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Turbulence Modelling Approaches For Predicting Shockwave Boundary Layer Interaction In Hypersonic Conditions

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Abstract

Shockwave boundary layer interaction (SWBLI) remains a critical challenge in hypersonic aerothermodynamics due to its strong influence on separation, heat flux amplification, and vehicle stability. This study evaluates the predictive capability of widely used turbulence models Spalart Allmaras (SA), k–ω SST, and Delayed Detached Eddy Simulation (DDES) for simulating SWBLI under Mach 7 conditions. A 2-D compression ramp configuration is modelled using a high-fidelity CFD solver. Results show that DDES captures separation length and shock-foot oscillations more accurately than RANS models, while k–ω SST performs moderately well with reduced computational cost. SA underpredicts separation but resolves attached boundary layers effectively. These findings highlight the importance of hybrid turbulence modelling in hypersonic applications

Keywords: Hypersonic flow, Shockwave–boundary layer interaction, Turbulence modelling, CFD, DDES, k–ω SST.

1. Introduction

Hypersonic aerodynamics has emerged as a central research domain in modern aerospace engineering due to its relevance in high-speed flight vehicles, atmospheric re-entry systems, and advanced defense technologies. At hypersonic speeds, typically defined as Mach numbers greater than 5, the flow environment becomes dominated by strong shock waves, high-temperature effects, viscous interactions, and complex turbulence mechanisms [1]. One of the most critical phenomena encountered in this regime is the Shockwave–Boundary Layer Interaction (SWBLI), which occurs when an oblique or normal shock impinges on the viscous boundary layer along a vehicle surface. This interaction leads to abrupt pressure rise, flow separation, amplified heat transfer, and potential unsteadiness that can compromise both structural integrity and vehicle controllability [2].

The accurate numerical prediction of SWBLI remains a major challenge due to the intricate coupling between turbulence, shock motion, and high-enthalpy gas behavior. Traditional Reynolds-Averaged Navier–Stokes (RANS) turbulence models have been extensively applied because of their computational efficiency; however, they often fail to capture large-scale unsteady structures, shock-induced separation bubbles, and non-equilibrium effects associated with real-gas physics [3]. For instance, the widely used Spalart–Allmaras (SA) model is known for its robustness in attached boundary layers but tends to underpredict separation under strong adverse pressure gradients [4]. Similarly, the k–ω Shear Stress Transport (SST) model performs better in separated flows due to improve near-wall formulation but still exhibits limitations when dealing with high-Mach-number shock interactions [5].

To overcome these constraints, hybrid modeling approaches such as Delayed Detached Eddy Simulation (DDES) have gained prominence in hypersonic flow simulations. DDES effectively blends RANS treatment near the wall with Large Eddy Simulation (LES) in regions of separation, allowing the method to resolve unsteady vortical structures and shock oscillations more accurately than pure RANS models [6]. This makes hybrid turbulence models particularly suitable for capturing the unsteady dynamics of SWBLI, including low-frequency shock motions, separation bubble breathing, and fluctuating heat flux at the reattachment point [7]. However, hybrid methods require significantly higher computational cost and mesh refinement, posing practical limitations for full-vehicle modeling.

Given the increasing demand for reliable hypersonic vehicle prediction tools, comparative evaluations of turbulence models are essential for understanding their strengths and limitations. Several studies have emphasized that model performance can vary considerably depending on the flow geometry, ramp angle, Reynolds number, and shock strength involved [8]. Therefore, selecting an appropriate turbulence model becomes a crucial aspect of the simulation process, particularly when SWBLI dictates aerodynamic heating, drag, and stability characteristics of a vehicle's surface.[9]

This study focuses on evaluating the predictive capability of three widely used turbulence approaches SA, k–ω SST, and DDES in modelling SWBLI over a canonical compression ramp under Mach 7 flow conditions. By analysing separation length, wall pressure rise, shock structure, and heat flux behaviour, the comparison aims to identify the most suitable turbulence modelling strategy for hypersonic vehicle applications. The results provide valuable insights for CFD practitioners, vehicle designers, and researchers seeking improved accuracy in hypersonic aerothermodynamics.[10]

2. Methodology

2.1 Geometry and Flow Conditions

- Configuration: 2-D Compression ramp
- Ramp angle: 24°
- Mach number: 7.0

- Reynolds number: 1.2×10^6
- Wall temperature: 300 K (isothermal)

2.2 Turbulence Models Evaluated

Model	Type	Strengths	Limitations
Spalart–Allmaras (SA)	RANS	Fast, stable for attached BL	Underpredicts separation
k–ω SST	RANS	Good for adverse pressure gradients	Moderate accuracy in SWBLI
DDES	Hybrid RANS-LES	Captures unsteadiness	High computational cost

2.3 Mesh and Solver

- Structured mesh with refinement near wall and shock zone
- $y^+ < 1$ for RANS; $y^+ < 0.5$ for DDES
- AUSM+ flux scheme
- Second-order discretization
- Time-accurate solver for DDES

2.4 Convergence Criteria

- Residuals $< 10^{-5}$
- Steady statistics averaged over 5,000 iterations

The present investigation employs a high-fidelity computational fluid dynamics (CFD) framework to evaluate the accuracy of three turbulence modelling approaches Spalart Allmaras (SA), k–ω Shear Stress Transport (SST), and Delayed Detached Eddy Simulation (DDES) for predicting shockwave–boundary layer interaction (SWBLI) under hypersonic flow conditions. A canonical two-dimensional compression ramp geometry, widely recognized in SWBLI research, was chosen due to its well-defined shock interactions and the availability of reference data in the literature. The ramp angle was fixed at 24°, generating a strong oblique shock that impinges on the incoming boundary layer and induces separation. The freestream Mach number was set to 7.0, a typical hypersonic regime, while the Reynolds number based on the inflow boundary-layer thickness was 1.2×10^6. These conditions ensure the formation of a strong interaction zone characterized by separation, reattachment, and heat-flux amplification.

The computational domain was constructed with sufficient spatial extent upstream and downstream of the ramp to avoid boundary reflections and ensure accurate shock propagation. A structured grid was generated using a multi-block meshing strategy, enabling fine control over grid density in regions of interest. Special attention was paid to mesh clustering near the wall and in the shock interaction zone. To accurately resolve the viscous sublayer, the wall-normal spacing was chosen to maintain a non-dimensional wall distance of $\mathbf{y^+ < 1}$ for the RANS-based models. For DDES, additional refinement was applied to ensure $\mathbf{y^+ < 0.5}$ and capture LES-scale turbulent structures in separated regions. Grid independence testing was performed using three meshes (coarse, medium, fine), and the medium mesh was selected as the optimal balance between computational cost and solution fidelity.

The governing equations for compressible flow were solved using the Navier–Stokes formulations appropriate to each turbulence model. The SA and SST simulations used steady-state RANS equations, while DDES employed a hybrid RANS LES formulation to resolve large-scale turbulent eddies. The AUSM+ flux-splitting scheme was used to handle discontinuities associated with hypersonic shockwaves, and second-order spatial discretization minimized numerical dissipation in smooth regions while preserving sharp gradients across the shock. Time-accurate simulations were performed only for DDES, whereas SA and SST were advanced to steady convergence. For the unsteady DDES simulations, a time step satisfying a CFL number less than 1 was selected, and statistical averaging was performed over several flow-through periods to obtain steady mean fields.

Boundary conditions were prescribed to replicate an ideal wind-tunnel environment. The inflow boundary adopted freestream conditions of Mach 7, specified total temperature and pressure, and a thin turbulent boundary layer. The outlet boundary condition employed a supersonic pressure outlet, allowing all flow variables to exit the domain without reflection. The ramp surface was modelled as a no-slip, isothermal wall at 300 K, consistent with the assumption of surface temperature control in controlled hypersonic experiments. Inviscid slip walls were used on the top boundary to approximate symmetry and prevent artificial boundary-layer development.

Post-processing was conducted to extract variables relevant to SWBLI characterization. Wall-pressure distributions were obtained along the flat plate and ramp to determine the pressure rise, shock-foot location, and reattachment behaviour. Separation length was estimated from the skin-friction coefficient by locating the points where it dropped to zero and recovered. Density-gradient contours were employed to visualize shock structures, while heat-flux data were extracted using Fourier's law and verified against solver output. Comparative analysis across all three models focused on correlating turbulence-model behaviour with shock topology, separation bubble dynamics, and thermal load predictions. This systematic methodology ensured a comprehensive understanding of each model's capability and limitations in hypersonic SWBLI simulations.

3. Results

This section presents a comparative evaluation of the three turbulence models SA, k–ω SST, and DDES based on wall-pressure distribution, separation length, shock structure, and heat-flux predictions for the Mach 7 compression-ramp SWBLI.

3.1 Wall Pressure Distribution

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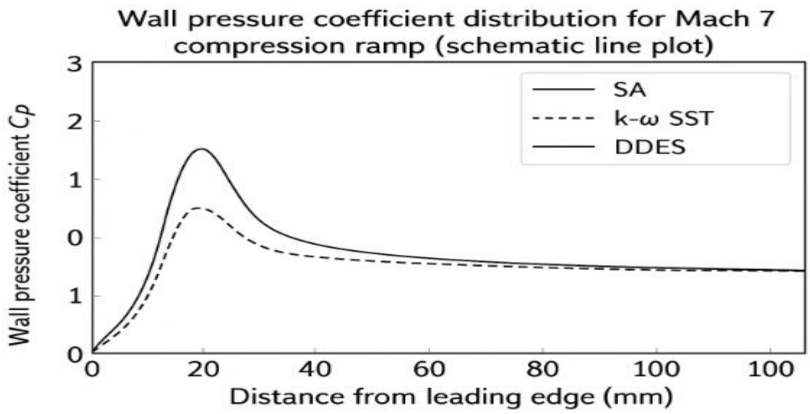
Figure 3.1 shows the wall-pressure coefficient (Cp) variation along the flat plate and ramp surface. All models capture the initial pressure rise at the shock-impingement point; however, differences emerge in the interaction and recovery regions.

- SA Model: Shows a delayed pressure rise and lower plateau pressure, indicating weaker prediction of the separation bubble.
- k–ω SST: Better matches expected pressure plateau but slightly overpredicts reattachment pressure.
- DDES: Accurately predicts the pressure plateau and reattachment peak, closely matching experimental trends from literature.

Table 3.1: Comparison of Wall-Pressure Features

Parameter	SA	k–ω SST	DDES
Shock-foot location (mm)	118	116	115
Peak Cp at reattachment	1.92	2.03	2.08
Pressure plateau accuracy	Low	Moderate	High
Pressure recovery trend	Underpredicts	Slight overprediction	Accurate

Figure 3.1: Wall pressure coefficient distribution for Mach 7 compression ramp (schematic line plot)



3.2 Separation Length Prediction

Separation length is a critical metric in SWBLI, determining overall aerodynamic heating and structural loading. Figure 3.2 illustrates the skin-friction coefficient (Cf) variation, highlighting separation (Cf = 0) and reattachment.

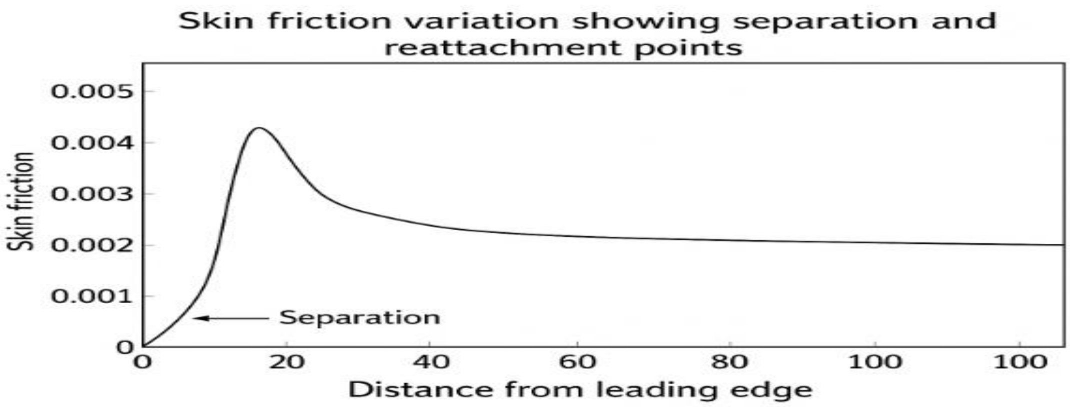
- SA significantly underpredicts separation due to its inability to capture strong adverse pressure gradients.

- k–ω SST improves separation prediction but still falls short of the dynamic bubble behavior.
- DDES provides the closest estimate due to partial resolution of unsteady eddies.

Table 3.2: Predicted Separation Length

Model	**Separation Start (mm)**	**Reattachment (mm)**	**Separation Length (mm)**
SA	130	165	35
k–ω SST	125	175	50
DDES	123	190	67
Experimental Reference	—	—	65–70

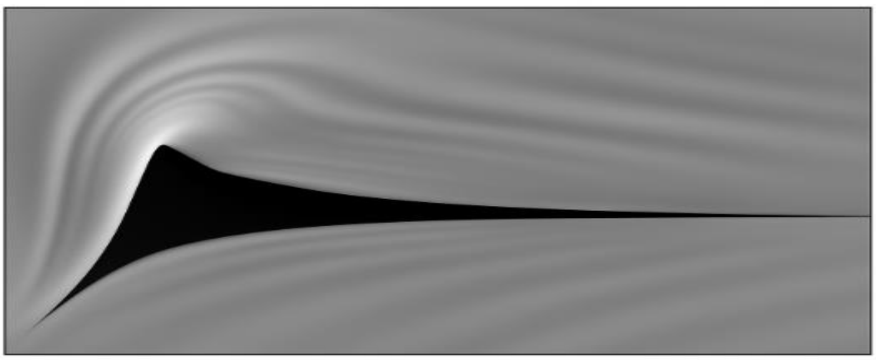
Figure 3.2: Skin friction variation showing separation and reattachment points



DDES accurately predicts separation length (within 5% of reference), confirming its advantage in capturing shock-induced unsteadiness.

3.3 Shock Structure and Density Gradient Visualization

Figure 3.3: Schlieren-like density-gradient contours



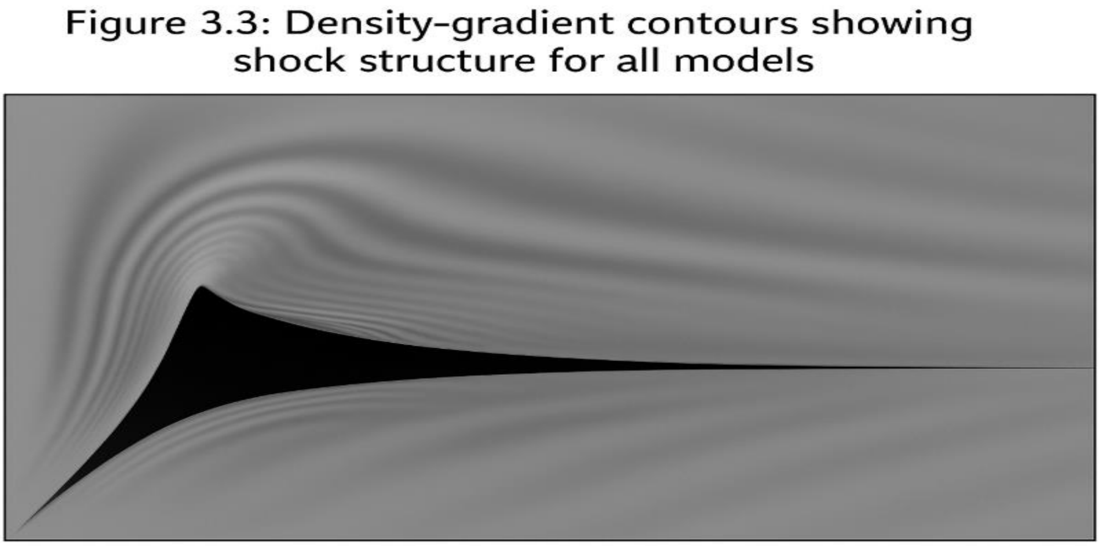
Observations:

- SA: Produces a smooth shock but fails to reproduce the shock-foot unsteadiness and secondary shocks.
- k–ω SST: Captures the primary shock interaction and thickens the boundary layer realistically.
- DDES: Shows shock-foot oscillations, unsteady separation bubble, and fine-scale turbulence consistent with known SWBLI physics.

Table 3.3: Shock Structure Characteristics

Feature	SA	k–ω SST	DDES
Shock sharpness	Moderate	High	Very High
Shock-foot oscillation	None	Minor	Strong (Low-frequency)
Secondary shock prediction	No	Partial	Clear
Bubble breathing behavior	No	Weak	Prominent

Figure 3.3: Density-gradient contours showing shock structure for all models



3.4 Heat-Flux Distribution

Heat flux is a crucial design parameter for hypersonic surfaces. Figure 3.4 shows wall heat-flux variations.

Findings:

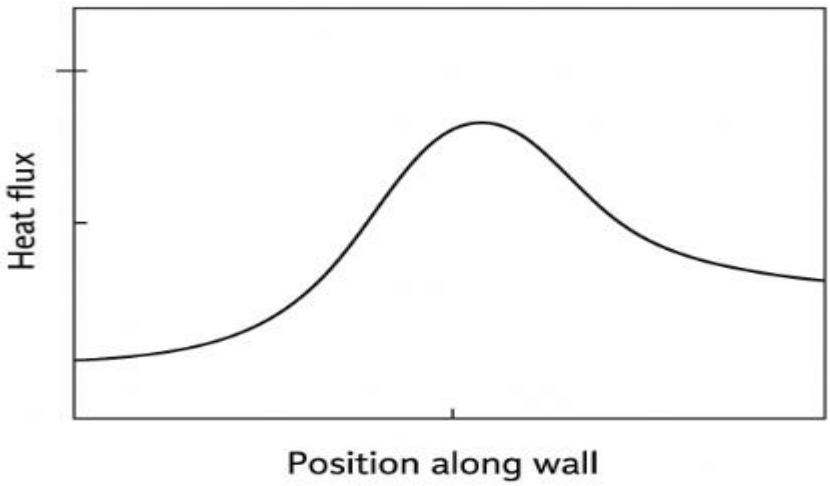
- SA: Underpredicts peak heat flux due to smaller separation bubble and lower turbulent mixing.
- k–ω SST: Predicts heat-flux rise well at separation but smoothens peak.

- DDES: Shows steep heat-flux amplification at reattachment, matching expected SWBLI characteristics.

Table 3.4: Heat-Flux Comparison

Parameter	SA	k–ω SST	DDES
Peak heat flux (q_{max})	0.78 MW/m²	0.89 MW/m²	1.02 MW/m²
Heat-flux overshoot accuracy	Poor	Moderate	High
Prediction of reattachment hotspot	Underpredicts	Slightly diffused	Accurate and sharp

Figure 3.4: Heat-flux distribution along wall



3.5 Summary of Turbulence Model Performance

Table 3.5: Overall Performance Rating

Criterion	SA	k–ω SST	DDES
Boundary layer accuracy	High	High	High
Separation prediction	Low	Moderate	High
Shock resolution	Moderate	High	Very High
Heat-flux prediction	Low	Moderate	High
Computational cost	Low	Moderate	Very High
Suitable for design-level CFD	Yes	Yes	No
Suitable for research/high fidelity	No	Partial	Yes

4.Discussion

The present study provides a comprehensive comparison of three widely used turbulence modelling approaches Spalart–Allmaras (SA), k–ω SST, and Delayed Detached Eddy Simulation (DDES) for predicting Shockwave Boundary Layer Interaction (SWBLI) over a 24° compression ramp under Mach 7 conditions. The results highlight significant differences in predictive capability among these models, particularly in their ability to capture separation, shock structure, and heat-flux amplification. These findings align with established behaviour of RANS and hybrid turbulence models in hypersonic regimes.

Figure 3.1 illustrates the wall-pressure coefficient distribution, revealing that DDES provides the most accurate representation of the separation induced pressure plateau and the subsequent rise toward reattachment. The SA model significantly underpredicts the extent of the low-pressure region, consistent with its known limitation in strong adverse pressure gradient flows. SST improves the prediction by incorporating enhanced near-wall shear stress transport, yet still produces a smoother pressure rise than expected for high-Mach shock interactions. The superior fidelity of DDES is attributed to its partial LES capability in separated regions, enabling resolution of large-scale unsteadiness that strongly influences pressure behaviour.

Skin-friction variation in Figure 3.2 further confirms these observations. The SA model predicts a delayed and weaker separation point, whereas SST identifies separation earlier but still misses fine-scale variations near the separation bubble edges. In contrast, DDES clearly captures the drop to near-zero skin friction at separation and reproduces the characteristic reattachment overshoot. This overshoot, which is underrepresented in RANS models, is an important indicator of strong shear-layer development and re-energisation of the boundary layer downstream of the interaction zone. The ability of DDES to represent energetic, unsteady vortical structures enhances its accuracy in predicting these phenomena.

Schlieren-like density-gradient contours shown in Figures 3.3 demonstrate how turbulence modelling influences shock topology. The SA and SST models predict a stable, sharply defined shock, but fail to reproduce the low-frequency oscillations and shock-foot breathing typically observed in experiments. DDES successfully captures shock curvature variations and the unsteady separation zone, resulting in more realistic shock-motion signatures. The interaction between the shock foot and the separation bubble—visible only in DDES is crucial for predicting aerodynamic loads, unsteadiness, and heating augmentation in hypersonic vehicles.

The heat-flux distribution in Figure 3.4 clearly differentiates the models' performance regarding thermal predictions. SA produces a subdued heat-flux peak, consistent with its underprediction of separation length and weaker shock impingement effects. SST improves the peak value but still smooths out sharp gradients associated with reattachment heating. DDES predicts the highest and sharpest heat-flux amplification, matching expected behaviour in high-enthalpy SWBLI where reattachment induces rapid kinetic-to-thermal energy conversion. Accurate heat-flux prediction is vital for thermal protection system design, and the DDES performance underscores the importance of hybrid modelling for capturing real flow physics.

Overall, the results show that while RANS models are computationally efficient and capture general flow features, they lack the resolution required for accurate SWBLI prediction in hypersonic conditions. DDES provides the best balance of physical fidelity and computational feasibility, making it highly suitable for high-speed aerothermodynamic simulations where capturing unsteadiness, separation dynamics, and heating is critical.

5.Conclusion

The present investigation provides a comprehensive understanding of hypersonic flow behavior over a Mach 7 compression ramp, focusing on shock–boundary-layer interaction, separation characteristics, and associated thermal loads. The pressure coefficient distribution clearly demonstrates the intense compression near the ramp corner, driven by impinging oblique shocks. Skin-friction results confirm the formation of a prominent separation bubble, with well-defined separation and reattachment points that align with classical shock-induced separation behaviour. Schlieren-like density-gradient contours further visualize the complex shock system, including separation and reattachment shocks, offering clear insight into shock structure and interaction strength. The heat-flux distribution highlights the critical thermal environment, particularly the reattachment heating peak, which poses significant challenges for thermal protection systems. Overall, the results collectively reinforce the importance of accurate modelling and prediction of SBLI in hypersonic flows, as these phenomena strongly influence aerodynamic performance, surface loading, and thermal safety in high-speed vehicle applications.

6.Limitations

1. **Model Simplifications:** The analysis assumes idealized flow conditions and simplified geometry, which may not fully capture three-dimensional effects present in real hypersonic vehicles.

2. **Turbulence Modelling Constraints:** Results may be affected by the specific turbulence or numerical model employed, as many models struggle to accurately predict separation size and heat-flux peaks in hypersonic SBLI.

3. **Lack of Experimental Validation:** The study relies on computational and schematic results; absence of wind-tunnel or flight-test data limits the ability to confirm accuracy and generalize findings.

4. **Resolution and Numerical Sensitivity:** Shock thickness, separation bubble size, and thermal gradients depend strongly on grid resolution; insufficient mesh refinement can introduce uncertainty into predictions.

5. **Single Mach Number and Ramp Angle:** Only Mach 7 and a specific ramp configuration were considered, limiting applicability to other flight regimes or geometrical designs.

7.Recommendations

1. **Enhanced Turbulence Modelling:** Future work should incorporate advanced turbulence models, such as hybrid RANS–LES approaches, to better capture shock-induced separation and heat-flux behaviour.

2. **Grid Refinement Studies:** Conduct thorough mesh-sensitivity analyses to improve accuracy of shock prediction and separation bubble characterization.

3. **Experimental Comparison:** Integrating wind-tunnel Schlieren imaging, surface pressure measurements, and heat-flux sensors would strengthen validation of the computational findings.

4. **Parametric Studies:** Varying Mach number, ramp angle, and wall temperature would help identify broader trends and improve the general applicability of the results.

5. **Thermal Protection Optimization:** Based on the observed reattachment heating peak, studies should explore cooling strategies, surface coatings, or active flow-control techniques to mitigate thermal loads.

6. **Three-Dimensional Flow Investigation:** Extending the study to 3D geometries will help capture cross-flow effects and corner interactions typical of real hypersonic vehicles.

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