Experimental Facility and Lab Test Conditions

White Field Mach 0.6 Wind Tunnel Facility:

All experiments have been performed in the Notre Dame Mach 0.6 closed-circuit wind tunnel facility at White Field. This is a large-scale, variable-speed, low-turbulence wind tunnel designed for fundamental aerodynamic research. A schematic of the wind tunnel is shown in Figure 1. Some key features of this facility are its low freestream turbulence level of $\sqrt{\overline{u^2}}/U_\infty \leq$ 0.5%, its large test section size of 0.91 m x 0.91 m (3 ft x 3 ft) cross-section by 2.74 m (9 ft) length, its high 1,750 horsepower variable r.p.m. AC motor, and its chilled water temperature controlled environment. The tunnel air is driven by a 2.44 meter diameter, two-stage fan with variable pitch blades. The model for this experiment is installed in its own dedicated removable test section which allows for the ease of repeated experimental entries.

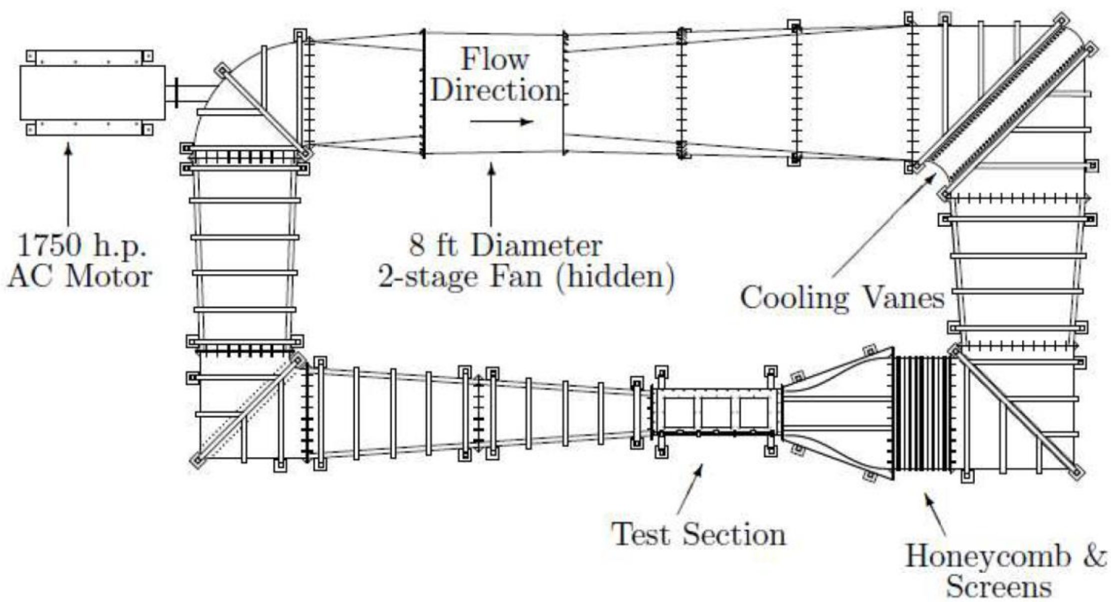

Figure 1 Schematic of the White Field Mach 0.6 wind tunnel facility

Test Conditions:

The test conditions were recorded at least once per day and included, lab temperature, pressure, and relative humidity. These measurements are the ones recorded in the archival data files and were made using a Fisher Scientific digital barometer model #14-650-118. From these measurements, density, viscosity, freestream velocity, and Reynolds number were calculated using the procedures and equations outlined in this document.

In addition to this, wind tunnel temperature and relative humidity were measured throughout the duration of several tests to characterize their typical variation, which is largely a function of the flexible ceiling position, (i.e. which separation case was being examined, and the run duration).

a. Temperature

The wind tunnel temperature was recorded using a thermocouple located in the wind tunnel contraction. A typical temperature variation for Case C is shown in Figure 2 and includes both tunnel and lab temperature. For reference, in the following figures each data point is taken approximately 15 minutes apart and the time is non-dimensionalized to yield a test duration that goes from 0 to 1 corresponding to the start and end of the test, respectively.

Due to the lowered flexible ceiling position, this case required the most power from the drive motor. This in combination with the significant tunnel test section blockage caused the chilled water-cooling system to not be able to fully maintain a constant temperature throughout each test. It was not uncommon for tunnel temperature to vary 5 - 15 °C throughout the duration of each run. A typical LDV test duration was 1 - 3 hours, and often the tests were closely spaced which prevented the tunnel temperature from returning to that of the lab before the start of the next test.

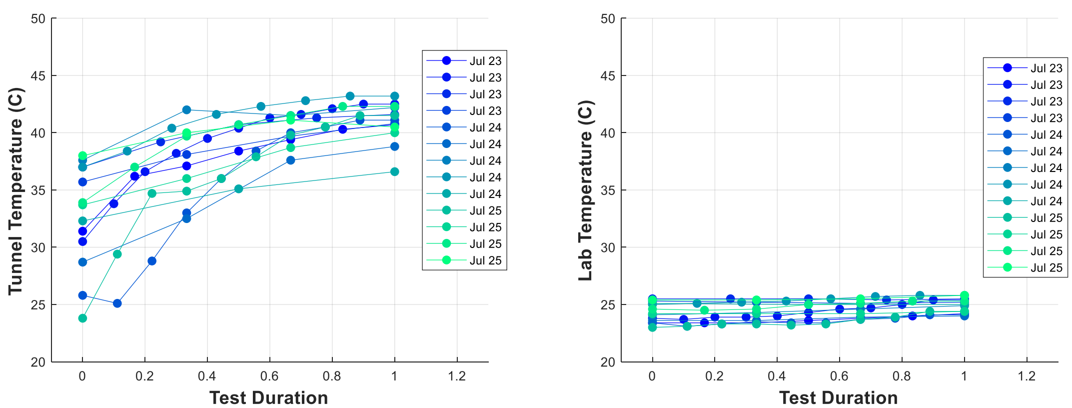

Figure 2 A typical temperature variation for Case C showing both the tunnel temperature (left) and lab temperature (right). Each test is plotted over its duration which goes from start (0) to finish (1) with each data point being taken approximately 15 minutes apart.

A typical temperature variation for Case B is shown in Figure 3 and includes both tunnel and lab temperature. Due to flexible ceiling being positioned higher up, the blockage was not as significant as in Case C, causing the typical temperature rise to be lower. For Case B the tunnel temp usually only varied by about 5 °C. For reference, the lab temperature is also shown to indicate that the tunnel temperature rise is not due to any sort of temperature variation in the lab.

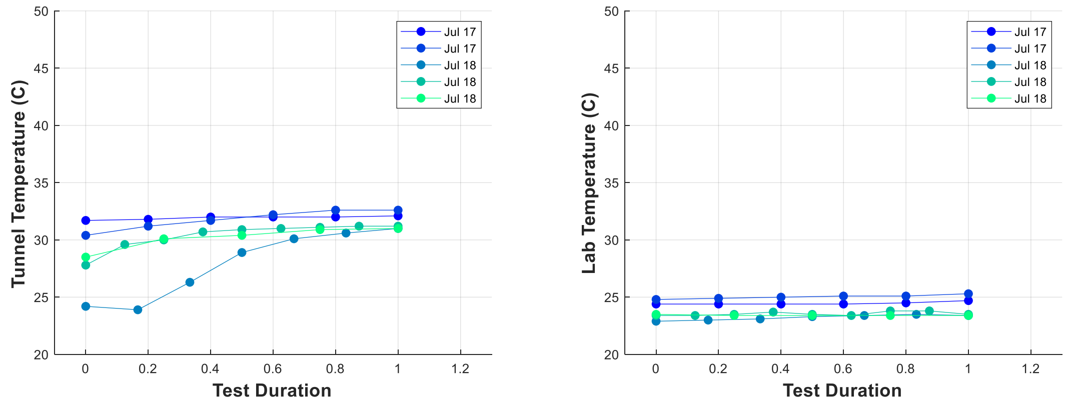

Figure 3 A typical temperature variation for Case B showing both the tunnel temperature (left) and lab temperature (right). Each test is plotted over its duration which goes from start (0) to finish (1) with each data point being taken approximately 15 minutes apart.

A typical temperature variation for Case A is shown in Figure 4 and includes both tunnel and lab temperature. Unlike Cases C and B, the higher position of the flexible ceiling reduced both the blockage and required drive motor input power. This allowed the chilled water-cooling system to do a decent job of maintaining the tunnel temperature throughout the duration of each test. Here the tunnel temp usually only varied by about 2 °C.

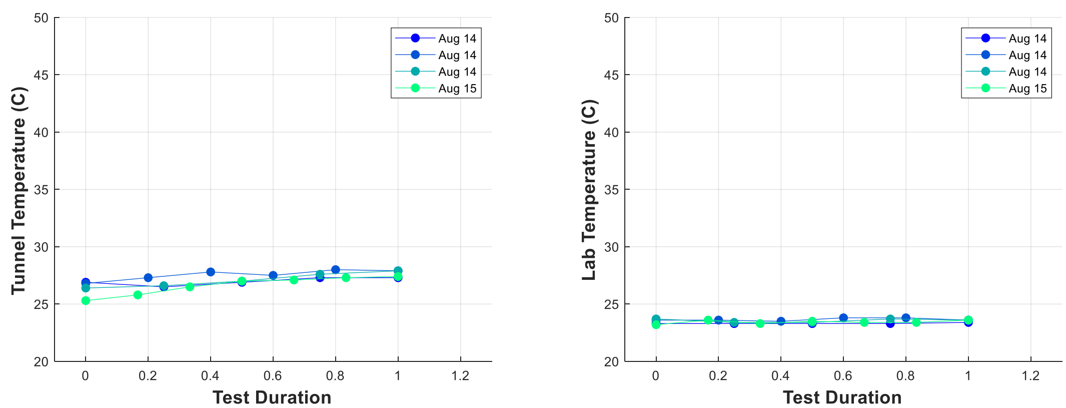

Figure 4 A typical temperature variation for Case A showing both the tunnel temperature (left) and lab temperature (right). Each test is plotted over its duration which goes from start (0) to finish (1) with each data point being taken approximately 15 minutes apart.

b. Pressure

Absolute pressure measurements of the laboratory environment were recorded at least once per day. From multiple measurements recorded over the period of the day, it is estimated the lab pressure may vary by about 1-2 hPa.

c. Relative Humidity

Relative humidity was also recorded both in the wind tunnel and in the lab and typical variations for Cases, C, B, and A are shown below in Figure 5-7. As was done for the temperature plots, here each data point is taken approximately 15 minutes apart and the test duration is non-dimensionalized to yield a test duration that goes from 0 to 1 which correspond to the start and end of the test, respectively. While the lab humidity may vary by about 5% during a test, the tunnel humidity for all cases start out high and quickly drop and stabilize to a value far below that in the lab.

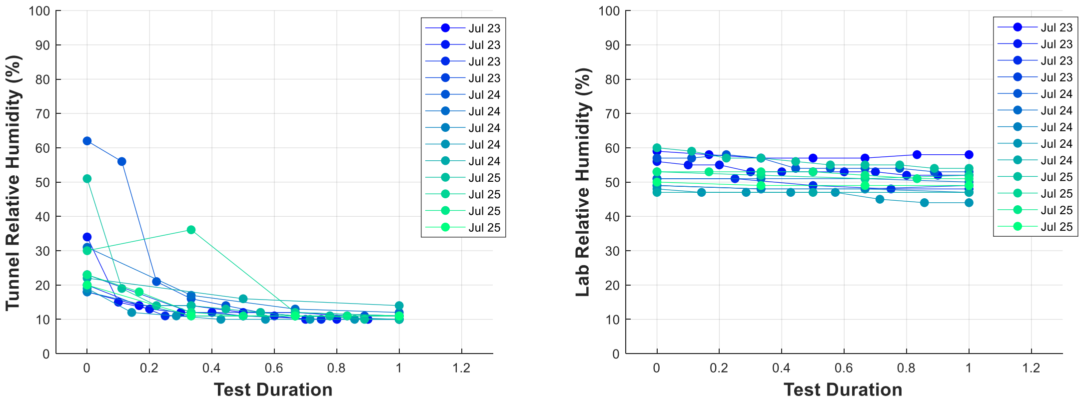

Figure 5 A typical relative humidity variation for Case C showing both the tunnel humidity (left) and lab humidity (right). Each test is plotted over its duration which goes from start (0) to finish (1) with each data point being taken approximately 15 minutes apart.

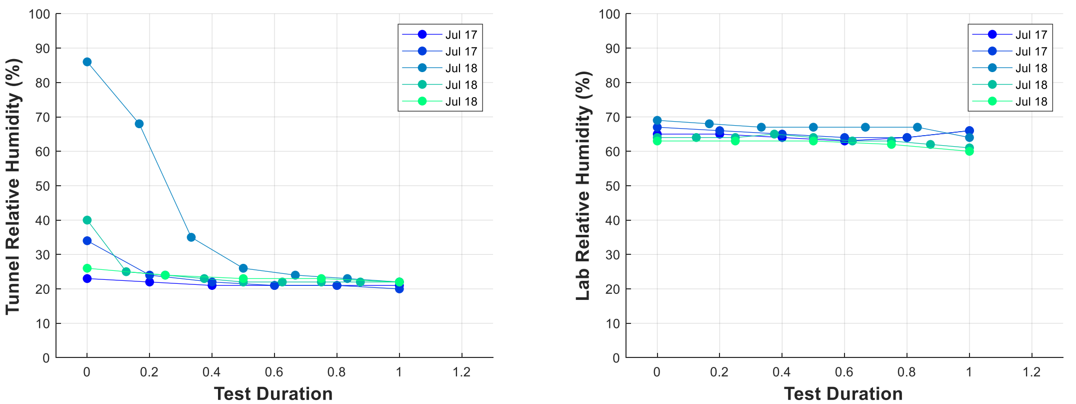

Figure 6 A typical relative humidity variation for Case B showing both the tunnel humidity (left) and lab humidity (right). Each test is plotted over its duration which goes from start (0) to finish (1) with each data point being taken approximately 15 minutes apart.

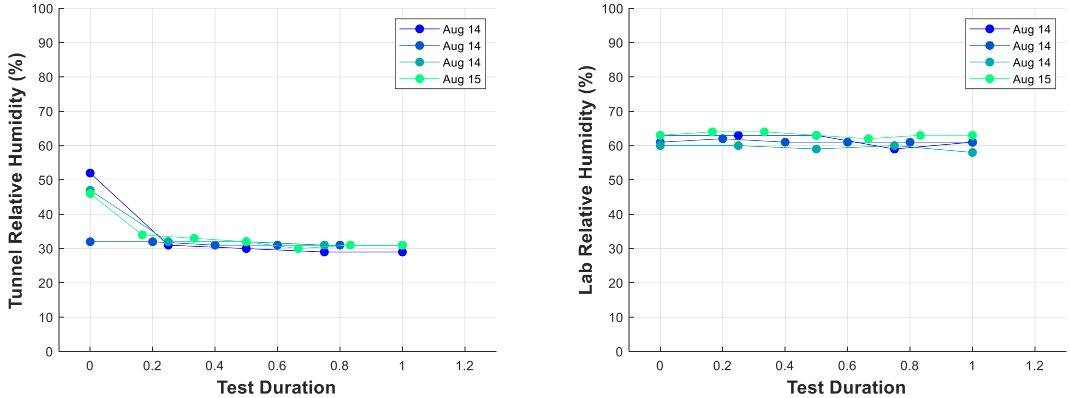

Figure 7 A typical relative humidity variation for Case A showing both the tunnel humidity (left) and lab humidity (right). Each test is plotted over its duration which goes from start (0) to finish (1) with each data point being taken approximately 15 minutes apart.

d. Density

The air density, $\rho\ [kg/m^3]$, was calculated as a function of pressure temperature and relative humidity using Jones's formula [1]

$$\rho = \frac{0.0034848}{T+273.15}(P - 0.0037960 * RH * P_s) \tag{1}$$

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

$$P_s = 611 \times 10^{7.5T/(T+237.3)} \tag{2}$$

e. Viscosity

The dynamic viscosity of the air was calculated using Sutherland's law [2] with three coefficients which has the form:

$$\mu = \mu_0 (\frac{T}{T_0})^{\frac{3}{2}} (\frac{T_0+S}{T+S}) \tag{3}$$

Where T is the temperature [K], $\mu_0 = 1.7894 \times 10^{-5}\ [kg/m * s]$ is a reference viscosity, $T_0 = 273.11\ [K]$ is a reference temperature, and $S = 110.56\ [K]$ is the effective temperature. The kinematic viscosity is related to the dynamic viscosity and density as follows:

$$\nu = \frac{\mu}{\rho} \tag{4}$$

and has units of [m^2/s].

f. Freestream Velocity

A pitot-static tube located in the test section freestream at X = -0.97 [m] and Y = 0.58 [m] was used to measure dynamic pressure which was then converted to velocity and Mach number. Two built-in Setra model 270 absolute pressure transducers were used in conjunction with this pitot-static tube and recorded the total P_T and static pressure P_S respectively. The Mach number, M, was then determined as follows:

$$M = \sqrt{\frac{2(P_T - P_S)}{\gamma P_S}} \tag{5}$$

where γ = 1.4 is the specific heat ratio of air. The wind tunnel freestream velocity was then primarily dictated by the Mach number, which was fixed at M = 0.2, and the temperature which varied as discussed previously. This relation can be written as:

$$U_\infty = M\sqrt{\gamma RT} \tag{6}$$

where R = 287.05 [J/(kg*K)] is the gas constant for air, and T is the air temperature [K]. The sensitivities of M with respect to each of the dependent values were obtained by partial differentiation.

$$\frac{\partial M}{\partial P_T} = \frac{1}{M\gamma P_S} \tag{7}$$

$$\frac{\partial M}{\partial P_S} = \frac{-P_T}{M\gamma {P_S}^2} \tag{8}$$

This gives the uncertainty of the Mach number, b_M as:

$$b_M = \left[\left(\frac{\partial M}{\partial P_T} b_{P_T}\right)^2 + \left(\frac{\partial M}{\partial P_S} b_{P_S}\right)^2 \right]^{\frac{1}{2}} \tag{9}$$

where b_{P_T} and b_{P_S} are the uncertainties of the Setra pressure transducers given as 25 Pa. Since the Mach number, M is held constant at 0.2 throughout the duration of the tests, the freestream velocity must change in proportion to the local speed of sound. This inherently introduces uncertainty that may be accounted for by examining the relationship between freestream velocity, U_∞, Mach number, M, and temperature, T, using equation (6). The uncertainty in freestream velocity can be written as:

$$b_{U_\infty} = \left[\left(\frac{\partial U_\infty}{\partial T} b_T\right)^2 + \left(\frac{\partial U_\infty}{\partial M} b_M\right)^2 \right]^{\frac{1}{2}} \tag{10}$$

or equivalently,

$$b_{U_\infty} = \left[\left(\frac{M}{2}\sqrt{\frac{\gamma R}{T}}\, b_T\right)^2 + \left(\sqrt{\gamma RT}\, b_M\right)^2 \right]^{\frac{1}{2}} \tag{10}$$

where b_T is the uncertainty in temperature taken as half the estimated greatest change in temperature over the course of all the tests, as seen in Figures 2-4. Using the estimates of temperature and temperature change from Figures 2-4, as well as the uncertainty introduced from the two Setra pressure transducers, the estimated uncertainty in freestream velocity is given in Table 1.

Table 1. Estimated uncertainty in freestream velocity for Cases A, B and C.

	Case A	**Case B**	**Case C**
T_{mean} [°C]	27	30	35
$U_\infty [m/s]$	69.46	69.81	70.38
b_T [°C]	1.5	3.5	9
b_M	0.0013	0.0013	0.0013
b_{U_∞} [m/s]	0.49	0.61	1.13

g. Reynolds Number

The Reynolds number was based off the ramp height, *H* = 0.2 [m], and is given as follows:

$$Re_H = \frac{U_\infty H}{\nu} \tag{11}$$

where U_∞ is the freestream velocity recorded with the pitot tube and ν is kinematic viscosity.

References

[1] Jones, F. E. *The Air Density Equation and the Transfer of the Mass Unit*. 1977.

[2] 7.3.2 Viscosity as a Function of Temperature. *Fluent Incorporated*. http://jullio.pe.kr/fluent6.1/help/html/ug/node294.htm. Accessed Nov. 22, 2019.