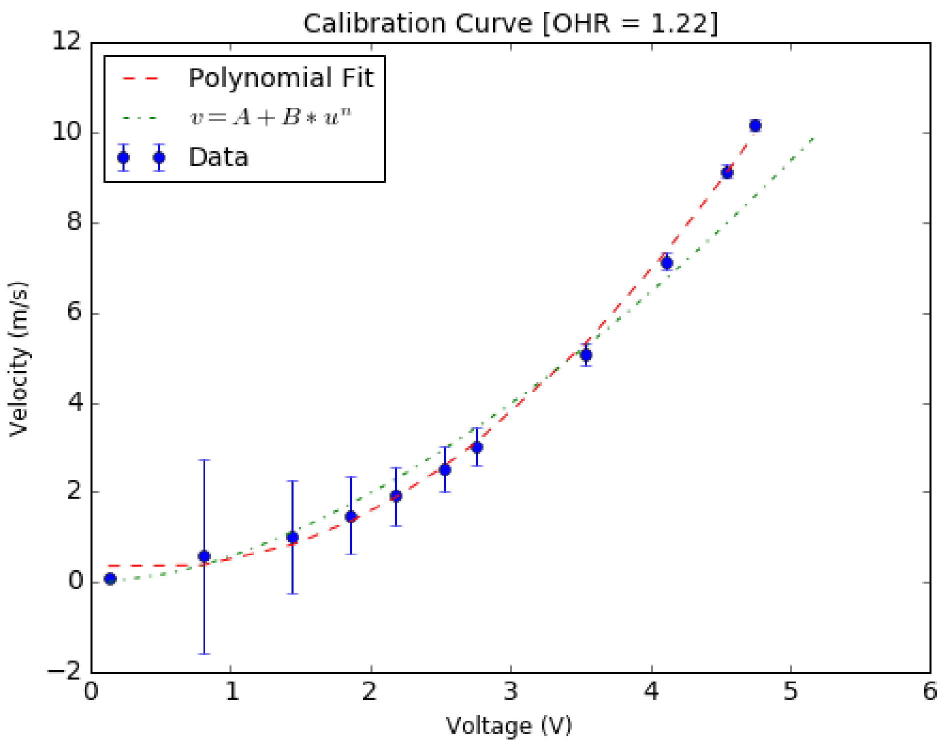

Figure 1: Calibration Curve for 1.22 Overheat Ratio

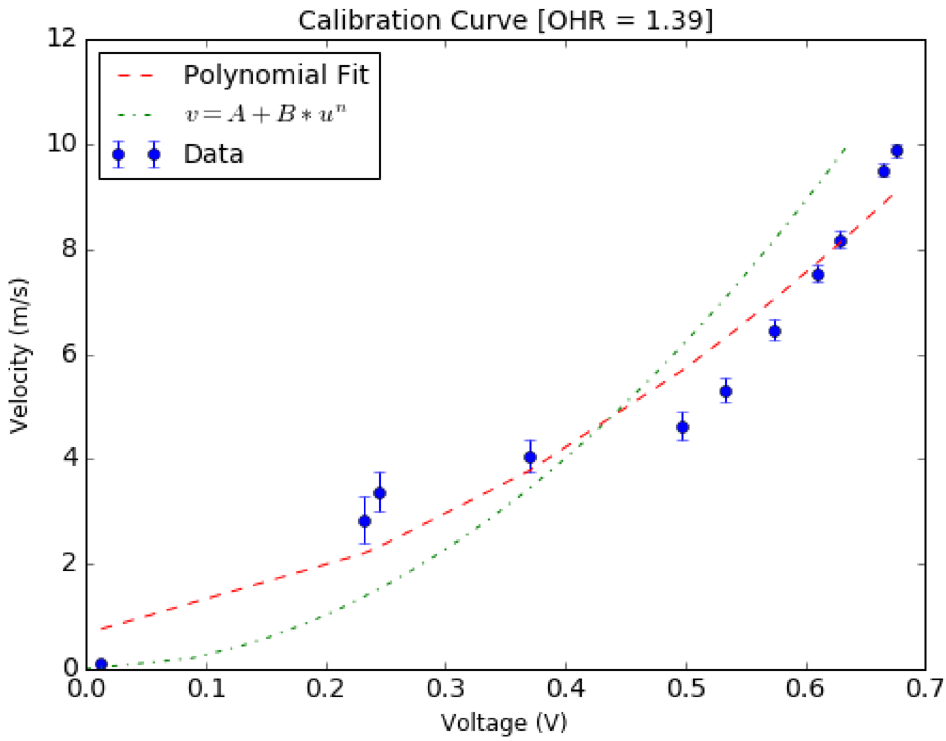

Figure 2: Calibration Curve for 1.39 Overheat Ratio

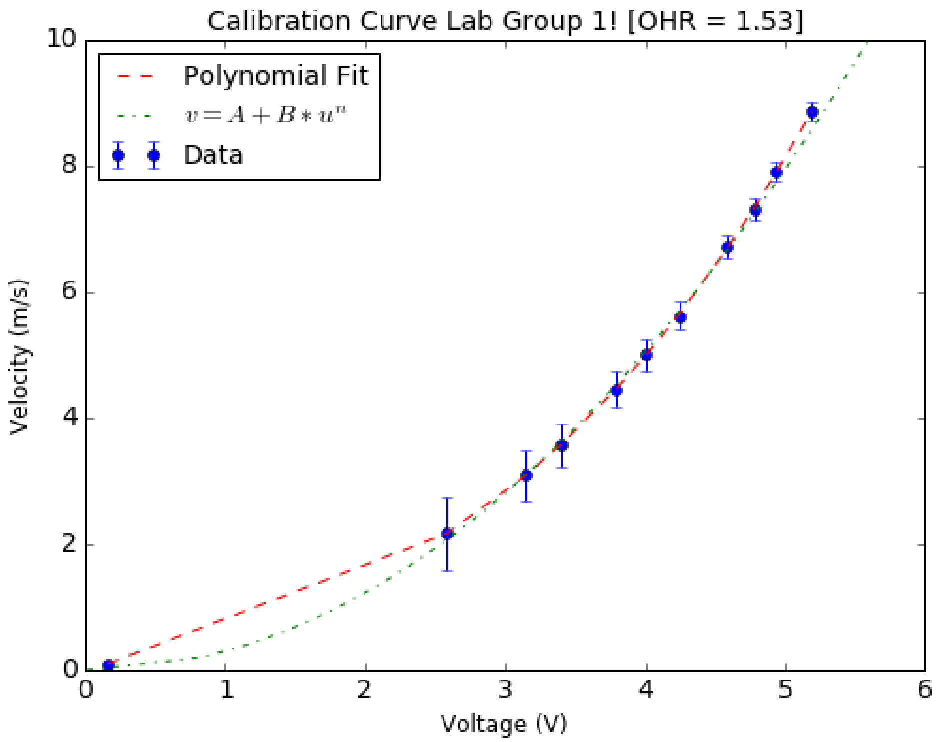

Figure 3: Calibration Curve for 1.53 Overheat Ratio

Next, the velocity sensitivity, S_u, for the three overheat ratios was calculated from Equation 17 in Appendix B and plotted in Python, as shown in Figure 4 below. Based on this plot, and the fact that the velocity for the 1.39 OHR is incredibly low, the data obtained is highly suspect. If time permitted, this setting should have been repeated. When compared to Equation 13 in Appendix B,

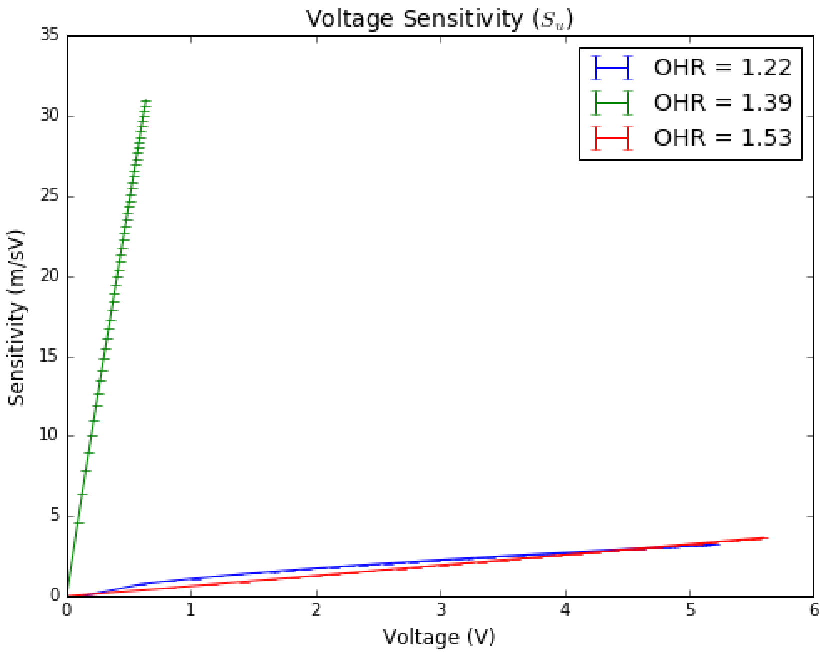

Figure 4: Voltage Sensitivity

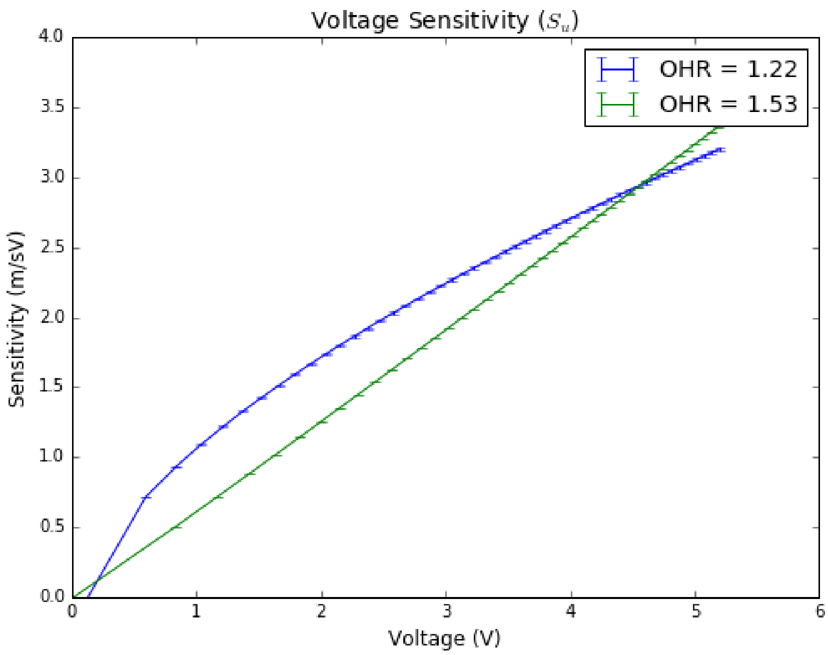

Figure 5: Voltage Sensitivity Close-up

5 Jet Flow Experiment

5.1 Procedure

For this part of the lab exercise, velocity and turbulence of coflow exiting a MILD flame burner were measured and the volumetric flow rate was recorded through LabVIEW. The recently calibrated probe was again positioned perpendicular to the flow at a height of about 2 mm. After the outer diameter of the tube jet and inner diameter of the coflow tuber were recorded, the pressure regulator at the build was set between 60 and 80 PSI while the upstream pressure regulator was increased to the desired flow rate. After testing the LabVIEW recording capabilities with this test, flow was turned off and the signal voltage for the energized hot-wire at the standard overheat ratio was recorded. This was repeated for the first Reynolds number condition and then for 5mm increments across the burner at this given Reynolds number. The height of the probe was increased to 30mm and signal voltages were again recorded as the probe traversed the burner in 5mm increments.

After collecting all data at the two heights across the entirety of the burner, this is repeated for a second Reynolds number. Then, to complicate matters further, the overheat ratio is changed by energizing the hot wire and the process is repeated twice more for two more overheat ratios. In summary, sensor voltages for all combinations of two Reynolds numbers, two heights, and three overheat ratios were collected. For data analysis purposes, only one overheat ratio will be used.

5.2 Analysis

For the hot wire within 2 mm of the fuel jet, the velocity profile forms an 'm' shape where there is minimal velocity at the boarders and at the center by the fuel jet. The velocities at the center is close to zero because the fuel jet is not releasing any gasses. Without any flow from the jet a stagnation point is formed. At the boarders the velocity is also close to zero because the just outside of the coflow cylinder the air is stagnant.
As the flow raises in height the m shape is still present. A difference is that the flow at the edges and the center have increased in velocity. This occurs because the stagnant and dynamic gasses have been mixing. This mixing can be seen when examining the turbulence intensity plot.
The turbulence intensity measured for the hot wire within 2 mm of the fuel jet forms backwards 'j' then a forward 'j' with a dip in the middle. The boundaries have the largest turbulence intensity because around the flow the gas is stagnant. In between the fuel jet and the coflow wall cylinder the turbulence intensity is small. This is because the flow is not interacting with the stagnant gasses at the boundary or the center. The center (fuel jet location) forms a stagnation point. This point has minimal turbulence intensity and is most likely cause by flow separation. Surrounding the stagnation point are points of higher turbulence intensity. This is most likely caused by mixing along the separation boundary.
As the flow moves further away from the fuel jet the turbulence intersity increases at the fuel jet. This is caused by the The center has more turbulence intensity because the flow wake

6 Conclusion

More coffee is required for further analysis.

7 Appendices

This section contains all supplementary materials required to complete this lab exercise. The appendices are arranged in the following order:

(A) Nomenclature

(B) Equations

(C) Python Code

(D) Uncertainty Tree

A Nomenclature

- Variables:
  - Density (ρ, kg/m^3)
  - Electrical Current (I, A)
  - Electrical Resistance (R, Ω)
  - Energy (E, J)
  - Height (z, m)
  - Velocity (u, m/s)
  - Ideal Gas Constant (R_{gas}, J/kg*K)
  - Overheat Ratio (a)
  - Pressure (P, Pa)
  - Temperature (T, K)
  - Turbulence Intensity (Y)
  - Velocity (u, m/s)
  - Voltage (V, V)
  - Volume (v, m^3)
- Subscripts:
  - Across the bridge (bridge) (Example: V_{bridge})
  - At/Across the Hot Wire (w) (Example: V_w)
  - Ambient Conditions (amb) (Example: x_{amb})
  - Average (avs) (Example: x_{avs})
  - Internal to Probe (int) (Example: x_{int})
  - Operating to Probe (op) (Example: x_{op})
  - Plenum Conditions (pln) (Example: x_{pln})
  - Reference Conditions (o) (Example: x_o)
  - Relative to Gauge (g) (Example: $P_{pln,g}$)
  - Root Mean Squares (rms) (Example: x_{rms})
  - Measured (meas) (Example: x_{meas})
  - When Flow is Zero (zero) (Example: V_{zero})
- Known:
  - $g = 9.81\ m/s^2$
  - $P_{amb} = 100,200\ Pa$
  - $R_{0^\circ C} = 5.85\ \Omega$
  - $R_{100^\circ C} - R_{0^\circ C} = 1.33$
  - $R_{gas} = 286.9\ J/kg * K$
  - $R_{int} = 0.50\ \Omega$
  - $T_{amb} = 293.5\ K$

B Equations

Ideal Gas Law

$$P * v = R_{gas} * T \tag{1}$$

$$\rho_{amb} = \frac{P_{amb}}{R_{gas} * T} \tag{2}$$

Bernoulli's Equation

$$\left(P + \frac{1}{2} * \rho * u^2 + \rho * g * h\right)_{pln} = \left(P + \frac{1}{2} * \rho * u^2 + \rho * g * h\right)_{amb} \tag{3}$$

$$u_{amb} = \sqrt{\frac{2 * P_{pln,g}}{\rho_{amb}}} \tag{4}$$

where:

$$P_{pln,g} = P_{pln} - P_{amb} = \Delta P \tag{5}$$

Ohm's Law

$$I = \frac{V}{R} \tag{6}$$

Overheat ratio from lab derivations:

$$a = \frac{R_{op} - R_{int}}{R_{meas} - R_{int}} \tag{7}$$

Resistance vs. temperature of wire (values given in Appendix A):

$$R_{op}(T_w) = R_{0^\circ C} + (R_{100^\circ C} - R_{0^\circ C})\frac{T_w - 0^\circ C}{100^\circ C} \tag{8}$$

Thus:

$$T_w = 100^\circ C * \frac{R_{op} - R_{0^\circ C}}{R_{100^\circ C} - R_{0^\circ C}} \tag{9}$$

Energy out at the wire:

$$\frac{E_w^2}{R_w} = (A + B * u^n) * (T_w - T_{amb}) \tag{10}$$

where:

$$R_w = R_{op} \tag{11}$$

For one overheat ratio and assuming the ambient temperature is constant:

$$E_w^2 = (A + B * u^n) \tag{12}$$

This can be reduced for the constant temperature circuit:

$$V = A + B * u^n \tag{13}$$

Which can be rewritten as:

$$u = \left(\frac{V - A}{B}\right)^{1/n} \tag{14}$$

Best Fit Powerlaw Trend Lines:
Over heat ratio of 1.22 ($R^2 = 0.9594$):

$$A = 0.128165$$

$$B = 1.2324$$

$$n = 0.6148$$

Over heat ratio of 1.39 ($R^2 = 0.9695$):

$$A = 0.0$$

$$B = 0.1975$$

$$n = 0.5079$$

Over heat ratio of 1.53 ($R^2 = 0.9977$):

$$A = 0.013131$$

$$B = 1.7954$$

$$n = 0.4928$$

Turbulence Intensity:

$$Y = \frac{u_{rms}}{u_{avg}} \tag{15}$$

where:

$$u_{rms} = \sqrt{\frac{1}{N}\sum_i u_i^2} \tag{16}$$

Velocity Sensitivity:

$$S_u = \frac{\partial u}{\partial V} = \frac{1}{n}\left(\frac{V - A}{B}\right)^{\frac{1}{n}-1}\left(\frac{1}{B}\right) \tag{17}$$

C Python Code

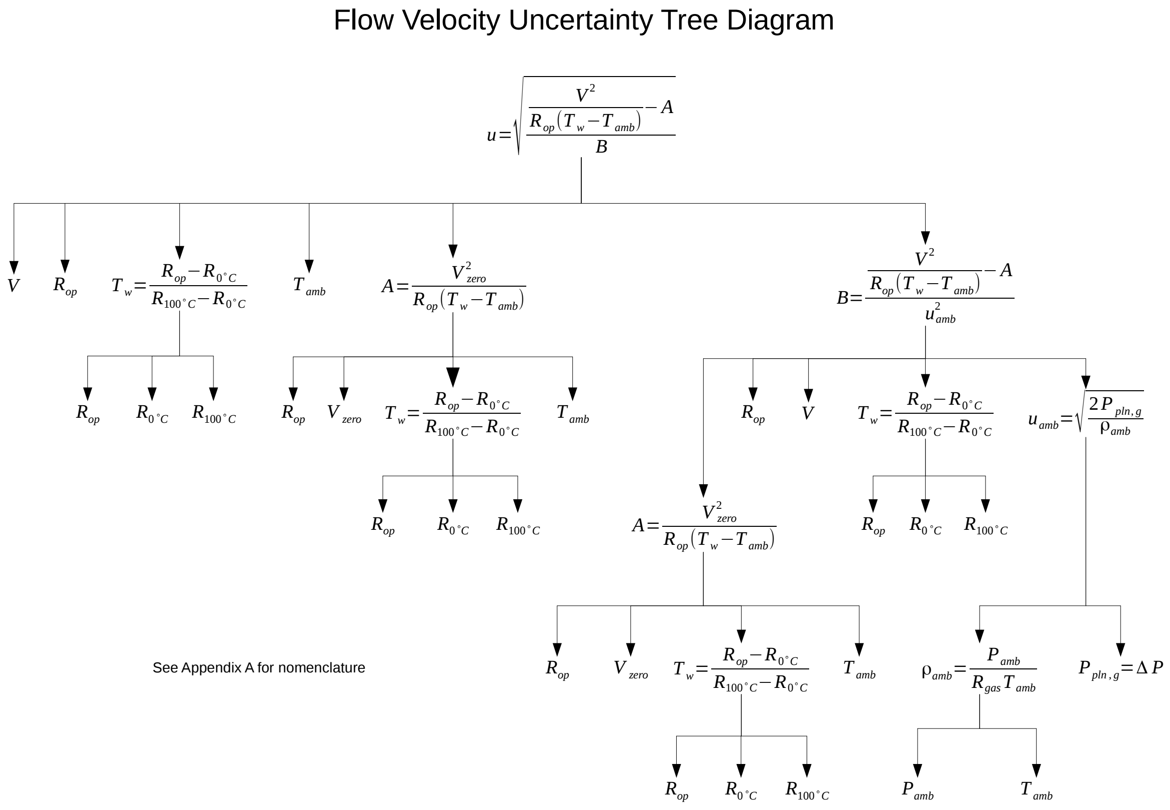

Figure 6: Flow Velocity Uncertainty Tree Diagram

D Uncertainty Tree

Omega PCL-MA-10WC uni-directional plug-in pressure module used has a range of 0 to 10 in H20. No uncertainty discovered from the specification sheet.

A TSI 1201-6 hot wire probe was used. No additional uncertainty data was found for this model.