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Engineering Feasibility Analysis of a Surface-Based Mars Habitat Using Integrated Structural, Thermal, Solar, and Aerodynamic Models

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Abstract: Human habitation on the Martian surface presents significant engineering challenges due to low atmospheric pressure, extreme thermal conditions, solar radiation exposure, and wind-induced environmental loads. Surface habitat systems must therefore maintain structural integrity, thermal stability, and aerodynamic robustness under combined Martian conditions. This study presents an integrated numerical assessment of a conceptual surface-based Mars habitat addressing these key design requirements. Structural performance is evaluated under the pressure differential between a pressurized interior and the Martian atmosphere for different habitat geometries. Thermal behavior is investigated through steady-state heat transfer analysis of a multilayer wall system comprising an aluminum structural shell, Martian regolith, and a low-conductivity insulation layer. Solar radiation effects are examined using date-specific solar flux conditions for multiple representative Martian years. Aerodynamic response under Martian wind conditions is analyzed to assess external flow behavior and wind-induced loading. The results demonstrate that habitat geometry and wall configuration play a decisive role in overall performance. Curved configurations exhibit significantly reduced deformation and lower aerodynamic drag compared to cylindrical forms. The multilayer wall system effectively limits heat loss and moderates temperature variations, with insulation identified as critical for maintaining thermal stability. Overall, the study highlights the importance of integrated structural, thermal, solar, and aerodynamic analysis in guiding early-stage design of surface-based Mars habitats under realistic environmental conditions.

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1. Introduction

Human habitation on the Martian surface introduces engineering challenges that differ fundamentally from those encountered in terrestrial environments. Extremely low atmospheric pressure, large diurnal temperature variations, persistent solar radiation exposure, and wind-driven surface flows impose demanding constraints on the design of surface-based habitat systems. Ensuring structural safety, thermal stability, and environmental resilience is therefore essential for sustained human presence on Mars. Surface habitats must withstand a substantial pressure differential between a pressurized interior and the surrounding Martian atmosphere while maintaining acceptable internal living conditions. Thermal control becomes critical due to low ambient temperatures and limited atmospheric insulation, necessitating effective passive thermal protection strategies. Solar radiation, although lower than Earth levels, introduces additional thermal loading during daytime exposure, while Martian winds and dust-laden flows influence external loading, flow separation, and potential dust accumulation around surface structures. Previous studies have highlighted the importance of habitat geometry, material selection, and multilayer wall configurations in addressing these challenges. However, many investigations consider isolated physical effects or single environmental conditions. For early-stage habitat design, an integrated assessment that simultaneously accounts for structural, thermal, solar, and aerodynamic responses is required to support informed design decisions. In this work, a conceptual surface-mounted Mars habitat is analyzed using a unified numerical framework. Structural performance under internal pressurization, thermal response of a multilayer wall system, solar radiation effects for multiple representative Martian dates, and aerodynamic behavior under Martian wind conditions are systematically evaluated. By comparing cylindrical and curved habitat geometries and examining

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the role of insulation and regolith integration, this study identifies key design trends relevant to preliminary Mars habitat development.

2. Martian Environmental Conditions and Adopted Parameters

The design and evaluation of a surface-based Mars habitat require a realistic representation of the Martian environment, particularly atmospheric pressure, thermal conditions, solar radiation, and near-surface winds. The environmental parameters adopted in this study are selected to represent typical daytime conditions at an equatorial Martian location and are applied consistently across all analyses to enable direct comparison between different cases.

2.1 Atmospheric and Pressure Conditions

Mars is characterized by extremely low atmospheric pressure, resulting in a substantial pressure differential across pressurized habitat structures. For the present study, the following pressure conditions are adopted:

- External atmospheric pressure: 600 Pa
- Internal habitat pressure: 101,325 Pa

These values represent a conservative and realistic scenario for human-rated surface habitats, corresponding to Earth-like internal conditions and typical near-surface Martian atmospheric pressure.

2.2 Thermal Environment

The Martian surface experiences low average temperatures along with significant diurnal variation. Based on available Martian climate data, a representative ambient temperature is adopted for all thermal and solar analyses:

- Ambient surface temperature: 211 K (−62 °C)
- Internal habitat temperature: 20 °C

To maintain clarity and ensure consistent comparison across cases, the ambient temperature is held constant in all simulations. This approach allows the influence of wall configuration and external loading conditions to be isolated from temperature variability.

2.3 Solar Radiation Conditions

Solar radiation represents an important external thermal load for surface-mounted habitats during daytime exposure. To account for seasonal variability, solar flux values corresponding to four representative Martian dates are considered. These values are applied under steady-state conditions at local noon.

Table 1. Adopted solar radiation parameters for selected Martian dates (Meridiani Planum, 12:00 LMST).

Mars Year	Earth Date	Ambient Temperature (K)	Solar Flux (W/m²)	Wind (m/s)
MY48	February 01, 2045	211	326	8.1
MY49	December 18, 2046	211	333 (highest)	4.3
MY50	November 3, 2048	211	320	2.8
MY51	September 20, 2050	211	327	9.8

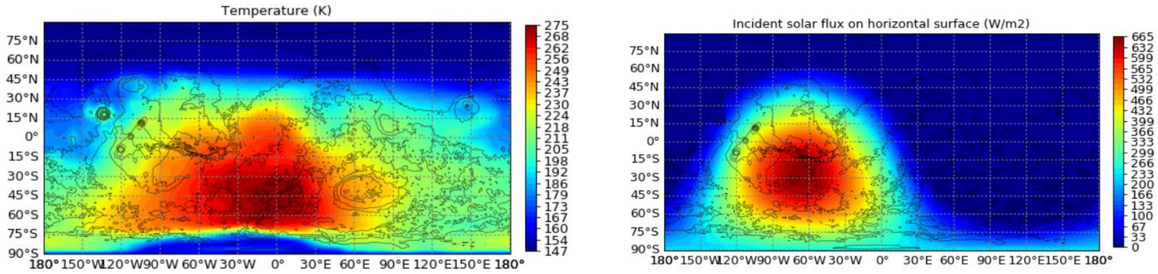


Figure.1 - Representative Martian surface temperature and solar flux distribution at Meridiani Planum (Mars Climate Database v6.1).

The selected dates span multiple Martian years and allow assessment of habitat thermal response under varying solar loading while maintaining identical ambient temperature conditions.

2.4 Wind Conditions

Near-surface winds on Mars can influence external loading and flow behavior around surface structures. In the present study, aerodynamic analysis is conducted using a single representative wind velocity of 25 m/s, corresponding to a conservative high-wind scenario. This approach is adopted because the primary objective of the aerodynamic analysis is geometric comparison, and the drag coefficient consistently remains lower for curved configurations irrespective of wind speed variation.

2.5 Summary of Adopted Parameters

For clarity, the key environmental parameters used throughout this study are summarized below:

- External pressure: 600 Pa
- Internal pressure: 101,325 Pa
- Ambient temperature: 211 K
- Internal temperature: 20 °C
- Solar flux: 320-333 W/m² (date-specific)
- Wind velocity (aerodynamic analysis): 25 m/s

3. Methodology

An integrated numerical methodology is adopted in this study to evaluate the structural, thermal, solar, and aerodynamic performance of a conceptual surface-based Mars habitat. The primary objective of the methodology is to enable consistent comparison between different habitat configurations and environmental loading scenarios while maintaining reasonable computational efficiency suitable for early-stage design assessment. All simulations are performed using a finite element and computational fluid dynamics framework. Structural behavior is evaluated independently under internal pressurization, while thermal and solar effects are analyzed using steady-state heat transfer models. Aerodynamic performance is assessed through external flow simulations around surface-mounted habitat geometries under representative Martian wind conditions. To ensure consistency across all analyses, geometric dimensions, material properties, and boundary conditions are kept identical wherever applicable. Parametric variations are introduced only where required, such as in the application of date-specific solar flux values. A two-dimensional modeling approach with a unit-depth assumption is employed throughout the study. This approach is commonly adopted in preliminary design investigations and allows direct comparison of habitat responses under identical conditions while significantly reducing computational cost.

The overall analysis procedure followed in this study is summarized as follows:

- Definition of representative Martian environmental and operating conditions
- Geometry modeling of candidate habitat configurations
- Structural pressure analysis under internal pressurization
- Steady-state thermal analysis of the multilayer wall system
- Solar flux analysis for selected Martian dates
- Aerodynamic analysis under representative wind conditions

Material behavior is assumed to be linear elastic for structural analysis, and heat transfer is modeled using conduction through solid layers with convective heat loss at external surfaces. Radiative heat exchange, coupled thermo-structural effects, and particle-based dust transport are not explicitly modeled in order to maintain focus on the primary structural, thermal, and aerodynamic responses relevant to early-stage habitat design.

4. Geometry Modeling and Structural Assessment

Two candidate habitat geometries are considered to evaluate the influence of shape on structural and aerodynamic performance: a cylindrical configuration and a curved configuration represented by a hemispherical shell. These geometries are selected due to their relevance in pressurized habitat design and their contrasting curvature characteristics.

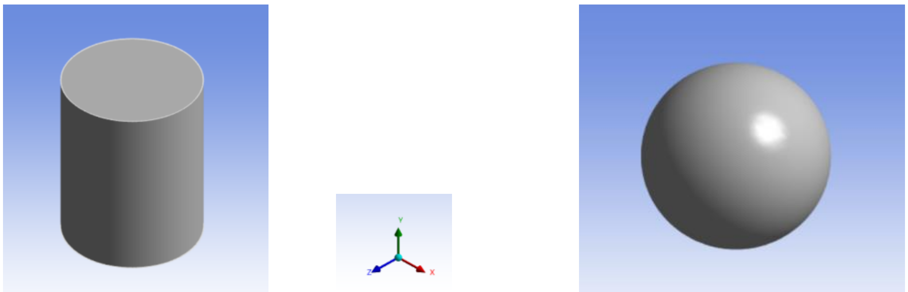


Figure.2- Representation of cylindrical and curved/dome habitat geometries considered in this study.

The cylindrical habitat is modeled with a radius of 4 m and a height of 10 m, representing a vertically oriented surface-mounted module. The curved habitat is modeled as a hemispherical shell with a radius of 4 m, representing a dome-type configuration placed directly on the Martian surface. Both geometries are represented using a two-dimensional model with a unit-depth assumption to enable efficient and consistent comparison.

For both configurations, the primary structural shell is assumed to be made of an aluminum alloy with a uniform wall thickness of 0.005 m. In subsequent thermal analyses, additional wall layers are added on the interior side of the structural shell, consisting of a regolith layer of thickness 0.015 m and an insulation layer of thickness 0.01 m, resulting in a total wall thickness of 0.03 m.

Structural assessment is performed by subjecting each geometry to internal pressurization representative of a human-rated environment, while the external surface is exposed to the low ambient Martian atmospheric pressure. The base of each habitat is constrained to represent contact with the Martian surface. Identical material properties, wall thicknesses, and loading conditions are applied to both configurations to isolate the influence of geometry on structural response.

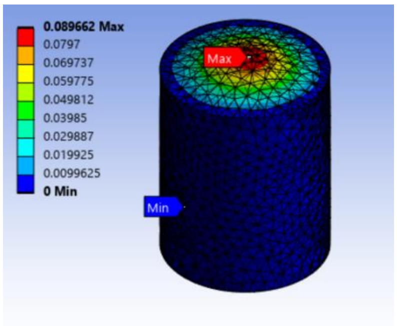


Figure. 3- Total deformation contour of Cylindrical Habitat Configuration.

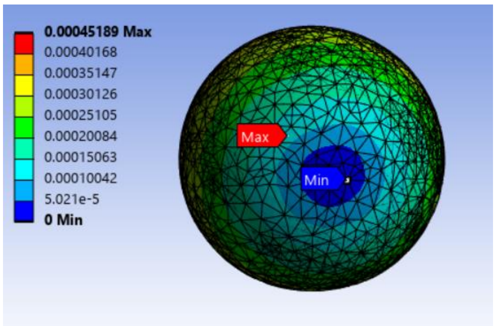


Figure. 4- Total deformation contour of the curved habitat configuration .

The structural response is evaluated in terms of total deformation resulting from the applied pressure differential. The maximum deformation values obtained for each geometry are summarized in Table 2.

Table 2. Structural deformation comparison

Geometry	**Max Deformation (m)**
Cylinder	0.089
Curved/Dome structure	0.00045

The results indicate a substantial reduction in deformation for the curved configuration compared to the cylindrical form. This behavior is attributed to the more uniform distribution of stresses in the hemispherical geometry under internal pressurization. Based on this comparison, the curved configuration is identified as structurally more efficient and is therefore selected for subsequent thermal, solar, and aerodynamic analyses.

4.1 Structural Stress Assessment

Along with the overall deformation, the structural behavior of both habitat shapes was checked with the equivalent, or von Mises, stress idea. In Figure 5 and Figure 6, you can see the stress patterns that came out for the cylindrical and the curved habitat layouts respectively.

For the cylindrical setup, the maximum equivalent stress reached 164.38 MPa, and the maximum principal stress was 165.33 MPa. Meanwhile for the curved habitat, the equivalent stress was much lower at 7.81 MPa, and its maximum principal stress was 9.29 MPa. This big drop, is generally explained by the fact that the curved geometry helps spread the pressure- induced loads more evenly across the structure, so the stress doesn’t spike as much.

On the material side, the structural shell was represented as a general aluminum alloy, with a tensile yield strength of 280 MPa. Then, using those peak equivalent stress numbers, the factors of safety were computed for both designs. The cylindrical habitat ended up with a factor of safety close to 1.70, while the curved habitat gave a much higher value, around 35.86.

Table 3. Structural stress assessment of the habitat configuration.

Parameter	Cylindrical Configuration	Curved Configuration
Maximum Principal Stress (MPa)	165.33	9.29
Maximum Equivalent (von Mises) Stress (MPa)	164.38	7.81
Yield Strength (MPa)	280	280
Factor of Safety	1.70	35.86

From the stress distribution, you can see that higher stresses mostly show up in limited zones, mostly around areas where the pressure- induced loading is strongest, and where structural constraints are tight. But even so the maximum equivalent stress still stays under the material tensile yield strength. So basically the habitat structure is staying in the elastic regime for the loading case that was applied.

Overall these findings suggest that the chosen structural layout can handle the imposed pressure differential, without transitioning into yielding, which is good and all.

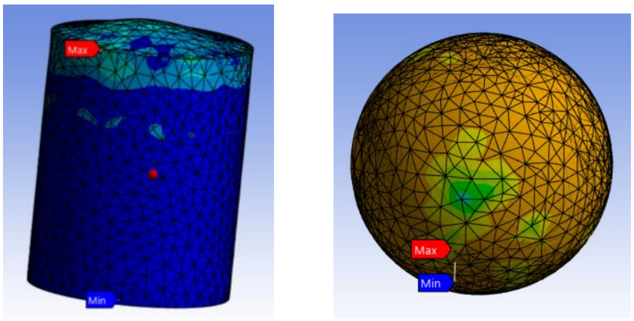


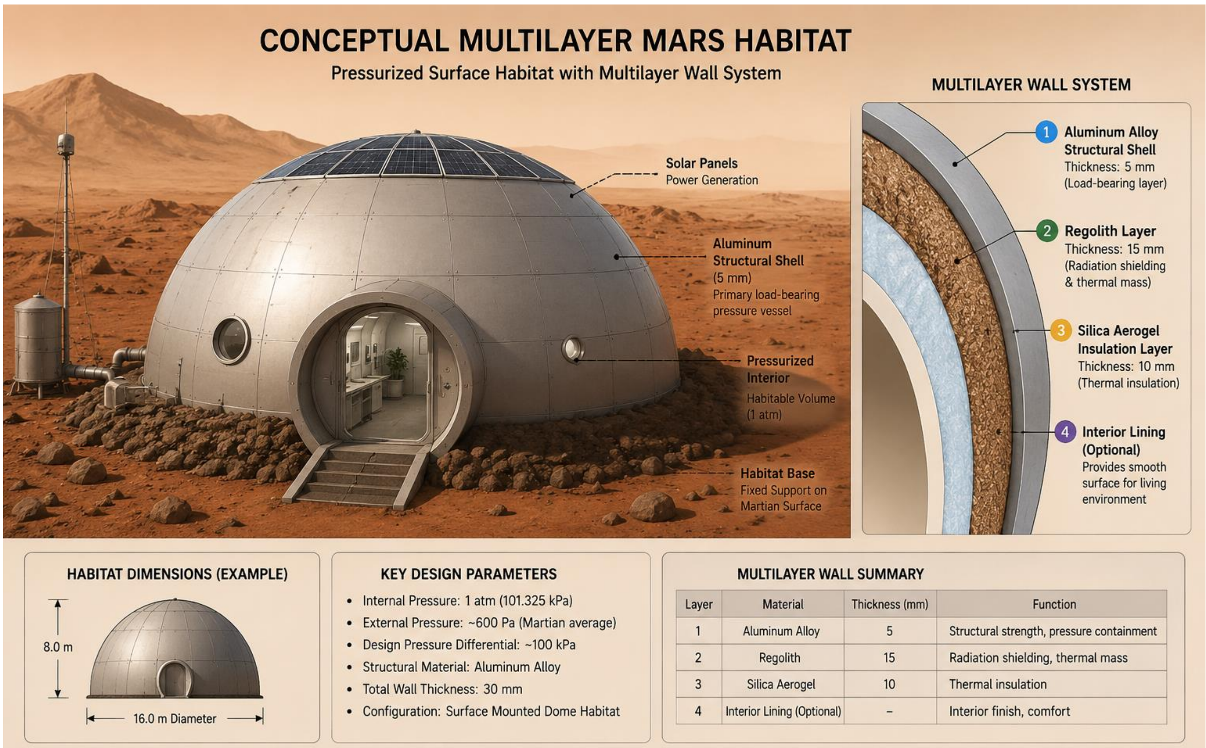
Figure 5. Equivalent (von Mises) stress distribution for the cylindrical and curved habitat configurations under internal pressurization.

4.2 Conceptual Habitat Configuration

Figure X presents a conceptual illustration of the proposed surface-based Mars habitat considered in this study.The whole idea uses a curved dome shaped geometry , which came up from the structural check as being a more efficient setup than the cylindrical option when the habitat is under internal pressurization. This concept also has a multi layer wall arrangement, meaning there is an outer aluminum structural shell, then a Martian regolith layer, and finally a silica aerogel insulation layer around the pressurized area that people would actually live in.

The aluminum shell works as the main load carrying component, so it has to hold the internal pressure and also push back against the external environmental forces. The regolith layer, on the other hand , is mainly there for thermal buffering and thermal mass effects, basically it helps damp temperature swings. Meanwhile the silica aerogel insulation layer reduces conductive heat transfer, between the inside of the habitat and the Martian exterior. In combination these layers become one integrated wall system , aimed at improving both structural behavior and thermal steadiness under the kind of Martian conditions we consider representative in this work.

The conceptual configuration shown in Figure X is provided to illustrate the design approach adopted throughout the structural, thermal, solar, and aerodynamic analyses presented in this study. The illustration is intended for visualization purposes only and is not drawn to scale.



KEY DESIGN PARAMETERS

- Internal Pressure: 1 atm (101.325 kPa)
- External Pressure: ~600 Pa (Martian average)
- Design Pressure Differential: ~100 kPa
- Structural Material: Aluminum Alloy
- Total Wall Thickness: 30 mm
- Configuration: Surface Mounted Dome Habitat

MULTILAYER WALL SUMMARY

Layer	Material	Thickness (mm)	Function
1	Aluminum Alloy	5	Structural strength, pressure containment
2	Regolith	15	Radiation shielding, thermal mass
3	Silica Aerogel	10	Thermal insulation
4	Interior Lining (Optional)	–	Interior finish, comfort

Figure 6. Conceptual illustration of the proposed surface-based Mars habitat showing the curved habitat geometry and multilayer wall configuration adopted in the present study.

5. Thermal Analysis of the Habitat Wall System

Thermal analysis is conducted to evaluate the ability of the habitat wall system to maintain internal thermal stability under Martian surface conditions. A multilayer wall configuration is adopted to provide passive thermal protection against low ambient temperatures and external thermal loads. Steady-state thermal analysis is performed to quantify heat loss characteristics under representative Martian environmental conditions.

5.1 Multilayer Wall Configuration and Material Properties

The habitat wall is modeled as a three-layer system consisting of an external aluminum structural shell, an intermediate regolith layer, and an internal insulation layer. This configuration combines structural integrity, utilization of locally available materials, and effective thermal insulation.

- Aluminum alloy (structural shell): thickness = 0.005 m
- Martian regolith (thermal mass layer): thickness = 0.015 m
- Insulation layer (silica aerogel): thickness = 0.01 m

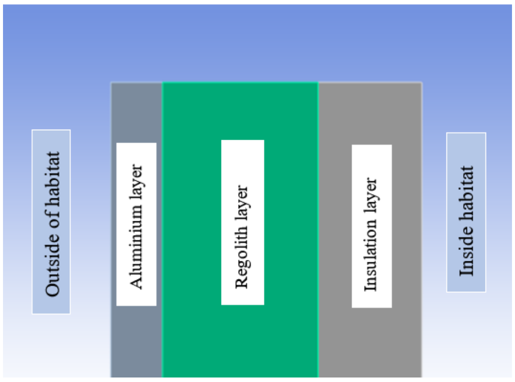


Figure. 7 - Multilayer wall schematic

Silica aerogel is selected as the insulation material due to its extremely low thermal conductivity and established use in aerospace thermal protection systems. Martian regolith is modeled as a homogeneous solid to represent its thermal mass contribution and insulating behavior when compacted.

The material properties adopted for thermal modeling are summarized in Table 3. These values are selected from published experimental and numerical studies and represent typical ranges reported for Martian regolith simulants and silica aerogel insulation.

Table 4. Material properties used in thermal analysis.

Material	**Density (kg/m³)**	**Thermal Conductivity (W/m·K)**	**Specific Heat (J/kg·K)**
Aluminum alloy	2700	205	900
Martian regolith (simulant)	1600	0.9	750
Silica aerogel (insulation)	120	0.02	1000

These properties are assumed to be temperature-independent over the range considered, which is reasonable for early-stage thermal assessment.

5.2 Steady-State Thermal Analysis

Steady-state thermal analysis is performed to quantify conductive heat loss through the habitat wall under constant ambient conditions. The internal surface temperature is maintained at 20 °C, while the external surface is exposed to a representative Martian ambient temperature of 211 K. Heat transfer through the multilayer wall is modeled using conduction within the solid layers and convective heat loss at the exterior surface.

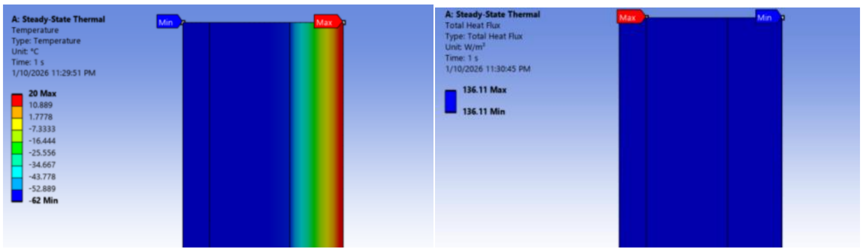


Figure. 8- Temperature contour and Heat flux contour for multilayer wall configuration with insulation

The resulting temperature distribution shows a pronounced temperature drop across the insulation layer, indicating its dominant role in limiting heat transfer. The regolith layer further enhances thermal resistance by reducing the temperature gradient reaching the structural shell. These results provide a baseline assessment of wall thermal performance under cold Martian surface conditions.

5.3 Insulation Effectiveness Assessment

To isolate the contribution of the insulation layer, an additional steady-state thermal analysis is conducted using a wall configuration consisting only of aluminum and regolith, while maintaining the same total wall thickness.

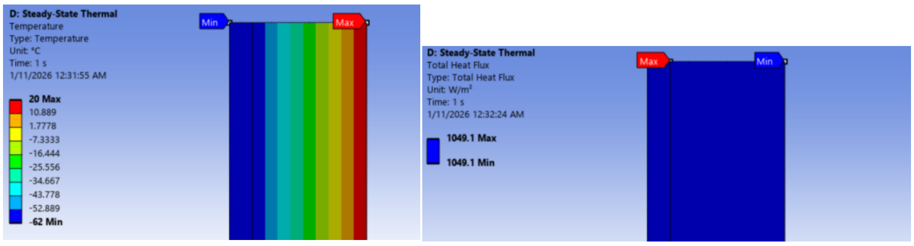


Figure. 9- Temperature contour and Heat flux contour for wall configuration without insulation .

The results show a substantial increase in conductive heat flux through the wall compared to the insulated case, indicating significantly higher heat loss.

Table 5- Heat flux comparison

Configuration	**Average heat flux (W/m^2)**
Aluminium + Regolith	1049.1
Aluminium + Regolith + Insulation	136

This comparison clearly demonstrates that regolith alone is insufficient for effective thermal protection. The inclusion of a low-conductivity insulation layer is shown to be critical for maintaining habitable internal thermal conditions under Martian surface environments.

6. Solar Flux Analysis for Multiple Martian Dates

Solar radiation introduces an additional external thermal load on surface-mounted habitats during daytime exposure on Mars. Although overall solar irradiance on Mars is lower than that on Earth, its influence on external wall temperature and conductive heat transfer remains relevant, particularly for long-duration surface operations. In this study, solar flux analysis is performed to evaluate the thermal response of the habitat wall system under representative seasonal conditions .

Table 6- Solar flux values for four representative Martian dates.

Mars Year	**Solar Flux (W/m^2)**	**Wind (m/s)**
MY48	326	8.1
MY49	333 (high)	4.3 (low)
MY50	320	2.8
MY51	327	9.8

Solar loading is modeled using steady-state thermal analysis by applying a uniform heat flux to the exterior aluminum surface of the habitat wall. Convective heat transfer between the habitat surface and the Martian atmosphere is included to account for wind-driven heat dissipation. The internal habitat temperature is maintained at 20 °C, consistent with previous thermal analyses, while the ambient external temperature is fixed at 211 K to isolate the effect of solar radiation. To capture seasonal variation, solar flux values corresponding to four representative Martian dates are considered. These dates span multiple Martian years and reflect variations in incident solar radiation under local noon conditions. The adopted solar flux values range from 320 to 333 W/m², as summarized in Section 2.

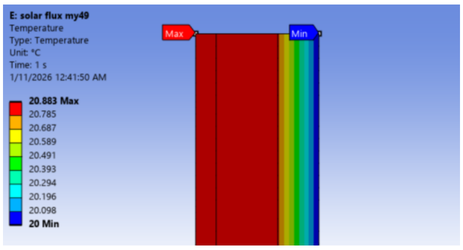


Figure. 10 - Temperature contour under solar flux loading for MY49 (worst-case solar condition).

The results indicate that solar radiation causes a moderate increase in external surface temperature; however, the multilayer wall system effectively limits heat penetration into the habitat interior. Across all four cases, the conductive heat flux transmitted through the wall remains low, and the internal surface temperature remains close to the regulated value. A comparison across the four Martian dates shows only minor variation in heat flux and internal temperature despite changes in solar irradiance. This demonstrates that the proposed wall configuration maintains robust thermal performance across seasonal variations in solar loading, supporting its suitability for long-term surface habitation.

7. Aerodynamic Analysis under Martian Wind Conditions

Aerodynamic analysis is performed to evaluate external flow behavior and wind-induced loading on surface-mounted Mars habitat configurations. Although the Martian atmosphere has low density, high wind speeds associated with dust storm events can influence external pressure distribution, flow separation, and drag forces acting on surface structures. Understanding these effects is important for assessing habitat stability and surface interaction under realistic Martian conditions.

The analysis considers two habitat geometries: a cylindrical configuration and a curved configuration represented by a hemispherical shape. Both geometries are placed on a flat ground surface within a sufficiently large computational domain to minimize boundary effects. The Martian atmosphere is modeled as carbon dioxide with constant thermophysical properties representative of near-surface conditions.

A steady-state flow analysis is conducted using a representative wind velocity of 25 m/s, corresponding to a conservative high-wind scenario. Turbulence effects are captured using the shear-stress transport (k–ω SST) model, which is well suited for predicting flow separation and wake formation around bluff bodies. The ground and habitat surfaces are modeled with a uniform surface roughness to represent regolith-covered terrain.

Flow field characteristics are examined using velocity contours and streamlines. The cylindrical configuration exhibits early flow separation and the formation of a large downstream recirculation region, resulting in an extended wake. In contrast, the hemispherical configuration promotes smoother flow attachment and delayed separation, producing a smaller wake and a more uniform downstream velocity distribution.

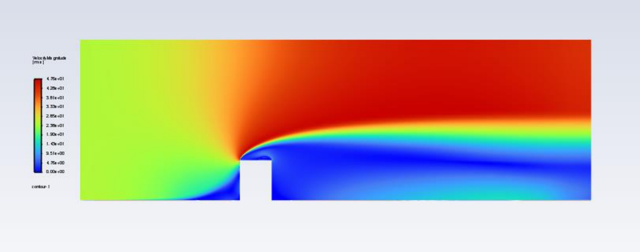


Figure. 11. Velocity contour for the cylindrical habitat configuration.

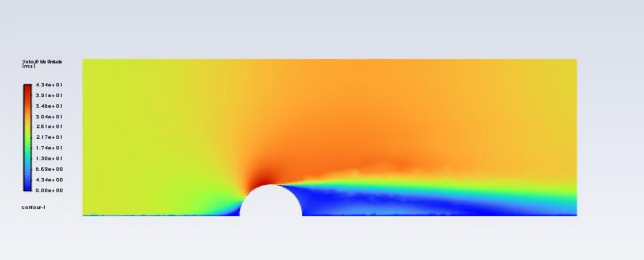


Figure. 12. Velocity contour for the hemispherical habitat configuration.

Aerodynamic performance is quantified using drag force values. The cylindrical geometry exhibits significantly higher drag due to pronounced flow separation and wake formation. The hemispherical configuration shows a substantially lower drag value, indicating improved aerodynamic efficiency. This trend remains consistent across wind speed variations, demonstrating that habitat geometry is the dominant factor governing aerodynamic response.

Table. 7- Aerodynamic comparison of habitat geometries.

Habitat Geometry	**Drag Force (N)**
Cylinder	191.07
Curved/Dome structure	27.32

Overall, the results confirm that curved habitat geometries offer clear aerodynamic advantages for Mars surface applications. Reduced drag and smoother flow behavior lower wind-induced loading and may also mitigate dust accumulation around surface structures, supporting the selection of curved configurations for surface-based Mars habitation.

8. Integrated Discussion

The integrated structural, thermal, solar, and aerodynamic analyses provide complementary insights into the performance of surface-based Mars habitat configurations under representative Martian conditions. When considered collectively, the results highlight the strong influence of habitat geometry and wall composition on overall feasibility and performance.

Structural pressure analysis demonstrates that habitat geometry plays a critical role in resisting the large pressure differential between a pressurized interior and the Martian atmosphere. Curved configurations exhibit significantly reduced deformation compared to cylindrical forms due to more uniform stress distribution, making them structurally more efficient for sustained pressurized operation.

Thermal analyses further emphasize the importance of wall configuration. Steady-state results show that the combined use of low-conductivity insulation and regolith significantly limits conductive heat loss and moderates temperature gradients across the habitat wall. The insulation layer is identified as the dominant contributor to thermal resistance, while the regolith layer provides additional resistance and beneficial thermal mass. Comparative analysis without insulation confirms that regolith alone is insufficient to maintain thermal stability under Martian surface conditions.

Solar flux analysis conducted for multiple representative Martian dates indicates that seasonal variations in solar irradiance introduce only minor changes in conductive heat transfer when an appropriate multilayer wall system is employed. Internal habitat temperatures remain effectively regulated across all cases, demonstrating the robustness of the proposed wall configuration against solar-induced thermal loading.

Aerodynamic analysis reveals that external flow behavior and wind-induced loading are strongly governed by habitat geometry. Curved configurations promote smoother flow attachment, smaller wake regions, and significantly lower drag coefficients than cylindrical geometries. These characteristics reduce wind-induced loading and may also help mitigate dust accumulation around the habitat during high-wind events.

Overall, the combined results indicate that a curved habitat geometry integrated with a multilayer wall system consisting of an aluminum structural shell, regolith, and low-conductivity insulation offers a balanced solution to the primary structural, thermal, and aerodynamic challenges associated with Mars surface habitation. The integrated approach adopted in this study supports informed design trade-offs during early-stage habitat development.

9. Conclusions

An integrated numerical assessment of a conceptual surface-based Mars habitat has been conducted to evaluate structural, thermal, solar, and aerodynamic performance under representative Martian environmental conditions. The study focuses on early-stage design considerations relevant to long-duration surface habitation. Structural pressure analysis shows that habitat geometry has a strong influence on deformation under internal pressurization. Curved configurations demonstrate significantly improved structural efficiency compared to cylindrical forms due to more uniform load distribution, supporting their suitability for pressurized Mars habitats. Thermal analysis of a multilayer wall system highlights the importance of combining low-conductivity insulation with a regolith layer. Steady-state results confirm that insulation is the dominant factor in reducing conductive heat loss, while regolith provides additional thermal resistance and beneficial thermal mass. A comparative case without insulation reveals substantially higher heat transfer, confirming that regolith alone is insufficient for maintaining habitable thermal conditions. Solar flux analysis performed for four representative Martian dates indicates that seasonal variations in solar irradiance produce only minor changes in internal thermal response when an appropriate multilayer wall system is employed. The habitat interior remains effectively regulated across all cases, demonstrating robustness against solar-induced thermal loading. Aerodynamic analysis under representative high-wind conditions shows that curved habitat geometries result in lower drag coefficients and reduced wake formation compared to cylindrical configurations. This behavior reduces wind-induced loading and may help mitigate dust accumulation around surface structures. Overall, the results indicate that a curved habitat geometry combined with an aluminum structural shell, regolith integration, and low-conductivity insulation provides an effective and balanced solution to the primary structural, thermal, and aerodynamic challenges of Mars surface habitation. The integrated methodology adopted in this study offers a practical framework for preliminary habitat design and can be extended in future work to include radiation shielding, dust transport, and coupled thermo-structural effects.

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11. Conflict of Interest

The author declares no competing conflict of interest.

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