Design and Fabrication of Small-Scale Supersonic Wind Tunnel

Deron Hurley, Johnny Arteaga, Amir Elzawawy
Vaughn College of Aeronautics and Technology, 86-01 23rd Ave. Flushing NY 11369

Objective

The objective of designing and fabricating a small-scale supersonic wind tunnel is to represent a convenient platform for supersonic flow testing. The scale considered in this work, with maximum cross-sectional area of 1"x1", requires simpler structure in addition to the low budget costs and minor space requirements. While the small size tunnel may limit the data acquisition capabilities, it still makes it possible to construct the tunnel with limited space and resources. This tunnel will be part of the thermo-fluid laboratory (TFL) at Vaughn College and intended to be used primarily for educational purposes.

Background History of Wind Tunnels

- In the 19th century forms of wind tunnels existed, however they were not very effective
- One of the most successfully used wind tunnels was a 30-foot by 60-foot machine manufactured by NACA in 1931.
- Three categories of wind tunnels are, indraft, blowdown, and pressure vacuum [1]
- Blowdown tunnels consists of a high pressure at the inlet via chambers of compressed air and atmospheric conditions at the exhaust
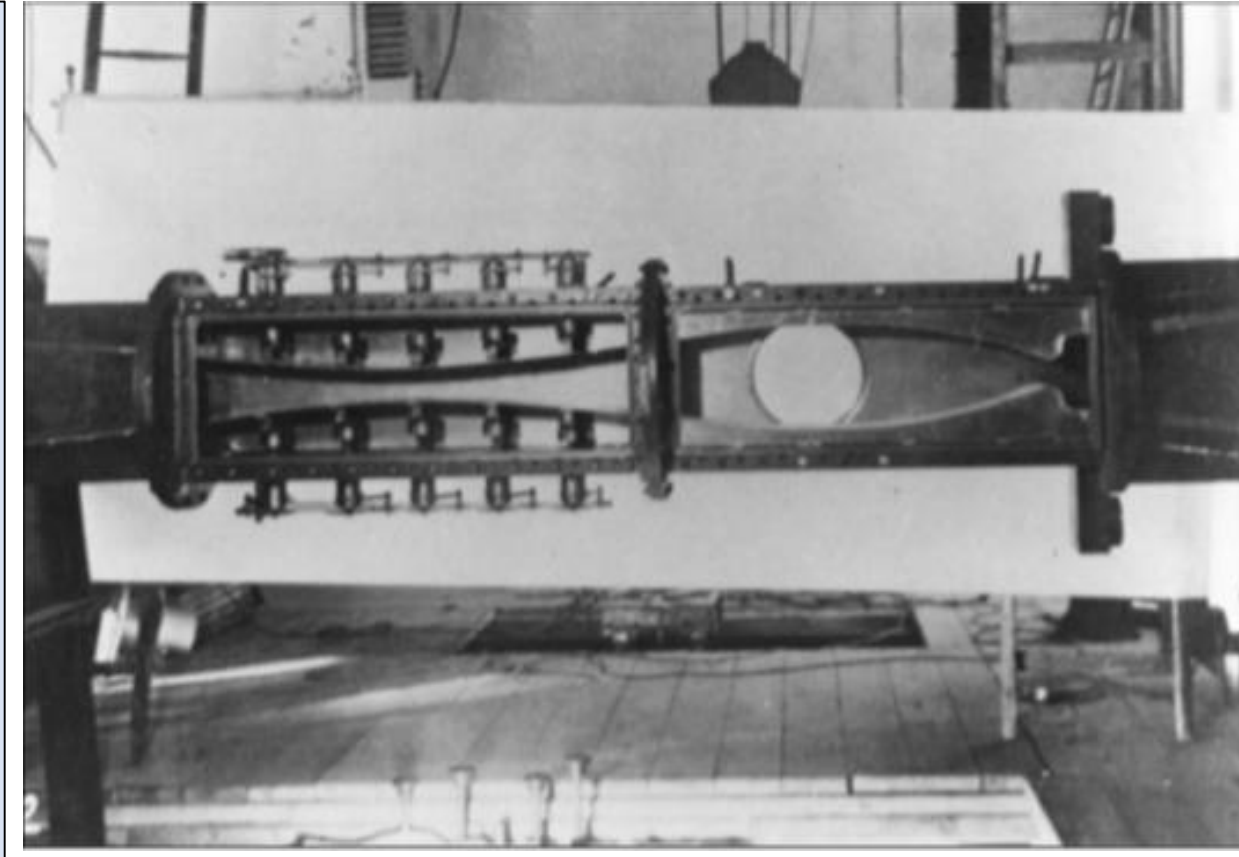
Fig. (a) The first practical supersonic wind tunnel, built by A. Busemann, Germany mid-1930's [2]

Analytical Calculation

- **Eq. 1** represents the pressure ratio of the ambient atmospheric temperature to the pressure in the compression chamber. T_0 is the total pressure, T^* is the desired temperature. P_0 is the total pressure, P^* is the desired pressure. γ is the specific heat ratio
- **Eq. 2** is the ratio of exit to throat area. A^* is the area of the throat in the C-D Nozzle, A is the area of the exit, γ is the specific heat ratio, M represents the Mach number
- **Eq. 3** was used to calculate the temperature of the flow at its highest Mach value. These values are dependent on Mach value (M) and the universal gas constant of Gamma γ
- **Eq.4** represents the deflection angle of the geometry, where v is the Prandtl-Meyer angle based on the input Mach value before or after the wave and θ is the deflection angle [2]

$$\frac{P_0}{P^*} = \left(\frac{T_0}{T^*}\right)^{\frac{\gamma}{\gamma-1}} \quad (1) \qquad \left(\frac{A}{A^*}\right)^2 = \frac{1}{M^2}\left[\frac{2}{\gamma+1}\left(1 + \frac{\gamma-1}{2}M^2\right)\right]^{\frac{\gamma+1}{\gamma-1}} \quad (2)$$

$$\frac{T_0}{T^*} = 1 + \frac{\gamma-1}{2}(M)^2 \quad (3) \qquad \theta = v(M_2) - v(M_1) \quad (4)$$

Structural Mechanics

- An FEA analysis was done to determine the force experienced by the compression chamber, viewing window, and the entire assembly
- Gasket material and bolts will be used to seal and connect each major section of the tunnel

	Force (lbs.)	Force per bolt (lbs.)
Compression Chamber	198.8	22.09
Window	3.63	0.9075
Entire Assembly	73.78	4.098

Procedure

Phase (1) Analytical Calculation: Verification of results through analytical calculation and comparison with simulated results is a vital step to move forward with the fabrication process. Area, temperature, and pressure are vital factors to gather.

Phase (2) Simulation: In order to achieve the correct geometry necessary to achieve Mach flow and above, diffuse the wave, and find the best flow conditions, a simulation is required to verify these conditions.

Phase (3) Fabrication: After analytical and simulated data are verified, the fabrication process using CNC can be conducted followed by the assembly and testing of a real life model.

Results

- The initial selection of inlet pressure was too large to effectively diffuse the flow within a short range, resulting in a pressure of less magnitude
- The curvature of the C-D nozzle has no sharp corners, only filleted edges
- The direction of the diffuser in the Y and Z direction created better results, considering an angle of 19 degrees in all directions.
- The utilization of an expansion wave rather than an oblique shockwave was a key factor in producing diffusion results.
- To ensure accuracy of results a mesh conversion study was performed, and a comparison of the results were obtained.
- The flow becomes steady with no alteration due to time at less than .005 of a second.
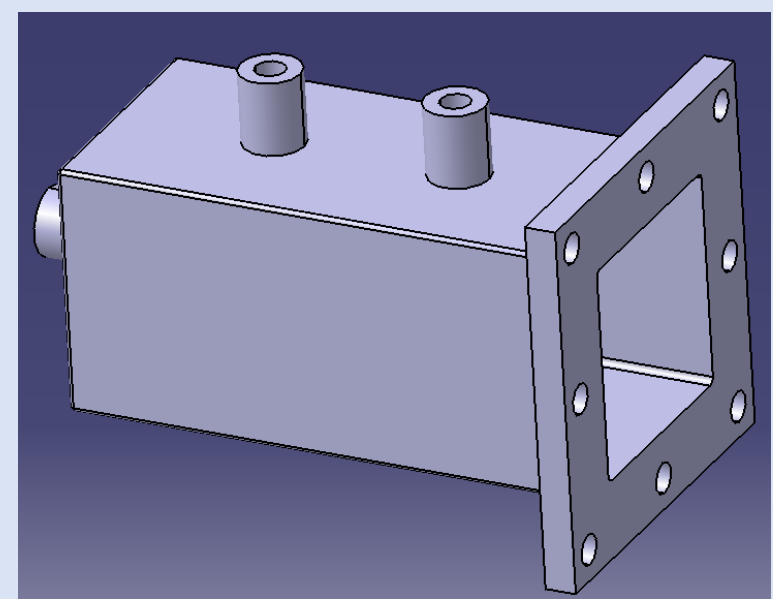
Components

Fig. (b) Compression Chamber

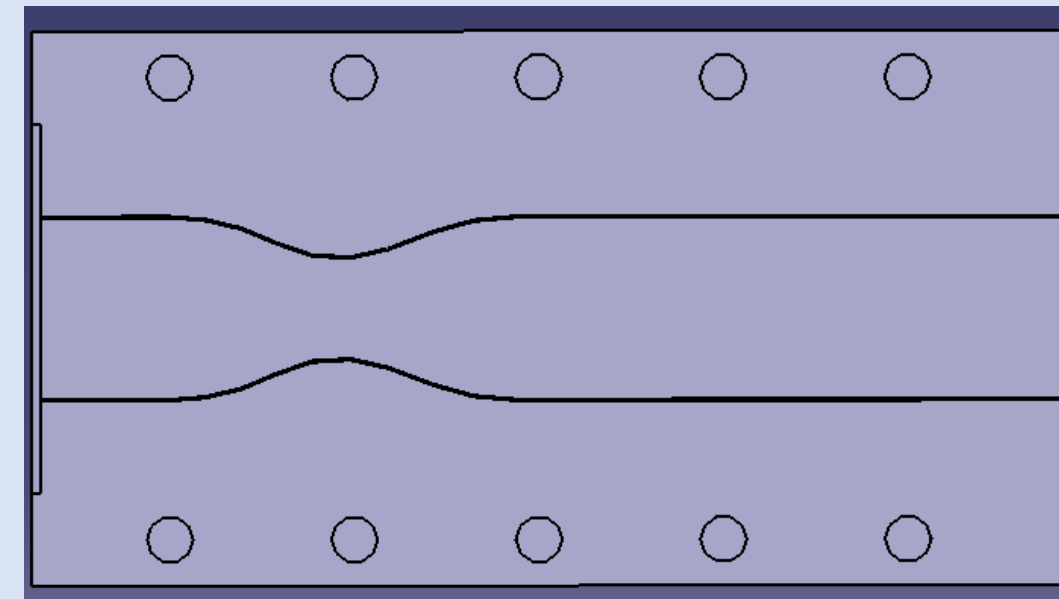(Compresses and stores air required to produce Mach flow)

Fig. (c) Convergent-Divergent Nozzle

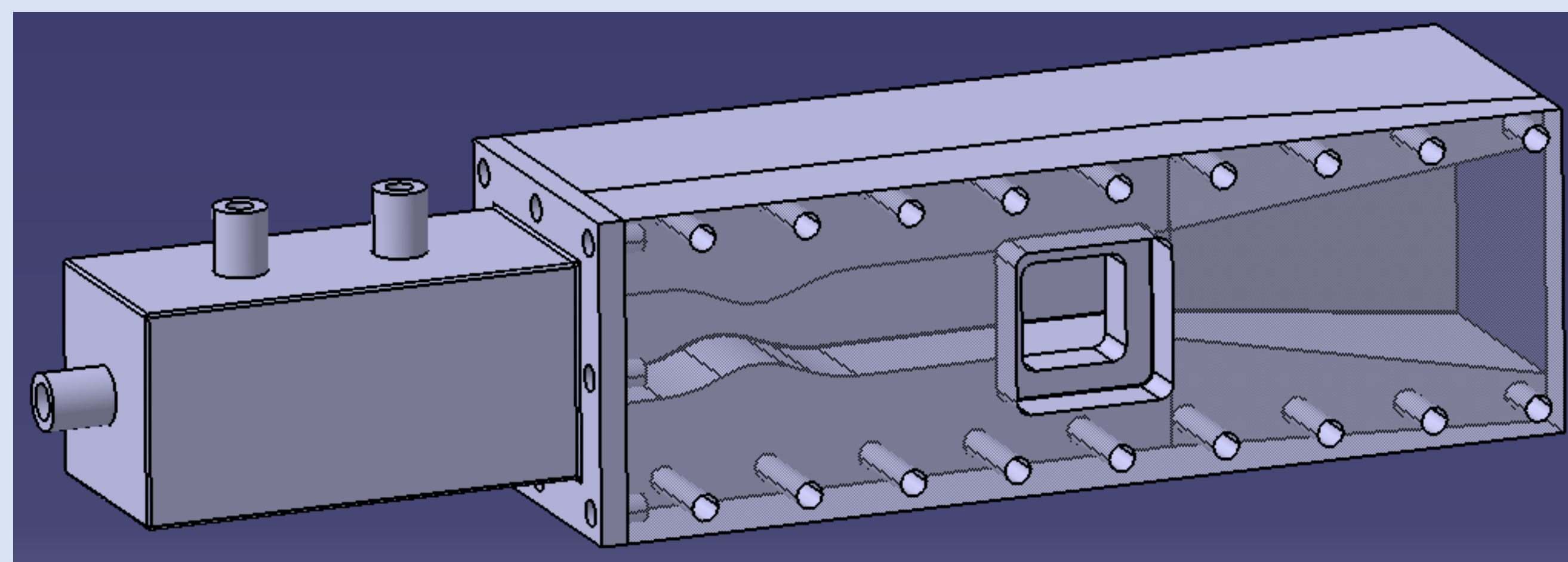(Speeds up the flow from sub to supersonic)

Fig. (d) Isometric view of Wind Tunnel
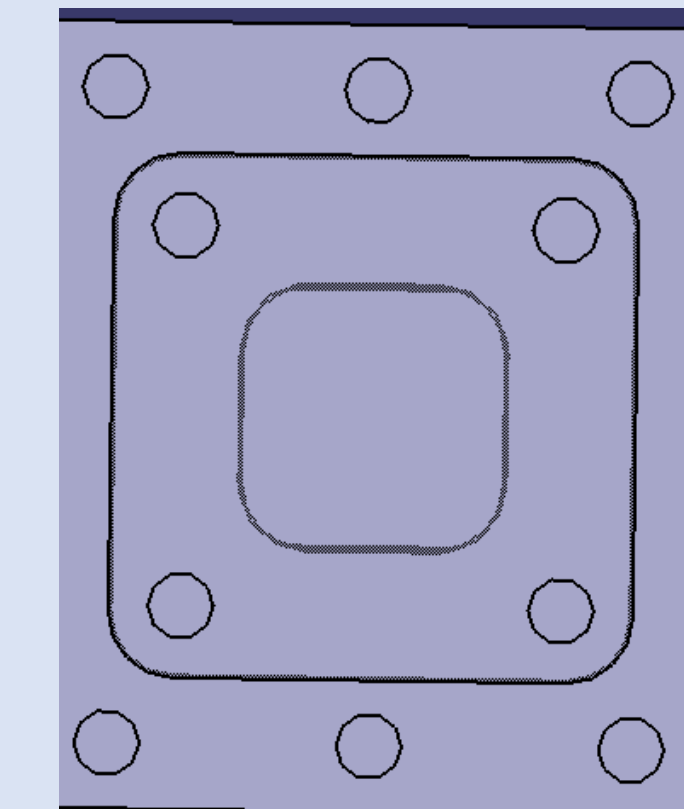
(Assembled Wind Tunnel CAD model)

Fig. (e) Viewing Window
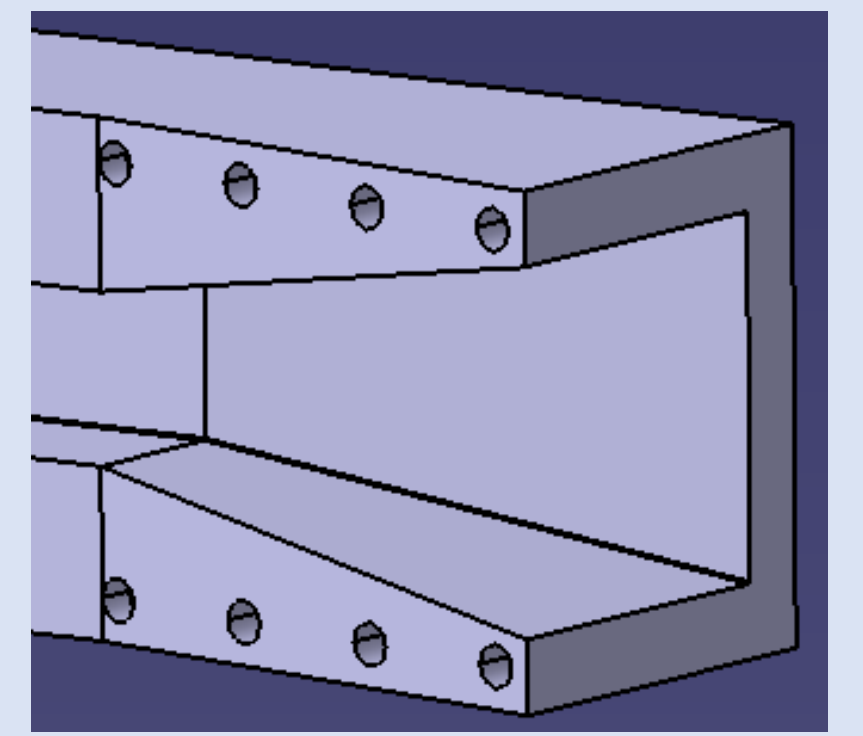
(Allows user to view flow and material effects)

Fig. (f) Diffuser

(Slows down the flow from super to subsonic)

Simulation

The utilization of Computational Fluid Dynamic analysis software such as COMSOL Multiphysics is vital for determining the Mach flow received within the C-D Nozzle, Testing Chamber, and seeing how the flow will diffuse [3].

- The initial conditions were set to 70 psi at the inlet and 1 atm at the exhaust.
- Supersonic flow was achieved past the throat of the C-D Nozzle, resulting in a Mach flow of 1.8.
- The use of oblique shock waves proved to be ineffective.
- The implementation of expansion waves are necessary to better diffuse the flow.
- To better simulate atmospheric conditions, an enclosure was added to the exhaust.
- COMSOL solutions were compared using a mesh analysis ranging from a Fine mesh with 78,713 elements to a finer mesh with 1,613,751 elements.

Conclusion

A final geometry configuration is designed and selected for the fabrication of the Small-Scale Supersonic Wind Tunnel. The analysis of the Supersonic Wind tunnel is conducted using COMSOL Multiphysics, along with analytical calculation for the geometry configuration, and a mesh conversion study to produce more accurate results. An inlet pressure of 70 psi produces supersonic flow at speeds of Mach 1.82 in the testing chamber while diffusing the flow to subsonic at Mach 0.25 in the exhaust. Flow loads are identified to verify loading conditions. Manufacturing and fabrication will be done to produce a model fit for testing and analysis of aerospace structures and components.
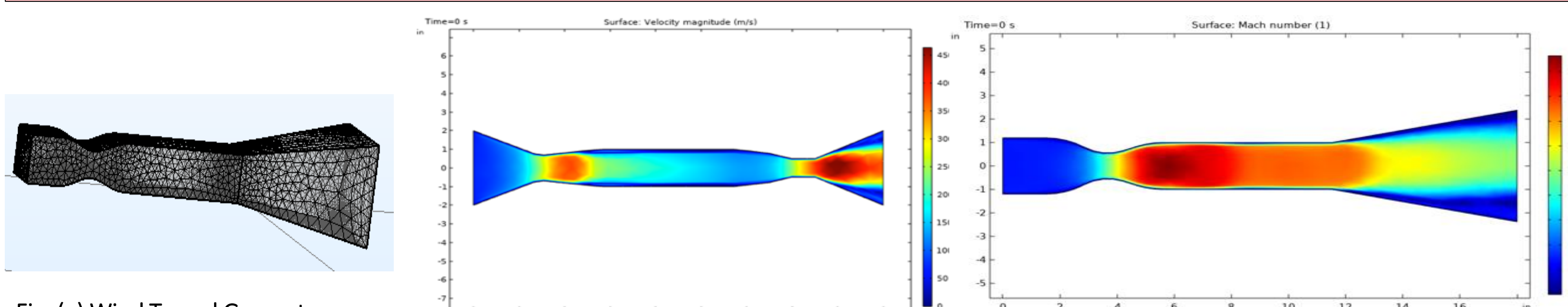
Fig. (g) Wind Tunnel Geometry with Mesh added

(Visual of Meshed CAD model)

Fig. (h) Before

(Initial geometry simulation)

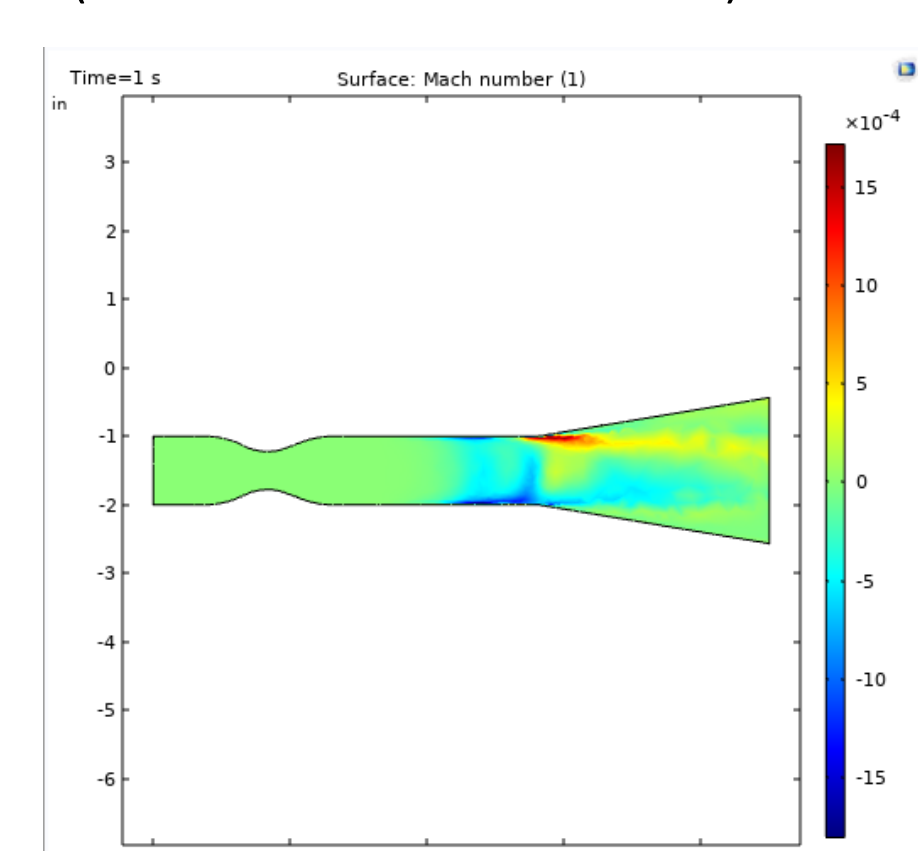Fig. (I) After

(Redesigned geometry simulation)

Fig. (j) Mesh analysis
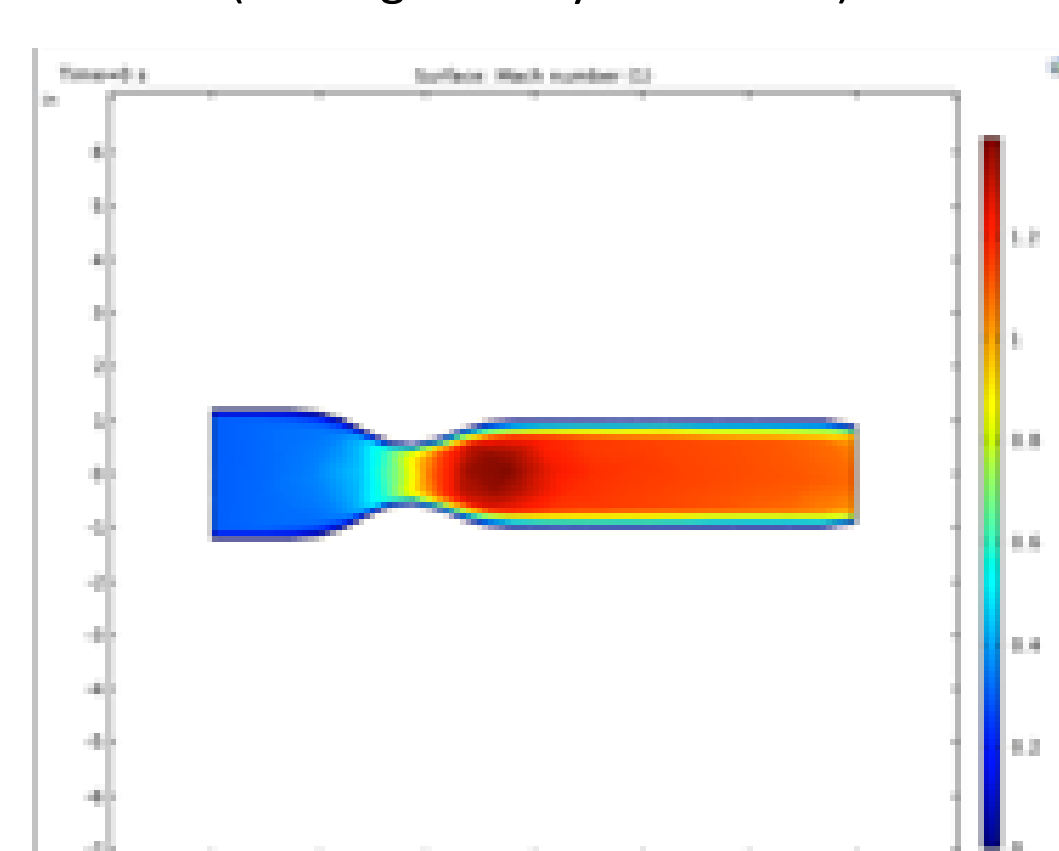
(analysis based on fine and finer elements)

Fig. (k) Oblique Shock waves

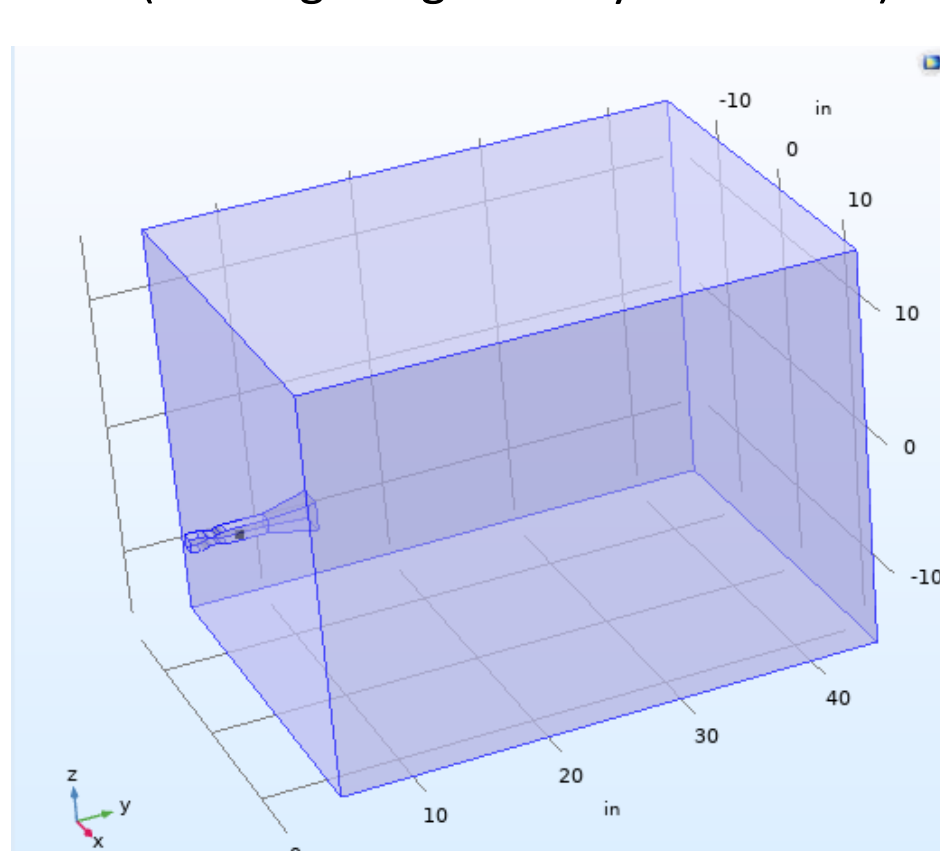(Diffuser attempted using oblique shock waves)

Fig. (l) Enclosed exhaust

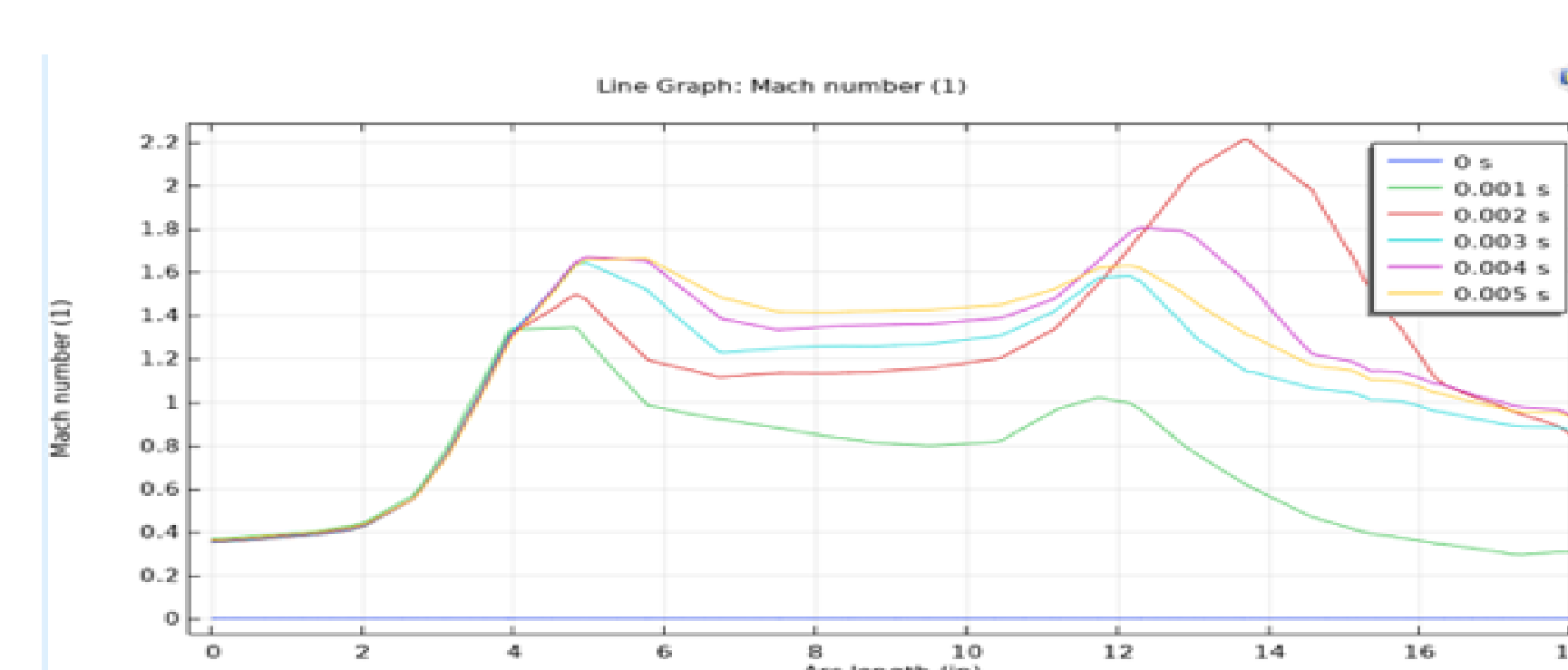(an enclosed section at the exhaust simulates a natural environment)
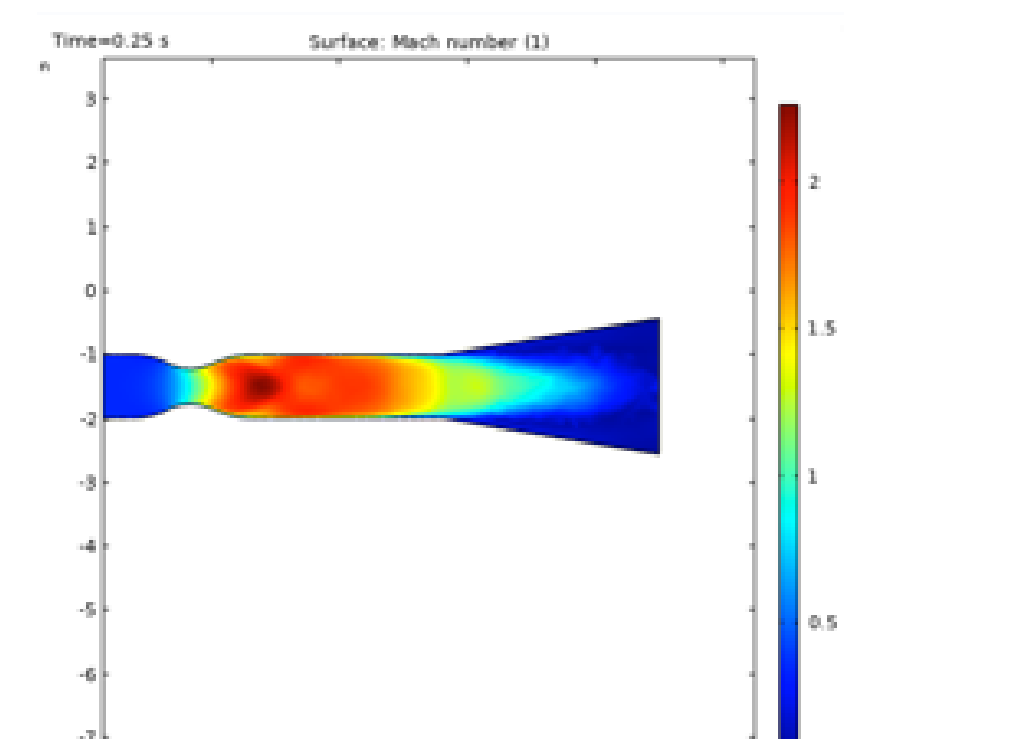
Fig. (m) Mach Number vs. Arc Length

Fig. (n) Final Simulation

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