Design and Diagnostics of a Supersonic Wind Tunnel

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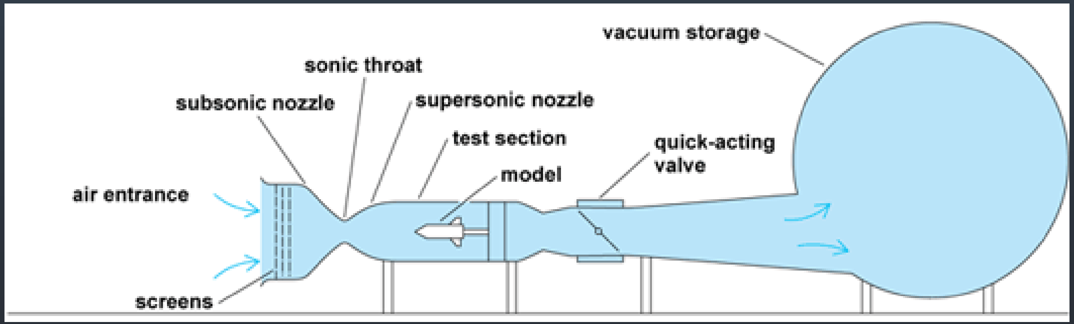
Outline

- Project Description
- Project Overview
- Channel and Flange
- Humidity Control
- Diagnostics
- Flow Visualization
- Conclusions
- Recommendations

Project Description

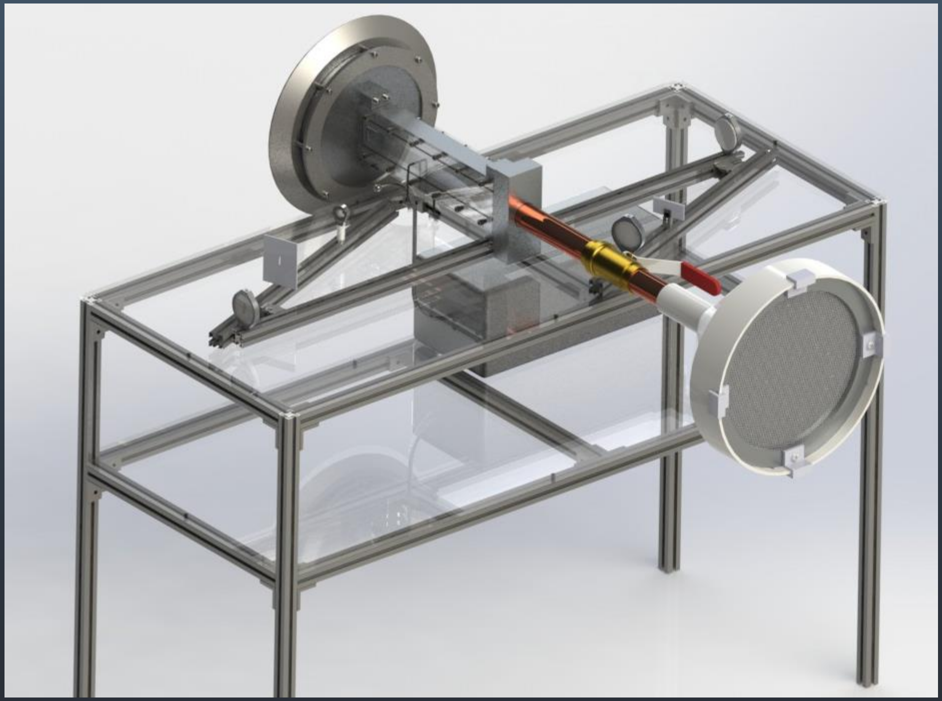
- Design, construct, and conduct preliminary testing of a supersonic wind tunnel (SWT)
- Indraft type
  - Pressure ratio across tunnel determined by vacuum and ambient air
- Modular design
  - Can replace channel contours with future test-specific designs



Indraft Wind Tunnel Layout (Ref [7] McGraw-Hill, 2013)

Project Overview

- Three areas of focus
  - Channel, Flange, Humidity Control (Design)
  - Pitot Probe and Mounting (Diagnostics)
  - Schlieren System (Flow Visualization)



Channel/Flange: Background

- Goals:
  - Solve sealing issues encountered in previous designs
  - Create interchangeable geometry system to expand functionality
  - Attain a supersonic airflow in test section

Channel/Flange: Calculations

- Shaped the contour using the Method of Characteristics
- Mach number by Cross-Sectional Area

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

- Mass Flow Rate

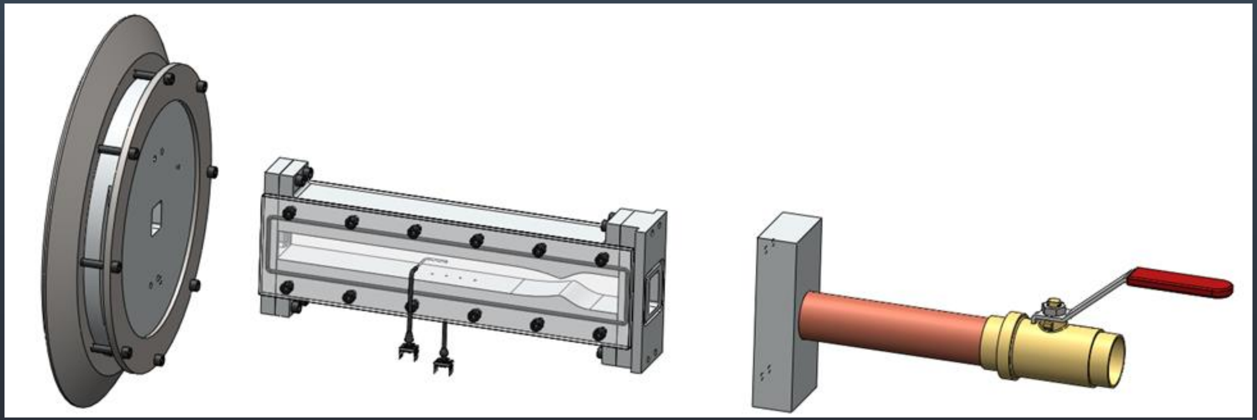
$$\dot{m} = \frac{P_{atm}A^*}{\sqrt{T_{atm}}}\sqrt{\frac{\gamma}{R}\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}}}$$

- Test Time

$$\mathrm{t} = \frac{\forall_{\mathrm{chamber}}\mathrm{P}_{\mathrm{dif}}}{\dot{\mathrm{m}}\mathrm{R}\mathrm{T}_{\mathrm{dif}}}\left(1-\frac{\mathrm{P_i}}{\mathrm{P}_{\mathrm{dif}}}\right)$$

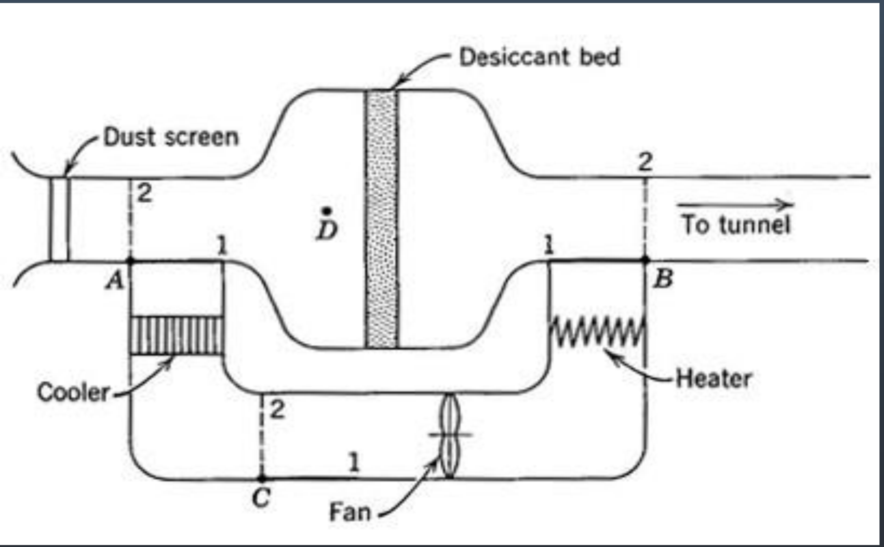
Channel/Flange: Design

- Modular Construction
  - Tunnel can be easily taken apart to allow the use of additional test sections
- Discrete O-ring seals
  - Removable components are hermetically sealed with O-rings to prevent leakage
- Flange
  - Use of existing steel flange allows tunnel to be replaced with window on vacuum chamber



Humidity Control: Background

- Previous work determined that humidity control will be necessary at Mach 1.6 or higher
  - Condensation (fog) in the test section causes error in flow diagnostics
  - Temperature and pressure gradients change optical visualization



Indraft Wind Tunnel Drier Layout
(Ref [2] © 1965, John Wiley & Sons)

Humidity Control: Calculations

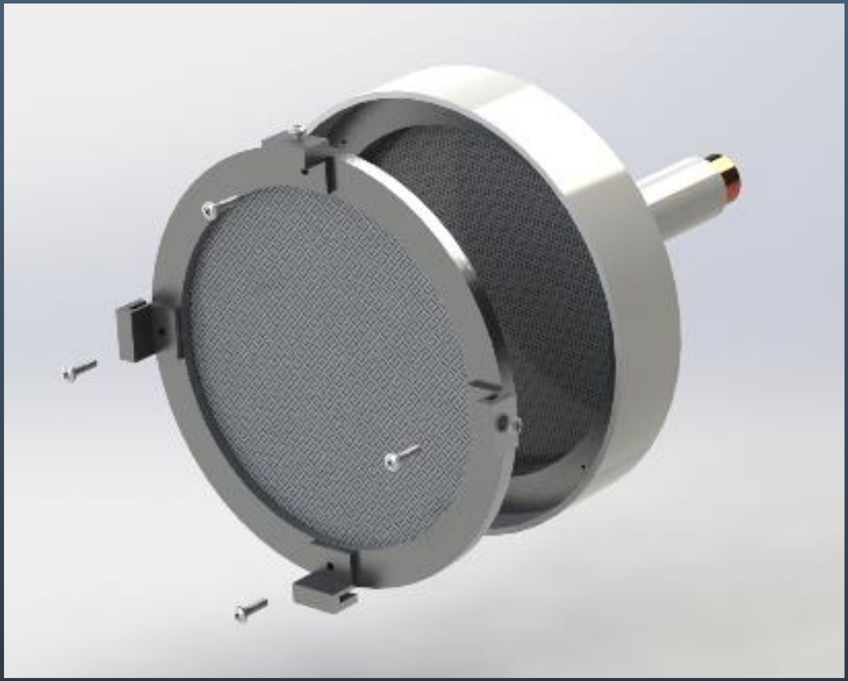
- Operating Conditions:
  - Room temperature (70˚F)
  - Relative humidity between 60 – 80%
- Amount of desiccant required determined based off:
  - Mass flow (assumed constant)
  - Test time
  - Moisture content of air
- Dimensions based off requirements for pressure differential

Humidity Control: Design

- 2.5 pounds of desiccant required at 80% relative humidity
- Pressure differential must be below 1.5 inches of mercury to maintain mass flow [2]

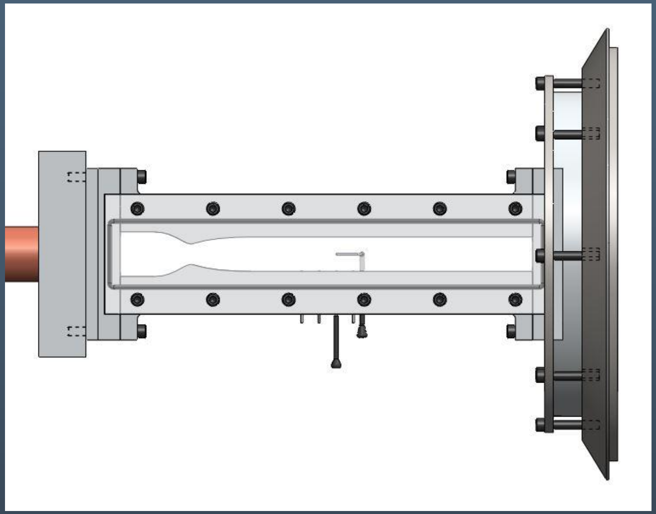
  $$\Delta p = 0.0883(1.715U)^{1.38}$$

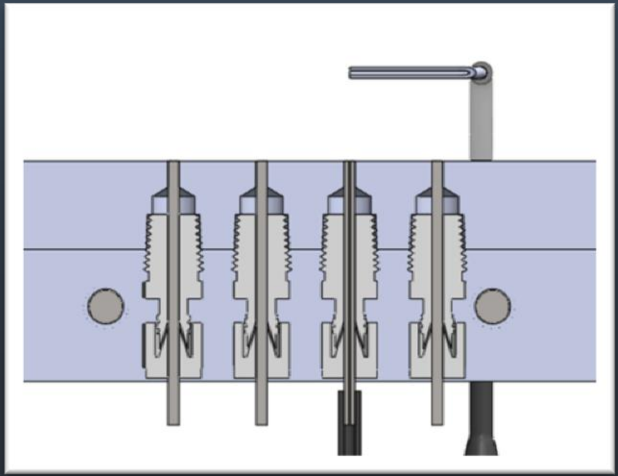
- Result:
  - 10.5 inch diameter
  - 1 inch deep
  - Δp = 1.0 in. Mercury



Probe Interface: Background

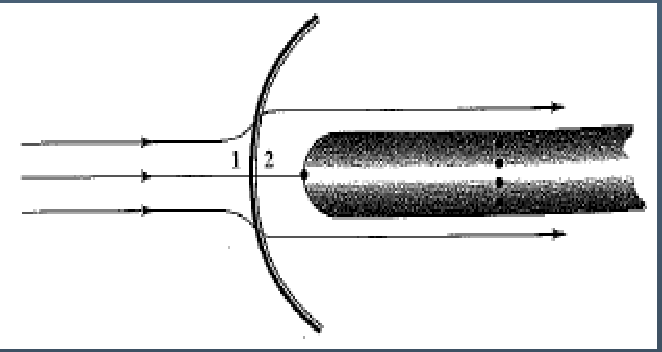
- Previous MQPs unable to confirm if design flow was achieved
- Pitot-static system measures pressure difference
- Interchangeability of Pitot probe and static taps
  - Pitot probe mounted on interchangeable side windows
  - Interchangeable static taps secure 1/16” OD rod or tube
    - Some taps plugged for test-specific use





Probe Interface: Data Acquisition

- Transducer and electronics
  - Circuit configured for 5 analog channels to measure simultaneously
- LabVIEW operation
  - Bow-Shock formation
  - Identifies whether flow is subsonic or supersonic based on critical pressure ratio
  - Applies corresponding (subsonic or supersonic) equation to find Mach number
    - Supersonic solver is iterative



Pitot Static Tube in Supersonic Flow (Ref. [3], ©2006, Pearson Prentice Hall)

$$\frac{p_{02}}{p_1} = \frac{\left(\frac{\gamma+1}{2} M_1^2\right)^{\frac{\gamma}{\gamma-1}}}{\left(\frac{2\gamma}{\gamma+1} M_1^2 - \frac{\gamma-1}{\gamma+1}\right)^{\frac{1}{\gamma-1}}}$$

Normal Shock Pressure Ratio Relation

Schlieren System: Project Goals

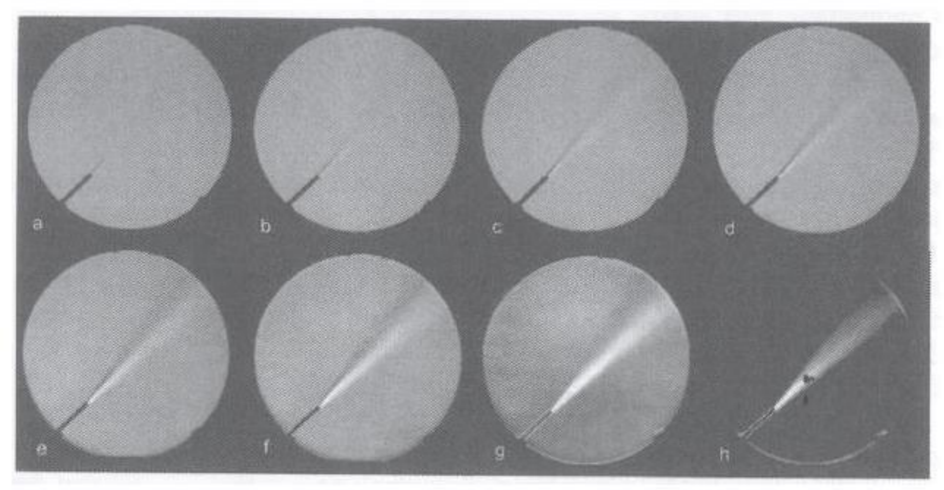
- Develop low and moderate cost systems
- Construct and evaluate moderate cost system
  - Refine through testing
- Design apparatus to integrate with tunnel
- Test system with wind tunnel

Schlieren System: Background

- Sensitive optical system that employs the light's refractive index $n = \frac{C_0}{C}$ and its weak dependence on density

$$n - 1 = k\rho$$

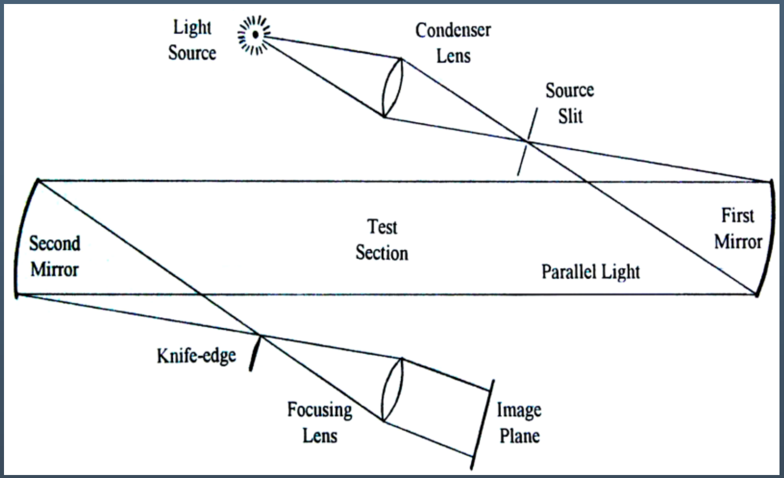
- Provides Flow Visualization
  – Density gradients creates refracted light
    - Velocity and temperature differences



Schlieren image of a gas jet at a) 0%, b) 20%, c) 40%, d) 60%, e) 80%, f) 90%, g) 95%, and h) 100% of the measuring range (Ref [5] © 2001, Springer)

Schlieren System: Design

- Z – Type system
- Dual Mirror system
  - Lower cost
  - Larger viewing area
- Component Breakdown
  - Optical Rail
  - Adjustable Mounts
  - Mirrors and Lenses
  - Point Light Source
  - Knife Edge Linear Adjuster

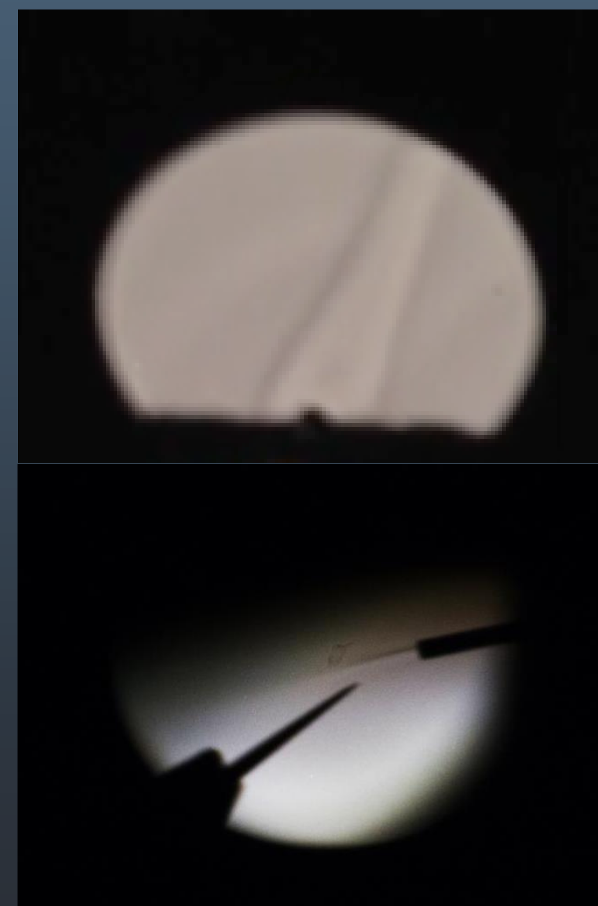


Conventional Z-Type Schlieren System
(Ref [5] © 2001, Springer)

Schlieren System: Results

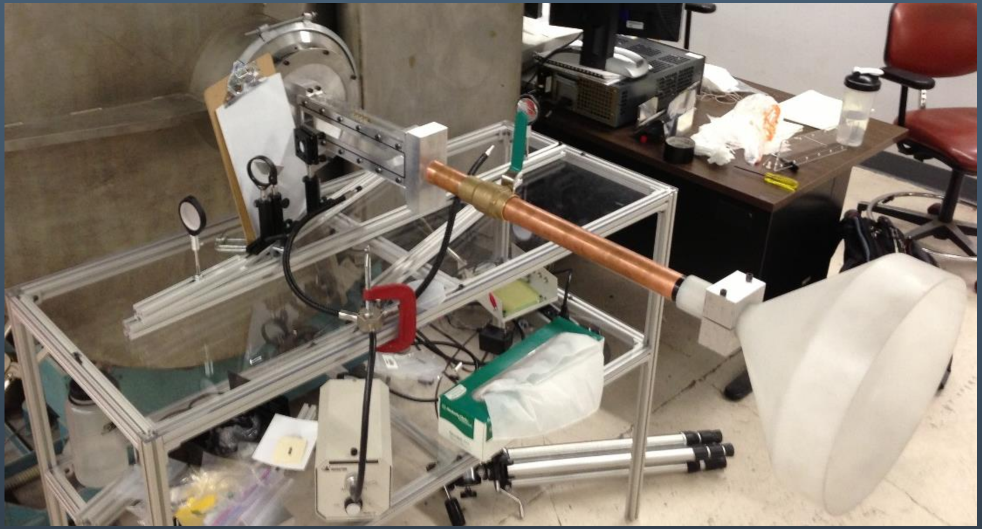
Optimization

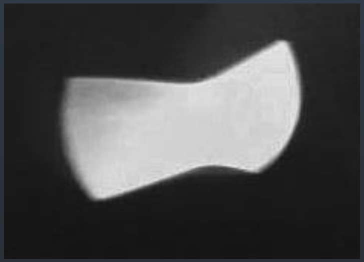
Final



Testing

- Channel
  - Vacuum chamber reached designed pressure
- Probe
  - Subsonic
- Schlieren
  - Integrated results
- Humidity Control
  - Inconclusive





Recommendations

- Channel
  - incorporate interchangeable contours
- Diagnostics
  - calibrate probe to known supersonic/subsonic flow
  - stiffer tubing
  - additional static pressure transducers
- Schlieren System
  - optical mounts
  - high intensity light source
  - larger mirrors

References

[1] "NPTEL :: Mechanical Engineering - Gas Dynamics." NPTEL :: Mechanical Engineering - Gas Dynamics. N.p., n.d. Web. 03 Oct. 2012.

[2] A. Pope and K. Goin, *High-Speed Wind Tunnel Testing.* New York, NY, USA: John Wiley and Sons, 1965.

[3] John J, Keith T. Gas Dynamics, 3rd Ed. New Jersey: Pearson Prentice Hall; 2006.

[4] Mouser Electronics
http://www.mouser.com/ProductDetail/Honeywell/HSCMAND001BAAA5/

[5] Settle, G.S. Schlieren And Shadowgraph Techniques. Springfield: Springer, 2001.

[6] WPI Major Qualifying Project: Design and Construction of a Supersonic Wind Tunnel, 2010.

[7] "Wind Tunnel" McGraw-Hill Education, 2013