Supersonic Boundary Layer Investigation

This lab investigates the formation of the boundary layer on the bottom wall of the Supersonic Wind Tunnel operating at a nominal free stream Mach number of 4. An automated traverse system moves a measurement probe up through the boundary layer, and the control computer records temperature and pressure data. These data can be post-processed to give files of Mach number, velocity and density across the layer.

Apparatus

Supersonic Tunnel

This experiment, and the Schlieren photography lab, are run using the Virginia Tech 23x23 cm Supersonic Wind Tunnel. The tunnel was designed and built at NASA Langley Research Center. The tunnel was acquired by Virginia Tech in 1958 and put into operation in 1963. During recent years, several modifications were introduced into the air pumping, tunnel control, and instrumentation equipment, which increased the capabilities of the facility. Schematic views of the tunnel are given in Figure 1 and Figure 2. The air pumping system consists of an Ingersoll-Rand Type 4-HHE-4 4-stage reciprocating air compressor driven by a 500 hp, 480V Marathon Electric Co. motor. The compressor can pump the storage system up to 51 atm. A drying and filtering system is provided which includes both drying by cooling and drying by absorption. The air storage system consists of two tanks with a total volume of 23 m^3. Tunnel control system includes a quick opening butterfly valve and a hydraulically actuated pressure regulating 30.5 cm diameter valve. A PID feedback control is used to keep the desired plenum pressure steady through each run.

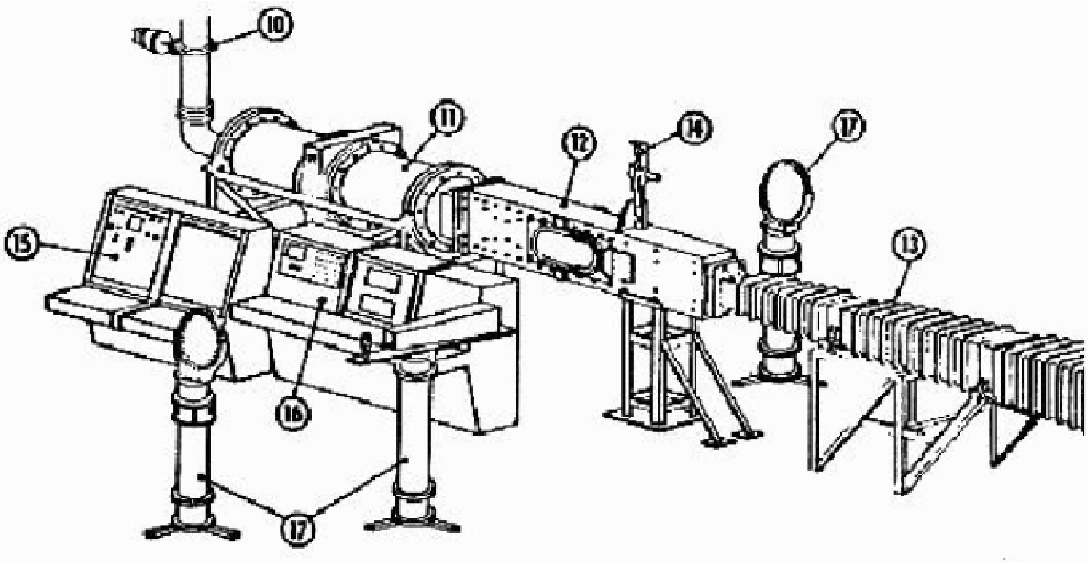

Figure 1: Supersonic Wind Tunnel Facility Layout
10-Pressure Regulator, 11-Settling Chamber, 12-Test Section, 13-Diffuser, 14-Model Support

and Drive System, 15-Tunnel Control Panel, 16-Measurement Panel, 17-Schlieren Apparatus

The working section of the tunnel is equipped with a remotely controlled model support which allows one to vary the position of a model in the vertical plane. An arrangement for side wall model mounting is also available. Access to the model is available through the side opening doors each with an optical quality window. After passing through a diffuser the air flow is discharged into the atmosphere through a muffler located outside of the building.

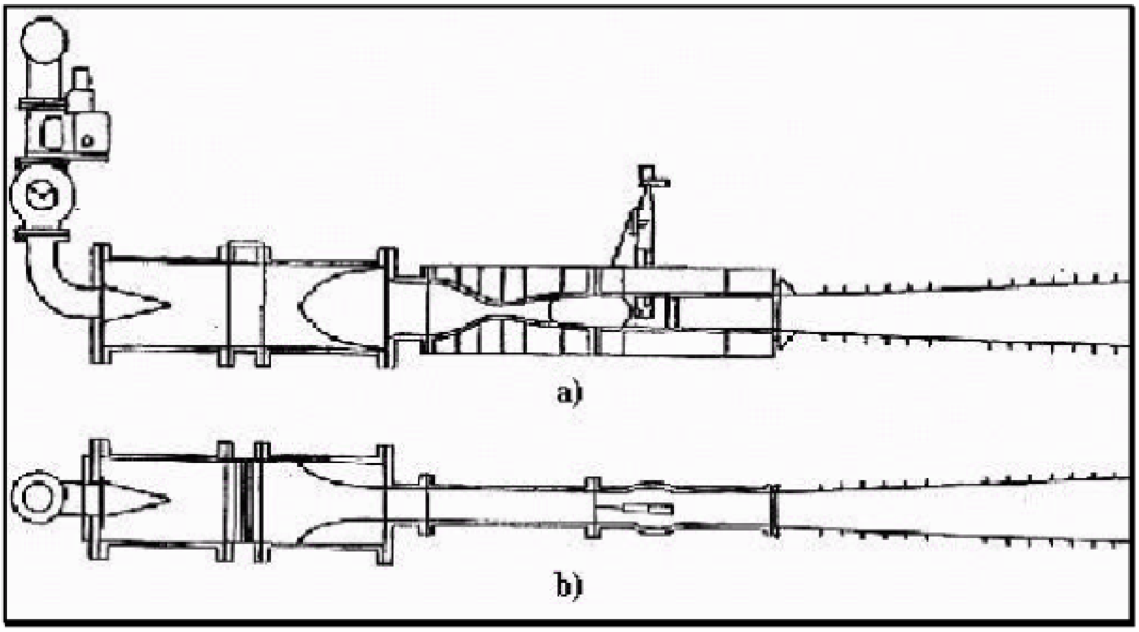

Figure 2: Supersonic Wind Tunnel Test Section a) Top View b) Side View

Data Acquisition Equipment

The analog signals from the pressure transducers, thermocouples, and Linear Variable Differential Transformer (LVDT) are sent to a PC via a National Instruments AT-MIO-16XE-50 multifunction high speed analog/digital I/O expansion board through a National Instruments AMUX-64T Multiplexor board. For the experiments at hand, the AT-MIO-16XE-50 was operated in a 32 channel differential mode. The GUI data acquisition software used in the experiment is called LabView, and the program is called: Boundary_Layer_Lab.vi. The program is set **to sample at a rate of 100 Hz for 18 seconds** and controls the operation of the wind tunnel. When it is time to run the tunnel, the data acquisition system operates the tunnel and records the data from the experiment to the directory: f:\sstunnel\bldata.. The program will create a file named bltravX.dat. The traverse is set to move up about 1 inch in 32 station movements. At each station, the probe will sample for 300 milliseconds at 100 Hz. During the first several points of data at each station, the temperature and pressure measurements will converge to a steady state value. This is called the purge time. The last 10 samples at each station represent the

steady state value there. **This is the portion of data at each individual station that should be used to generate the boundary layer profiles!**
The milli-volt signals produced from the exposed junction thermocouples in the total temperature probe and the tunnel plenum chamber read directly from the National Instruments AMUX-64T Multiplexor board with a board mounted electronic icepoint reference. The electronic icepoint converts the thermocouple voltages into 0°C referenced signal, which read 0 Volts at 0°C. Make note during the lab of the pressure transducers used and the details of their operation since they change from year to year.

Probe Traverse System

The traverse uses a 4-Phase stepper motor made by Rapid Syn (Model 34D-9209A) and an American Precision Industries (Model DMA-64) stepper motor controller. The step angle is 1.8 degrees. The tunnel control program is set to move 240 steps up at a speed of 300 steps a second over ~8 seconds (32 Locations) and then 300 steps per second down to the original position. The traverse motor is powered by a 24 Volt DC power supply. The position of the traverse is measured by an LVDT (Linear Variable Differential Transformer). The LVDT is calibrated with dial calipers and a voltmeter. The dial calipers allow an accuracy of 0.0001 inches, which is sufficient for the experiment at hand.

Lab Procedure

During the experiment, the tunnel will be operated by a qualified tunnel operator. It is the responsibility of each student to make observations during the lab in preparation for reducing the acquired data.

1. Examine the experimental setup and take note of any deviations from the lab write-up to include in your report. Note the type of instrumentation used for the data acquisition and the conversion factors used for the traverse control stepper motor.

2. **Before running the tunnel**, all persons MUST wear the proper safety glasses and *required* ear protection. While the tunnel is operating, stand clear of the test section windows.

3. The tunnel operator will start the tunnel and the control computer will acquire the data and operate the traverse automatically. The data is stored to an ASCII text file specified in the tunnel control LabView program. Be sure to note the name of the file for copying of the data to disk, etc.

4. After tunnel shutdown, examine the data as plotted by the control computer program. Verify the traverse operation was successful by examining the position plot. Was the probe traversed outside the boundary layer? If not, check for a malfunction or increase the total number of traverse steps and then repeat the lab.

Do these pressure and temperature plots agree with your expectations? For example, choose a steady state point in the free stream and compare the plenum chamber pressure ($P_{t,\infty}$) to the Pitot pressure $P_{t,2}$.. Using the normal shock relations, we can relate this pressure ratio to the upstream mach number, M_∞ by;

$$\frac{P_{t,2}}{P_{t,\infty}} = e^{-\left(\frac{\Delta s}{R}\right)} = \left(\frac{(\gamma+1)M_\infty^2}{(\gamma-1)M_\infty^2+2}\right)^{\frac{\gamma}{\gamma-1}} \left(\frac{\gamma+1}{2\gamma M_\infty^2-(\gamma-1)}\right)^{\frac{1}{\gamma-1}}.$$

Verify that the probe pressures reach a steady state value at each traverse point. If a reasonable steady state is not achieved, increase the number of samples acquired at each point. The default number of samples at each station is 25 at a sample rate of 100 Hz.

Check the total temperature measured in the plenum chamber, $T_{t,\infty}$ and the probe total temperature T_t.. Due to the recovery factor of the probe, the probe temperature (in the free stream) should be a few degrees lower than the plenum total temperature.

5. Copy the acquired data to disk, or e-mail, for each of the students in the lab section.

Data Reduction

The following is an algorithm for the reduction of the data obtained in the supersonic boundary layer investigation. In the development of this algorithm, the following assumptions are made:

1. Stagnation pressure $P_{t,\infty}$ is constant.
2. Stagnation temperature $T_{t,\infty}$ is constant.
3. The nominal freestream Mach number, $M_\infty = 4$
4. $\gamma=1.4$

Note the static pressure is not assumed to be constant across the boundary layer as is typically done in analytical analyses. Furthermore, $P_{t,\infty}$ and $T_{t,\infty}$ are settling chamber conditions which are assumed to be constant throughout the duration of the test run. You are not to assume that P_t and T_t are constant throughout the boundary layer. All values computed in these procedures are local values unless denoted by the subscript *e*, which designates the boundary layer edge value.

The relations involved in Steps 1 and 2 are a custom curve fit relating local Mach number to cone-static pressure, P_c, and Pitot pressure, $P_{t,2}$, according to the Rayleigh-Pitot formula and solutions to the Talyor-Maccoll differential equation governing flow over an axisymmetric cone. All other relations may be found in any text regarding compressible and / or boundary layer flows.

Reduction Algorithm

There are three zones in the boundary layer which require different data reduction methods. The Outer Supersonic Region reduction applies to the region of the flow where the local Mach number is supersonic, the shock is attached to the cone, and the polynomial curve fit solution of the Talyor-Maccoll equation is valid. The Inner Supersonic Region reduction applies to the flow region with a local Mach number down to 1.0 and outside the solution range of the polynomial. The Subsonic Flow Region is the small region near the wall where the flow becomes subsonic.

Depending on the resolution of the traverse points and the boundary layer thickness, your data may not contain many points in the Inner Supersonic Region or the Subsonic Region. For these cases, reduce the data as far as possible.

INPUT: y, $P_{t,2}(y)$, $P_c(y)$, and $T_{t,(y)}$
OUTPUT: θ, δ_*, M(y), U(y), $\rho(y)/\rho_e$

Outer Supersonic Region

Follow these steps to reduce data from the Outer Supersonic Region.
Note: The boundary layer edge Mach number may not reach 4 due to the oblique shock which occurs off of the test section floor plate.

0. Begin with data at the largest value of y.

1. Calculate local Mach number (valid for 1.2 < M < 4.5)

$$M = 0.6926\left(\frac{P_c}{P_{t,2}}\right)^{-0.6905}$$

Note: The determination of Mach number requires two different pressure measurements as can be seen in the above equation. P_c is measured using the cone static probe while $P_{t,2}$ is measured with a Pitot probe. The Taylor-Maccoll solution gives the ratio of local total pressure to the surface static pressure on the given cone, P_c, as a function of Mach number. The normal shock relations give the ratio of measured Pitot pressure, $P_{t,2}$, to the local total pressure as a function mach number. The solution of this system of 2 equations with 2 unknowns (Mach number and local total pressure) produces the above equation.

2. Calculate the local mean velocity;

$$U = M\sqrt{\frac{\gamma R T_t}{1+\frac{(\gamma-1)}{2}M^2}}$$

3. Calculate Pt from the normal shock relation;

$$P_t = P_{t,2}\left[\left[\frac{(\gamma+1)M_1^2}{(\gamma-1)M_1^2+2}\right]^{\frac{\gamma}{\gamma-1}}\left[\frac{\gamma+1}{2\gamma M_1^2-(\gamma-1)}\right]^{\frac{1}{\gamma-1}}\right]^{-1}$$

4. Calculate the local static pressure;

$$P = P_t\left[1+\frac{(\gamma-1)}{2}M^2\right]^{\frac{-\gamma}{\gamma-1}}$$

5. Calculate the Recovery Factor, this should be done once by averaging a few data points beyond the edge of the boundary layer in the local free stream. This is the Recovery Factor of the total temperature probe and is assumed constant throughout the boundary layer.

$$r = \frac{T_{t,e}-T_\infty}{T_{t,\infty}-T_\infty}$$

Recall $\left[\frac{T}{T_t}\right]_\infty = \frac{1}{1+\frac{(\gamma-1)}{2}M_\infty^2}$

6. Next, calculate the corrected total temperature at the sampling probe location.

$$T_{t,corr} = T_t\left[\frac{1+\frac{(\gamma-1)}{2}M^2}{r\left(1+\frac{(\gamma-1)}{2}M^2\right)-r+1}\right]$$

7. Calculate the local static temperature;

$$T = T_{t,corr}\left[1+\frac{(\gamma-1)}{2}M^2\right]^{-1}$$

8. Compute the edge values
Repeat Steps 1-4, 6 and 7 for the first 5 or 10 y locations outside the boundary layer and take the average of the edge values, Pe and Te.

9. Calculate the density ratio;

$$\frac{\rho}{\rho_e} = \frac{PRT_e}{P_eRT} = \frac{PT_e}{P_eT}$$

10. Compute local values throughout the Supersonic Region of the boundary layer with local Mach number >1.2.
CONTINUE REPEATING STEPS 1-4, 6-7, AND 9 for every remaining y location.

Inner Supersonic Region

For this region, defined as local Mach number less than 1.2 and greater than 1.0, we make the common boundary layer assumption that the static pressure is constant across the rest of the layer.

0. From the innermost static pressure in the Outer Supersonic Region (P_{os}), calculate the static pressure ratio $P_{os}/P_{t,\infty}$ which will be constant throughout the remaining inner portion of the boundary layer. Note that this is the lowest point in the Outer Supersonic Region.

1. Calculate the local static pressure $P = (P_{os}/P_{t,\infty})P_{t,\infty,i}$, where $P_{t,\infty,i}$ is the i_{th} plenum total pressure value recorded in the data file. Note this value is at the same time as the local probe values.

2. Having the local static pressure and the Pitot pressure, it is possible to solve for the local P_t and Mach number, M using the two equations from Steps 3 and 4. Solution of these equations will require a table lookup for P/P_{t2} as a function of Mach number or a numerical solution technique such as Newton's method.

3. Having the local Mach number, all other quantities can be calculated including the static temperature as done in the Outer Supersonic Region reduction procedure.

Subsonic Flow Region

If the acquired data recorded values in the Subsonic Region the reduction steps are simple. Use the static pressure ratio obtained from the Inner Supersonic Region reduction process and remember that in subsonic flow the Pitot pressure is the total pressure. This allows direct solution of the local Mach number using the equation from Step 4 of the Outer Supersonic Region reduction process. Having the local Mach number, all other quantities can be calculated including the static temperature as done in the Outer Supersonic Region reduction procedure.

Final Calculations

Now that all required aerothermodynamic properties of the boundary layer are known, you may compute the displacement and momentum thickness. Before this calculation, correct the y position by subtracting the first point value (offset) and adding half the diameter of the probe. This should place the first data point at approximately y=1/32 in.

$$\delta^* = \int_0^\infty \left(1 - \frac{\rho U}{\rho_e U_e}\right) dy \qquad \theta^* = \int_0^\infty \frac{\rho U}{\rho_e U_e}\left(1 - \frac{U}{U_e}\right) dy$$

You may use the trapezoidal method to numerically integrate the above expressions over all the acquired data points.

Results and Discussion

Make plots of P_t, T_t, P, T, M, U and ρ/ρ_e as functions of the corrected y position. Discuss possible sources of error in your calculations and the experiment. What improvements could be made to the experiment to acquire better data?

Using your favorite boundary layer text, try to determine if this supersonic boundary layer is laminar, turbulent, or in transition.