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CFD-Based Design of a Supersonic Blow-Down Wind Tunnel

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Abstract

This work presents the design and numerical characterization of a modular supersonic blow-down wind tunnel. The facility targets a nominal operating condition at $M = 3.5$ and implements interchangeable nozzles to cover $M = 2.5$–4.5. The design couples Method-of-Characteristics nozzle contours with viscous boundary-layer corrections, a controlled diffuser featuring a second throat for robust startability, and a reconfigurable test section with optical windows and a model support system. Computational fluid dynamics (CFD) is employed to verify start-up and steady operation under realistic ambient conditions, to quantify test-section flow quality, and to evaluate aerodynamic loads on the structure. These loads are used to perform a preliminary structural analysis to assess the thermo-mechanical response of windows, frames, and structural joints. A preliminary structural sizing is also provided for support legs adopting conservative allowables and safety factors. The results indicate that the facility can be reliably started and delivers a uniform supersonic core at the design Mach number, providing a repeatable platform for airbreathing propulsion and supersonic aerodynamics experiments.

1. Introduction

Supersonic wind tunnels have historically played a central role in the advancement of high-speed aerodynamics and propulsion research. From the pioneering facilities developed in the mid-twentieth century for military and space applications [1, 2], to the more compact blow-down tunnels designed for academic and industrial testing, these infrastructures have consistently provided the only reliable means of reproducing and studying controlled supersonic flows under laboratory conditions. Unlike flight testing, which is expensive and limited by safety and operational constraints, ground-based facilities allow systematic and repeatable investigations of aerodynamic phenomena, structural responses, and propulsion integration in a controlled environment. In the present context of renewed interest in reusable launchers, hypersonic vehicles, and airbreathing propulsion systems such as ramjets and scramjets [3–6], the availability of versatile supersonic blow-down facilities is of even greater importance [7]. They not only enable performance validation of intakes, nozzles, and combustors, but also provide critical data for the calibration and validation of computational fluid dynamics (CFD) codes, which remain limited in their ability to fully capture the complex interactions between shocks, boundary layers, and chemical processes [**?**, 8]. Despite their long history, the design and operation of supersonic tunnels remain highly challenging. The first difficulty is *startability*: ensuring that the tunnel can reach and sustain the target Mach number without flow breakdown or unstart. Startability depends strongly on the nozzle contour, the diffuser configuration, and the interaction between shocks and boundary layers [10, 12]. Inadequate diffuser sizing, in particular, can lead to flow separation or choking, preventing stable operation. A second challenge is the achievement of *flow uniformity* in the test section. For meaningful experimental results, the flow must be steady, repeatable, and as close as possible to one-dimensional ideal conditions. In practice, however, several factors degrade uniformity: the growth of boundary layers along the nozzle walls, residual turbulence from the settling chamber, imperfect alignment of flow-conditioning devices, and the presence of models and supports inside the test section [13]. Managing these effects requires careful nozzle design, accurate boundary layer correction, and the use of large settling chambers with honeycomb and screens to reduce flow distortions [2]. Another fundamental limitation is related to *run time*. Blow-down facilities operate by discharging compressed air (or other gases) from a reservoir into the test section. As the reservoir depressurizes, the stagnation conditions change, eventually altering the static pressure in the test section. The useful test window is therefore limited to a few seconds, particularly at higher Mach numbers where the required pressure ratios are larger. This restriction makes fast-response instrumentation and high-speed diagnostics indispensable [11]. Structural and thermal constraints also play a decisive role. Operating at Mach numbers between 2.5 and 4.5 requires stagnation pressures up to 15 bar and stagnation temperatures exceeding 1000 K. These conditions impose severe loads on the tunnel structure, especially in the nozzle and settling chamber. Stainless steels or nickel-based alloys are often required to withstand the combined mechanical and thermal stresses, and preliminary sizing must always be supported by finite element analyses to verify safety margins. In addition, support structures must be carefully designed to sustain both the weight of the facility and the reaction forces generated by the diverted supersonic jet. A further difficulty arises from the integration of *diagnostic systems*. Optical access through large windows is essential for flow visualization, particle image velocimetry (PIV), and laser-based diagnostics [11]. However, windows must be designed to minimize deflection under load, avoid optical distortion, and maintain sealing at high pressures and temperatures. The presence of these components, together with model supports and instrumentation, inevitably perturbs the internal flow, and thus must be considered already at the design stage. Finally, cost and safety considerations cannot be neglected. High-pressure storage, heating systems, and reinforced structures significantly increase the complexity and expense of supersonic tunnels. Safe operation requires multiple levels of redundancy, including pressure relief devices, rigid anchoring, and remote control of valves and heaters. At the same time, modularity and ease of reconfiguration are increasingly demanded in modern research facilities, as they must accommodate a wide variety of experimental campaigns without requiring complete redesign.

In summary, while supersonic blow-down wind tunnels remain indispensable for high-speed aerodynamics and propulsion research, their design involves a delicate balance between aerodynamic performance, structural integrity, diagnostic accessibility, cost, and operational safety. The present work addresses these challenges by presenting the design and characterization of a modular supersonic blow-down facility able to reproduce Mach numbers from 2.5 to 4.5 with good flow quality and robust structural margins, integrating both CFD-based analyses and preliminary structural assessments.

2. General Layout and Architecture

The layout follows the conceptual scheme of Pope and Goin [1], further developed within recent projects [13]. It includes: high-pressure storage tanks, pressure regulators and fast valves, an electric heater, a settling chamber with honeycomb screens, a modular nozzle, a test section with optical access, and a diffuser with vertical exhaust.

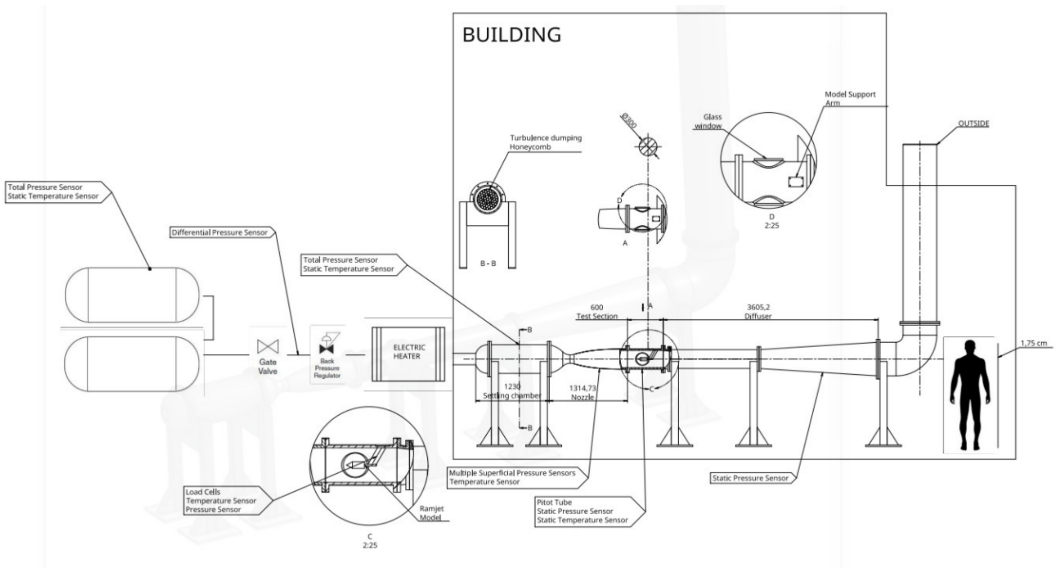


Fig 1. General schematic of the modular supersonic wind tunnel layout.

The model support system (Figure 2) adopts a wedge-shaped sting with a diamond cross-section, representative of standard practice in supersonic facilities [7]. The model diameter is 5 cm with a length of 30 cm, suitable for initial validation of the test section flow.

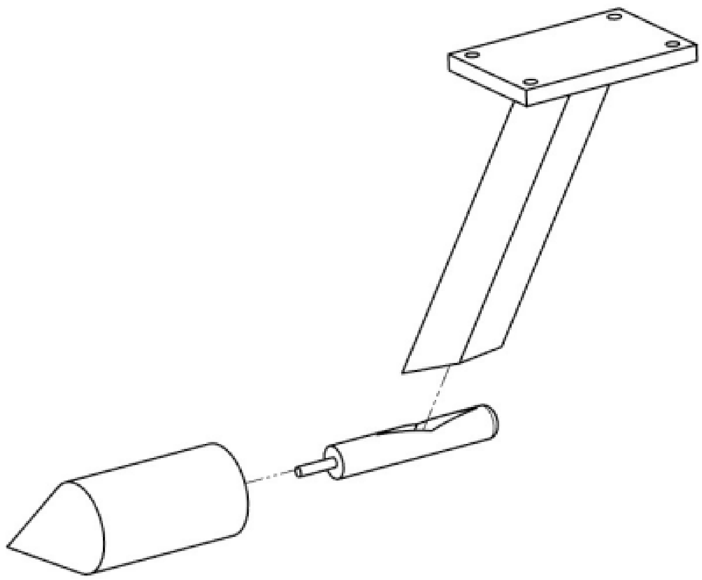


Fig 2. Wedge-shaped model support system with diamond cross-section.

The modularity lies in the interchangeable nozzle blocks, which allow rapid switching between Mach 2.5, 3.5, and 4.5 configurations. Coupled with the possibility of selecting different upstream pressures and temperatures, this enables the facility to reproduce a wide range of real flight conditions. While the design of the wind tunnel builds upon the classical work of Pope and Goin [1], several key aspects have been improved to enhance performance and ensure greater flow uniformity in the test section. This paper presents the nozzle optimization methodology, and the results are discussed based on CFD analyses that provided detailed visualization of the relevant flow variables inside the tunnel. In addition, a preliminary design of the model support arm is introduced, together with an assessment of its influence on tunnel start-up and steady-state behavior.

3. Nozzle Design Methodology

3.1. Method of Characteristics

Axisymmetric MOC was applied to generate minimum-length nozzle contours achieving the target Mach numbers with uniform exit flow [8].

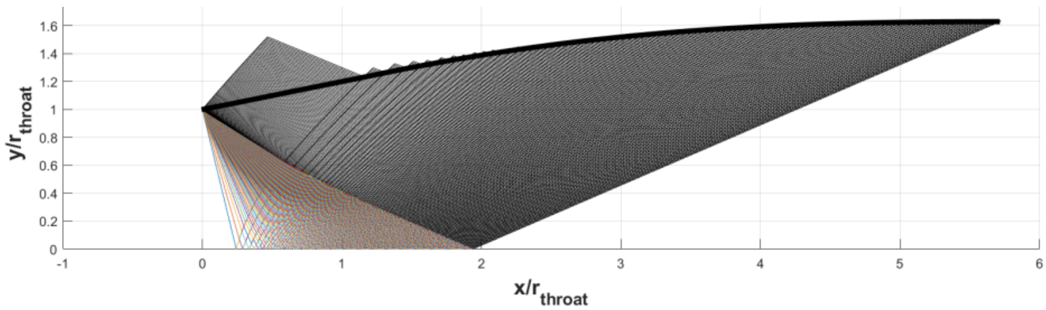


Fig 3. MOC-generated nozzle contour for Mach 2.5., [13].

3.2. Boundary Layer Correction

Viscous effects were incorporated using von Kármán's momentum integral equation for compressible boundary layers. Iterative correction yielded effective nozzle exit areas consistent with target Mach numbers [2].

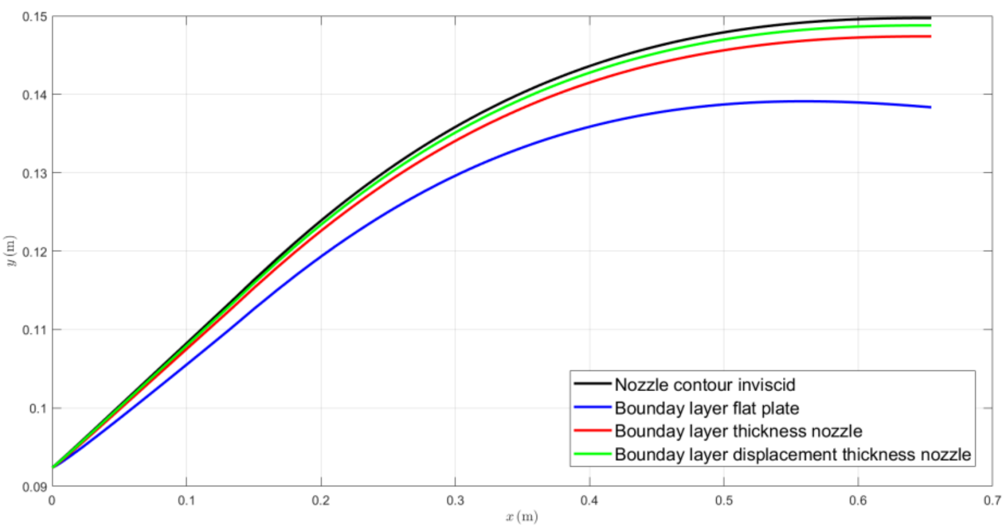


Fig 4. Boundary-layer correction applied to Mach 2.5 nozzle contour, [13].

4. CFD Validation

4.1. Simulation Setup

CFD analyses were performed with ANSYS Fluent using the k–ω SST turbulence model, for Mach numbers 2.5, 3.5, and 4.5. Boundary conditions were derived from ISA conditions (Table 1) [12].

M	Alt. [m]	P_0 [bar]	T_0 [K]	p_{test} [bar]	T_{test} [K]
2.5	13368	2.9	484	0.17	216
3.0	14560	4.7	606	0.128	216
3.5	16500	8.7	747	0.114	216
4.0	19370	10.0	916	0.064	218
4.5	21370	13.9	1080	0.048	218

Table 1. Reference nozzle operating conditions based on ISA.

Figure 5 shows a section of the three-dimensional unstructured mesh generated for the CFD simulations. The grid includes the complete tunnel geometry together with the support arm and the test model. The use of an unstructured topology allowed local refinement around critical regions, such as the nozzle throat, the test section, and the model vicinity, ensuring adequate resolution of shock structures and boundary-layer development while maintaining a reasonable overall cell count.

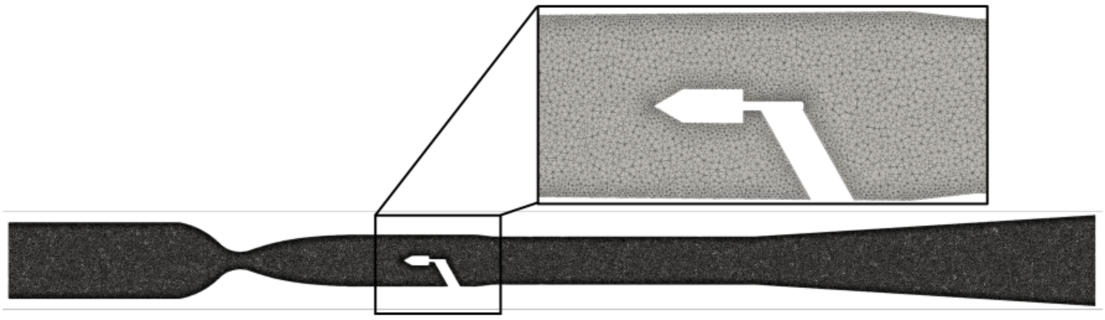


Fig 5. Three-dimensional CFD mesh with model included.

4.2. Results

The CFD confirmed correct tunnel startability and attainment of target Mach numbers in the test section. Flow uniformity was assessed via centerline Mach distribution and contour plots [12, 13].

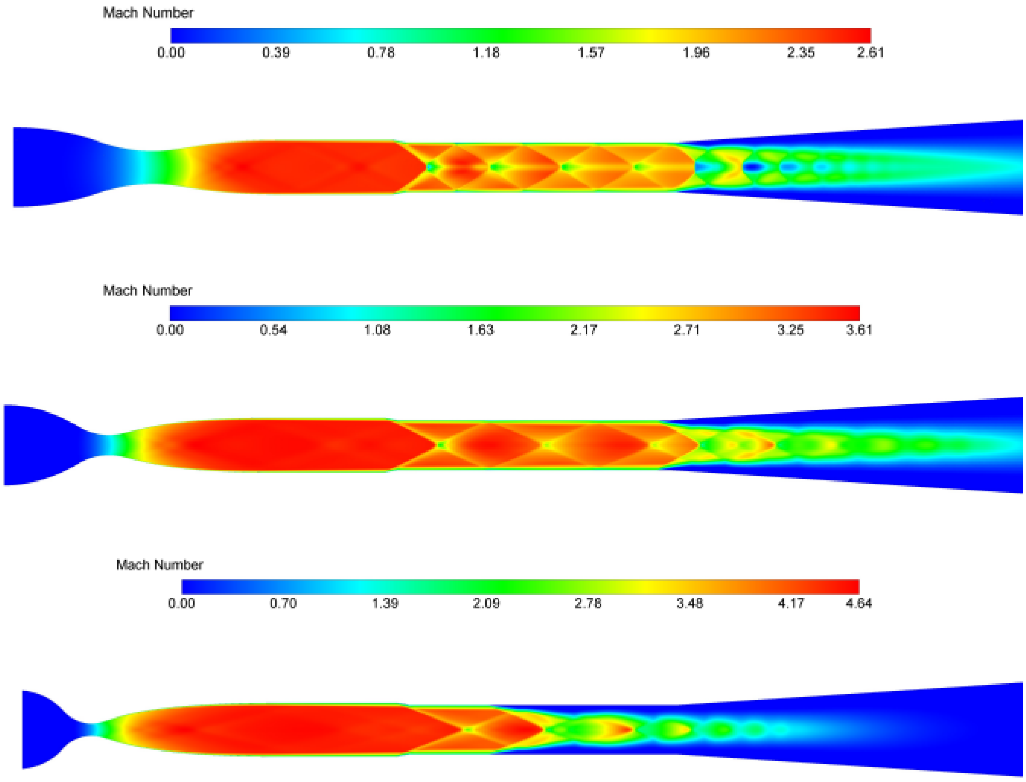


Fig 6. Mach number contours at Mach 2.5, 3.5, and 4.5.

The Mach number contours reported in Figure 6 confirm that the tunnel is able to start correctly and reach the target operating conditions at Mach 2.5, 3.5, and 4.5. In all cases, a uniform supersonic core is established within the test section, while shock structures remain confined downstream in the diffuser region. As expected, increasing Mach numbers correspond to stronger expansion fans and a more complex shock-cell pattern, yet without compromising the flow uniformity required for reliable testing. These results demonstrate that the nozzle design and boundary-layer corrections provide stable operation across the intended Mach range.

5. Extended 3D Analysis

A refined 3D domain including windows, support arm, and a representative model was analyzed. Meshes exceeded 8.7M elements. And two different cases where studied. The first one is without the support arm, this was important to define the effects of the optical windows. The other is with both windows and support arm.

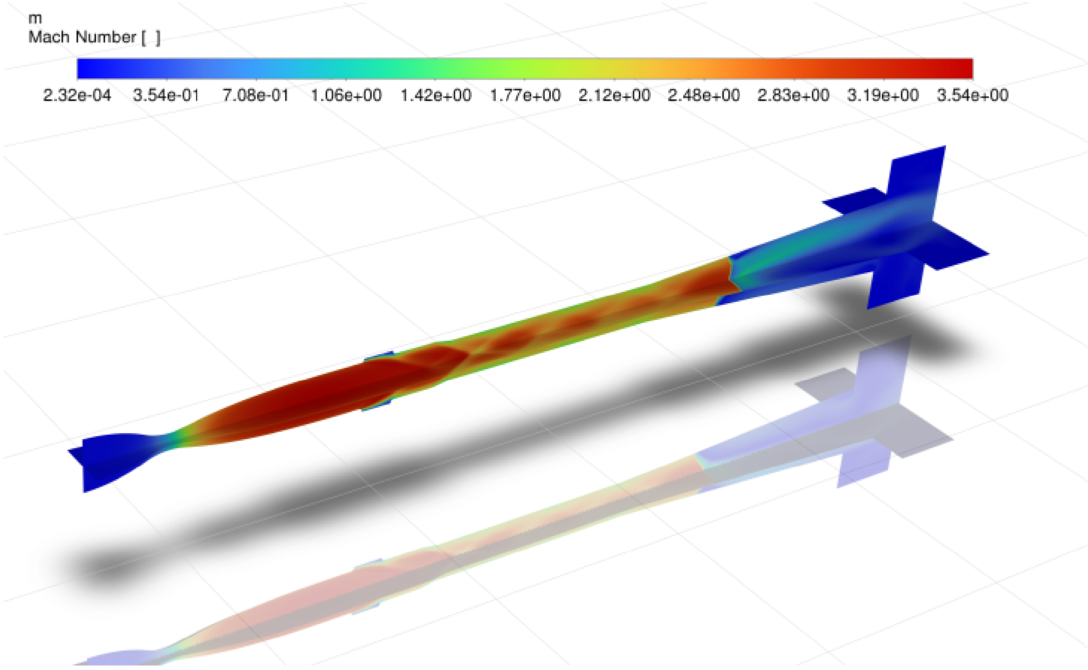


Fig 7. 3D Mach number contours at Mach 3.5 including optical windows.

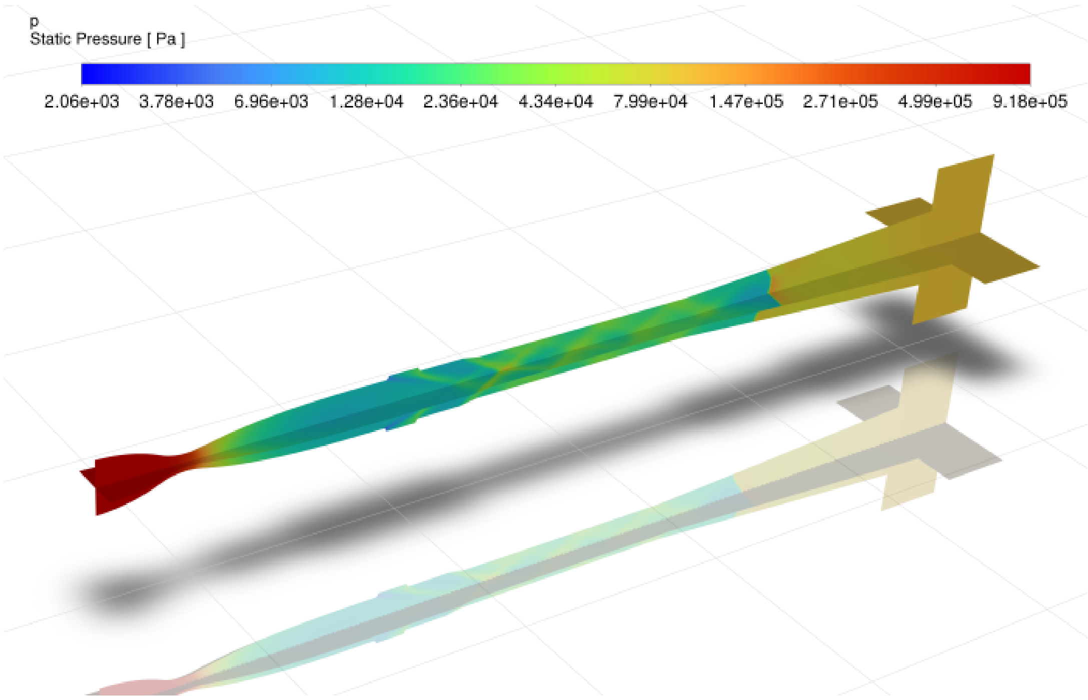


Fig 8. 3D static pressure contours at Mach 3.5 including optical windows.

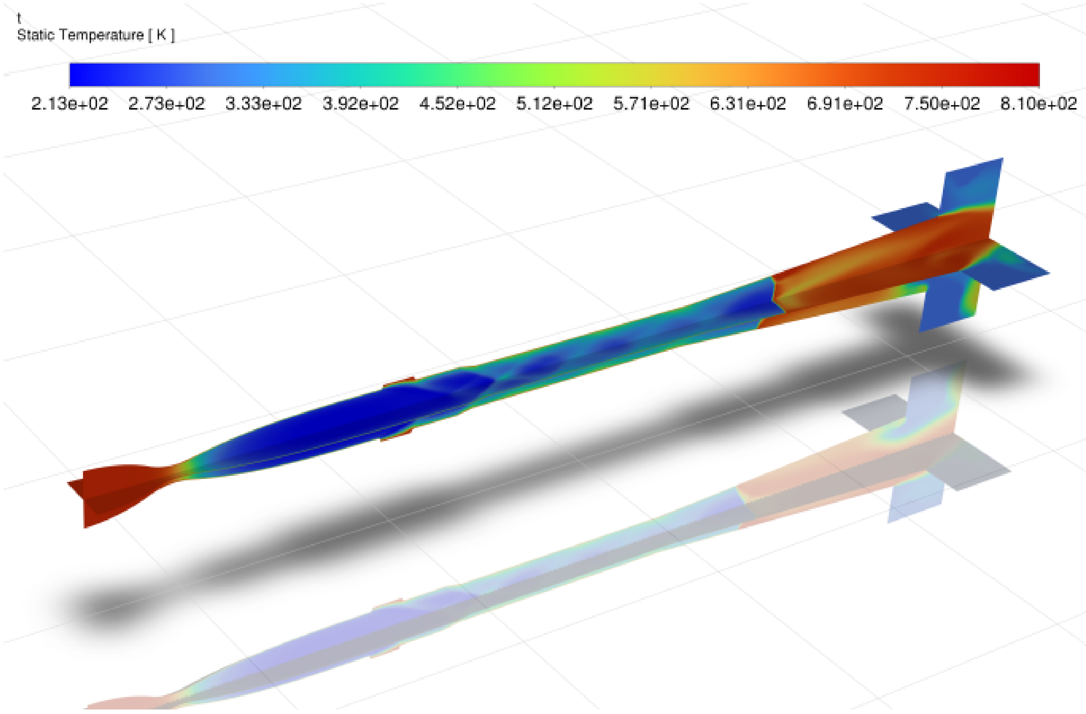


Fig 9. 3D static temperature contours at Mach 3.5 including optical windows.

Figures 7, 8, and 9 present the three-dimensional CFD results at $M = 3.5$ including the optical windows in the computational domain. The Mach number contours demonstrate that the uniform supersonic core established in the nozzle exit is preserved throughout the test section, with only localized perturbations in proximity to the window recesses. The static pressure distribution confirms that no major shock reflections or boundary-layer separations occur in the vicinity of the optical inserts, and the pressure field remains stable along the tunnel axis. Similarly, the static temperature contours show smooth gradients consistent with the expected isentropic expansion, further confirming that the inclusion of windows does not significantly alter the global flow topology. A slight reduction in total pressure was observed in the regions immediately adjacent to the windows due to local flow disturbances, but this effect remains minor and does not compromise the overall test-section flow quality. These results validate the structural integration of optical access while ensuring that aerodynamic uniformity is maintained, a key requirement for accurate flow visualization and advanced diagnostic techniques in supersonic facilities.

The three-dimensional CFD analysis provided critical insight into the actual performance of the facility once the effects of windows, support arm, and model were included. Two outlet boundary conditions were investigated. In the first case, a zero-gradient condition was imposed at the diffuser exit. Under this assumption, the flow remained fully supersonic up to the tunnel exit, with no signs of separation or shock formation. This configuration represents an idealized scenario, equivalent to exhausting into a vacuum, where the supersonic jet expands freely without encountering any downstream resistance. In contrast, when a more realistic back-pressure of 1 atm was applied at the outlet, the solution exhibited a normal shock located within the diffuser. This behavior is physically consistent, as the diffuser is required to decelerate the supersonic stream to subsonic conditions before discharge into the ambient environment. The shock system stabilized inside the diffuser, while the test section continued to exhibit a uniform Mach 3.5 core flow, thereby confirming the tunnel's startability under realistic conditions. Additional simulations with the presence of the model, optical window, and support arm showed that the flow field remains robust. While localized disturbances and additional total-pressure losses were introduced, the overall flow uniformity in the test section was preserved. These results highlight the resilience of the design and its capability to provide stable supersonic operation even when experimental hardware and diagnostics are integrated.

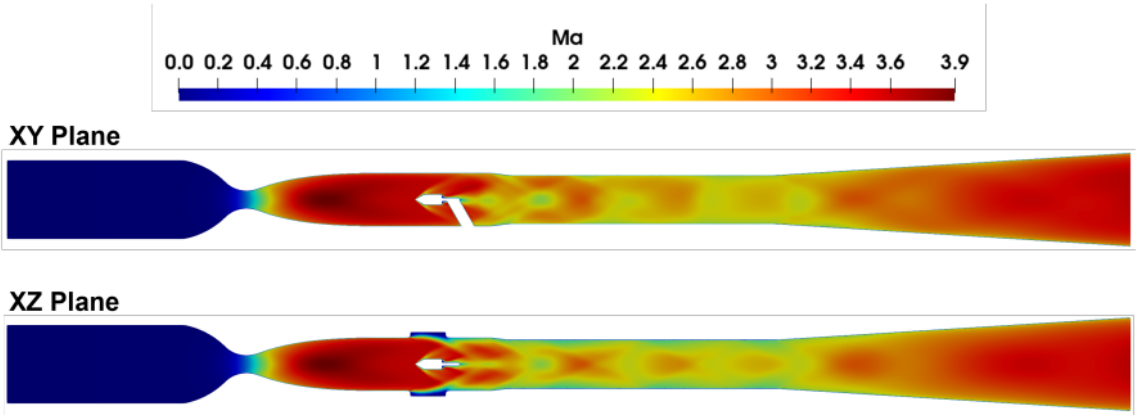


Fig 10. Mach contours with model under vacuum-like outlet condition.

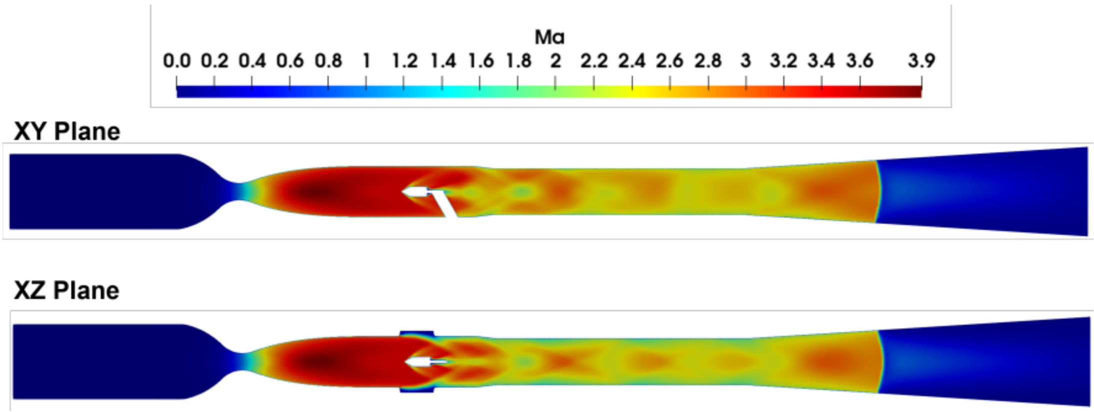


Fig 11. Mach contours with model under ambient outlet condition.

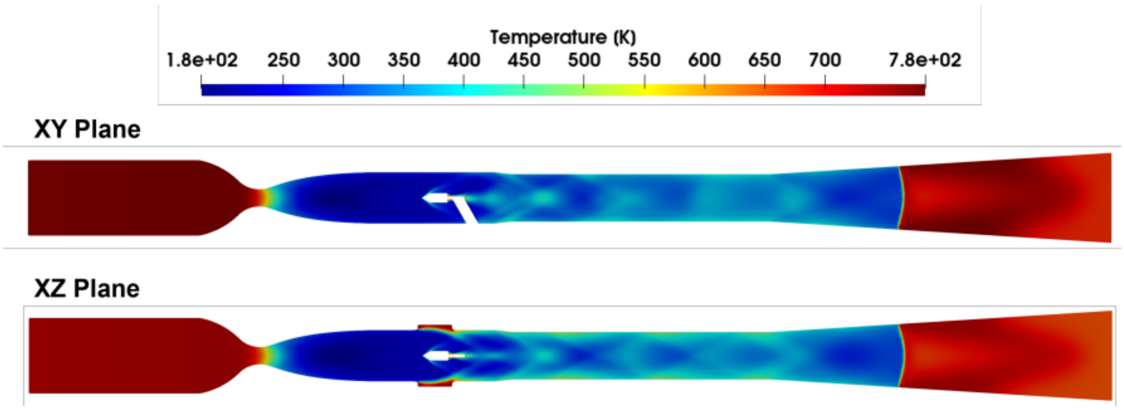


Fig 12. Static temperature contours with model under ambient outlet condition.

6. Structural Sizing

Following the aerodynamic validation, structural sizing was carried out for the critical components, including the test section, settling chamber, and support legs. Figure 13 presents the complete CAD model of the blow-down wind tunnel. As shown, a vertical silencer is implemented to redirect the exhaust flow outside the hosting building. This configuration also ensures that the thrust vector remains aligned with the support legs, thereby improving the overall structural stability of the facility.

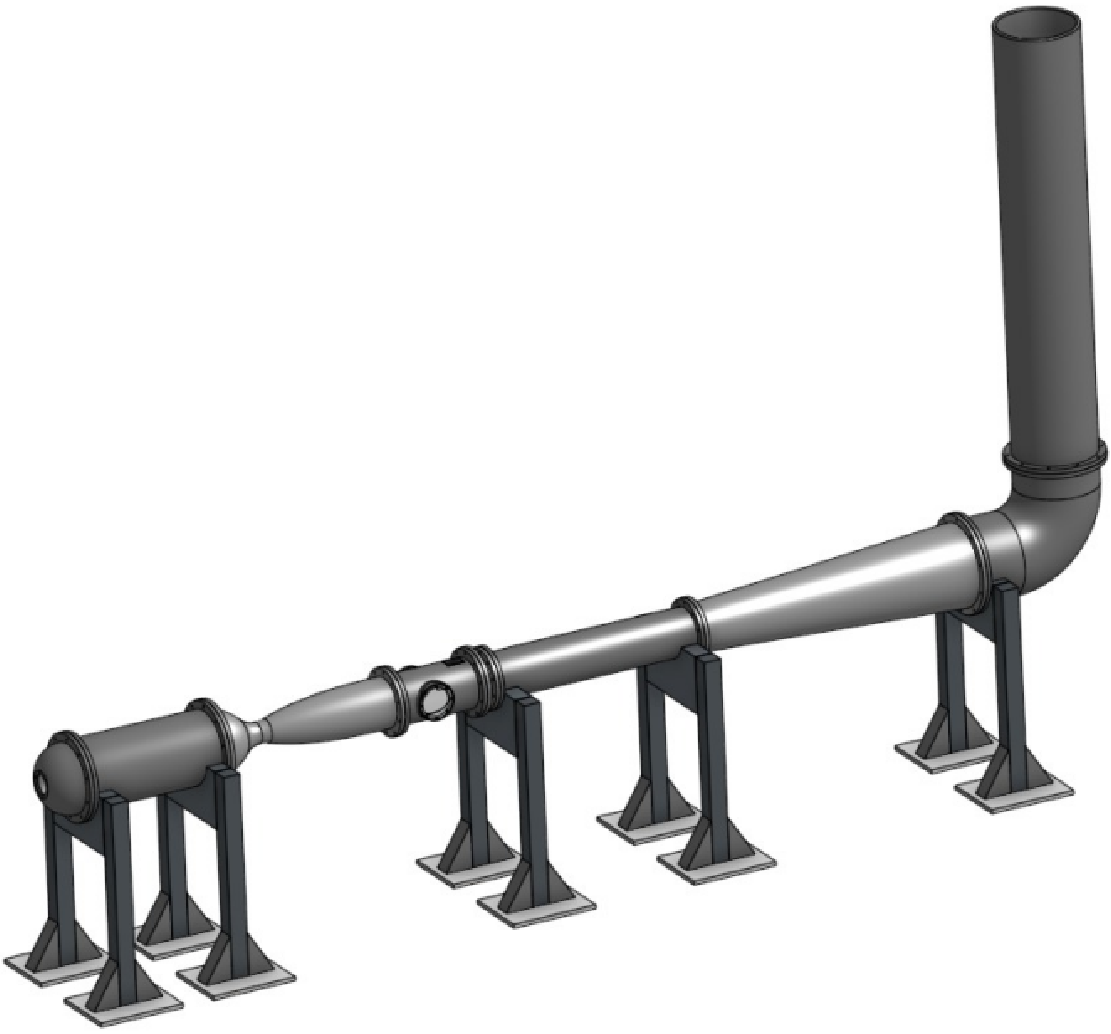


Fig 13. Preliminary CAD model of the supersonic blow-down wind tunnel.

6.1. Test Section

Critical conditions at Mach 4.5 ($p_0 = 15$ bar, $T_0 = 1080$ K) were assessed using AISI 304 steel ($\sigma_y = 210$ MPa at 300 K). With a safety factor of 10, a thickness $t = 15$ mm was adopted. FEM predicted $\sigma_{max} = 57$ MPa $\ll \sigma_y$.

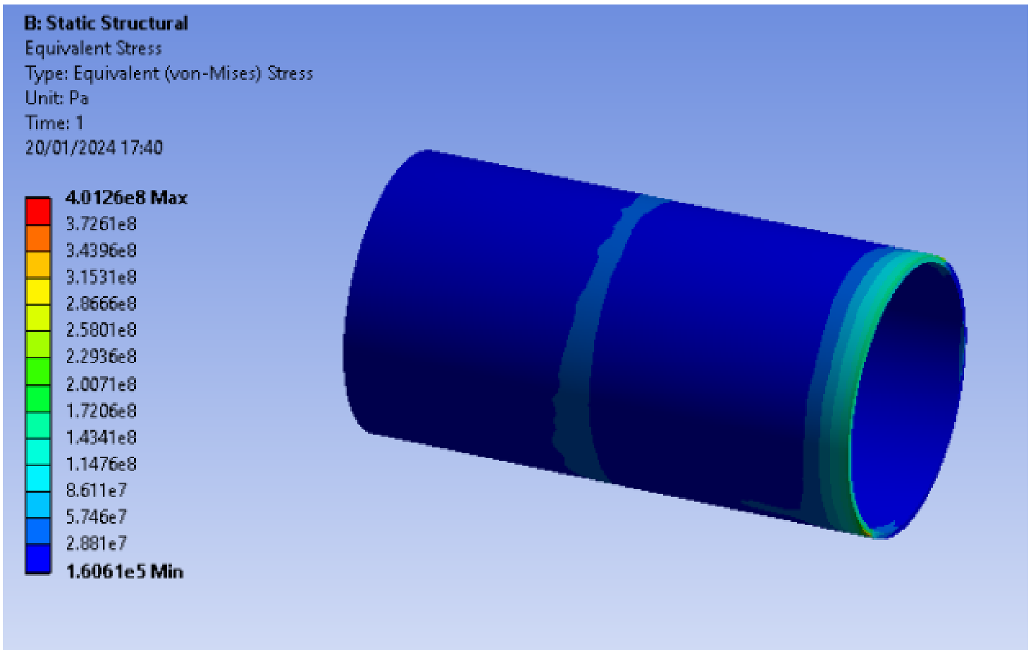
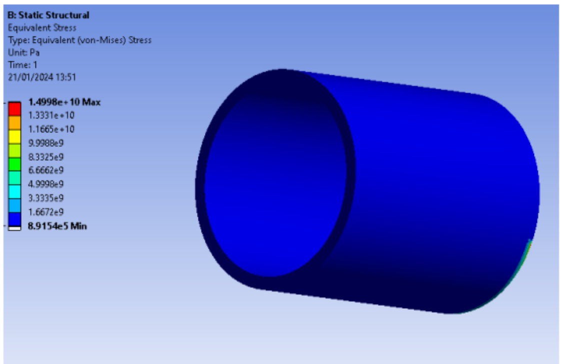


Fig 14. Von Mises stress distribution in the test section.

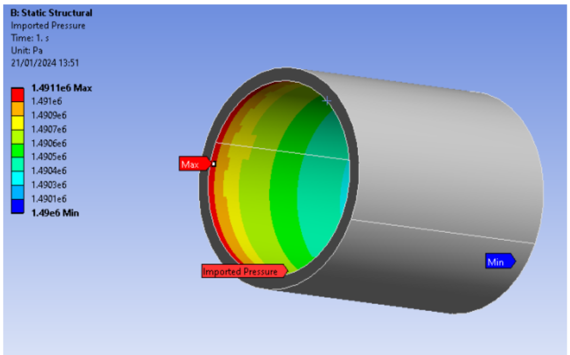
The results for the test section confirm that the chosen wall thickness of 15 mm provides a wide safety margin under the most demanding operational condition at Mach 4.5. The FEM analysis, showing a maximum von Mises stress of 57 MPa, represents less than one third of the yield strength of AISI 304 steel at room temperature. This outcome highlights the robustness of the design against both pressure loading and thermal stresses, even without yet including temperature-dependent material degradation. It is worth noting that at elevated temperatures ($T_0 \approx 1080$ K), the strength of stainless steels may decrease, but the adopted safety factor of 10 ensures that the structure remains well within allowable limits. Furthermore, the stress distribution suggests that critical regions are localized near the optical window interfaces and at the junction between the nozzle and the test section, underlining the importance of accurate sealing and bolted joint design in future detailed analyses.

6.2. Settling Chamber

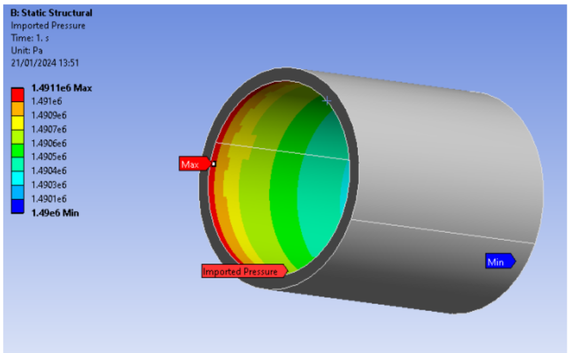
At $T \approx 1000$ K, yield strength reduces to 90 MPa. A wall thickness of 60 mm was selected. FSI analysis confirmed $\sigma_{max} = 0.89$ MPa $\ll \sigma_y$.



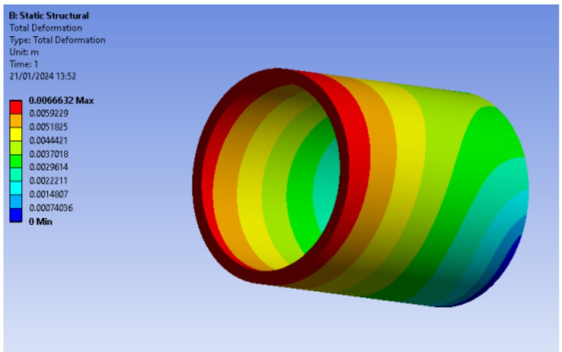
(a) Stress distribution in the chamber



(b) Pressure load distribution (1)



(c) Pressure load distribution (2)



(d) Predicted deformation under load)

Fig 15. Static structural analysis of the settling chamber.

The settling chamber analysis revealed extremely low stress levels compared to material limits, with $\sigma_{\text{max}} \approx 0.89$ MPa against a reduced high-temperature yield stress of 90 MPa. This is primarily due to the large wall thickness (60 mm) that provides high structural stiffness. The FSI simulations confirm that the geometry can safely withstand both the stagnation pressure (up to 15 bar) and the thermal environment ($T \approx 1000$ K), with only limited deformations. However, the large thickness inevitably contributes to the overall mass of the tunnel, accounting for a significant fraction of the estimated $m \approx 1850$ kg. This trade-off highlights a key design compromise: the need to guarantee structural safety and sealing reliability while minimizing mass, which directly impacts the cost and support requirements of the facility.

6.3. Support Legs

With an estimated tunnel mass of $m \approx 1850$ kg, load per support leg was calculated as $F \approx 7.4 \times 10^3$ N (with $n = 5$ supports and SF $= 2$). Maximum stress $\sigma_{\text{vm,max}} \approx 18$ MPa remained far below stainless steel yield ($\sigma_y \approx 210$ MPa).

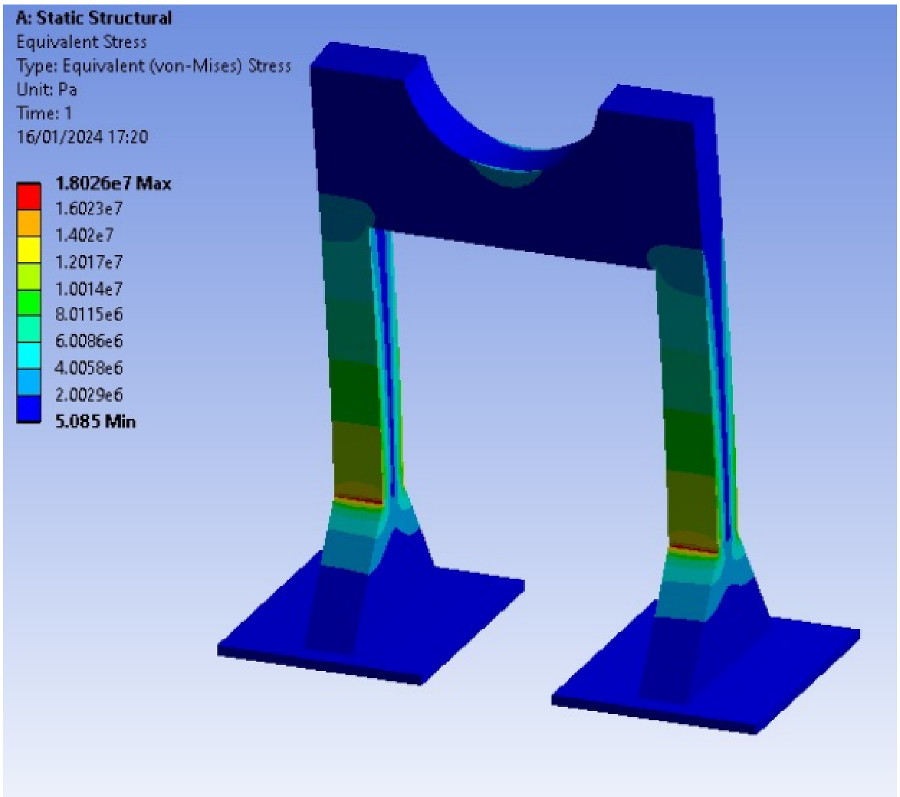


Fig 16. Structural support system under load.

The support system analysis indicates that each of the five legs sustains a design load of approximately 7.4×10^3 N, considering both the total mass and a safety factor of 2. The maximum von Mises stress of about 18 MPa is far below the yield stress of stainless steel, confirming that static stability is guaranteed. Stress concentrations appear at the base of the legs and at their upper attachments to the main structure, which is consistent with the expected load paths. These results suggest that the current configuration provides ample strength; however, dynamic effects such as vibrations induced by valve operations or acoustic loads during high-speed exhaust have not yet been included. Future refinements should therefore assess the dynamic stiffness of the supports and the possible need for damping elements or reinforced anchoring systems to the facility foundation.

7. Conclusions

The present work has demonstrated the feasibility and robustness of a modular supersonic blow-down wind tunnel, integrating aerodynamic and structural analyses to assess performance within the Mach 2.5–4.5 range. On the aerodynamic side, nozzle contours generated via the Method of Characteristics and corrected for boundary-layer growth achieved the intended exit Mach numbers, while the diffuser with a second throat ensured stable shock positioning under realistic ambient back-pressure conditions [10, 12]. CFD simulations confirmed reliable tunnel startability, the establishment of a uniform supersonic core in the test section, and acceptable levels of flow uniformity even in the presence of windows, support arms, and representative models. These intrusions produced only localized perturbations and minor total-pressure losses, which did not compromise the overall flow quality required for meaningful testing. The analysis of vacuum-like and ambient outlet conditions further highlighted the resilience of the design, with the tunnel capable of operating stably under both idealized and realistic boundary conditions. From a structural perspective, preliminary finite element simulations verified that the main components—settling chamber, test section, and support legs—are capable of withstanding the predicted thermal and mechanical loads. For the critical case at Mach 4.5, stresses remained well below the yield limits of stainless steel, confirming ample safety margins. The structural design of the support system was shown to provide adequate stability, with vertical alignment of the exhaust flow achieved through the use of a silencer to minimize off-axis loads. These results indicate that the proposed facility can operate safely and reliably under demanding supersonic conditions.

Overall, the combination of CFD-based aerodynamic validation and structural sizing establishes confidence in the design of this modular facility. The tunnel is expected to provide a repeatable and versatile platform for high-speed aerodynamics and propulsion experiments, including investigations on ramjet and scramjet technologies, intake optimization, and model testing under realistic flight conditions. Limitations of the present stage include the reliance on RANS turbulence modeling without explicit transition prediction, the assumption of constant material properties at elevated temperatures, and simplified reservoir decay models. Future work will therefore focus on experimental validation of nozzle and diffuser performance, incorporation of temperature-dependent material properties, and development of calibration procedures linking second-throat settings to recovery and shock positioning. The facility's modularity, coupled with robust startability and structural margins, positions it as a valuable infrastructure for advancing both fundamental research and applied investigations in supersonic aerodynamics and propulsion.

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