Pitot-Tube Measurements

Acquisition Procedures:

The archival data that are reported here, was taken in September of 2019. Sidewall boundary layer profiles of mean velocity were taken using a United Sensor type BA-020-12-C-650 total pressure probe. The probe is made of a 0.020 inch [5.1 mm] nominal diameter steel tube that is flattened on the tip to an opening of 0.011 inches [2.8 mm]. The measured total pressure was referenced to a wall-normal static pressure line located nominally at the boundary layer profile location. The profile was traversed via a hand operated traverse with 1 mm gradations. Each profile started with the probe contacting the wall and ended with the probe in the freestream. All measurements were conducted using the Scanivalve SSS-48C pneumatic scanner housing a PDCR23D differential pressure transducer and a SCSG2 signal conditioner. This system has an internal pressure transducer with a differential range of 10 in of H2O with an accuracy of 0.30% of full scale. The data were sampled digitally via an NI USB 6343 DAQ and samples were taken at 100 Hz for 30 seconds per point. The lab atmospheric conditions were recorded at the start of each run with wind tunnel temperature recorded both at the start and end of each run.

This Scanivalve device was calibrated in the wind tunnel against the same Setra pressure transducers used for setting the wind tunnel freestream speed. An example calibration curve for this device is shown in Figure 1 below. The Mach 0.6 wind tunnel uses two Setra Model 270 absolute pressure transducers, to measure static and total pressures respectively, with a range of 600-1100 kPa and an accuracy of 0.05% of full scale. The calibration was done by varying wind tunnel freestream Mach number between 0 - 0.217 and recording the static and total pressure output of each Setra as well as the Scanivalve voltage output corresponding to the dynamic pressure. The difference in the Setra outputs, the pitot dynamic pressure, was used as the known pressure to calibrate the Scanivalve.

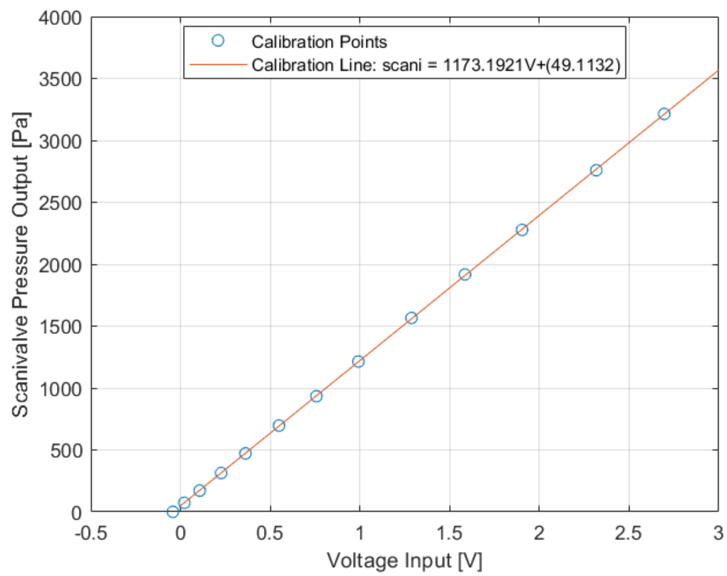

Figure 1 Calibration curve for the Scanivalve SSS-48C pneumatic scanner using an NI USB-6343 DAQ.

The starting location of each profile within the wind tunnel is listed in Table 1. Notice that the height off the boundary layer development plate, or *Y* coordinate, is not the same on each side. This occurs because the same removable window mounted traverse was used for all the pitot-tube profiles and the window openings of the test section sidewall on the outer loop side are lower than the inner loop side, i.e. the window positions are not symmetric about the tunnel centerline. For additional clarity, see the experimental setup documentation.

Table 1 Coordinate starting locations of sidewall boundary layer profiles acquired via pitot tube for Case A.

	X (m)	**Y (m)**	**Z (m)**
Inside Loop	-0.090	0.457	0.457
Outside Loop	-0.090	0.406	-0.457

Processing of Data

The individual data file for each location was loaded into and processed in MATLAB. Streamwise velocity was calculated from pressure via Bernoulli's equation as follows:

$$U = \sqrt{\frac{2\Delta P}{\rho}} \quad (1)$$

where ΔP is the local dynamic pressure, measured as the difference in the pitot pressure and the wall static pressure. The density, ρ $[kg/m^3]$, was calculated as a function of pressure, temperature and relative humidity using Jones's formula [1],

$$\rho = \frac{0.0034848}{T+273.15}(P_a - 0.0037960 * RH * P_{sat}) \quad (2)$$

where P_a is the atmospheric pressure [Pa], T is the temperature [C], RH is the relative humidity [%], and P_{sat} is the saturated water vapor pressure. Teten's formula was used to calculate the saturated water vapor pressure as follows:

$$P_s = 611 \times 10^{7.5T/(T+237.3)} \quad (3)$$

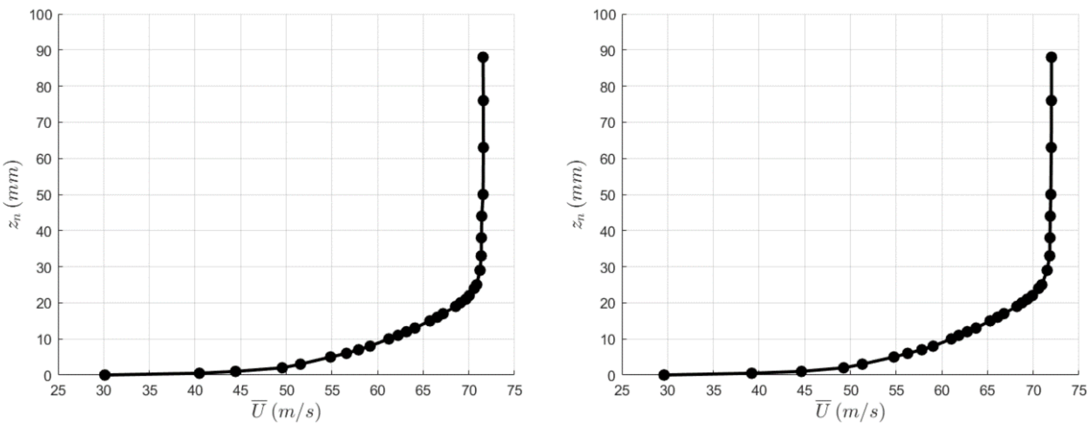

Figure 2 Wall-normal sidewall boundary layer profiles for inside loop (left) and outside loop (right) for Case A. The uncertainty intervals are on the order of the symbol size. Note that the profile location is not that same on either side, see Table 1.

Sample plots of the sidewall boundary layer for Case A are shown in Figure 2 above. For both the inside and outside loop, the shape factors are approximately the same at $H \approx 1.3$, and the boundary layer thicknesses differ only by about 2 mm even though the locations are not the same on either side.

Uncertainty Analysis

The uncertainty analysis procedure followed the general guidelines laid out in the ASME PTC 19.1-2005 Test Uncertainty manual [2]. This section will outline the procedure used to calculate the uncertainty for the sidewall boundary layer streamwise mean velocity, U, measurements which are reported in accompanying data files. The combined standard uncertainty of U is a combination of the random uncertainty, s_U, and the systematic standard uncertainty, b_U.

$$u_U = [\, b_U^2 + s_U^2]^{\frac{1}{2}} \tag{4}$$

The functional dependence of the mean velocity on the measured pressure and density are as follows:

$$U = f(\Delta P, \rho) = \sqrt{\frac{2\Delta P}{\rho}} \tag{5}$$

The sensitivities of U with respect to each of these dependent values were obtained by partial differentiation.

$$\frac{\partial U}{\partial \Delta P} = \frac{1}{\sqrt{2\rho\Delta P}} \tag{6}$$

$$\frac{\partial U}{\partial \rho} = -\sqrt{\frac{\Delta P}{2\rho^3}} \tag{7}$$

The random uncertainty, s_U, is a function of the random uncertainty s_P and was obtained from equations (5) and (6) as follows:

$$s_U = \left[\left(\frac{\partial U}{\partial \Delta P} s_P\right)^2 \right]^{\frac{1}{2}} \tag{8}$$

or equivalently,

$$s_U = \frac{1}{\sqrt{2\rho\Delta P}} S_P \tag{9}$$

The random standard uncertainty s_P is related to the estimator variance as follows:

$$s_P = \sqrt{\frac{var_P}{N}} \tag{10}$$

where N is the number of samples.

Propagation of the systematic uncertainties was done in a similar manner to that of the random uncertainties except here we need to consider the uncertainty due to the variation in freestream velocity with temperature. The freestream velocity is related to the temperature, T, via the definition of the Mach number, M, written as:

$$U = M\sqrt{\gamma RT} \tag{11}$$

where M is held constant at 0.2 throughout the duration of the tests. Including the sensitivity of this term, the systematic uncertainty can be written as:

$$b_U = \left[\left(\frac{1}{k_P}\frac{\partial U}{\partial \Delta P} b_P\right)^2 + \left(\frac{1}{k_\rho}\frac{\partial U}{\partial \rho} b_\rho\right)^2 + \left(\frac{1}{k_T}\frac{\partial U}{\partial T} b_T\right)^2 \right]^{\frac{1}{2}} \tag{12}$$

or equivalently,

$$b_U = \left[\frac{1}{2\rho P k_P} b_p^2 + \frac{P}{2\rho^3 k_\rho} b_\rho^2 + \frac{M^2\gamma R}{4T k_T} b_T^2\right]^{\frac{1}{2}} \tag{13}$$

where k_P, k_ρ, and k_T are the coverage factors taken as $\sqrt{3}$ while b_P, b_ρ, and b_T are the systematic uncertainties in pressure, density, and temperature respectively. The systematic uncertainty of the density was estimated using:

$$b_\rho = \frac{|\rho_{start} - \rho_{end}|}{2} \tag{14}$$

where ρ_{start} and ρ_{end} are the respective densities calculated from the temperature variation from the start to end of the experiment. As was done for the pressure measurements, the systematic uncertainty of the Scanivalve pressure transducer was divided into two components, the calibration uncertainty, b_{cal}, and the instrument uncertainty, b_{inst}.

$$b_p = [\, b_{cal}^2 + b_{inst}^2]^{\frac{1}{2}} \tag{15}$$

The instrument uncertainty is that given with the pressure transducer, 0.3% of full-scale with the full-scale range being 10 inches of water. Once converted to the metric system, this yields b_{inst} = ±7.4652 [Pa]. The calibration uncertainty is based off the linear regression used to convert the

Scanivalve transducer output voltage to pressure. The calibration curve is shown in Figure 1 and the linear fit equation is:

$$P = 1205.207\,V + 45.5483 \quad (16)$$

where V is the transducer output in Volts and P is the respective pressure in Pascals. From this regression curve fit the uncertainty was calculated using the procedure outlined in section 8-6 of the ASME PTC 19.1-2005 Test Uncertainty manual [2]. The calibration uncertainty is dependent on the voltage and hence varies for each point. For the range used in these measurements b_{cal} is about 45-91% of b_{inst}. The temperature uncertainty is a combination of the variation in the temperature over the course of the run, ΔT, and the uncertainty in the thermocouple, b_{TC}. This can be written as:

$$b_T = [\,\Delta T^2 + b_{TC}^2]^{\frac{1}{2}} \quad (17)$$

where b_{TC} is taken as 2 °C.

The combined standard uncertainty was given in equation (4) and is a combination of the random uncertainty and the systematic standard uncertainty. The expanded uncertainty is the combined standard uncertainty multiplied by the Student's t-table value, $t_{\nu,p}$ where ν is N – 1 and p is the selected confidence interval. At 20:1 odds or p = 95% confidence and assuming a large sample size, $t_{\nu,p}$ = 1.96. Using this analysis, the true value is expected to lie within:

$$U \pm t_{\nu,p} u_U \quad (18)$$

where $t_{\nu,p}\, u_U$ is the expanded uncertainty or simply the uncertainty of the quantity.