High-fidelity numerical simulation and modeling of boundary layer transition and heat transfer in hypersonic flows over blunt bodies with surface roughness and mass flux

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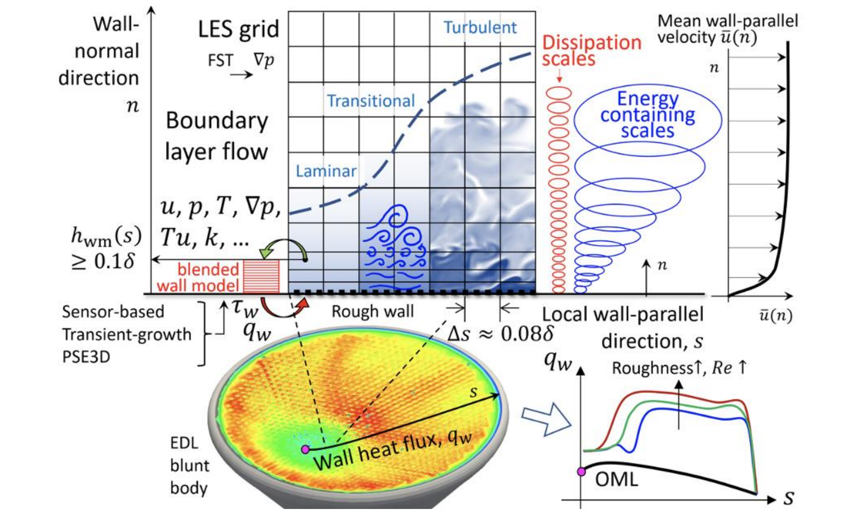
Research Objectives:

- To characterize the effects of distributed surface roughness, freestream turbulence, and mass flux on bypass transition and heat transfer augmentation in blunt-body hypersonic flows via high-fidelity numerical simulations.
- To enable accurate and feasible predictions of bypass transition by novel approaches to wall-modeled large-eddy simulation (WMLES).

+ Innovation: augmented, sensor-based, blended wall models that extend the range of applicability of WMLES throughout laminar, transitional, and turbulent regimes.
+ TRL level: 1 (start) and 1-2 (end).
Level 1: fundamental physical insight.
Level 2: model formulation, implementation, validation and testing in full-vehicle simulations.



Schematic of proposed method for improved prediction of surface heat flux on EDL blunt-body vehicles with roughness (bottom) with blended wall models that receive flow variables from the LES at a height (h_{wm}) and return wall shear stress (τ_w) and heat flux (q_w) for all flow regimes (top). Surface heat flux contour map (bottom left) adapted from Hollis (2019).

Approach:

- To augment WMLES by blending equilibrium wall models with:
  - A. Pohlhausen polynomials and transient-growth theory (in transitional regions).
  - B. 3D Parabolized Stability Equations (modeling laminar and transitional regions).
- Robust sensors will be integrated to identify flow regions (laminar, transitional, turbulent) and blend different boundary conditions.
- Three numerical simulation campaigns will be conducted, addressing different bypass transition scenarios relevant to EDL of blunt bodies:

1) Impact of distributed hexcomb-pattern roughness (e.g., ablative TPS).
2) Impact of large-scale roughness resulting from aero-induced deformation of flexible TPS.
3) Impact of mass flux injected by gas blowing through a porous surface (surrogate for ablative TPS out-gassing).

Potential Impact:

- The proposed research addresses critically missing elements of our understanding of blunt-body transition and provides high-fidelity, accurate modeling of heat flux distribution on EDL vehicles with complex geometric features, reducing uncertainties in the design of thermal protection systems for future space missions.
- The resulting insight and accurate modeling of bypass transition can directly impact other areas of aerospace (e.g., turbine design, engine stall, aerodynamic drag reduction), and multiple areas of mechanical, civil, environmental, and industrial engineering involving fluid flows.