Performance study of the MSU Mach 3 wind tunnel
by Bradley Barney Rogers

A thesis submitted in partial fulfillment of the requirements for the degree of MASTER OF SCIENCE
in Mechanical Engineering
Montana State University
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Abstract:
The aerodynamic parameters governing the operation of a supersonic wind tunnel are considered. These parameters are determined from measurements of the supersonic flow stream. The Mach Number is found to be near 3 while the Reynolds Number can be varied between 30,000 and 60,000 per centimeter. The capabilities of the facility as a research tool are presented in a form that will be useful to future users of the facility.
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Date 2/18/81
PERFORMANCE STUDY OF THE MSU MACH 3 WIND TUNNEL

by

BRADLEY BARNEY ROGERS

A thesis submitted in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

in

Mechanical Engineering

Approved:

[Signatures]

Chairperson, Graduate Committee

Head, Major Department

Graduate Dean

MONTANA STATE UNIVERSITY
Bozeman, Montana
February, 1981
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</tr>
<tr>
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<td>Area of nozzle throat</td>
</tr>
<tr>
<td>a</td>
<td>Speed of sound</td>
</tr>
<tr>
<td>a*</td>
<td>Speed of sound at nozzle throat</td>
</tr>
<tr>
<td>a_o</td>
<td>Speed of sound at stagnation conditions</td>
</tr>
<tr>
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</tr>
<tr>
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<td>Universal gas constant</td>
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<td>Pump inlet temperature</td>
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<td>V_i</td>
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<td>\gamma</td>
<td>Ratio of specific heats (1.4 for air)</td>
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The aerodynamic parameters governing the operation of a supersonic wind tunnel are considered. These parameters are determined from measurements of the supersonic flow stream. The Mach Number is found to be near 3 while the Reynolds Number can be varied between 30,000 and 60,000 per centimeter. The capabilities of the facility as a research tool are presented in a form that will be useful to future users of the facility.
CHAPTER I

INTRODUCTION

In the summer of 1979, the Ford Aerospace and Communications Corporation, located in Newport Beach, California, donated the supersonic wind tunnel facility that was located on company grounds to the Mechanical Engineering Department of Montana State University. The facility was dismantled in California and moved to Bozeman, Montana in June of 1979. The wind tunnel was reassembled, with extensive modification, in Room 5-D of the Ryon Laboratory building on the campus of MSU. The facility was successfully operated in its new location in June of 1980.

When the tunnel was first operated in California, in 1965, a brief report concerning its operation was published. This report had not been based on measurements extensive and accurate enough to provide a good understanding of the capabilities of the wind tunnel. Also, since the facility underwent extensive modification when it was reassembled in Montana, the applicability of the original report was questionable.

The purpose of this thesis is to provide, by measurement, the aerodynamic characteristics of the Supersonic Wind Tunnel (SWT), and to detail its capabilities as a research tool. Questions to be answered include the following:

1) What modifications have the components of the SWT undergone since being moved to MSU? How have these changes affected the performance of the tunnel?
2) Have the pump characteristics changed because of fatigue or other mechanical deterioration? If so, what is the characteristic now? At what stagnation pressure can flow breakdown ("choking") be expected?

3) What is the Mach Number along the nozzle? How does it differ from theory? How is it affected by stagnation pressure changes?

4) Are there any waves present in the test section? Is the flow in the test section uniform?

5) How thick are the boundary layers in the test section? Are they laminar or turbulent?

6) What range of stagnation temperatures are attainable in the tunnel?

These and other questions are addressed in this document.

The second chapter of this thesis deals with the components of the SWT. A description of each component and major accessory is provided. A brief discussion of the history and original purpose of the SWT is also provided.

The third chapter deals with the aerodynamic parameters governing the operation of the wind tunnel. Questions 2 - 6 above are, for the most part, answered by the results and discussions which are presented in this chapter.

The fourth chapter is a short section outlining the conclusions drawn from the results of Chapter 3.
A short appendix giving a condensed set of operating instructions for the SWT is also included.
CHAPTER 2
DESCRIPTION OF COMPONENTS

2.1 HISTORY

The supersonic wind tunnel at MSU is an open circuit, continuous wind tunnel. The tunnel was first operated in Newport Beach, California in February of 1965. It was originally designed to study supersonic wakes; specifically, to generate information leading to an adequate description of the flow field behind re-entry vehicles. The original design parameters of the SWT are contained in reference 2.

When the tunnel was reassembled at MSU some repairs and routine maintenance were done on several of the major components. Some of the work that was done is listed below:

1) The dryer was taken apart and cleaned, and then refilled with desiccant.
2) Several components of the air drying mechanism were repaired.
3) The throttling valve was cleaned and repaired.
4) The piping was cleaned of rust and scale.
5) The interiors of the pumps were cleaned.
6) The controls and control console were modified.

Other repairs were also done on any part that was not obviously in good condition.

There has been no change in the broad design goals of the SWT since it has been moved to MSU. Several changes have been made to the individual parts of the tunnel, however, mostly in the form of new safety
Figure 2-1 Wind Tunnel Circuit

KEY
1 Air Inlet
2 Chiller
3 Dryer
4 Relief Valve
5 Throttling Valve
6 Stilling Tank
7 Upstream Transition
8 Nozzle and Test Section
9 Downstream Transition
10 Subsonic Diffuser
11 Bellows Expansion Joint
12 Pump Motor
13 Pump First Stage
14 Pump Second Stage
15 Bypass Valve
16 Silencer
17 Exhaust
interlock systems. The rest of this chapter describes the components of the SWT as they exist today.

2.2 INLET SYSTEM

The MSU SWT draws its air supply from the atmosphere. Because of this, an air drying system is necessary to prevent condensation of moisture at the low static temperatures that occur in the test section. The system on the MSU tunnel is made by Desomatic Products of Alexandria, Virginia. The dryer is designed to provide a dewpoint of -30°F at dryer inlet flows ranging as large as 700 SCFM (Standard Cubic Feet per Minute).

The ambient air enters through a screen located on the side of the dryer. The air then passes through a chiller unit that lowers the air temperature to around 40°F. Some water is condensed off at this point. The air then passes through approximately 550 pounds of silica gel which dries the air further to a dewpoint of around -30°F.

Above the desiccant bed (silica gel bed) is a three-phase, 480 volt, 30 KW heater which is used to control the stagnation temperature of the air during an experiment. This heater is controlled from the main control panel.

Above the heater is a plenum filter section which removes any particles of silica gel which may be carried along with the stream.
Figure 2-2  Inlet System
The dryer is designed to permit up to four hours of continuous operation at maximum flow. The dryer can operate longer at lower flow rates and, since the tunnel is not normally operated at maximum flow for such a long period of time, an experiment can be tailored to provide a full day's operation.

After the desiccant has become saturated it is necessary to regenerate the desiccant bed. This is accomplished by flowing air over the heater coils and down through the silica gel. Absorbed water is then carried out of the desiccant bed. The regeneration cycle lasts four hours and is normally done overnight. The desiccant bed can take as long as 72 hours to cool off after a regeneration cycle if it is left alone. Once the tunnel is started, however, it cools off in less than 20 minutes.

The only major modifications on this section are that the on-off switch for the regeneration cycle has been removed and an on-off switch has been installed for the chiller. The reason for the removal of the on-off switch for the regeneration cycle is that when the desiccant tank was inspected its bottom was found rusted from insufficient regeneration of the silica gel. To make sure that the bed is always fully regenerated the on-off switch for the regeneration cycle was removed so that, once started, the cycle must run its full course.

The four-hour regeneration time was arrived at experimentally. It was found, by placing a temperature probe in the desiccant bed and
starting the regeneration cycle, that the bed temperature stabilized after slightly less than four hours at a temperature of 350°F, indicating the bed was dry.*

In its previous installation, the chiller unit did not have an on-off switch. The only way it could be turned off after the main power was activated was by undergoing a safety shutdown, such as overheating. The chiller automatically "came on" when the main power was turned on. An on-off switch has been installed on the main control panel so the operator can shut the chiller off and continue operating the tunnel if the need should arise.

2.3 THROTTLING VALVE

After passing through the plenum filter, the air moves on through four feet of 12-inch pipe. The flow channel then converges to a 6-inch flange, to which is connected a Mason-Neilan Model 37-3312 soft-seat butterfly valve. After passing through this valve, hereafter referred to as the throttling valve, the flow diverges back to a 12-inch diameter pipe and continues on to the stilling tank, which is described in the next section. (See Figure 2.3).

The throttling valve is used to regulate the air flow rate and, as a consequence, the stagnation pressure. This valve is pneumatically controlled by the operator from the main control panel. A Mason-Neilan

*This measurement was performed by Mr. D. H. Drummond.
Figure 2-3  Throttling Valve
7000 series spring-diaphragm control valve positioner operates the valve and positions the butterfly for air flow control during operation.

A Mason-Neilan Model 141-2 Manual Loading Station is located on the main control panel so the operator can position the valve in order to obtain the desired stagnation pressure. There are two modes of operation for this system. These are a manual mode and an automatic mode. The manual mode is normally used when starting and stopping the tunnel, but will not provide stable operation during an experiment. In the manual mode, the position of the valve is fixed and, if left alone, no correction will be made for varying inlet or atmospheric conditions, thereby causing the stagnation pressure to fluctuate several millimeters of Mercury. For this reason, during a tunnel run, the automatic mode is normally used once the tunnel has been started and allowed to come into equilibrium. In this mode the desired stagnation pressure is set once by the operator and the system automatically maintains that condition by varying the position of the butterfly as inlet conditions change.

The throttling valve is opened by increasing the pneumatic pressure. If, for any reason, the control system loses its air pressure, the throttling valve will shut. When this happens the vacuum pump will pull a large vacuum throughout the system. This will cause the safety relief valve (check valve) that is located near the pumps to open, as is described later in this chapter. This valve does not open, however, until there is already a large vacuum throughout the wind-tunnel circuit.
Because of this vacuum, the pumps will start freewheeling backwards after the motor shuts off, blowing whatever might be in the pumps, mostly rust and water, back through the test section. This can be very damaging to the test section and whatever might be in it at the time. For this reason, extreme care is always taken to never allow the throttling valve control pressure to get too low. As another safeguard against this possibility, a safety interlock system has been installed to prevent the vacuum pump motor from starting if the throttling valve is closed. A low-air-pressure shutdown sequence has also been installed to stop the motor if the building air supply pressure should fall too low to operate the pneumatic devices on the wind tunnel, such as the throttling valve. This sequence is set to start if the supply pressure falls below 70 psi.

2.4 STILLING TANK

Directly downstream from the throttling valve is the stilling tank. The purpose of this tank is to allow chance disturbances, such as large scale turbulence, to damp out before the air enters the test section. It consists of a 7.5 feet long by 3 feet wide cylindrical vessel (see Figure 2.4). The humidity of the wind tunnel air is measured from an air sample taken from this tank during an experiment.

Air enters the stilling tank from the 12-inch line through a pipe flange that is welded to the top of the vessel. The air exits the tank
Figure 2-4  Stilling Tank
through the end as is shown in Figure 2.4. At the downstream end of the stilling tank, directly before the air enters the test section, is a honeycomb flow straightener. Each passage in this flow straightener measured one-half inch square in cross-section and is three inches long. The purpose of the flow straightener is to break up large eddies that may be coming from the stilling tank. It does little to damp out small scale turbulence. These small scale fluctuations are damped out to some degree by turbulence filter screens that are located at each end of the flow straightener. The upstream screen is 32 mesh, .006 inch diameter wires while the downstream screen is 40 mesh, .006 inch diameter wires (see Figure 2.5).

Hot wire measurements of the turbulence content of the free stream were made when the facility was at its previous location. The turbulence level was measured at both low (420 mm Hg) and high (735 mm Hg) stagnation pressures. The energy spectrum of the turbulence level was taken at these pressures primarily to ensure that the frequency level of the electronics was adequate and infer the scale of the disturbances. The mass flow fluctuations were 1.47 percent for the low pressure and .82 percent for the high pressure. The absolute temperature fluctuations were .42 percent for the low pressure and .23 percent for the high pressure. The correlation coefficient between these two fluctuations was found to be +.87 for the low pressure and +.50 for the high pressure. These figures are a factor of two or three higher than was originally
Figure 2-5  Supersonic Sections
desired, but they still represent an acceptable stream turbulence level. That is, they represent a level considerably lower than that which is found in a turbulent wake, which is what this tunnel was designed to study. The level has also been found to be uniform throughout the test section. Hot wire tests have suggested that these measurements have not changed to any great degree.

2.5 UPSTREAM TRANSITION SECTION

The geometrical transition between the 6-inch circular cross-section at the exit of the stilling tank and the 3.1 x 6 inch rectangular section that forms the test section inlet channel is handled by the upstream transition section. A 3 x 6 inch channel was first milled along the axis of this section, followed by a 6-inch base diameter right angle cone being milled along the same axis. The fluid enters through the plane of the cone, converges gently toward its apex, then gradually transits into the rectangular channel.

The intersection of the cone and the triangle forms a sharp edge and it was originally feared that this would generate vortices. Fortunately, the edge is nearly parallel to the flow and the flow component normal to it is practically nonexistent.

Total temperature and total pressure measurements of the tunnel air flow are performed by pressure and temperature probe connections in this section. Also, the support strut for axisymmetric test models is
located in this section.

2.6 NOZZLE

The wind tunnel test section consists of a rectangular parallel piped made of brass and contains a two-dimensional DeLaval nozzle, a short straight section, and a supersonic diffuser, all made of aluminum.

The nozzle coordinates were computed by appropriate scaling from a Mach 3 nozzle calculation supplied by the Jet Propulsion Laboratory (JPL). The JPL design was for a 20 x 20 inch square nozzle exit with a turbulent boundary layer growing along the nozzle wall. For reasons of expediency, the JPL coordinates were reduced by a factor of 3:20 to obtain a 3 x 3 inch uniform or inviscid flow core. The turbulent boundary layer thickness was reduced by a factor of \((3:20)^{4/5}\) to account for the usual scaling of the turbulent boundary layer with linear distance. No account of the Reynolds Number was taken in this simple transformation of coordinates. In this manner, the actual distance from the floor to the ceiling in the test section was found to be 3.2 inches for a uniform flow core measuring 3 inches high. The nozzle coordinates are given in Table 2.1.

The distance between sidewalls could be calculated precisely only by accounting for the boundary layer growth along these walls which remained plane and parallel, a very difficult calculation. Instead, a sidewall-to-sidewall distance of 3.1 inches was chosen as an empirical
Table 2-1

Nozzle Coordinates (X is 0 at the throat, Y is 0 at the plane of symmetry)

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<td>1.0792</td>
<td>15.1411</td>
<td>1.6844</td>
</tr>
</tbody>
</table>
compromise. Equally empirical was the design of the section between the test section entrance and the nozzle throat. The contour chosen allows the flow to converge smoothly toward the throat and is tangent to the nozzle contour at the nozzle throat.

Sixteen .024 inch static pressure ports are drilled on the lower nozzle block extending along its centerline beginning at the exact location of the throat. The first port is 1.14 inches downstream of the throat. The ports are spaced one inch apart thereafter. The degree of choking can be easily determined by glancing at a Mercury manometer bank that is located next to the stilling tank and connected to these pressure ports.

A 5-inch long aluminum extension in the form of separate upper and lower blocks, is located immediately downstream of the nozzle. These blocks form a straight section and extend the useful test area.

2.7 SUPersonic DIFFUSER

The fixed supersonic diffuser was designed by simply contracting the flow channel to the minimum diffuser throat area allowing a normal shock to be swallowed during the starting operation. The pressure ratio required to run the tunnel with this diffuser was deduced from data accumulated from other wind tunnels and found to be about 5.2.\(^4\)

The pertinent area ratio, without boundary layer corrections, is found to be:
Diffuser boundary layer corrections were not made. Instead the diffuser throat was enlarged by milling the apex of its triangular profile so that the profile became trapezoidal. Rough computations showed that by this means the displacement thickness of the boundary layer, as well as the model support struts passing through the nozzle throat, could be accounted for.

2.8 DOWNSTREAM TRANSITION

The transition from the downstream test section end back to a 6-inch diameter pipe is accomplished with the same configuration as is described in Section 2.5 (Upstream Transition). The section is simply turned around to allow transition back to the round piping configuration.

Three four-inch pipe studs are arranged in a "T" around the centerline of the tunnel through this transition. These studs are equipped with four-inch pipe flanges and allow access to the flow channel for instrumentation. The X-actuator mechanism is located on the top flange of this section.

2.9 SUBSONIC DIFFUSER

This section of the tunnel is located directly downstream of the downstream transition section. It is a conically-shaped tube, 36 inches long, diverging from a 6-inch diameter at the downstream transition.
connection to a 12-inch diameter at the diffuser exit for connection to the standard 12-inch wind tunnel plumbing.

A 12-inch diameter bellows expansion joint downstream of this section allows enough in-line movement to remove and replace any wind tunnel component from this point to the stilling tank exit.

2.10 VACUUM SYSTEM

A Roots-Connersville No. 36-RGVS-2 vacuum pump generates the flow in the wind tunnel. The pump consists of two Roots blowers connected on the same shaft with a 200 Horsepower Westinghouse 480 Volt, three-phase induction motor, turning at 890 revolutions per minute (see Figure 2.6).

Near the first stage inlet, a check valve is located to protect against pump overloading should an excessive vacuum occur. If the pump inlet pressure goes below 48 mm Hg this valve will open and allow air into the inlet of the blower, since dangerous overheating will occur if the pump operates below this pressure for any other than a very short period of time. The opening of the check valve should not be confused with the low air pressure safety shutdown sequence. (The low air pressure shutdown occurs when the building supply pressure is too low to operate the pneumatically controlled devices on the wind tunnel.) The check valve does not shut the system off when it opens. Its only function is to prevent overheating of the pumps due to excessively low inlet
Figure 2-6  SWT Pump
pressure.

Just upstream from the inlet to the first stage of the vacuum pumps is the tunnel bypass valve. This is a pneumatically operated valve that allows atmospheric air into the first stage of the vacuum pumps. This valve is closed except during the startup of the tunnel. It opens as the motor is started to allow the blowers to get up to speed without having to "pull" a vacuum throughout the entire wind tunnel circuit. Once the blowers have reached operating speed, the bypass valve is shut and the tunnel is in operation.

The blowers are water sealed. Each blower has a pipe running into the air duct on the inlet side. Water is directed, in the form of a fan-shaped spray, over the surface of the rotor to provide sealing.

A low water pressure safety shutdown sequence has been installed and is activated should the water pressure in the lines feeding the blowers fall below 25 psi. At times, this shutdown has been activated by sudden momentary drops in the water pressure. To prevent this, it has become necessary to install a surge tank to maintain the pressure in the water lines during these momentary pressure drops. Thus, the water pressure must fall below 25 psi and stay there for a finite period of time (a few seconds) before the low water pressure shutdown is activated.

The oil system on the blowers also has two safety interlocks installed in it, one for low oil pressure and another for high oil temperature. The motor will automatically shut off if either one of these
sequences is activated. A warning light will also be displayed on the main control panel should either one of these problems arise.

When the blowers arrived here at MSU they were very rusted. This had occurred because in the past they had been allowed to remain inactive for long periods of time with water in them. To prevent this from occurring again, a dry shutdown sequence has been installed. When the dry shutdown is activated the sealing water flow to the blowers is shut off and air is blown through the water system around the blowers and through the spray nozzles themselves. This is done to protect the blowers from the corrosion problems that arise when stagnant water is left in them. After three minutes of operation in the dry shutdown mode the motor automatically shuts off. The dry shutdown is normally used only when the tunnel is not going to be restarted again for the rest of the day.

Inside the motor is a thermistor imbedded in the armature windings that will shut the motor off if it gets too hot. If this should occur, there will be no indication of the cause of the shutdown.

It has been observed that the nozzles directing the fan-shaped spray over the lobes of the blowers often get plugged due to particles that have been carried along through the water system. When this occurs the nozzles must be taken out and cleaned.

The first indication of loss of water is a temperature rise at the blower outlets. Because of the damage that could result to the blowers
if this went unnoticed, these temperatures must be watched continuously while the tunnel is in operation.

After the air has passed through the blowers, the wet exhaust is directed into a large discharge line silencer which removes some collected water to a drain and reduces the pump discharge noise. After leaving the silencer, the air is directed up through the ceiling and is discharged outside into the atmosphere.

2.11 WIND TUNNEL X-Y-Z PROBE ACTUATORS

A probe actuator system capable of moving a probe in three directions at variable speeds and at closely calibrated distances is installed in the wind tunnel test section. Positioning to 0.001 inch is accomplished with direct geared mechanical output while an electric position output is provided by a 10-turn helipot on each axis. The actuator drives the electric motors with associated reversible variable speed control. The vertical actuator is equipped with an adjustable limit system. Actuator speeds and limits of travel are given in Table 2.2.

2.12 SCHLIEREN SYSTEM

An 8-inch portable Schlieren system has been fabricated for observing the wind tunnel test section flow. The system consists of two wheeled tables supporting all optics and electronics in a pre-aligned position. Two light sources are used with associated condensers and plane mirrors providing either continuous illumination for optical
### TABLE 2.2

**Actuator Speeds and Limits of Travel**

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<thead>
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<th>Axis</th>
<th>Linear Speed</th>
<th>Limits of Travel</th>
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</thead>
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<td>X</td>
<td>.003 in/sec</td>
<td>.070 in/sec 8 in</td>
</tr>
<tr>
<td>Y</td>
<td>.002 in/sec</td>
<td>.066 in/sec 3 in</td>
</tr>
<tr>
<td>Z</td>
<td>0.0 in/sec</td>
<td>.016 in/sec 0.40 in</td>
</tr>
</tbody>
</table>
alignment and timed photography, or a spark source for use in high speed photography at exposure times of 0.5 microseconds. The 8-inch parabolic mirrors cover the working section adequately while their 64-inch focal length allows a compact design. The camera is of fixed focal length design equipped with a shutter-diaphragm and polaroid back pack. Image magnification at the camera is 0.73, reducing the entire Schlieren field to a 4 x 5 inch polaroid pack film size. Optical components employed in the system are ground to within one-fourth wavelength of Mercury light per inch while the tunnel test section windows are of selected striation-free plate glass providing high system sensitivity and minimum distortion (see Figure 2.7).

2.13 WIND TUNNEL PRESSURE STATION

The SWT is equipped with a pressure measuring system capable of monitoring 12 separate input pressures. The system is equipped with three Wallace and Tiernan absolute pressure gages and three impedance type pressure transducers.

Pressure gage A reads from 0 to 20 mm Hg, gage B reads from 0 to 100 mm Hg, and gage C reads from 0 to 400 mm Hg. Pressure transducer B reads from 0 to 50 mm Hg, transducer c reads from 0 to 250 mm Hg, and transducer D reads from 0 to 750 mm Hg. The electrical output from these transducers can be fed into various other pressure-monitoring electronic components. A photograph of the system is shown in
KEY

1 Light Source
2 Slit
3 Mirrors
4 Field of View
5 Camera Box
6 Knife Edge

Figure 2-7 Schlieren System
Figure 2-8  Wind Tunnel Pressure Station
Figure 2-9  Schematic of Pressure Station
Transducer C
10/2/80
Excitation = 5 Vdc
Gain = 10

Figure 2-10 Example Transducer Calibration

\[ P = 104.7 \times V \]
Figure 2-8. A schematic of the system is shown in Figure 2-9. A typical calibration curve for the transducers is shown in Figure 2-10.
CHAPTER 3
WIND TUNNEL PERFORMANCE

3.1 INTRODUCTION

Before any experiment can be performed in a facility such as the MSU SWT, the various parameters under which the experiment is to be carried out must be outlined. For instance, one may wish to investigate the behavior of a boundary layer over a range of stagnation temperatures and pressures (a range of Reynolds Numbers). The experimenter will have to determine the range of data that he needs. He will then have to check to see if the facility that he was planning on using is capable of supplying the necessary range of conditions. If it is not, then he must either modify his experiment or find another facility. For these reasons, information about the conditions under which the SWT is capable of operating is vital. The purpose of this chapter is to outline the conditions under which the MSU SWT has been observed to operate.

There are several parameters normally considered in supersonic wind tunnel testing. The parameter that lies at the root of all compressible flows is the Mach Number. Mach Number measurements were taken by two means: static and stagnation pressure measurements with total pressure known. Static pressure measurements were taken along the length of the nozzle in order to observe the change of the Mach Number along the nozzle. The stagnation pressure measurements were taken both to measure the Mach Number throughout the test section (and thus verify the static pressure measurements), and to check the flow uniformity in the test
Another parameter affecting the tunnel flow is the stagnation temperature. Since the MSU SWT is equipped with an air heater at the inlet, a range of temperatures is possible.

The behavior of the boundary layers in the nozzle and test section is, of course, very important. Boundary layer profiles at one point along the nozzle have been taken and are included in this chapter.

The fundamental parameter limiting the range of operation of the wind tunnel is the minimum pressure ratio required to maintain supersonic flow. The stagnation pressure at which supersonic flow is lost in the test section is, obviously, the lower limit on stagnation pressure in this wind tunnel. Because of its importance, this parameter is dealt with in detail in the next section of this chapter.

3.2 WIND TUNNEL PRESSURE RATIO

One of the most important parameters governing the operation of the wind tunnel is the minimum attainable stagnation pressure. This comes about because a minimum pressure ratio across the tunnel is required in order to maintain supersonic flow in the test section. The minimum attainable stagnation pressure governs the range of tests that can be performed in the tunnel. This, in turn, tells us the limitations of the tunnel and whether or not a given problem can be adequately investigated in this facility.
From one-dimensional gasdynamics theory a relationship between the inlet stagnation pressure, $P_0^*$, and the pump inlet pressure, $P_i$, can be derived. This is accomplished by first equating the mass flow rates at two different points in the tunnel circuit. The mass flow rate at the pump inlet is:

$$ \dot{m} = \rho_1 \dot{V}_i $$  

(3-1)

where $\rho$ is density, $\dot{V}$ is volume flow rate, and the subscript "i" denotes pump inlet conditions. It is also known that the flow at the nozzle throat is sonic:

$$ \dot{m} = \rho a^* A^* $$  

(3-2)

where $a$ is the local speed of sound, $A$ is the cross-sectional area, and the * denotes conditions at the nozzle throat, where the Mach Number is unity. Assuming steady flow:

$$ \rho_i \dot{V}_i = \rho a^* A^* $$  

(3-3)

$$ \rho_i \dot{V}_i = \frac{\rho}{\rho_0} \frac{\dot{V}_i}{a_0 A_0^*} $$  

(3-4)

The zero subscript denotes stagnation conditions. We can now utilize the equation of state for a perfect gas, as well as the relationship for the speed of sound in a perfect gas:

$$ a = (\gamma RT)^{1/2} $$
\[ p = \frac{p}{RT} \]
to obtain the following:

\[ \frac{P_1 V_1}{RT_1} = \frac{\rho^*}{\rho_o} \frac{a^*}{a_o} \frac{P_0}{RT_0} (\gamma RT_0)^{1/2} A^* \]  

(3-5)

where \( T \) represents temperature, \( R \) is the universal gas constant, and \( \gamma \) is the ratio of specific heats. (For air, \( \gamma = 1.4 \).)

for air we get:

\[ \frac{\rho^*}{\rho_o} = .6339 \]

\[ \frac{a^*}{a_o} = .9129 \]

The throat area of the SWT is:

\[ A^* = 2.1954 \text{ in.}^2 \]

Simplifying equation (3-5) we obtain:

\[ P_0 = 2.3111 \frac{P_1 V_1}{T_1} (T_o)^{1/2} \]  

(3-6)

where the temperatures are in degrees Rankine, the volume flow rate is in cubic feet per second, and the pressures are in any consistent set of units. Equation (3-6) thus gives the "driving" pressure ratio:

\[ \frac{P_0}{P_1} = 2.3111 \frac{V_1}{T_1} (T_o)^{1/2} \]  

(3.7)
In order to determine this ratio, i.e. to find $P_i$ for any given $P_o$, we need to have $V_i$ as a function of $P_i$:

$$V_i = f(P_i)$$

The relationship is obtained from the manufacturer's operating curve of the SWT pumps. This curve has been fit using a least squares curvefit method, yielding the result:

$$V_i = 16.1190951n(P_i) - 7.5317078 \quad (3-8a)$$

$$V_i = 45.658371 + 2.69235041n(P_i) \quad (3-8b)$$

Equation (3-8a) is valid for the range of pump inlet pressures between 35 mm Hg and 60 mm Hg. Equation (3-8b) is valid for pump inlet pressures greater than 60 mm Hg. The graphical representations of equations (3-8a and b) are shown on Figure 3.1 superimposed on the manufacturer's specification for the pump volumetric characteristic $V_i(P_i)$.*

Combining equations (3-7) and (3-8a and b), it is now possible to find the driving pressure ratio, $P_o/P_i$ as a function of any chosen stagnation pressure, with the temperatures $T_o$ and $T_i$ as parameters. This has been done on Figures 3.2 through 3.6 for a set of four typical

* Using equations (3-7) and (3-8a and b), a Fortran program named HEET-LOSS has been written and is permanently on the wind tunnel account. To run the program, simply input the assigned stagnation temperature in °F, followed, on the same line, by the assumed pump inlet temperature in °F. The program will then execute and output the pressure ratios that are to be expected.
Figure 3-1 Curvefit of Pump Operating Curve
Figure 3-2  Flow Breakdown Predictions
Figure 3-3 Flow Breakdown Predictions
Figure 3-4  Flow Breakdown Predictions
Figure 3-5  Flow Breakdown Predictions
Figure 3-6  Operating Limits According to Temperature
operating stagnation temperatures, $T_0$. The maximum value shown of $T_0 = 125^\circ F$ is considered to be close to the maximum available using the present heater.

Different graphs are shown for each of four pump inlet temperatures. The $T_i$'s are assumed to be at 50, 75, 100, and 125°F. The exact value of the pump inlet temperature is hard to estimate since it depends on $T_0$ and complex heat losses along the tunnel-conduit. Presumably, the range of $T_i$ between 50 and 125°F covers all expected cases for the inlet temperature. As with $T_0$, the graphs allow interpolation within this range.

The curves on Figures 3.2 through 3.6 allow the computation of $P_i$ (or $P_0/P_i$) for each chosen $P_0$ (and the accompanying pair of temperatures) and represent the available pressure ratio for driving the SWT. The required pressure ratio, on the other hand, which will determine the realistic range of $P_0$, is controlled by a) the wind tunnel diffuser and b) the minimum possible operating pump inlet pressure as specified by the manufacturer.

Considering the diffuser limit first, a minimum pressure ratio is required in all supersonic wind tunnels before "unchoked" flow exists in the test section. This ratio is extremely complex to calculate, but for this tunnel has been found empirically to be on the order of 5.2. This is the value shown by a horizontal line drawn across Figures 3.2 through 3.5. The point where each driving pressure curve crosses the diffuser
limit gives the minimum $P_0$, for which SWT operation is possible for the prescribed temperatures. The minimum operating $P_0$'s are thus plotted vs. $T_0$ (with $T_i$ as a parameter) on Figure 3.6. Note that the situation improves (that is $P_0$ min. decreases) when the supply temperature $T_0$ is the highest, and when the heat losses in the wind tunnel circuit are at a maximum ($T_i$ is the smallest). The physical reason for this is that when $T_0$ is high, the mass flow through the nozzle throat is low. This arises from the fact that density is inversely proportional to temperature. At the same time a low pump inlet temperature means that the pumps are admitting a high mass flow rate, for the same reason: At this setting, therefore, pumping is efficient and loading is light. At the opposite extreme, the pump is required to absorb a high flow rate at a reduced efficiency and the tunnel chokes. It follows that the best operation is achieved at the highest possible $T_0$ setting, and by cooling as much as possible, the ducts between the test section and the pump entrance. For example, the benefit shown by the curves on Figure 3.6 causes an increase in the operating range of $P_0$ as follows:

Poor Operation: $T_0 = T_i = 100^\circ$F; $P_0$ min. = 228 mm Hg; 
\[
\frac{P_0 \text{ max}}{P_0 \text{ min}} = 2.76
\]
Good Operation: \( T_o = 125^\circ F; T_i = 50^\circ F; P_o \text{ min} = 153 \text{ mm Hg}; \)

\[
\frac{P_o \text{ max}}{P_o \text{ min}} = 4.12
\]

which is substantial. \( P_o \text{ max} \) is taken as 630 mm Hg for these calculations.

The second type of limit is the minimum absolute pump inlet pressure, \( P_i \text{ min} \), suggested by the manufacturer. At very low pump inlet pressures the latter states that the pumps may overheat if operated continuously, and therefore, one should not operate below this pressure. Also, the check valve described in Chapter 2 opens when the pump inlet pressure goes too low, thus causing flow breakdown in the test section. This minimum operating pressure is in the neighborhood of 48 mm Hg. In Figures 3.2 through 3.5, this limit appears as a straight line passing through the origin. To the left of this line, the pump inlet pressure is below the minimum.

For instance, in each case, it is seen that the curves cross the pump limit line before they cross the diffuser limit. Thus, one would expect the cause of flow breakdown in these cases to be the check valve opening. The exact pressure at which the check valve opens is not known and it is speculated that it could vary between 35 and 60 mm Hg.
3.3 PRESSURE RATIO OBSERVATIONS

Experimental observations of the wind tunnel pressure ratio are plotted on Figure 3.7 for two stagnation temperatures. The pump inlet temperature has not been observed to vary a great deal from the stagnation temperature (usually less than 5°F). Therefore, the curves on Figures 3.2 through 3.5 which indicate no heat loss, that is, \( T_0 = T_i \), are expected to better predict the performance of the tunnel.

Temperature is observed to play a major role in flow breakdown, as was predicted by the theory presented in Section 3.2. As can be seen from inspection of Figure 3.7, the flow breakdown for a stagnation temperature of 75°F occurs at a driving pressure ratio of about 4.88. It occurs when the curve crosses the minimum pump inlet pressure curve, \( P_i = 48 \text{ mm Hg} \). Therefore, in this case, flow breakdown is attributed to opening of the check valve and not to reaching the tunnel's minimum required driving pressure ratio, even though the pressure ratio of 4.88 is well below the predicted minimum of 5.2.

At the higher temperature, \( T_0 = T_i = 100°F \), flow breakdown occurs at a pressure ratio of 5.4, which is substantially above the predicted minimum. In this case, however, flow breakdown cannot be attributed to opening of the check valve since the pump inlet pressure is well above 48 mm Hg at the point where choking occurs. This was, in fact, observed. The only other possible reason for flow breakdown is the driving pressure ratio is less than the minimum pressure ratio required for these
Figure 3-7 Observations of Flow Breakdown
conditions. This leads one to the conclusion that the driving pressure ratio is dependent on the temperature of the air stream. This hypothesis has been supported by other observations of the tunnel that are not presented in this section. (These observations took place when performing other experiments, such as the static pressure Mach Number measurements of Section 3.5). As the temperature is increased, the flow breaks down at a higher pressure ratio. This observation can be explained to some degree by the conclusion reached in Section 3.2 that at the lower pump inlet temperatures the pumping efficiency is somewhat enhanced.

The conclusion one reaches from all of this is that the minimum pressure ratio of .52 is by no means an absolute guideline. Choking will occur in this neighborhood but the exact pressure ratio that will cause flow breakdown is complicated to predict, and will depend on the temperature. The pump inlet pressure of 48 mm Hg is a good prediction of when the check valve will open. For a great many of the experiments on this tunnel it will be this parameter that causes the tunnel to choke, especially when the stagnation temperature is low.

Finally, it should be noted that these results were obtained with the test section empty. It is doubtful that the minimum pressures that were attained could have been reached if large models or probes were positioned in the test section.
For the reasons outlined above, the conclusion is reached that one should not plan on being able to run the tunnel at stagnation pressures below 300 mm Hg. Pressures lower than this can be obtained under certain conditions, but at other times may be unattainable.

3.4 STATIC PRESSURE MEASUREMENTS

Along the bottom surface of the nozzle there are 16.024 inch holes drilled in the nozzle surface and located halfway between the sidewalls which are used for measurement of static pressure along the nozzle. These holes start at the nozzle throat, the first one downstream is located 1.14 inches from the throat, and they are spaced one inch apart thereafter. These ports are normally connected to a Mercury manometer bank that is located near the stilling tank in full view of the operator. For the static pressure measurements described in this section, the ports were connected to the wind tunnel pressure station.

Static pressure measurements were taken for seven stagnation pressures, ranging from 600 down to 300 mm Hg. The Mach Number was deduced from the isentropic relationship between static and stagnation pressure (measured in the upstream transition section) for an ideal gas:

$$\frac{P_o}{P} = \left(1 + \frac{\gamma - 1}{2} M^2\right)^{\gamma/\gamma - 1}$$  \hspace{1cm} (3-9)

where $P_o$ is the stagnation pressure, $P$ is the static pressure, and $\gamma$ is the ratio of specific heats ($\gamma = 1.4$ for air). The results are plotted
on Figure 3.8 and tabulated in Table 3.1.

3.5 STATIC PRESSURE MEASUREMENT RESULTS

The Mach Numbers obtained from these measurements are lower than one would expect from inviscid flow theory, as is illustrated in Figure 3.8. This was not unexpected, however, since the flow is not truly inviscid and there is a boundary layer growing along the nozzle wall.

The Mach Number is observed to increase slightly as the stagnation pressure decreases until a certain point where the Mach Number reaches a maximum and begins to decrease slightly as the stagnation pressure is decreased further (see Figure 3.9). For inviscid ideal gases, the only factor affecting the Mach Number is the cross-sectional area of the flow channel in relation to the cross-sectional area where the Mach Number is equal to unity. The flow area is not really the entire area of the channel since near the wall the flow is not inviscid and a boundary layer will be growing. The area of the channel must be modified to account for the displacement effect of the boundary layer. This is accomplished by taking into account the displacement thickness of the boundary layer, which is defined as the distance the wall must be displaced in order for the inviscid solution to correctly predict the characteristics of the flow. The mathematical definition of this quantity is as follows:

\[ \delta^* = \int (1 - \frac{\rho u}{\rho_\infty u_\infty}) \, dy \]
Table 3-1

Static Pressure Nozzle Calibration

<table>
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<th>Mach Number (P_n=450 mmHg)</th>
<th>Mach Number (P_n=400 mmHg)</th>
<th>Mach Number (P_n=350 mmHg)</th>
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**Design Mach Number**

**Range of Data**

**Mach Number From Area Change**

Figure 3-8 Results of Static Pressure Tests
Figure 3-9  Effect of Stagnation Pressure on Mach Number  ($X = 14.14$ inches)
where $U_\infty$ is the free stream velocity, $u$ is the velocity at any given point, $\rho_\infty$ is the free stream density, $\rho$ is the density at any given point, and $y$ is measured perpendicular to the wall. For laminar boundary layers the displacement thickness is known to vary inversely with the square root of the stagnation pressure:

$$\delta^* \propto \frac{1}{(P_0)^{1/2}}$$

(3-10)

For turbulent boundary layers, the displacement thickness does not depend, to any significant degree, on the stagnation pressure. However, when the boundary layer is turbulent, the displacement thickness will be somewhat larger than it is for most laminar flows, as is illustrated in Figure 3-10.

When the displacement thickness is at a minimum, the flow area will be at a maximum and hence the Mach Number will be at a maximum. It is also known that the point of transition from laminar to turbulent flow in the boundary layer moves upstream as the stagnation pressure is increased.

Using the principles outlined in the previous paragraph, it is now possible to offer an explanation of the observed variation of Mach Number with the stagnation pressure that has been observed in these measurements. At the furthest downstream port (15.14 inches downstream of the throat) the Mach Number is observed to increase as the stagnation pressure is increased from its minimum value of 303 mm Hg. This is
Figure 3-10 Change of the Displacement Thickness of a Boundary Layer due to Pressure
predicted by the relationship given in Equation (3-10). This phenomenon continues until a stagnation pressure somewhere between 450 and 500 mm Hg is reached. At this point the trend reverses and the Mach Number decreases as the stagnation pressure is increased further.

Assuming that the boundary layer is laminar at the minimum stagnation pressure* the increasing thickness of the boundary layer is correctly predicted by Equation (3-10). Assume also that the boundary layer transits from laminar to turbulent at a stagnation pressure between 450 and 500 mm Hg. As the stagnation pressure is increased further, the point of transition to turbulent flow moves upstream, giving the boundary layer more distance over which to grow before reaching the downstream static port. Since the boundary layer has had more distance to grow, the displacement thickness will be larger and the Mach Number will be smaller. As the stagnation pressure is further increased, this phenomenon will continue and the Mach Number will decrease further.

Although the above discussion is useful as far as pinpointing the point of transition, the overall effect of the boundary layers on the free stream Mach Number is very small. The variation of the Mach Number from maximum to minimum is less than two percent. Thus, there are no problems foreseen in this tunnel due to the variation of Mach Number due to the stagnation pressure.

* See Section 3.9 of this chapter.
3.6 STAGNATION PRESSURE MEASUREMENTS

The static pressure measurements described in the previous section are informative about the free stream Mach Number along the nozzle. They do not, however, give any information about the uniformity of the flow in the nozzle and test section or the presence of waves in the flow. For this reason, along with a desire to confirm the static pressure results of the previous section, it was deemed necessary to introduce pitot probes into the test section to measure stagnation pressure (and hence the Mach Number) at various planes along the nozzle and test section.

A cartesian coordinate system has been utilized to describe the position of the probes in the tunnel. The X-coordinate is along the direction of flow and is referenced to zero at the nozzle throat, the downstream direction being taken as positive. The Y-coordinate is the vertical axis and is referenced to zero halfway between the top and bottom surfaces of the nozzle, the positive direction being upward, the negative downward. The Z-axis is the horizontal coordinate, perpendicular to the flow. The zero position is that point halfway between the sidewalls. For an observer facing the direction of flow, positive is measured to the right, negative to the left. (South wall is positive Z, North wall is negative Z.) See Figure 3.11.

The Y-Z plane flow measurements have been taken at 10 X-positions along the nozzle and test section. These measurements were taken with
Figure 3-11  Coordinate System

Nozzle Block
the aid of a pitot (stagnation) tube rake that is illustrated in Figure 3.12. The individual pressure lines from each tube run into the body of the rake and out the back end. These lines were then connected to the wind tunnel pressure station.

The body of the rake was suspended from Y-actuator posts at two positions along the body of the rake so that the Y-actuator could be used to move the rake up and down along the Y-axis. The rake was carefully positioned and leveled before each run.

After the tunnel was started and allowed to come to equilibrium the port closest to the south wall was opened. The pressure in this line was then read with the aid of transducer C. The electrical output from this transducer was then fed into the X-axis actuator of a Hewlett-Packard model 7004B X-Y recorder. The signal from the Y-axis actuator on the wind tunnel was similarly fed into the Y-axis actuator of the X-Y recorder. See Figure 3.13. Thus, as the rake was moved down through the test section, the variation of stagnation pressure along the Y-axis at that particular X and Z position was traced on the X-Y recorder.

When the rake reached its lower limit in the test section, the port being measured was closed, the pen on the X-Y recorder was raised, and the rake was raised back to its upper limit near the top of the test section. The $X = 0$ position on the X-Y recorder was then shifted to the right by one half of a division (.25 volts) in order to prevent overlapping of the traces. The next port was then opened (in this example
Figure 3-12  Stagnation Tube Rake
Figure 3-13  Stagnation Pressure Measuring System
it would be port B on Figure 3.12), and the procedure was repeated until all of the traces for that particular X position had been obtained.

It is well known from the theory of supersonic flows that the pressure in the pitot tube is not the true stagnation pressure, but the pressure behind a normal shock as is illustrated in Figure 3.14. On the stagnation streamline, the shock is a normal shock and the total pressure relationship for a normal shock applies:

\[
\frac{P_{o2}}{P_{o1}} = \left[1 + \frac{2\gamma}{\gamma+1} (M_1^2 - 1)\right]^{-1/\gamma-1}\frac{(\gamma+1)M_1^2}{(\gamma-1)M_1^2 + 2} \tag{3-11}
\]

where \(P_{o1}\) is the stagnation pressure ahead of the shock, \(P_{o2}\) is the stagnation pressure behind the shock, \(M_1\) is the Mach Number before the shock, and \(\gamma\) is the ratio of specific heats. This ratio is known to be 1.4 for air. Since the ratio \(P_{o2}/P_{o1}\) is known, the only unknown is \(M_1\).

One X-Y plane measurement along Z = 0 has also been taken for the purpose of verifying earlier measurements and observing, on one plot, the variation of Mach Number with distance from the throat in the test region. This measurement was taken with the aid of a single pitot probe that was suspended from the Y-axis actuator posts at two positions and driven forward with the aid of the X-axis actuator mechanism (see Figure 3.15).

The probe traversed from 18.38 inches downstream of the throat to 11.68 inches downstream of the throat. Traces were taken for five Y
Figure 3-14  Stagnation Probe Behind Shock
Figure 3-15  Single Stagnation Probe For Use in X-Y Plane Traverse
positions. Transducer C was again utilized for pressure measurements. On this plot, however, the signal from the transducer was put into the Y-axis actuator of the X-Y recorder, while the output from the X-axis actuator of the wind tunnel was fed into the X-axis actuator of the X-Y recorder. The result is a plot where the pen moved horizontally instead of vertically. After one trace was completed, the physical positioning of the probe along the Y-axis in the test section was changed by use of the Y-actuator mechanism of the wind tunnel. The Y=0 position of the pen was also changed for each new trace so that overlapping of the trace was avoided. The result is Figure 3.27.

The flow profiles that have just been described are presented on the next several pages. The reader should note the labeling of the zero position of the horizontal axis of the plots (and the vertical axis of Figure 3.27). For the Y-Z profiles a trace was taken of port A using the left hand margin of the graph paper as the X=0 position (see Figure 3.16). When this was completed, port A was closed and port B opened. The X=0 position was then moved to the right by .25 volts and the profile for port B was taken. This was done for each port, in order, until a complete profile was obtained. The zero position of each trace is clearly labeled on the plots.

Figure 3.16 is a diagram of the positioning of the rake in the tunnel and refers to measurements taken upstream of X = 15.063 inches (Figures 3.17 through 3.20). Figure 3.21 is a similar diagram and
Figure 3-16 Positioning of Rake in Test Section
Zeroes of Traces

A B C D E F G H I J

Figure 3-17 Y-Z Plane Plot
Figure 3-18  Y-Z Plane Plot

Zeroes of Traces

+ y↑
y=0
- y↓

Origin of trace  Mach Number

A B C D E F G H I J

CALIBRATION OF TEST SECTION

DATE:  10/10/80
STAGNATION PRESSURE:  600 mm Hg
STAGNATION TEMPERATURE:  100 °F
ACTUATOR SPEED SETTING:  45
CALIBRATION:  Trans. C, 10/2/80
X POSITION:  10.14 inches
COMMENTS: I and J leak.
Figure 3-19  Y-Z Plane Plot

Zeroes of Traces

| A | B | C | D | E | F | G | H | I | J |

CALIBRATION OF TEST SECTION

- DATE: 10/10/80
- STATIC PRESSURE: 600 mm Hg
- STAGNATION TEMPERATURE: 100°F
- ACTUATOR SPEED SETTING: 45
- CALIBRATION: Trans. C, 10/2/80
- X POSITION: 12.14 inches

COMMENTS: 1 and 2 tear.
## Zeroes of Traces

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<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
<th>H</th>
<th>I</th>
<th>J</th>
</tr>
</thead>
</table>

**CALIBRATION OF TEST SECTION**

- **DATE:** 10/9/80
- **STAGNATION PRESSURE:** 600 mm Hg
- **STAGNATION TEMPERATURE:** 100 °F
- **ACTUATOR SPEED SETTING:** 45
- **CALIBRATION:** Trans. C, 10/2/80
- **X POSITION:** 14.14 inches
- **COMMENTS:** I and J leak.

---

**Origin of trace**

- Mach Number

---

**Figure 3-20** Y-Z Plane Plot
Figure 3-21  Positioning of Rake in Test Section
refers to measurements taken at 15.063 inches and further downstream (Figures 3.22 through 3.26). The position of the rake was carefully checked before each new plot was taken. The transducer was also frequently re-calibrated.

3.7 STAGNATION PRESSURE MEASUREMENT RESULTS

The plots obtained with the aid of the pitot tube rake show the flow to be uniform, although there is some evidence of some minor waves in the profiles taken downstream of $X = 16.563$ inches. The conical shaped wave that is evident in Figure 3.24 has been traced to a leak at the static port 10.14 inches downstream from the throat which has since been corrected.

The major contribution of these plots is to verify that the flow in the test section is, indeed, uniform. The measurements extend from the downstream end of the extension block, which is 21.063 inches downstream from the throat, to directly above the static port located 8.14 inches downstream from the throat. The waves that are evident in the further downstream measurements probably originate at the upstream end of the extension block. These disturbances are relatively small and do not significantly alter the free stream Mach Number. For instance, in Figure 3.25, waves appear approximately $1/4$ inch above and below the $Y=0$ position on the graphs, but the changes in Mach Number due to these waves is on the order of 2 percent. The effects of the leak at the
Figure 3-22  Y-Z Plane Plot

Zeroes of Traces

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<th>E</th>
<th>F</th>
<th>G</th>
<th>H</th>
<th>I</th>
<th>J</th>
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</thead>
</table>

CALIBRATION OF TEST SECTION

DATE: 10/9/80
STATION PRESSURE: 600 mm Hg
STATION TEMPERATURE: 100°F
ACTUATOR SPEED SETTING: 45
CALIBRATION: Trans. C, 10/2/80
I POSITION: 15.06 inches
COMMENTS: J is in boundary layer.
Zeroes of Traces

Figure 3-23  Y-Z Plane Plot
Zeroes of Traces

Figure 3-24 Y-Z Plane Plot
### Zeroes of Traces

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**Figure 3-25**  Y-Z Plane Plot

### Comments:
- J is in boundary layer

**Calibration of Test Section**
- **Date:** 10/3/80
- **Stagnation Pressure:** 600 mm Hg
- **Stagnation Temperature:** 100°F
- **Actuator Speed Setting:** 45
- **Calibration:** Trans. C. 10/2/80
- **X Position:** 19.56 inches

### Origin of Trace
- **Mach Number:** 2.3, 3.0, 2.9, 2.8, 2.7
Zeroes of Traces

Figure 3-26 Y-Z Plane Plot

CALIBRATION OF TEST SECTION

DATE: 10/3/80
STAGNATION PRESSURE: 600 mm Hg
STAGNATION TEMPERATURE: 100 °F
ACTUATOR SPEED SETTING: 45
CALIBRATION: Trans. C, 10/2/80
X POSITION: 21.06 inches
COMMENTS: J is in boundary layer.
Calibration of test section, X-Y plane along Z = 0

10/2/80  Pen moves to the left at 60°

Stagnation Pressure = 600 mm Hg
Stagnation Temperature = 55°F

Calibration: Trans. C, 10/2/80

$X_{downstream} = 18.375^\circ$  
$X_{upstream} = 11.675^\circ$

Figure 3-27 X-Y Plane Plot
static port 10.14 inches from the throat are thought to be minimal, even though this leak was not discovered until the rake had been moved forward to 15 inches from the throat. Furthermore, these slight defects can be (and were) corrected.

Boundary layer effects are clearly visible in the measurements that were taken further downstream. The tubes of the pitot rake that were nearest the wall were found to be completely in the boundary layer below 14 inches downstream of the throat (Figures 3.20, 3.22 through 3.26). This implies a boundary layer thickness of at least .2 inches at these points. Upstream from there the boundary layer thickening near the corners is observed, but the ports near the wall are out of the boundary layer for the major part of their traverse.

Downstream measurements were taken first, and after the measurement at \( X = 15.063 \) inches was taken the rake was removed from the test section and re-installed on supports that were located further upstream. When the rake was re-installed it was found that ports I and J were leaking rather badly. Efforts to correct this problem were unsuccessful so the rest of the measurements were taken without the use of these ports. The ports that were leaking were those that were located nearest the north wall, and it is unlikely that there is a disturbance in this region that could significantly affect the results without showing evidence of itself in the measurements that were taken further downstream.
The speed of traverse of the rake was determined experimentally. A setting of 45 on the Y-actuator speed control was settled on as being the fastest speed at which all significant disturbances would be adequately displayed on the plots. (=.03 inches per second)

All of the flow profiles were taken at a stagnation pressure of 600 mm Hg. It was decided at the outset that there was no need to take plots for other pressures since most disturbances of the flow are not functions of the stagnation pressure.

The Mach Number is observed to stay in the general vicinity of M=3. Deviations from this value are small and, for the most part, predictable. The Mach Number continues to grow with distance from the throat until around 15 inches downstream from the throat. It then begins to decline slowly. This is to be expected since the channel ceases to diverge at this point but the boundary layers continue to grow, providing the effect of a supersonic diffuser. This boundary layer growth is observed in the traces taken of port A in the flow profiles. The effect of the two dimensionality of the nozzle is observed in the traces taken in the diverging portion of the nozzle as a 'bowing out' of the traces.

The profiles presented in Figures 3.17 through 3.20 were purposely taken directly above static ports where the Mach Number had already been measured. The comparison is presented in Table 3.2. The results from the two methods are not in complete agreement but are well within the bounds of error which one would expect using the equipment used.
Table 3.2
Comparison of Results (X = 10.14 in)

<table>
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<th>Stagnation Pressure</th>
<th>600 mm Hg</th>
<th>500 mm Hg</th>
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<td>Mach Number From Area Change</td>
<td>3.025</td>
<td>3.025</td>
</tr>
<tr>
<td>Mach Number From Static Pressure Tests</td>
<td>2.889</td>
<td>2.869</td>
</tr>
<tr>
<td>Mach Number From Stagnation Pressure Tests</td>
<td>2.95</td>
<td>test not performed</td>
</tr>
<tr>
<td>Mach Number From Area Change with Boundary Layer Correction</td>
<td>2.902</td>
<td>2.898</td>
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The static pressure measurements involved measuring pressures an order of magnitude lower than the stagnation measurements and total agreement was not expected. Also, the two-dimensional nature of the nozzle is important since the static measurements only involved a pressure measured at the wall and the Mach Number varied to some degree across the nozzle. See Section 3.11 of this chapter for a more complete discussion of this question.

Figure 3.27 is the result of the X-Y plane profile that was taken with the single stagnation probe. The speed of translation of this probe was again determined experimentally. A setting of 60 (≈0.04 in/sec) on the X-axis actuator control was determined to be the best speed.

The results from this plot confirm earlier observations of the Y-Z plane plots. When compared to the Mach Number measurements obtained in the pitot rake measurements there is no noticeable difference. The plot confirms earlier observations of the variation of Mach Number with distance from the throat. The Mach Number grows along the divergent portion of the nozzle until reaching a maximum around 15 inches from the throat and begins to decline as the probe is moved further downstream.

There are some waves evident in this plot, but they are at the far downstream end of the extension block. The area where these waves are located is well out of the way of any test that might be performed in the tunnel. It is thought that the upstream support of the Y-actuator mechanism is the origin of these waves.
A plot of the Mach Number along the test section is presented on Figure 3.28. This plot was derived from the trace shown on Figure 3.27.

3.8 BOUNDARY LAYER PROFILES

Boundary layer profiles have been taken at \( X = 10.14 \) inches at the top surface of the nozzle, all at \( Z=0 \), for three stagnation pressures. A flattened pitot probe was utilized for these measurements, and is illustrated in Figure 3.29. An optical microscope was used to position the probe against the wall. The speed of traverse of the probe was again determined experimentally and a setting of 15 on the Y-actuator speed control knob was chosen as the best speed. It was hoped that the results of these measurements would further confirm observations made about the flow.

The X-Y recorder that was used for the earlier stagnation probe profiles was utilized for the boundary layer profiles. The pressure in the pitot probe was read by transducer C, whose output was fed into the X-axis actuator of the X-Y recorder. The wind tunnel Y-axis actuator output was put into the Y-axis input on the X-Y recorder. The profiles thus obtained are presented in Figures 3.30 and 3.31.

Boundary layer profiles were taken for stagnation pressures of 600, 500, and 400 mm Hg. The profile at 400 mm Hg was stopped as soon as the free stream was reached because of a flow breakdown. Because of the problem of flow breakdowns no profiles were attempted at stagnation
Figure 3-28  Variation of Mach Number Along Test Section
Figure 3-29  Flattened Pitot Probe
Boundary Layer Profiles X = 10.14 inches downstream of the throat Calibration: 10/2/80 trans C \( P = 109.7 \times 1 \)

\[ T = 24.7^\circ F \]

Figure 3-30 Boundary Layer Plots
Figure 3-31 Boundary Layer Plot
pressure below 400 mm Hg.

3.9 RESULTS OF BOUNDARY LAYER PROFILES

From inspection of the profiles on Figures 3.30 and 3.31 it is seen that the profile taken at a stagnation pressure of 600 mm Hg is turbulent while those taken at the lower pressures are laminar. This is demonstrated by the shape of the curves. These observations confirm the explanation that has been offered for the variation of Mach Number with stagnation pressure that has been offered in Section 5 of this chapter. At the higher stagnation pressure, the boundary layer is turbulent, and thus thicker, causing the effective area of the nozzle to decrease and forcing the Mach Number to go down. It should be noted at this point that it is not the total thickness of the boundary layer that causes this effect but, rather, the displacement thickness of the boundary layer. It is shown later on in this section that this displacement thickness does, indeed, increase when the boundary layer transitions from laminar to turbulent. As the pressure is reduced, the boundary layer becomes laminar and, at least initially, thinner. As the boundary layer at a point shrinks, the Mach Number will increase. As the pressure is reduced further, the boundary layer will obey the relationship of equation (3-10) and begin to grow again, causing the Mach Number to decrease.

At this point it is interesting to observe that the laminar boundary layers of Figures 3.30 and 3.31 provide the experimental test for
the relationship of equation (3-10). That is:

\[ \delta_1 = \frac{1}{(P_{o1})^{1/2}}; \quad \delta_2 = \frac{1}{(P_{o2})^{1/2}} \]  

(3-12)

The subscripts 1 and 2 denote 500 and 600 mm Hg respectively. Since the boundary layer profiles are taken at the same point it is reasonable to assume the proportionality is the same for each case. That is:

\[ \frac{\delta_1}{\delta_2} = \frac{1/(P_{o1})^{1/2}}{1/(P_{o2})^{1/2}} = (P_{o2}/P_{o1})^{1/2} \]  

(3-13)

Using the data we have, assume:

\[ P_{o1} = 500 \text{ mm Hg} \]
\[ P_{o2} = 400 \text{ mm Hg} \]

It can be seen from inspection of the profiles that:

\[ \delta_1 = 1.07 \text{ inches} \]
\[ \delta_2 = 1.21 \text{ inches} \]
\[ \frac{\delta_1}{\delta_2} = .884 \]
\[ (P_{o2}/P_{o1})^{1/2} = .892 \]

These two answers differ by less than one percent. This confirms that our data follows the relationship of equation (3-10).

Data taken off Figure 3.30 has been utilized to plot boundary layer profiles in the form of velocity ratio versus distance ratio. These plots are presented on Figure 3.32. Since the boundary layer at 400 mm Hg
Figure 3-32 Boundary Layer Profiles \((X = 10.14\, \text{inches})\)
is known to be laminar and of a similar profile to that at 500 mm Hg, it 
was not plotted.

From inspection of Figure 3.32, it can be deduced that the profile 
at a stagnation pressure of 500 mm Hg is laminar and the profile at 600 
mm Hg is turbulent.5

Displacement thicknesses of these two boundary layers have been 
calculated by a numerical procedure. As has already been stated, the 
displacement thickness is defined as that distance by which the wall 
must be displaced in order for the inviscid solution to apply. It is 
defined mathematically, for compressible flows, as the following:

$$\delta^* = \int_0^\infty (1 - \frac{\rho u}{\rho_\infty U_\infty})dy$$  \hspace{1cm} (3.14)

where: $\rho$ = the density at any point;
$\rho_\infty$ = the free stream velocity;
$u$ = the velocity at any point; and
$U_\infty$ = the free stream velocity.

Figure 3.33 illustrates the procedure used to determine the displace­
ment thickness. The results are tabulated in Table 3.3.

Using the displacement thickness to account for boundary layer 
effects, the Mach Number can now be calculated with some degree of con­
fidence. In this analysis the boundary layer at the throat will be 
ignored since it will obviously be very thin. The results that will be
Figure 3-33  Procedure for Calculating Displacement Thickness
Table 3-3
Boundary Layer Thicknesses

<table>
<thead>
<tr>
<th>Stagnation Pressure</th>
<th>600 mm Hg</th>
<th>500 mm Hg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boundary Layer Thickness</td>
<td>0.105 in</td>
<td>0.121 in</td>
</tr>
<tr>
<td>Displacement Thickness</td>
<td>0.038 in</td>
<td>calculation not performed</td>
</tr>
</tbody>
</table>
thus obtained do not take into account the two-dimensional nature of the nozzle, and will thus be difficult to compare to the stagnation pressure results which, at the point where the boundary layer profiles were taken, show the effect of the two-dimensional nature of the nozzle quite vividly. When the calculation is carried out, it is found that the Mach Number at this point is 2.902 for a stagnation pressure of 600 mm Hg, and 2.898 for a stagnation pressure of 500 mm Hg. These numbers are in good agreement with those obtained from the static pressure measurements.

3.10 TEMPERATURE OBSERVATIONS

It has been observed that the heater is capable of raising the temperature of the inlet air stream approximately 40°F at the maximum flow rate. The heater is capable of raising the temperature somewhat more than this, but will not provide stable operation if this is done. The reason that the operation will not be stable is that if the heater is used at maximum output it will be putting out a constant amount of energy while the ambient conditions can be varying considerably. Since the maximum heater output is a constant, the temperature of the wind tunnel air will vary with the ambient conditions, thus defeating much of the purpose of the heater.

3.11 MEASUREMENT ERROR

The question that always arises in a study such as this is "How good are the results?". An evaluation of the errors in the measurements
of this chapter has been carried out. This was done by adding all possible errors for each measurement and calling this sum the greatest possible error. For instance, for the stagnation pressure measurements the analysis was carried out as follows:

<table>
<thead>
<tr>
<th>Error</th>
<th>Magnitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>leaks in pressure system</td>
<td>±10 mm Hg</td>
</tr>
<tr>
<td>transducer error</td>
<td>±2 mm Hg</td>
</tr>
<tr>
<td>error in positioning</td>
<td>±4 mm Hg</td>
</tr>
<tr>
<td>graph on X-Y recorder</td>
<td>±2 mm Hg</td>
</tr>
<tr>
<td>error in reading</td>
<td>±5 mm Hg</td>
</tr>
<tr>
<td>ambient pressure</td>
<td>±2 mm Hg</td>
</tr>
</tbody>
</table>

Total magnitude of error = 23 mm Hg

Assuming a Mach Number of 3,

Total percent error = ±4.3 percent

An error analysis was also carried out for the static pressure measurements, the boundary layer measurements, and the temperature measurements. The results are as follows:

- Static pressure measurements: \( M_{\text{actual}} = M_{\text{exp.}} \pm 0.3\% \)
- Boundary layer thickness: \( \delta_{\text{actual}} = \delta_{\text{exp.}} \pm 8.0\% \)
- Temperature measurements: \( T_{\text{actual}} = T_{\text{exp.}} \pm 2^\circ\text{F} \)

This error analysis shows that the measurements contained in this chapter are reasonably accurate and thus are reliable.
CHAPTER 4

CONCLUSIONS

From the measurements and results in Chapter 3, one is led to conclude that the performance of the wind tunnel has not been detrimentally affected since moving to Montana. The facility operates much as it was expected to. The following are among the specific conclusions that have been reached:

1) The Mach Number is found to be in the general vicinity of 3, and deviations from the norm are predictable.

2) There are no waves present in the test section of sufficient magnitude which cannot be simply corrected or which can seriously affect the flow. The flow in the nozzle and test section is uniform.

3) The boundary layers are thin and behave as they were expected to.

4) The temperature of the air stream can be adequately controlled. The temperature of the stream can be raised 40°F, which means it is useful for control purposes only.

5) The minimum stagnation pressure attainable for unchoked flow is complicated to calculate, but is normally between 200 and 300 mm Hg.

Finally, it should be emphasized that the dimensionless parameter that variation in the flow conditions affect is the Reynolds Number. Figure 4.1 shows the operating range of the wind tunnel, along with the
Figure 4-1 Operating Range of SWT

Range of Operation

Increasing Re

Re = 30 x 10^3 cm\(^{-1}\)

Re = 60 x 10^3 cm\(^{-1}\)
direction of increasing Reynolds Number and the approximate magnitude of this parameter.
APPENDIX
OPERATING PROCEDURES

START-UP

1. Check the barometric pressure and adjust gages accordingly.
2. Flip control panel disconnect switch (10)\(^*\) to "on" position.
3. Check pumps to make sure they are in operating condition. Make sure the water lines are connected, etc.
4. Make sure that the test section and downstream ports are closed up tight and that any model or object in the test section and its associated measuring equipment is ready to go.
5. Press control power "on" button (15).
6. Press throttling valve "on" button (28). Make sure the bypass valve control is in the "auto" position (19). Make sure the warning beacon is on (21).
7. Make sure throttling valve has opened.
8. Press vacuum pump "start" button (24).
9. Press chiller "start" button (37).
10. Press heater "on" button (49). Adjust to desired temperature.

NORMAL SHUT-DOWN

1. Switch pressure control to manual (6).
2. Press chiller "stop" button (38).
3. Press heater "off" button (50).

\(^*\) Numbers in parentheses refer to Figure A-1.
4. Press vacuum pump "stop" button (25).
5. Press throttling valve "off" button (29).
6. Press control power "off" button (16).
7. Make sure there is no water flowing into the pumps by checking the flowmeter above the pumps. If there is any water going through the flowmeter, shut the water off IMMEDIATELY.

DRY SHUT-DOWN

For the dry shut-down steps 1-3 are the same as for the normal shut-down. Step 4 of the normal shut down is replaced with the procedure written below.

4. Press the dry shut-down button (31). Allow the dry shut-down to run its 6-minute cycle. If the pumps do not shut off after 3 minutes, press the vacuum pump "off" button (25). Allow the dry shut-down to finish running its cycle (3 more minutes).

Steps 5-7 are the same as for the normal shut-down.
Figure A-1  Control Console
Key to Figure A-1

1. Heise pressure gauge
2. Vacuum system control panel latch
3. Vacuum system automatic pressure control pointers
4. Vacuum system supply pressure gauge
5. Automatic vacuum system outlet pressure gauge
6. Vacuum system control knob
7. Vacuum system pressure gauge
8. Vacuum system control pressure knob
9. Pump inlet pressure gauge
10. Control panel disconnect switch
11. Digital stagnation pressure indicator
12. Temperature recorder panel latch
13. Temperature recorder chart
14. Control power indicator light
15. Control power "on" button
16. Control power "off" button
17. Bypass valve "open" indicator light
18. Bypass valve "closed" indicator light
19. Bypass valve position selector switch
20. Warning beacon indicator light
21. Warning beacon on-off switch
22. Vacuum pump "ready" indicator light
23. Vacuum pump "on" indicator light
24. Vacuum pump "start" button
25. Vacuum pump "stop" button
26. Throttling valve power indicator light
27. Throttling valve "open" indicator light
28. Throttling valve "on" button
29. Throttling valve "off" button
30. Dry shutdown indicator light
31. Dry shutdown "start" button
32. High oil temperature indicator light
33. Low oil pressure indicator light
34. Low water pressure indicator light
35. Low oil pressure indicator light
36. Chiller indicator light
37. Chiller "start" button
38. Chiller "stop" button
39. Supersonic flow indicator "ready" light
40. Supersonic flow indicator alarm
41. Supersonic flow indicator on-off switch
42. Supersonic flow indicator reset button
43. Stagnation temperature gage
44. Digital stagnation temperature indicator
45. Heater over temperature control gauge
46. Heater over temperature control adjustment knob
47. Heater temperature control adjustment knob
48. Heater temperature control gauge
49. Heater power "on" button
50. Heater power "off" button
51. Heater power on indicator light
52. Heater over temperature indicator light
53. Heater on indicator light
54. Heater fuse
55. Heater minimum output adjustment
56. Heater percent of maximum output adjustment
57. Heater percent of maximum output gauge
58. Regenerator indicator light
59. Regenerator "start" button
60. Panel lights dimmer knob
61. Warning sign indicator light
62. Warning sign "on-off" switch
63. Atmospheric reference dew point indicator
64. Tunnel dew point digital indicator
65. Dew point sample flow indicator
66. Dew point indicator water flow rate gauge
67. Dew point indicator scale multiplier switch
68. Dew point indicator housing
69. Dew point indicator inlet pressure gauge
70. Dew point indicator mixing chamber valve
71. Dew point indicator trim valve
REFERENCES


