Wind Tunnels

Ashish J. Modi
Wind Tunnels

Objective

- Accurately simulate the fluid flow about atmospheric vehicles
- Measure - Forces, moments, pressure, shear stress, heat transfer, flowfield (velocity, pressure, vorticity, temperature)
Compressible vs. Incompressible Flow

- A flow is classified as incompressible if the density remains nearly constant.
- Liquid flows are typically incompressible.
- Gas flows are often compressible, especially for high speeds.
- Mach number, $Ma = \frac{V}{c}$ is a good indicator of whether or not compressibility effects are important.
  - $Ma < 0.3$ : Incompressible
  - $Ma < 1$ : Subsonic
  - $Ma = 1$ : Sonic
  - $Ma > 1$ : Supersonic
  - $Ma >> 1$ : Hypersonic
Low Speed Vehicles - M<.3

Gallilean Transformation

Wind Tunnel - Model Scale = \( \ell \)
Stationary Walls

\( U_\infty \)

Flight in atmosphere
Scale = L

Issues
Flow Quality - Uniformity and Turbulence Level
Wind Tunnel Wall Interference
Reynolds Number Simulation

\[ \text{Re} = \frac{\rho U_\infty L}{\mu} \neq \frac{\rho U_\infty \ell}{\mu} \]
Reynolds Number Scaling

- Most important on vehicles with partial laminar flow. The transition is very sensitive to Reynolds Number.
- Use “trip strips” or roughness to cause boundary layer transition on the model at the same location as on the full scale vehicle.
Transonic Regime $0.7 < M < 1.2$

- Must Match Reynolds Number and Mach Number

\[
\text{Re} = \frac{\rho U_\infty L}{\mu}
\]

\[
M = \frac{U_\infty}{c}
\]

Must change fluid density and viscosity to match Re and M

Cryogenic Wind Tunnels are designed for this reason
History Whirling Arm
Eiffel Tunnel
Wright Brothers

The Wright Brother’s “Drift” Balance (Top view)

Condensed view, brace A removed for clarity

TORQUE ABOUT D IS ZERO FOR 'BALANCED' CONDITION
Wind Tunnel Test Trend
Wind Tunnel Layout

- Closed Return
- Open Return
- Double Return
- Annular Return
Closed Return
(open test section)
Open Return
Closed Test Section

High Contraction Wind Tunnel
Top View

15 Hp. Dual Centrifugal Blower

Test Section
18 inch Diameter

Screen
25 to 1 Contraction

Exhaust
Louvres for Speed Adjustment

Diffuser

Exhaust
Double Return

UNIVERSITY OF WASHINGTON
AERONAUTICAL LABORATORY
Kirsten Wind Tunnel
Annular Wind Tunnel
Types of Wind Tunnels

- Subsonic
- Transonic
- Supersonic
- Hypersonic
- Cryogenic
- Specialty
  - Automobiles
  - Environmental- Icing, Buildings, etc.
Subsonic Wind Tunnels
40’ x 80’ and 80’ x 120’

NASA Ames
40- by 80- Foot Wind Tunnel: Specifications

Primary Use:

The facility is used primarily for large-scale or full-scale testing of aircraft and rotorcraft, including high-lift and noise suppression development for subsonic and high speed transports, powered lift, high angle-of-attack for fighter aircraft and propulsion systems

Capability:

- Mach Number: 0-0.45
- Reynolds Number per foot: 3 X 10^6
- Stagnation Pressure: Atmospheric
- Temperature Range: 485 ° - 580 ° R
- Closed circuit, single return, continuous flow, closed throat wind tunnel with low turbulence
- Model-support systems available include a 3 strut arrangement with a nose or tail variable height strut, a semi-span mount and a sting
- The entire model support can be yawed a total of 290 °
- Six components of force and moment are measured by the mechanical, external balance under the test section, or by internal strain-gage balances in the sting or rotor testbeds
- Test section walls are lined with a 10" acoustic lining, and the floor and ceiling have a 6" acoustic lining

80- by 120- Foot Wind Tunnel: Specifications

Primary Use:

The facility is used primarily for large-scale or full-scale testing of aircraft and rotorcraft, including high-lift development for subsonic transports, V/STOL powered lift, high angle-of-attack for fighter aircraft and propulsion systems

Capability:

- Mach Number: 0-0.15
- Reynolds Number per foot: 1.2 X 10^6
- Stagnation Pressure: Atmospheric
- Temperature Range: 485 ° - 580 ° R
- Indraft, continuous flow, closed throat wind tunnel
Fans for 40x80 and 80x120
12 foot Pressure Tunnel
12ft Pressure Wind Tunnel
NASA Ames Research Center
12-Foot Pressure Wind Tunnel: Specifications

Primary Use:
The facility is used primarily for high Reynolds number testing, including the development of high-lift systems for commercial transports and military aircraft, high angle-of-attack testing of maneuvering aircraft, and high Reynolds number research.

Capability:
Mach Number: 0-0.52
Reynolds Number per foot: 0.1 - 12X10^6
Stagnation Pressure, PSIA: 2.0 - 90
Temperature Range: 540 ° - 610 ° R
Closed circuit, single return, variable density, closed throat, wind tunnel with exceptionally low turbulence
Model-support systems available:
  - Strut with variable pitch and roll capability
  - High angle-of-attack turntable system
  - Dual-strut turntable mechanism for high-lift testing
  - Semispan mounting system
Internal strain-gage balances used for force and moment testing
Capability for measuring multiple fluctuating pressures
Temperature-controlled auxiliary high-pressure (3000 psi)
Figure 2-5. 12-Foot PWT Performance Chart
Fig. 3
DNW's lay-out and main dimensions

Fig. 4
The two test sections used for road vehicle aerodynamics:
8 m x 6 m for cars,
9.5 m x 8.5 m for trucks.
Transonic Wind Tunnels
Transonic Wind Tunnels

Wall interference is a severe problem for transonic wind tunnels. Flow can “choke” Shock wave across the tunnel test section

Two Solutions
- Porous Walls
- Movable Adaptive Walls
The Unitary Plan wind tunnels are a set of three interconnected tunnels that share a central main drive system that can be used to drive either a transonic leg or a supersonic leg. The Unitary Plan wind tunnels are as follows:

- 11ft Transonic Wind Tunnel
- 9x7ft Supersonic Wind Tunnel
- 8x7ft Supersonic Wind Tunnel
The 8x6/9x15 Complex at the NASA Lewis Research Center in Cleveland, Ohio is unique in its dual capacity role as both a high-speed and low-speed test facility.

**8x6 Functions & Capabilities**

The 8x6 Foot Supersonic Wind Tunnel provides customers with a Facility capable of testing large scale aeropropulsion hardware:

- In a continuous Mach 0-2.0 airstream
- At varying Reynolds Numbers (3.6 - 4.8 x 10^6/ft) and altitude conditions (ambient to 38,000ft)
- In either aerodynamic (closed) or Propulsion (open) cycle without exhaust scoops
- Employing high data systems to support steady and transient data acquisition
- Supported by a variety of systems including: Schlieren, infrared imaging, sheet lasers, LDV, GH2 fuel, high pressure air, and hydraulics.

**8x6 Characteristics & Performance**

<table>
<thead>
<tr>
<th>Test section size</th>
<th>8ft H, 6ft W, 23.5ft L</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mach number range</td>
<td>0 - 2.0</td>
</tr>
<tr>
<td>Relative altitude</td>
<td>1000 - 35000 ft</td>
</tr>
<tr>
<td>Dynamic Pressure</td>
<td>3.6 - 4.8 x 10^6/ft</td>
</tr>
<tr>
<td>Stagnation Pressure</td>
<td>15.3 - 25 psia</td>
</tr>
<tr>
<td>Temperature</td>
<td>60 - 250°F</td>
</tr>
</tbody>
</table>
8x6 at NASA Lewis
9x15 at NASA Lewis
Back Leg of the 8x6
Modane-Avrieux

S1MA Wind Tunnel Atmospheric, closed-circuit, continuous flow wind tunnel, from Mach 0.05 to Mach 1

S1MA wind tunnel is equipped with two counterrotating fans, driven by Pelton turbines, the power of which is 88 MW; Mach number is continuously adjustable from 0.05 to 1 by varying the fan speed from 25 to 212 rpm.
A model of Boeing's 707 commercial jet undergoes testing in one of AEDC's large wind tunnels. The 707 tests were the first in a series of tests of Boeing's large commercial jets at the center. AEDC signed a twenty year alliance with Boeing to test commercial aircraft.
S2Ma Wind Tunnel
Supersonic
Wind Tunnels
Fig. 1:1 Diagrammatic layout of closed-circuit, continuous flow, supersonic wind tunnel.

Fig. 1:2 Diagrammatic layout of intermittent blowdown tunnel.

Fig. 1:3 Diagrammatic layout of intermittent indraft wind tunnel.
Purdue University
Aerospace Sciences Laboratory
M=2.5 Supersonic
Blowdown Wind Tunnel
Hypersonic Wind Tunnels
Principle Operation Detonation Driven Shock Tunnel
Set-up and wave plan:

Initial conditions:
- low pressure section: test gas air, about 25 kPa for tailored cond.
- deton. section: oxyhydrogen- helium/ argon mixtures, max. 7 MPa
- damping section: expansion volume; low initial pressures
High Enthalpy Shock Tunnel Göttingen (HEG)

The Facility

The free piston-driven shock tunnel HEG consists of an air buffer, a compression (driver) tube, separated from an adjoining shock tube via a metal diaphragm, and a subsequent nozzle and test section. A piston is accelerated through the compression tube by the air in the buffer, compressing the driver gas helium to high temperatures and pressures, whereby the diaphragm ruptures, leading to propagation of a strong shock through the shock tube. This shock reflects from the end wall, heating up the test gas (nitrogen, air, carbon dioxide, etc.) to high pressures and temperatures – this gas reservoir expands through the nozzle and provides the free stream conditions in the test section. Total available test time is about 1 millisecond.

<table>
<thead>
<tr>
<th>Condition</th>
<th>I</th>
<th>II</th>
<th>III</th>
<th>IV</th>
<th>V</th>
<th>VI</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_0$ (MPa)</td>
<td>40</td>
<td>90</td>
<td>45</td>
<td>110</td>
<td>50</td>
<td>95</td>
</tr>
<tr>
<td>$T_0$ (K)</td>
<td>9100</td>
<td>9700</td>
<td>7300</td>
<td>8100</td>
<td>6400</td>
<td>6500</td>
</tr>
<tr>
<td>$I_0$ (MJ/kg)</td>
<td>21</td>
<td>22</td>
<td>13</td>
<td>15</td>
<td>11</td>
<td>11</td>
</tr>
<tr>
<td>$p_{1000}$ (Pa)</td>
<td>430</td>
<td>1200</td>
<td>470</td>
<td>1300</td>
<td>520</td>
<td>980</td>
</tr>
<tr>
<td>$T_{1000}$ (K)</td>
<td>790</td>
<td>1040</td>
<td>550</td>
<td>720</td>
<td>470</td>
<td>480</td>
</tr>
<tr>
<td>$p_{\infty}$ (g/m$^3$)</td>
<td>1.6</td>
<td>3.6</td>
<td>2.8</td>
<td>6.2</td>
<td>3.8</td>
<td>6.9</td>
</tr>
<tr>
<td>$M_{\infty}$</td>
<td>9.7</td>
<td>9.0</td>
<td>10.0</td>
<td>9.5</td>
<td>10.0</td>
<td>10.0</td>
</tr>
<tr>
<td>$U_{\infty}$ (m/s)</td>
<td>5900</td>
<td>6200</td>
<td>4800</td>
<td>5100</td>
<td>4400</td>
<td>4400</td>
</tr>
</tbody>
</table>

HEG standard operating conditions
All Clean Stainless Steel from Second-Throat Section Upstream
Unique Low-Noise Flow due to Laminar Nozzle-Wall Boundary Layer
(Slow) Butterfly Valve

17.5-in. Driver Tube, 122.5-ft. long
Bleed-Slat Suction Plumbing

Max. 300 psig (20 bar) and 392°F (180°C), One 7-8, run per hour.
About $5/run operating cost.

9.5-in. Nozzle
Contraction Windows

Fixed Second Throat
(Double) Burst Diaphragm
Sliding Sleeve

2000 Cubic Ft. Vacuum Tank

Schematic of Boeing Mach-6 Quiet-Flow Ludwig Tube
The NASA Langley 8-Foot High Temperature Tunnel (8’ HTT)

enables the testing of large hypersonic airbreathing propulsion systems at flight enthalpies from Mach 4 to Mach 7.

Figure 2. Schematic drawing of the 8' HTT for airbreathing propulsion testing.

Figure 3. Schematic drawing of the 8' HTT combustor.
Hypersonic Shock Tunnels at Calspan

The performance chart shows that the high enthalpy 96-inch tunnel is capable of simultaneously duplicating velocity (total enthalpy) and density altitude over a wide range of hypersonic flight conditions. These test conditions cover the widest range of any in the country.
Fig. 1  Facilities of the Aerothermodynamic Facilities Complex.

\[ \text{Re}_\infty = 1.1 \times 10^6/\text{ft} \quad \text{Re}_\infty = 7.9 \times 10^6/\text{ft} \]

Fig. 6  Effect of Reynolds number on windward heating rates for X-34 at \( M_\infty = 6, \alpha = 0^\circ, \text{and} \delta_{CS} = 0^\circ \).
Cryogenic Wind Tunnels
Reynolds No. = \frac{\text{Inertia Force}}{\text{Viscous Force}} = \frac{\text{Gas Density} \cdot \text{Velocity} \cdot \text{Length}}{\text{Gas Viscosity}} = \frac{\rho VL}{\mu}

4 Ways to Increase Test Reynolds Number:
- Increase Test Model Size
- Increase Test Pressure of Gas
- Use a Heavy Test Gas
- Decrease Test Temperature of Gas

Effects of Decreasing Temperature

- Gas Properties
  - Relative Change
  - Density ($\rho$)
  - Speed of Sound ($a$)
  - Viscosity ($\mu$)

- Test Conditions at Constant Mach No.
  - Reynolds No.
  - Dynamic Pressure ($q$)
  - Drive H. P.
NATIONAL TRANSONIC FACILITY

Figure 6. Plan view of NTF tunnel circuit. All linear dimensions are in feet.
NTF Capability

![Graph showing NTF capability with different wind tunnels and models plotted on a graph with Mach number on the x-axis and Reynolds number based on model chord in millions on the y-axis. Key points include NTF Cryogenic, New Large Transport Semi-span, and MD-12X, 747-200, DC-10, MDU-11, 767, and 757.]
The Cryogenic Ludwieg-Tube at Göttingen (KRG)

Adaptive wall test section
Icing
Wind Tunnels
Wings
Automobile Wind Tunnels
Wind Tunnel Power Requirements
Energy Ratio

\[
(E.R.)_t = \frac{\text{Jet Energy}}{\sum \text{Circuit Losses}} = \frac{1/2 \rho_0 U_0^3 A_0}{\sum \text{Losses}} = \frac{q_0 U_0 A_0}{\eta P}
\]

Subscript 0 refers to the test section
P is the motor power
\(\eta\) is the fan efficiency
Wind Tunnel Circuit Elements

Transonic Wind Tunnel Circuit

High-Speed Section

divide wind tunnel circuit into basic elements
Losses

\[ K = \frac{p_{t1} - p_{t2}}{q} \quad \text{Local Pressure Loss Coefficient} \]

\[ K_0 = \frac{p_{t1} - p_{t2}}{q_0} = K \frac{q}{q_0} \quad \text{Pressure Loss Referred to Test Section} \]

\[ \Delta E = K_0 \frac{1}{2} \rho_0 U_0^3 A_0 \quad \text{Section Energy Loss} \]

\[ (E.R.)_t = \frac{\text{Jet Energy}}{\sum \text{Circuit Losses}} = \frac{1/2 \rho_0 U_0^3 A_0}{\sum K_0 1/2 \rho_0 U_0^3 A_0} = \frac{1}{\sum K_0} \]
Closed Return Tunnel
## Example - Closed Return Tunnel

<table>
<thead>
<tr>
<th>Section</th>
<th>Ko</th>
<th>% Total Loss</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Test Section</td>
<td>.0093</td>
<td>5.1</td>
</tr>
<tr>
<td>2 Diffuser</td>
<td>.0391</td>
<td>21.3</td>
</tr>
<tr>
<td>3 Corner #1</td>
<td>.0460</td>
<td>25.0</td>
</tr>
<tr>
<td>4 Straight Section</td>
<td>.0026</td>
<td>1.4</td>
</tr>
<tr>
<td>5 Corner #2</td>
<td>.0460</td>
<td>25.0</td>
</tr>
<tr>
<td>6 Straight Section</td>
<td>.0020</td>
<td>1.1</td>
</tr>
<tr>
<td>7 Diffuser</td>
<td>.0160</td>
<td>8.9</td>
</tr>
<tr>
<td>8 Corner #3</td>
<td>.0087</td>
<td>4.7</td>
</tr>
<tr>
<td>9 Corner #4</td>
<td>.0087</td>
<td>4.7</td>
</tr>
<tr>
<td>10 Straight Section</td>
<td>.0002</td>
<td>.1</td>
</tr>
<tr>
<td>11 Contraction</td>
<td>.0048</td>
<td>2.7</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>.1834</td>
<td>100.0</td>
</tr>
</tbody>
</table>

\[
(E.R.)_t = \frac{1}{\sum K_0} = \frac{1}{.1834} = 5.45
\]
Example - Open Return Tunnel

<table>
<thead>
<tr>
<th>Section</th>
<th>Ko</th>
<th>% Total Loss</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Inlet Including Screens</td>
<td>.021</td>
<td>14.0</td>
</tr>
<tr>
<td>2 Contraction and Test Section</td>
<td>.013</td>
<td>8.6</td>
</tr>
<tr>
<td>3 Diffuser</td>
<td>.080</td>
<td>53.4</td>
</tr>
<tr>
<td>4 Discharge at Outlet</td>
<td>.036</td>
<td>24.0</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>.150</strong></td>
<td><strong>100.0</strong></td>
</tr>
</tbody>
</table>

\[(E.R.)_t = \frac{1}{\sum K_0} = \frac{1}{.150} = 6.67\]
Turbulence Management System

Stilling Section - Low speed and uniform flow

Honeycomb - Reduces Large Swirl Component of Incoming Flow

$k = 0.30$

$k = 0.22$

$k = 0.20$

Fig. 2:16  Some honeycombs and their losses.

Screens  - Reduce Turbulence [Reduces Eddy size for Faster Decay]
- Used to obtain a uniform test section profile
- Provide a flow resistance for more stable fan operation
Contraction

Establish Uniform Profile at Test Section
Reduce Turbulence
Test Section

Test Section - Design criteria of Test Section Size and Speed Determine Rest of Tunnel Design

Test Section Reynolds Number
Larger JET - Lower Speed - Less Power - More Expensive

Section Shape - Round-Elliptical, Square, Rectangular-Octagonal with flats for windows-mounting platforms
Rectangular with filled corners
Not usable but requires power

For Aerodynamics Testing 7x10 Height/Width Ratio

Test Section Length - \( L = (1 \text{ to } 2)w \)
Diffuser
Corners

Abrupt Corner without Vanes  \( \eta = 1.0 \)

\[ \begin{align*}
    \eta &= 0.11 \\
    \eta &= 0.138 \\
    \eta &= 0.20
\end{align*} \]
Speed Control
Fan