Improvements to RANS Modeling for Aeroheating Predictions on Blunt Bodies

Clark Pederson
NASA Langley Research Center

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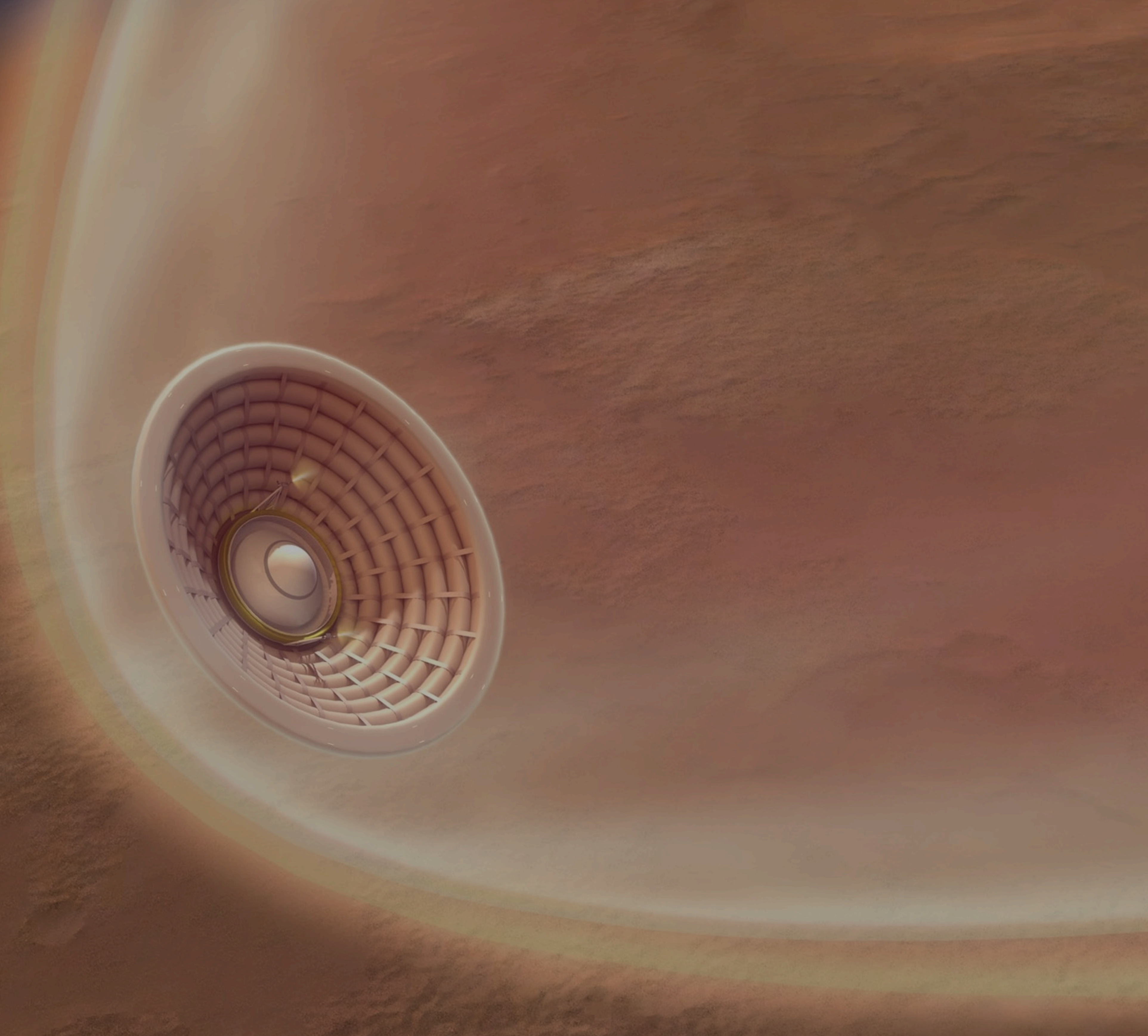
Motivation

- Missions are continually pushing for larger vehicles:
  - Orion crew module has a 28% larger diameter than the Apollo crew module
  - Crewed missions to Mars will require an order of magnitude larger payload
- Larger vehicles mean that turbulent convective heating is more significant
- There is a strong need for turbulence models that:
  - Predict heating on attached boundary layers with less than a 20% error
  - Give reasonable predictions for wake heating



Artist rendering of a Hypersonic Inflatable Aerodynamic Decelerator (HIAD) during Mars entry [Source: NASA].

Why RANS Models?

- Reynolds Averaged Navier-Stokes (RANS) models try to hit the right compromise of accuracy and computational cost.
- There are many cases where rapid solutions are desirable:
  - Comparing vehicle designs
  - Creating databases with hundreds of cases
  - Exploring parametric uncertainty
- While higher fidelity techniques such as wall-modeled LES are attractive, they are computationally expensive due to the wide range of scales on a flight vehicle.

Quick Survey of RANS Models

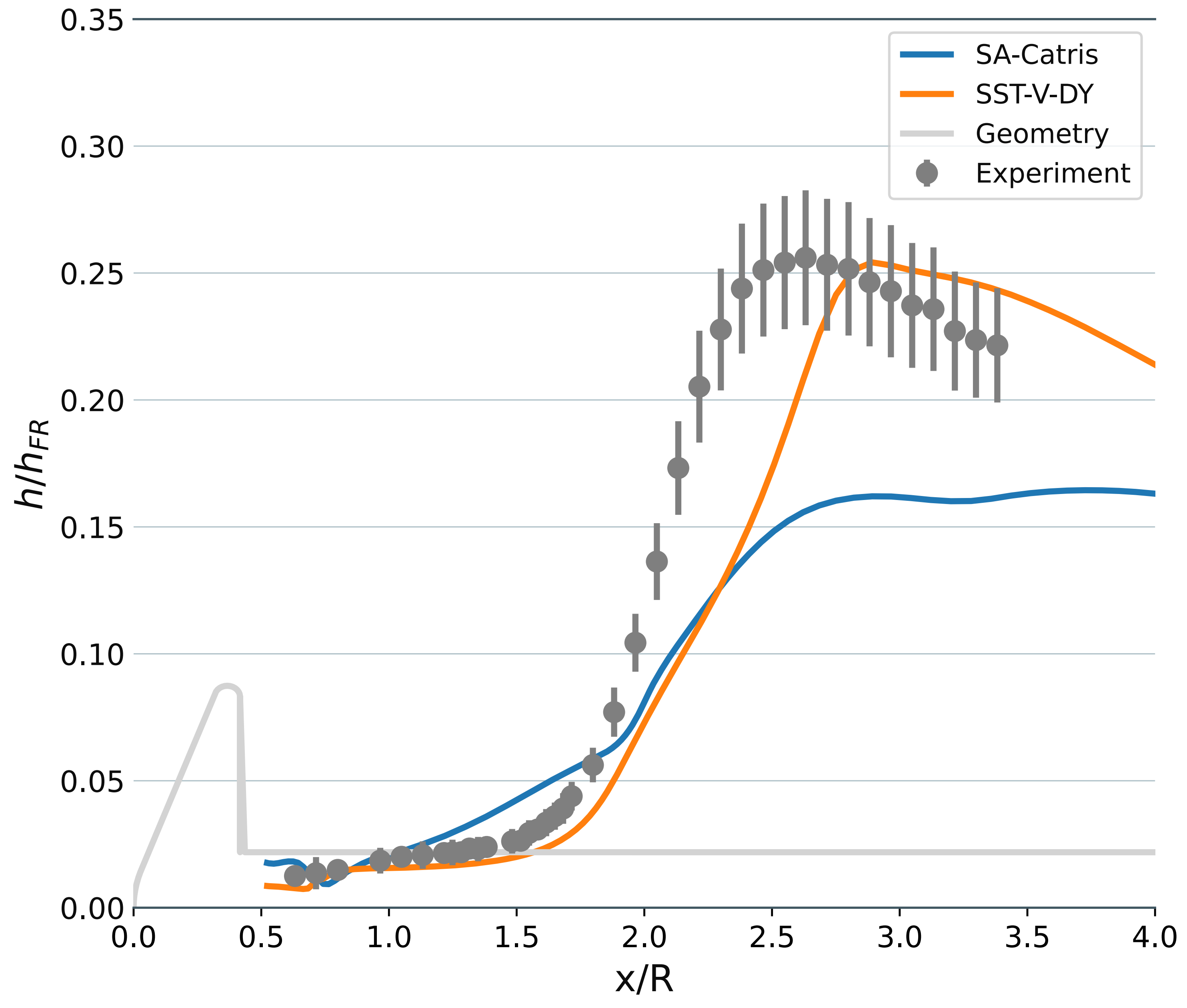
- Algebraic turbulence models **(Cebeci-Smith, Baldwin Lomax)**
  - ✔ Simple
  - ✔ Reasonable accuracy across various Mach numbers
  - ✘ Modeling assumptions fail for separated flows and wakes
- Spalart-Allmaras Models **(SA, SA-Catris)**
  - ✔ Robust
  - ✔ Correct behavior for strong shocks and stagnation-points
  - ✘ Poor predictions for supersonic, axisymmetric wakes
  - ✘ No model for turbulent kinetic energy
- k-ω Models **(SST, BSL, Wilcox2006)**
  - ✔ Have a model for turbulent kinetic energy
  - ✔ Good predictions for supersonic, axisymmetric wakes
  - ✘ Corrections needed for strong shocks and stagnation points
  - ✘ Not as robust

SA and SA-Catris are not accurate for supersonic, axisymmetric wakes

Quote from the original Spalart-Allmaras paper[1]:

> ⚠ **Warning**
>
> "We did not attempt to match any axisymmetric flow, partly because they are not prevalent in our applications and partly because, for most models, these flows conflict with the 2-D flows. The model is not intended to be universal."

Spalart has published multiple corrections for axisymmetric and compressible flows, which are outside the scope of this presentation.



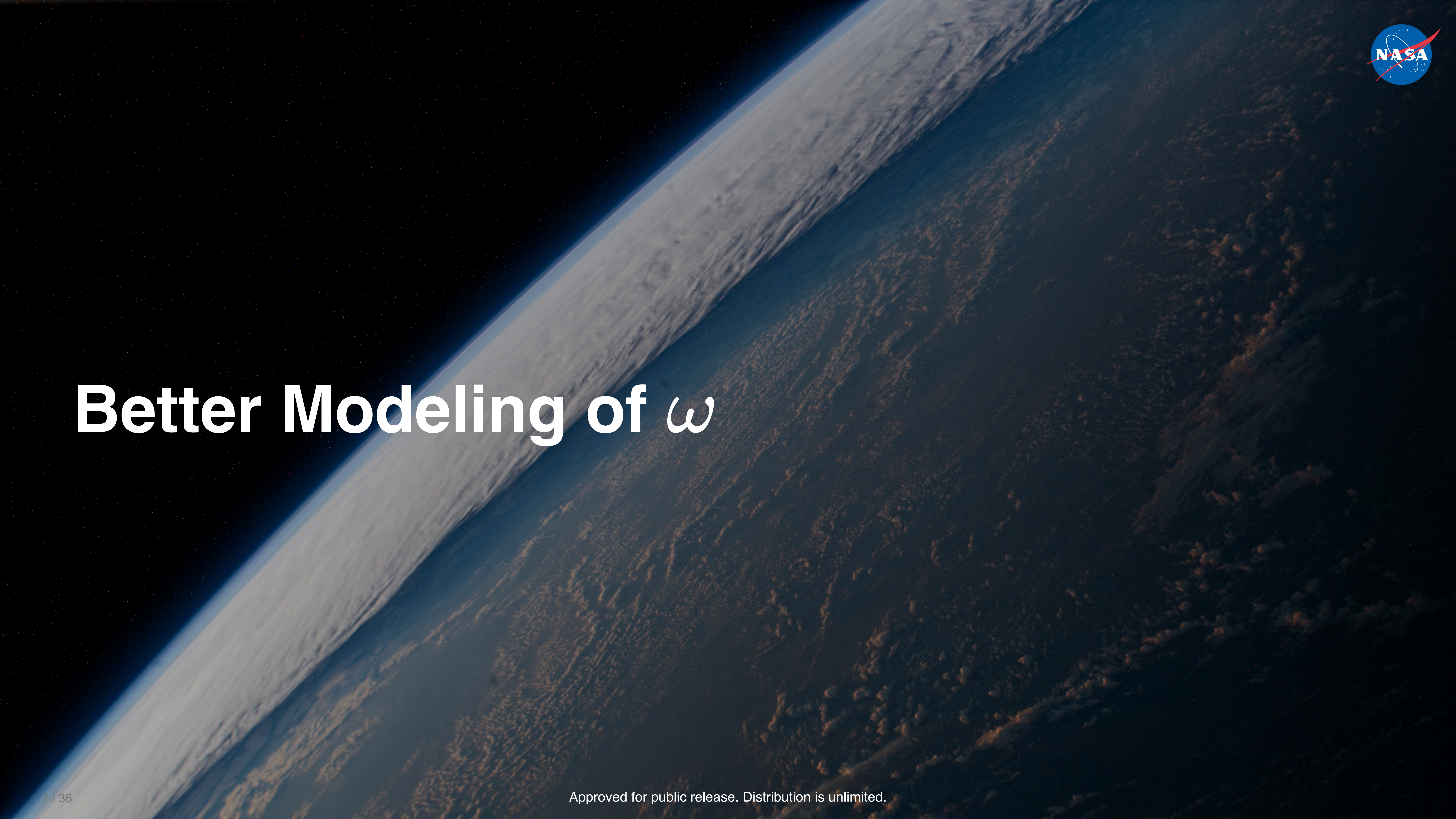
Film coefficient in the wake of a 70-degree sphere-cone at Mach 6, $Re_D = 3.6 \times 10^6$

1. Spalart-Allmaras, "A one-equation turbulence model for aerodynamic flows" doi:10.2514/6.1992-439

So How Can We Improve Predictions of Blunt-Body Aeroheating with k-ω Models?

Two key recommendations to improve k-ω simulations:

1. Better modeling of the ω equation
2. Limiting production at strong shocks and stagnation regions



Better Modeling of ω

Boundary Conditions on Omega

k-ω models solve and extra PDE for ω, which can be thought of as a turbulent frequency.

Unfortunely, the analytic boundary condition for ω at a solid surface is infinite.

For compressible flows, semi-local scaling suggests that ω should be:

$$\frac{\mu\omega}{\tau_w} \to \frac{6}{\beta(y^*)^2} \quad \text{as} \quad y^* \to 0$$

where $y^* = y\sqrt{\rho\tau_w}/\mu$ is the semi-local wall-distance and β is a model parameter.

Menter proposed the boundary condition:

$$\omega|_w = 10\frac{6\mu}{\rho\beta(\Delta y)^2}$$

where Δy is the first cell height.

Durbin-Yin Transformation

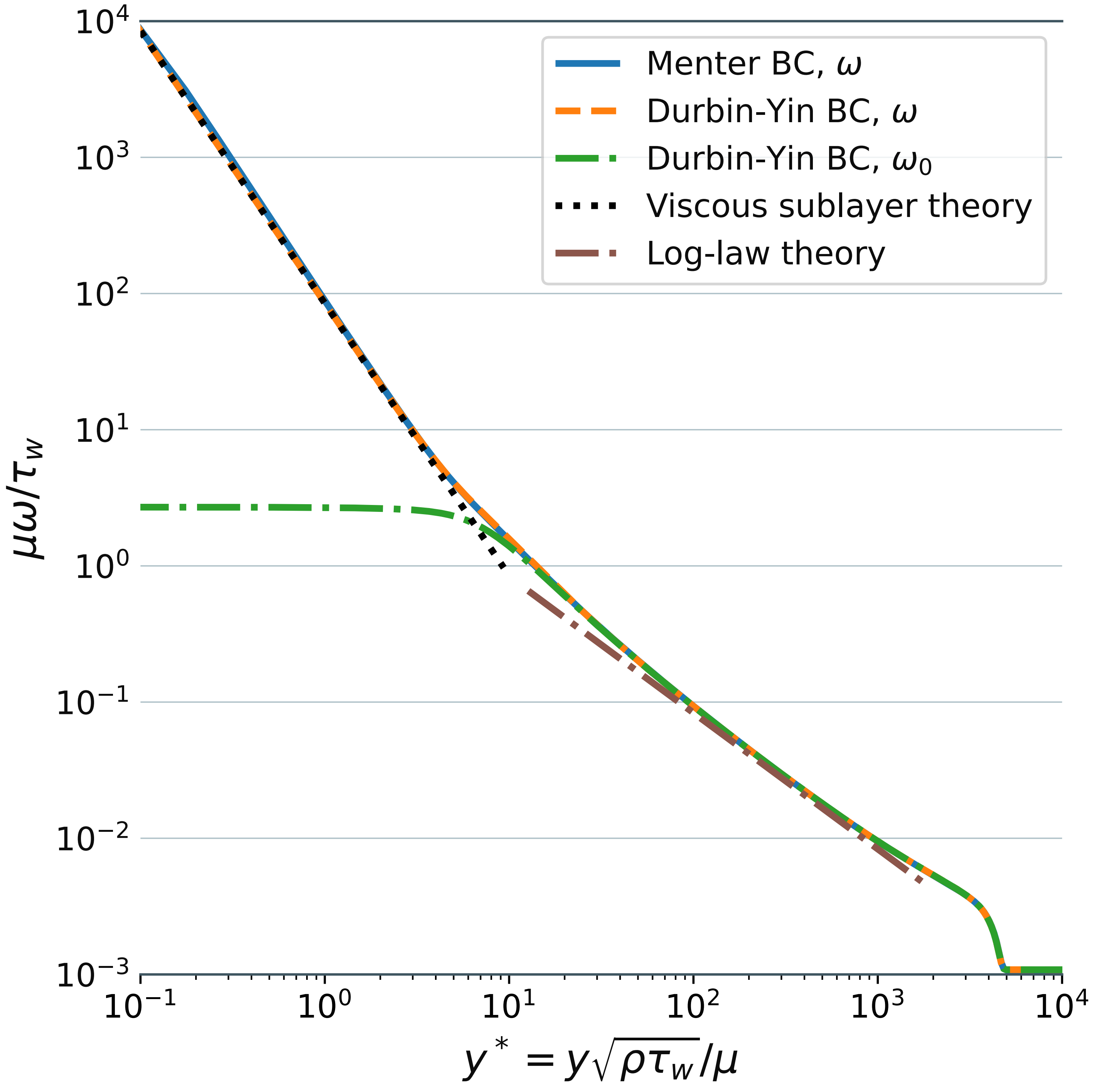
In a 2025 paper, Durbin and Yin[1] suggested a change-of-variables for ω:

- ω is replaced by a variable ω_0, which goes to a finite value at the wall.
- ω_0 and ω only differ in the viscous sublayer.

The two are related as:

$$\omega = \frac{6\mu}{\beta\rho y^2} F\left(\frac{\omega_0 \rho y^2}{\mu}\right)$$

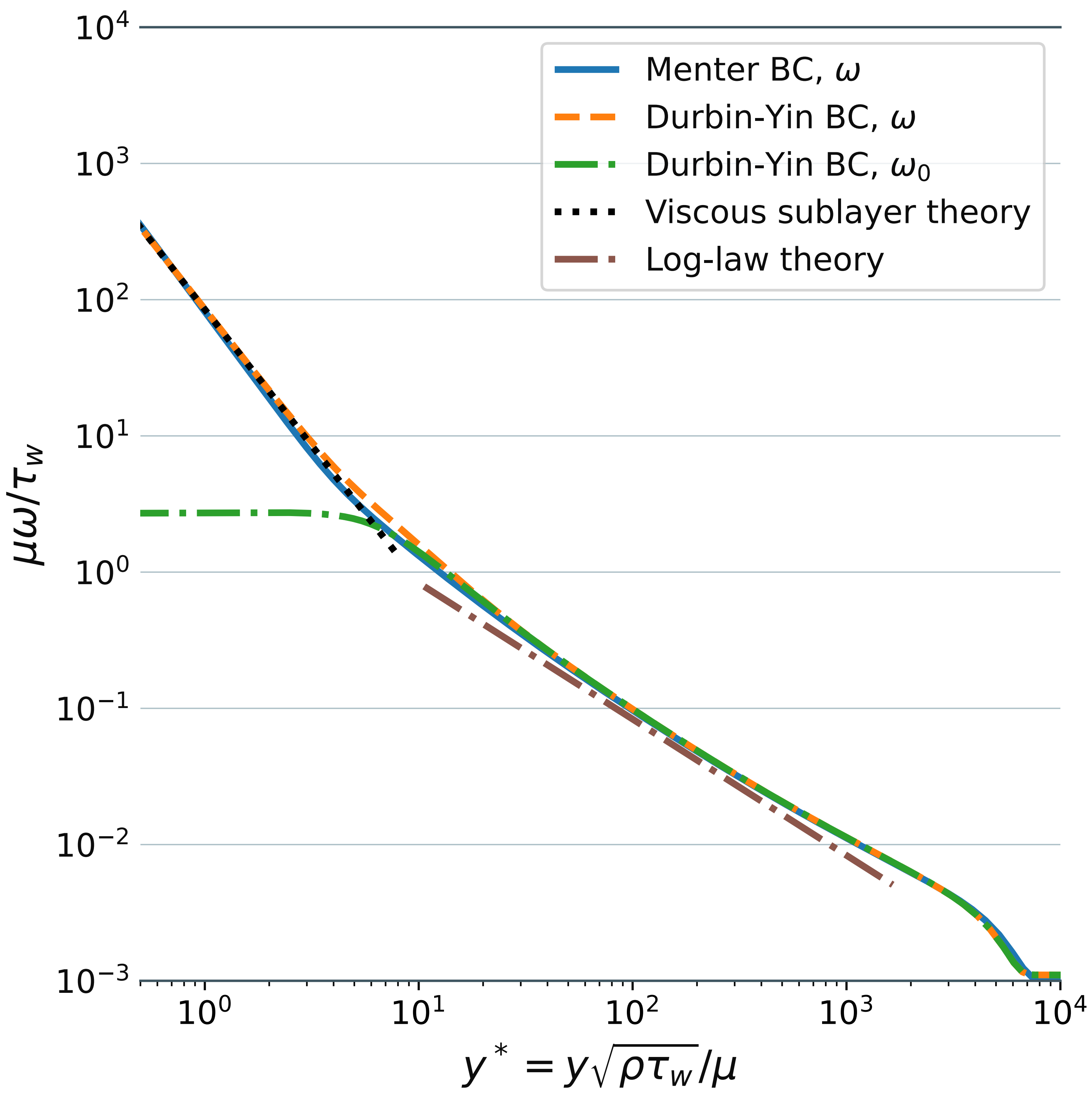
where $F(0) = 1$ and $F(x) \to x\beta/6$ as $x \to \infty$.



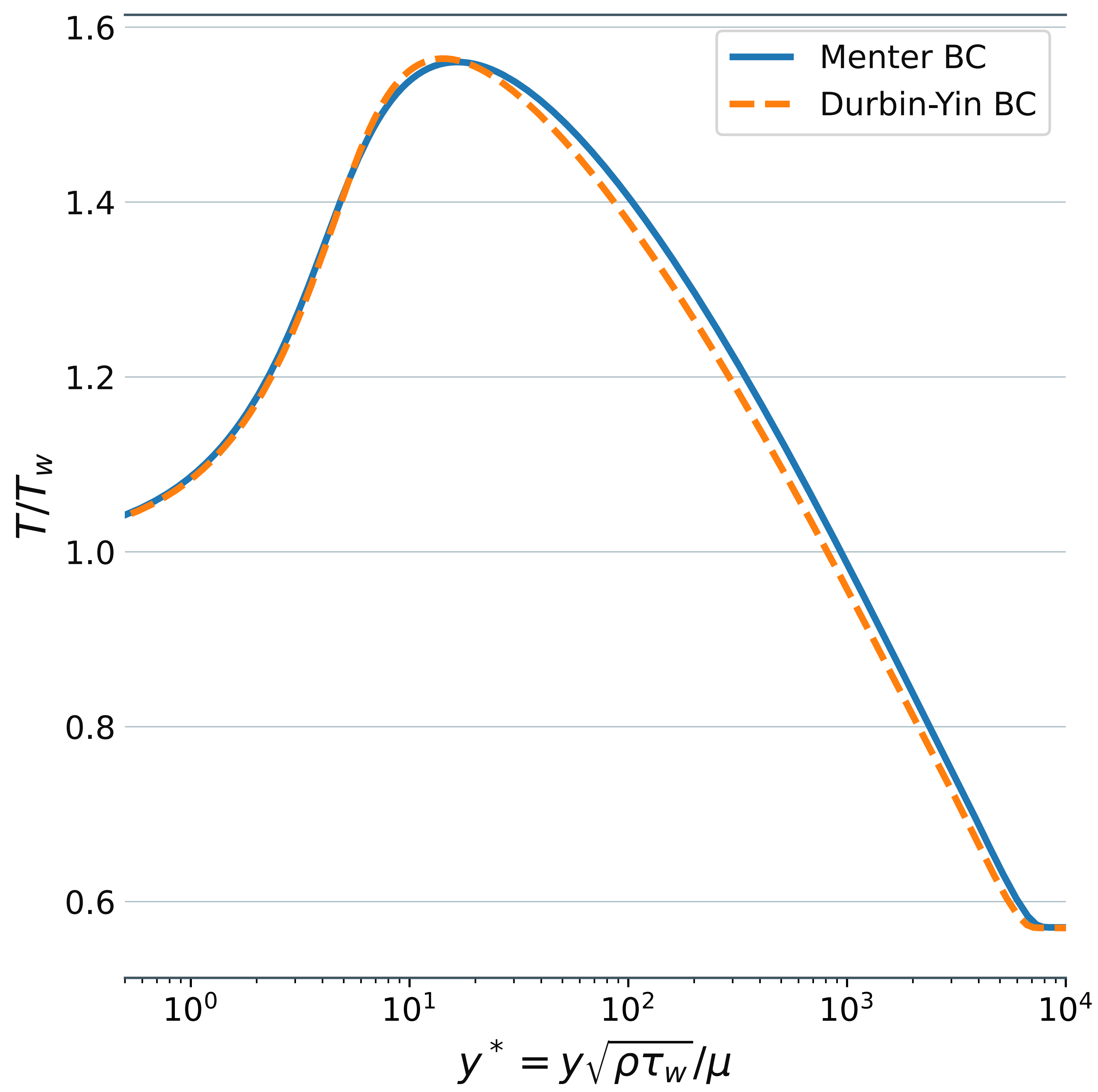
Wall-normal profile of ω and ω_0 in an adiabatic, flat-plate boundary layer at Mach 0.2

1. Durbin and Yin, “Reformulation of the ω Equation of the k–ω Model,” AIAA Journal, 2025, doi:10.2514/1.J066242

Effect of Durbin-Yin Transformation for Supersonic Flows

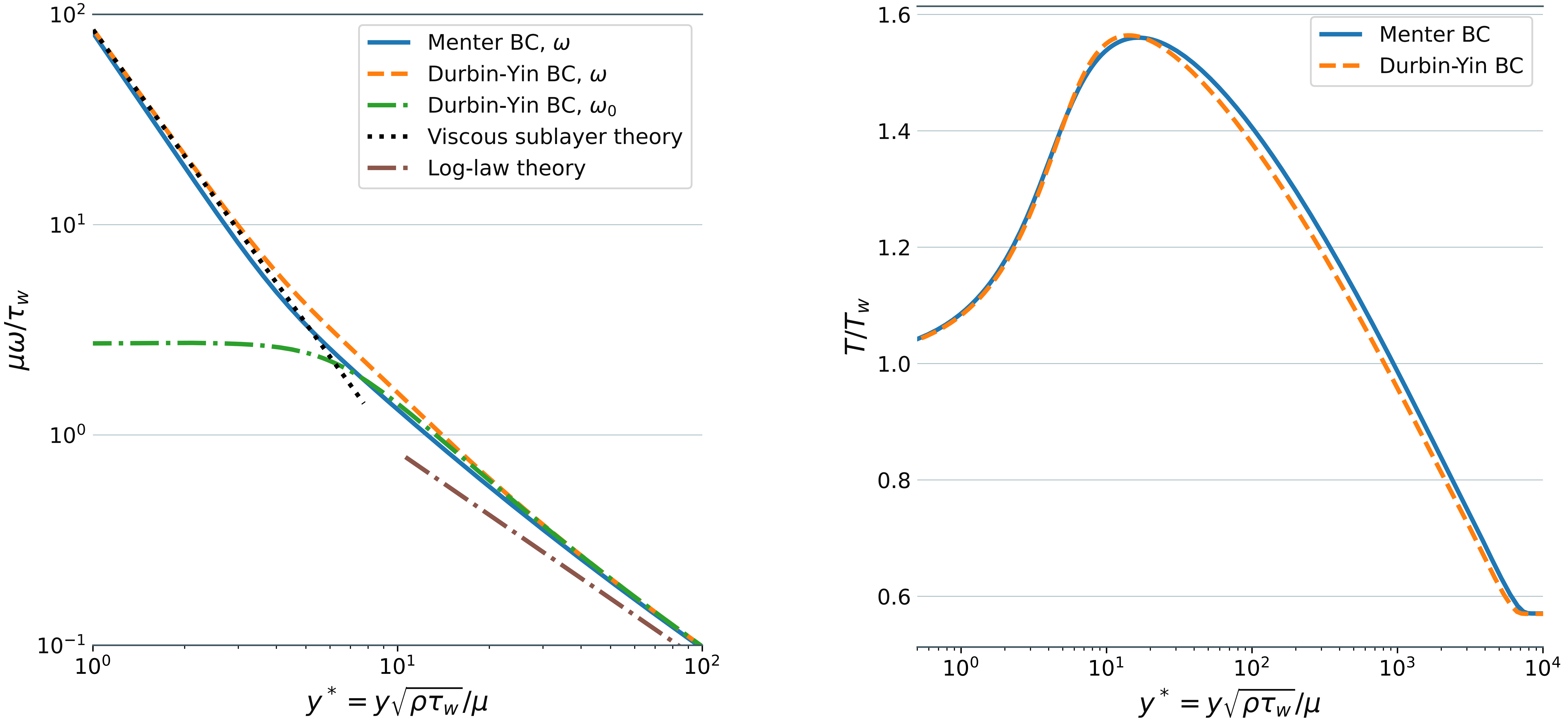


Wall-normal profile of ω and ω_0 in a flat-plate boundary layer at Mach 5.86, $T_w/T_{aw} = 0.25$



Wall-normal profile of temperature in a flat-plate boundary layer at Mach 5.86, $T_w/T_{aw} = 0.25$

Effect of Durbin-Yin Transformation for Supersonic Flows



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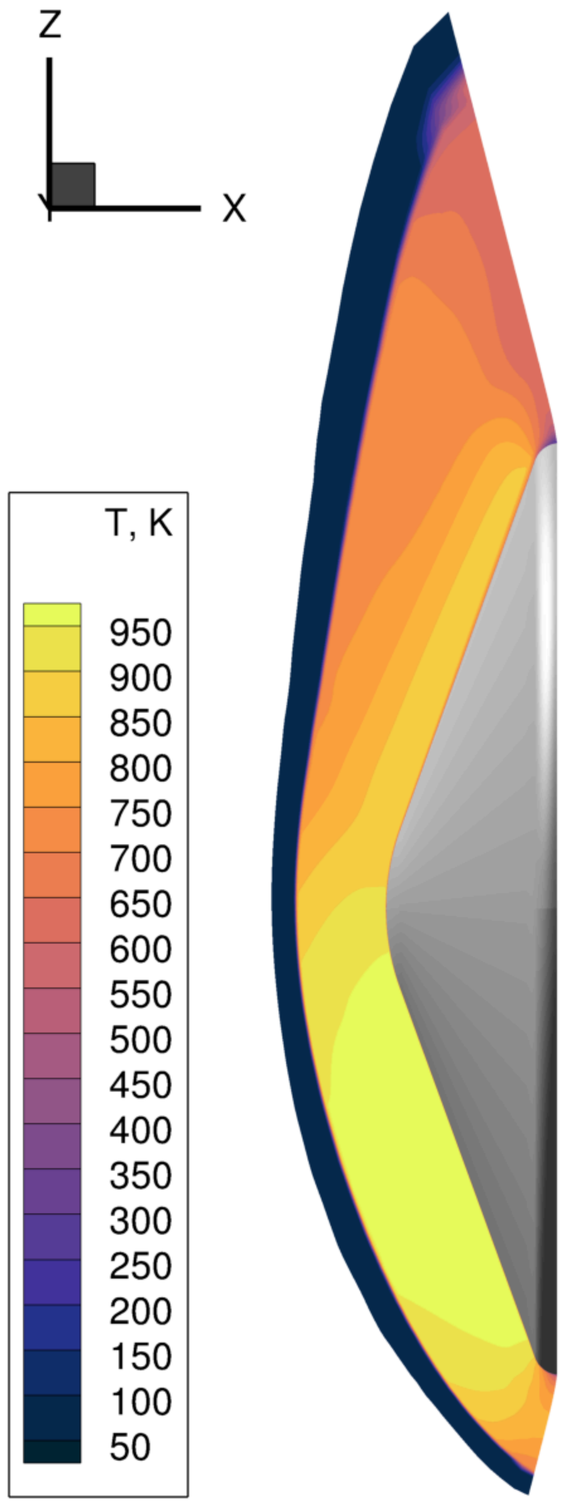
Wall-normal profile of temperature in a flat-plate boundary layer at Mach 5.86, $T_w/T_{aw} = 0.25$

Wind-Tunnel Data from Mars Science Laboratory (MSL)

Case	Mach	α	Re_D
3045	7.6	0°	8.6 x 10^6
3053	7.7	20°	15.7 x 10^6

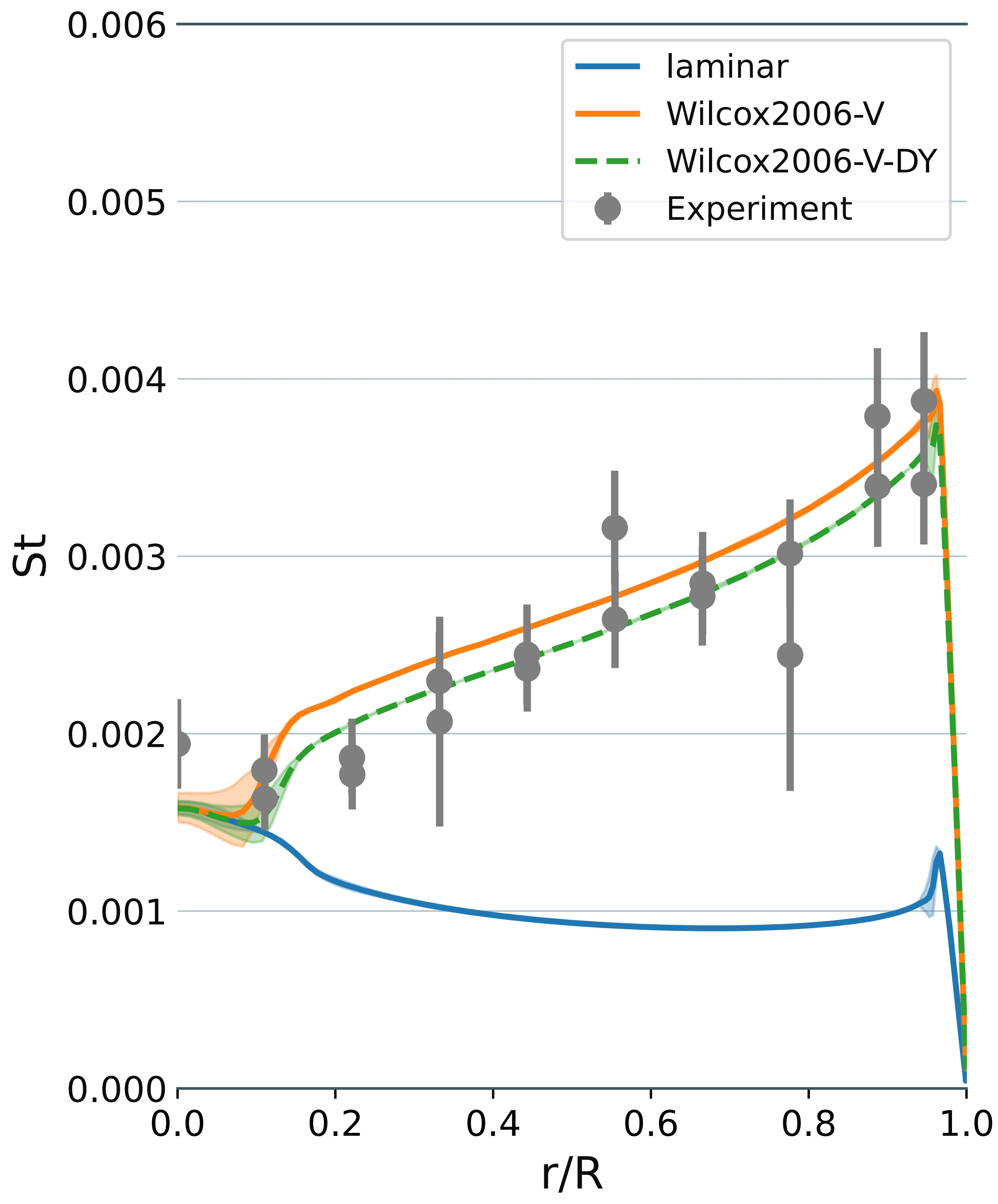
- Wind tunnel tests performed at AEDC Tunnel 9 by Hollis and Collier[1]
- Geometry
  - 70 degree sphere-cone
  - Max diameter: 6 inches
- One-temperature, thermal equilibrium
- Calorically perfect gas (N2)
- Isothermal wall boundary condition



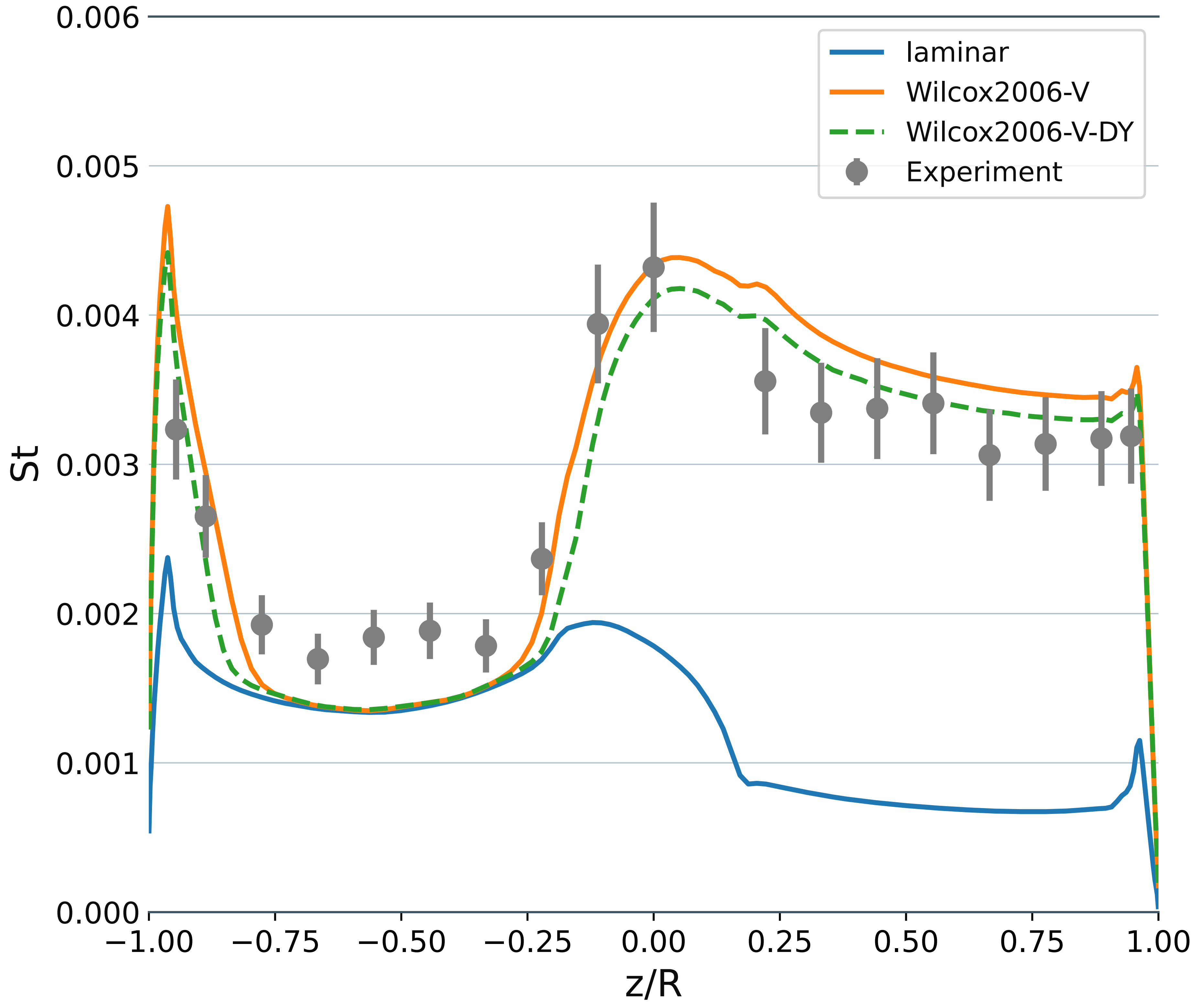
Contours of the temperature along a slice through the symmetry-plane of the MSL flowfield at M=7.6, $\alpha = 20$ °.

1. Hollis and Collier, 2017, NASA/TP–2017-219658

Effect of Durbin-Yin Transformation for MSL



Stanton number along the centerline at Mach 7.6, $\alpha = 0$. The shaded regions are estimates of the discretization error.



Stanton number along the centerline at Mach 7.6, $\alpha = 20°$.

Controlling Production of Turbulent Kinetic Energy

Amplification of Turbulent Kinetic Energy at a Strong Shock

The exact production of turbulent kinetic energy is:

$$P = \tau_{ij} \frac{\partial \bar{u}_i}{\partial x_j}$$

where $\tau_{ij} = \overline{\rho u_i'' u_j''}$ is the Reynolds stress tensor. The Spalart-Allmaras and the k-ω models typically model the Reynolds stress tensor with a linear eddy viscosity model:

$$\tau_{ij} \approx 2\mu_t \left(S_{ij} - \frac{1}{3} \frac{\partial u_i}{\partial x_j} \delta_{ij} \right) - \frac{2}{3} \rho k \delta_{ij}$$

In the transport equation for k, k-ω models will combine these two formulas to arrive at the following model for production of turbulent kinetic energy:

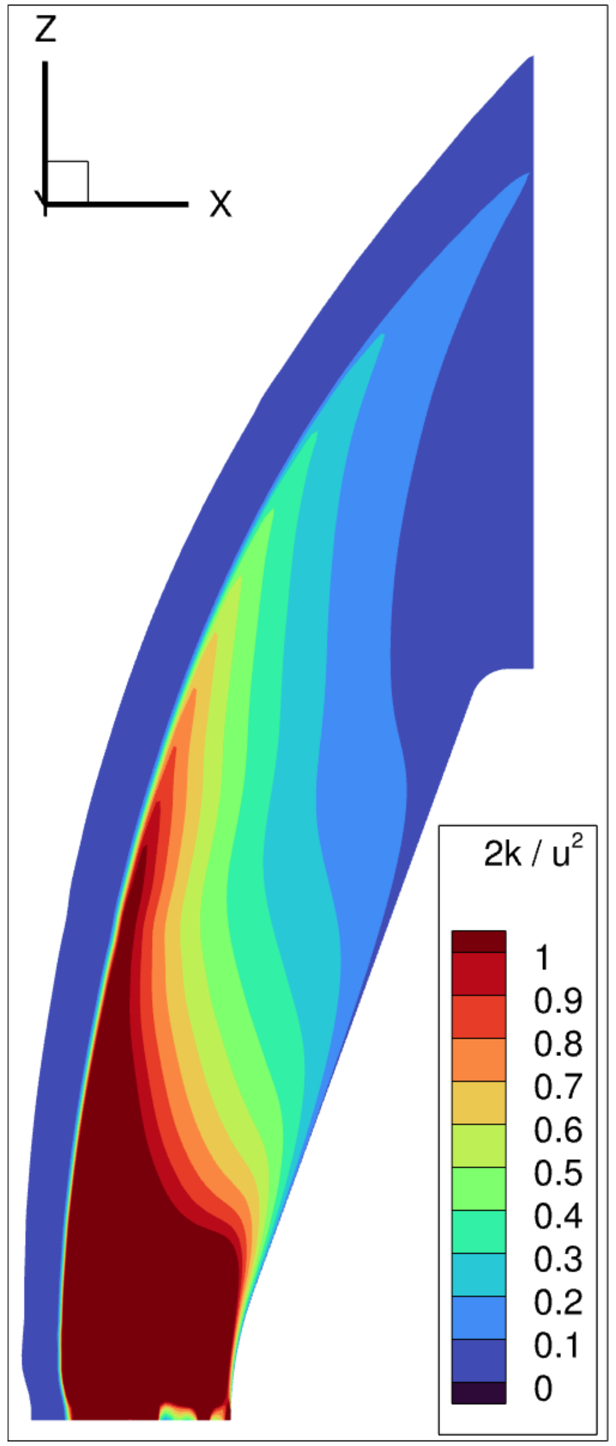
$$P \approx 2\mu_t \left(S_{ij} S_{ij} - 1/3 \frac{\partial u_i}{\partial x_i} \frac{\partial u_j}{\partial x_j} \right) - \frac{2}{3} \rho k \frac{\partial u_i}{\partial x_i}$$

Problems with Production

This model predicts excessive production at:

1. Strong shocks
2. Stagnation point regions

Production must be limited for *both cases* to keep the kinetic energy from growing to extreme levels.



Excessive production of TKE predicted by the standard SST model for Mach 7.6 wind-tunnel condition. $2k/u^2$ is the ratio of turbulent kinetic energy to mean kinetic-energy.

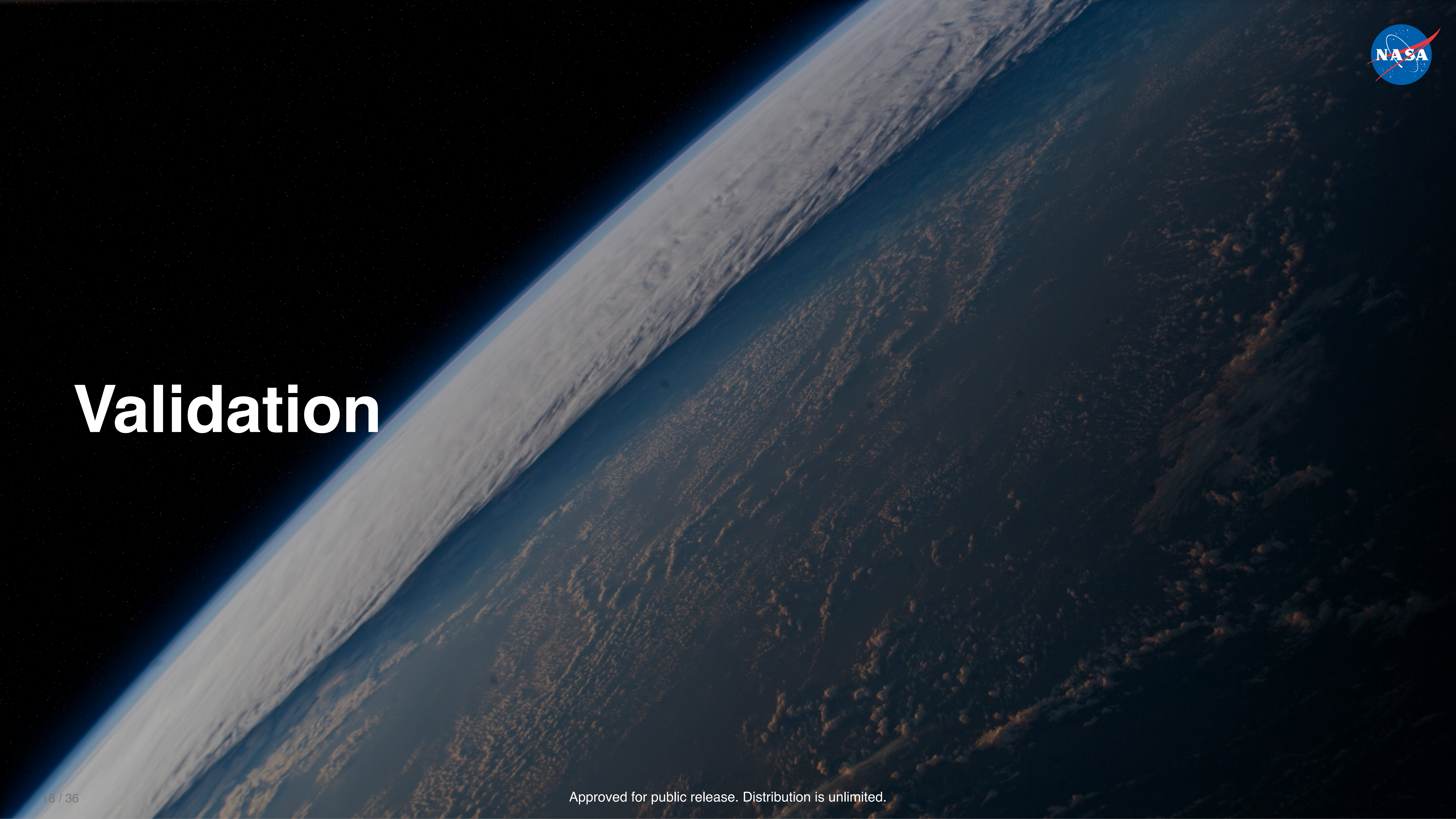
Several Options for Limiting Production

1. Replace the entire production model with $P = \mu_t |\Omega|^2$, since $|\Omega| << |S|$ at a strong shock.
2. Use a shock-unsteadiness model[1]
3. Limit the eddy-viscosity as $\mu_t \propto \rho k / |S|$, as is done in the Wilcox2006 model.

> **Recommendation**
>
> Using a vorticity-based production is a pragmatic solution that limits production for both cases, even though it is not physics-based.

Projects with shock boundary-layer interaction will need something better than a vorticity-production.

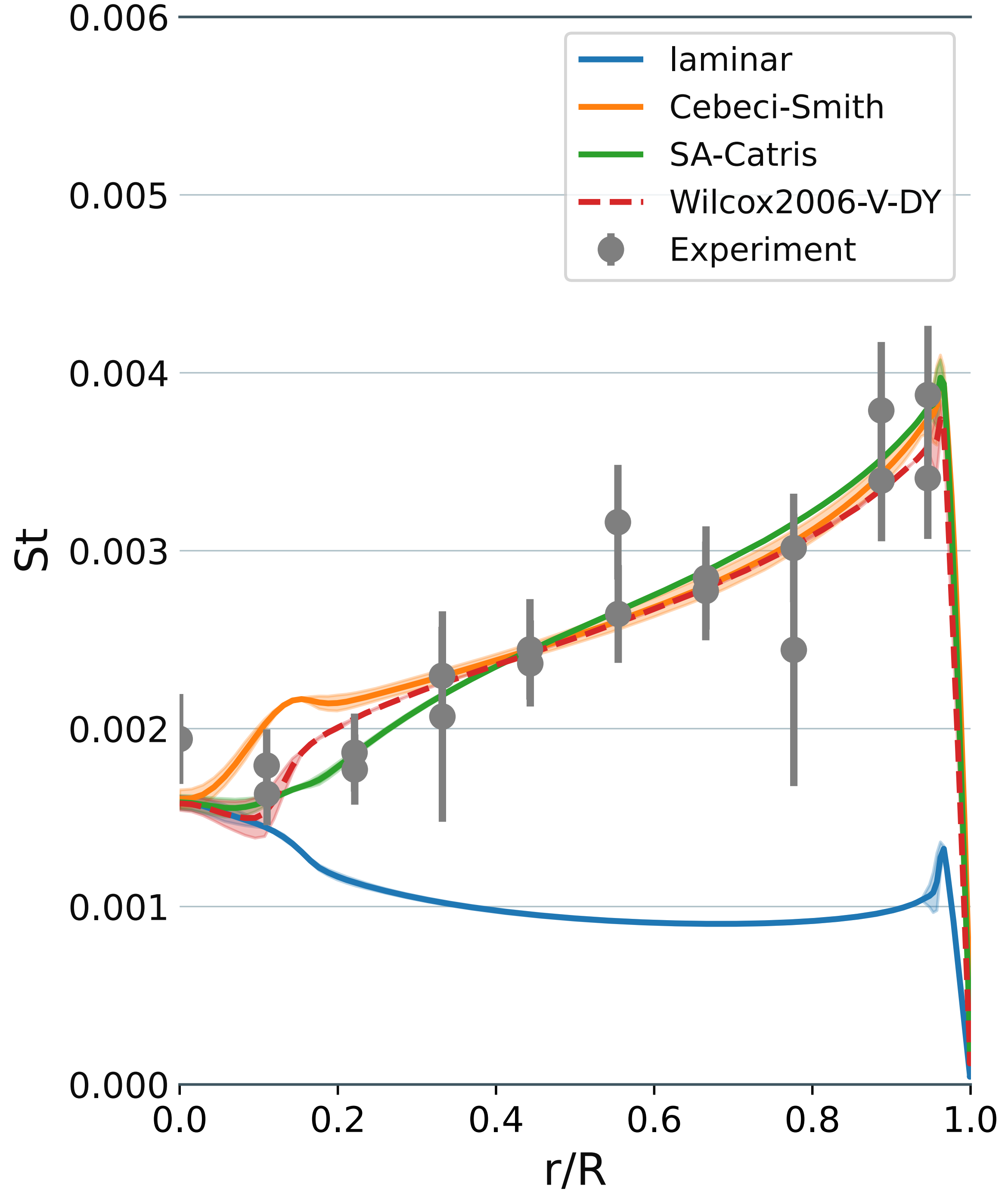
1. Sinha and Candler, AIAA Paper 2003-1265, doi:10.2514/6.2003-1265



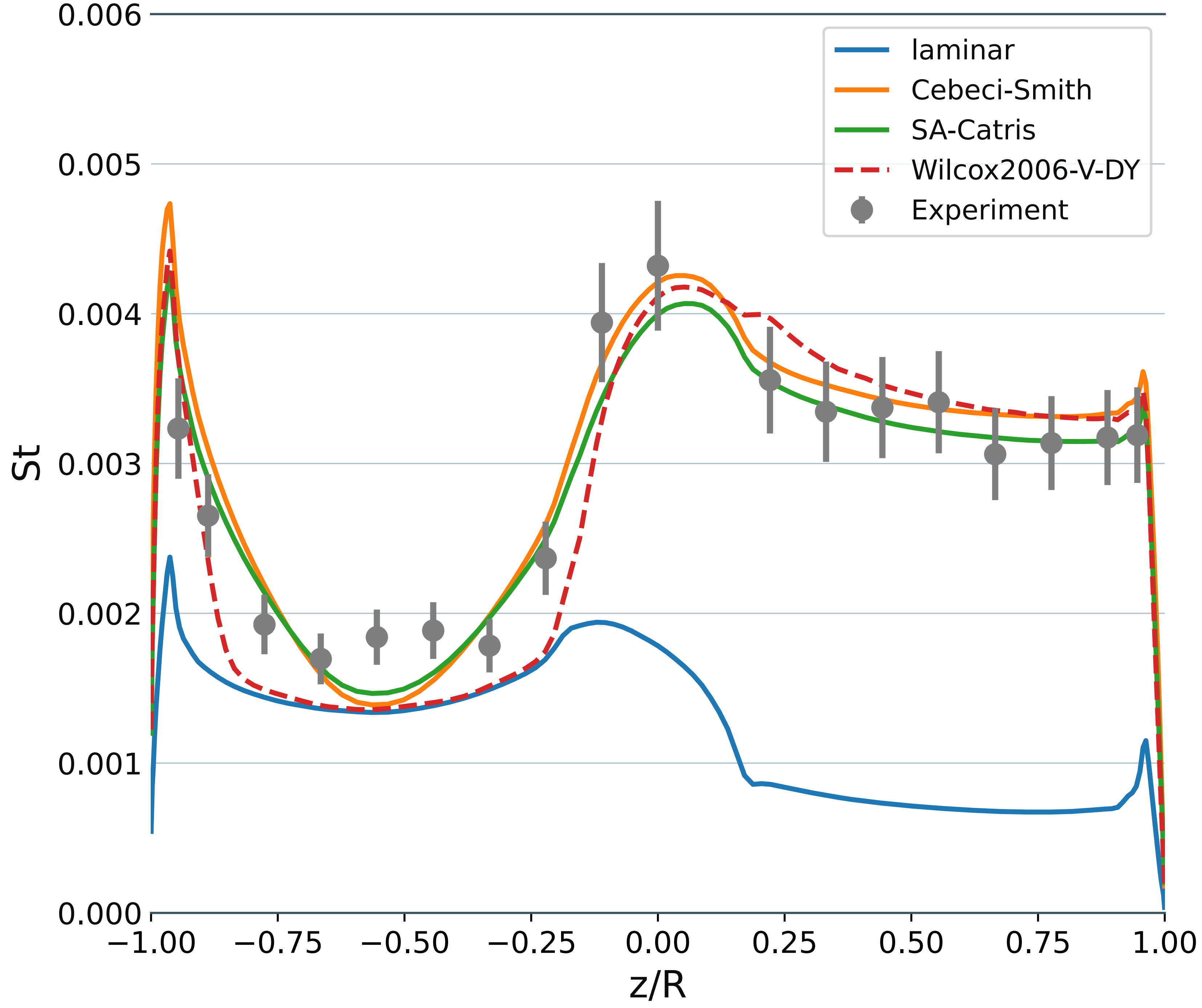
Validation

MSL at Mach 8 Wind-Tunnel Conditions

With the changes suggested, the turbulence models agree well with experimental data.



Stanton number along the centerline at Mach 7.6, $\alpha = 0$. The shaded regions are estimates of the discretization error.

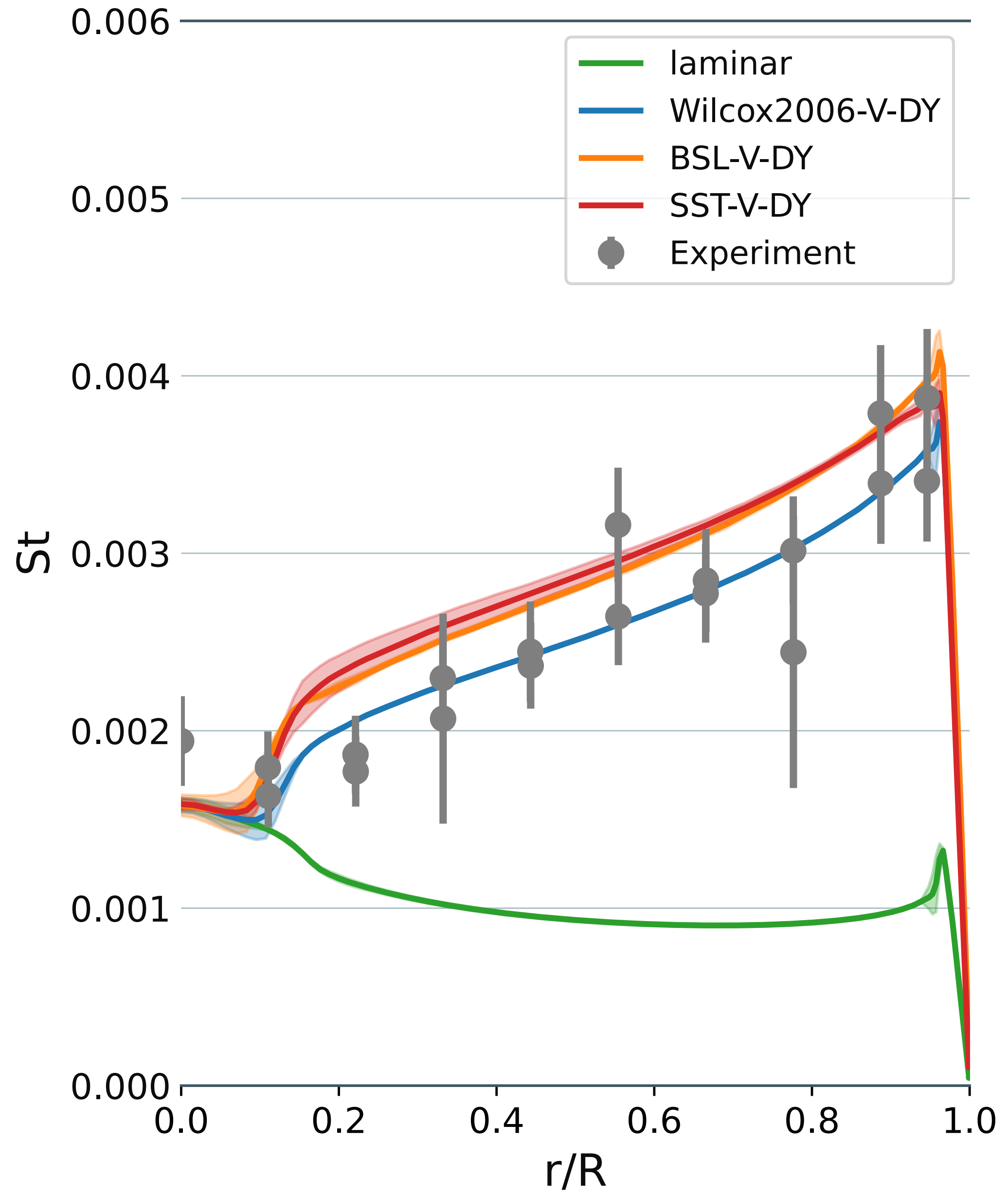


Stanton number along the center plane for various turbulence models at Mach 7.7, $\alpha = 20°$

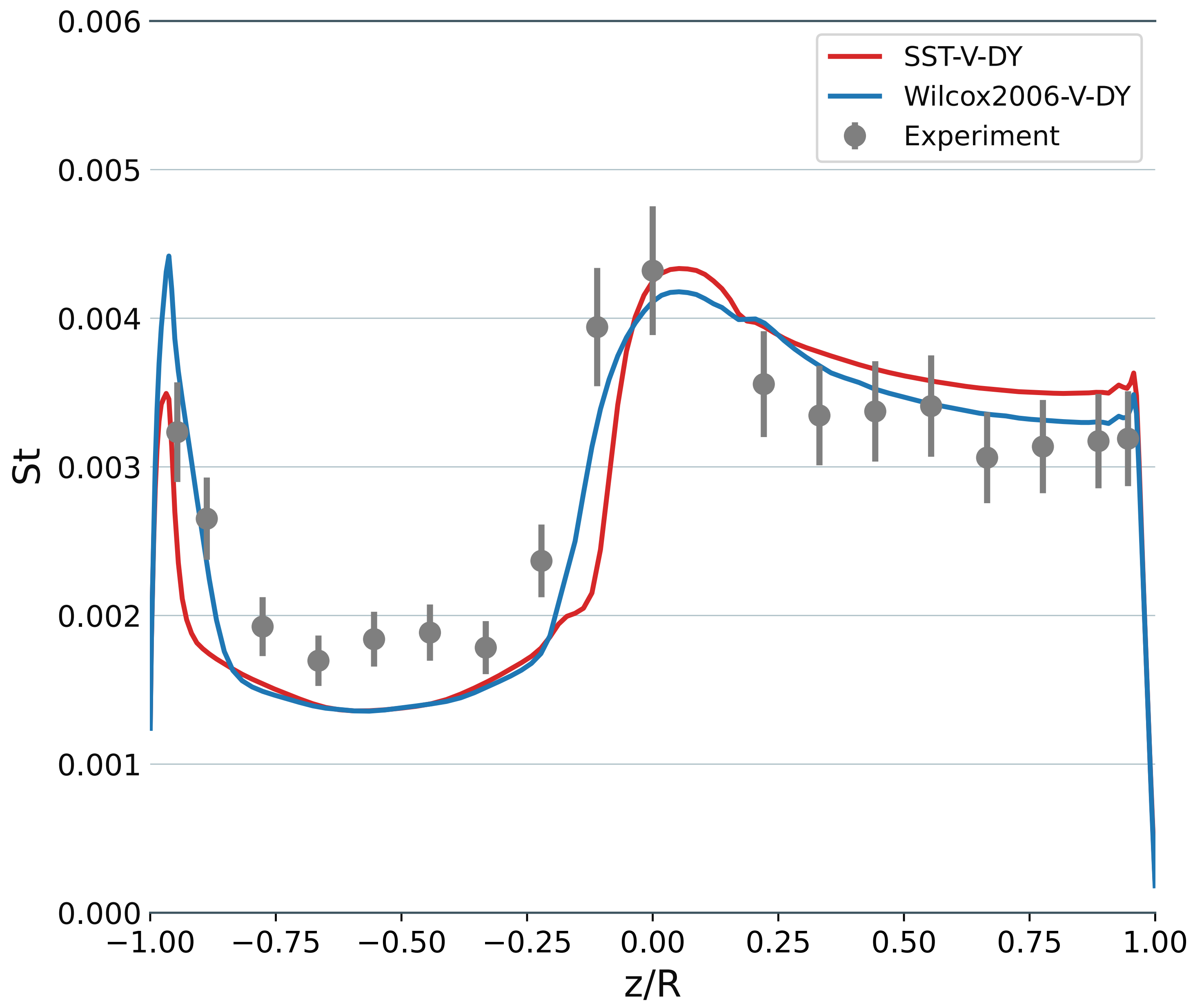
Does Blending with SST or BSL Provide an Advantage?

Menter introduced BSL and SST as an improvement to previous k-ω models, which doubles the number of tunable parameters and adds blending functions. This raises the question:

Does the extra complexity improve accuracy for blunt-body aeroheating predictions?



Stanton number along the centerline at Mach 7.6, $\alpha = 0$. The shaded regions are estimates of the discretization error.



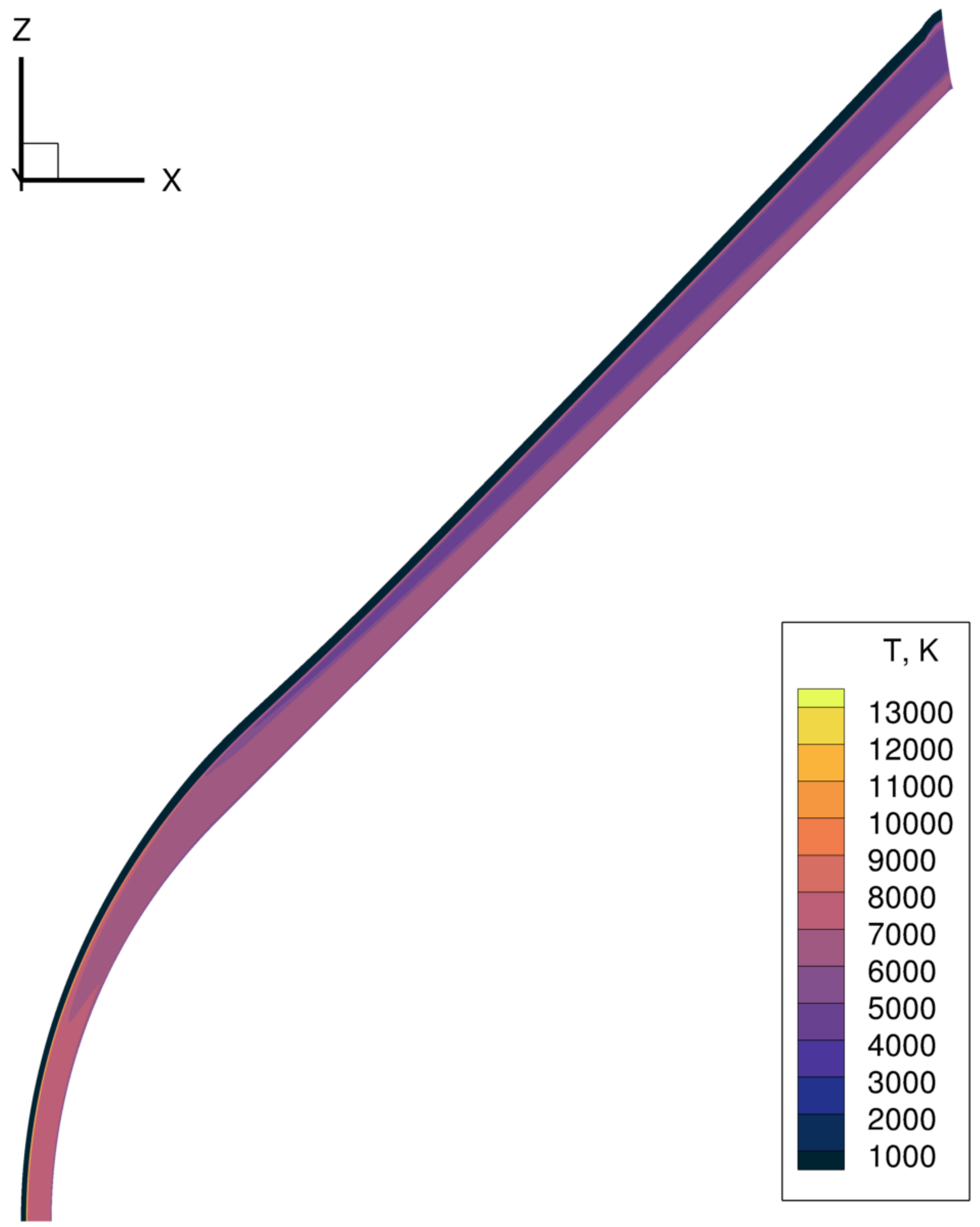
Stanton number along the center plane for various turbulence models at Mach 7.7, $\alpha = 20°$

Sensitivity Studies

Venus Entry: DAVINCI Flight Conditions

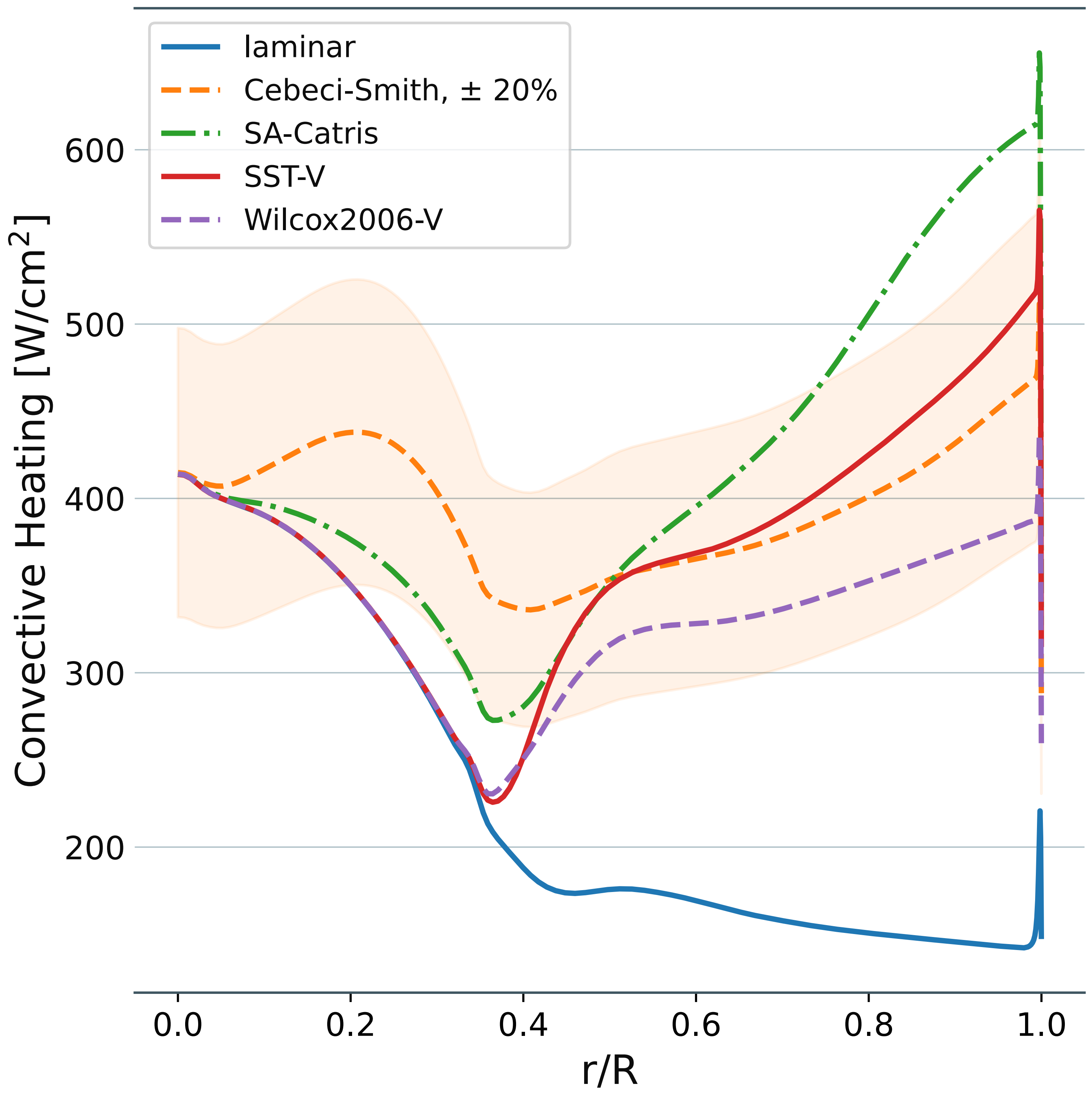
Mach	u_∞ [m/s]	α [°]	Re_D
38.8	8161	0	2.9 x 10^6

- Geometry
  - 45 degree sphere-cone
  - Max diameter: 2.57 m
- Two-temperature, thermal non-equilibrium
- Nineteen species model (97.4% CO2, 2.6% N2)
- Fully catalytic wall BCs
- Radiative equilibrium temperature BC



Contours of the temperature for DAVINCI at the $u = 8161$ m/s condition.

DAVINCI Flight Conditions

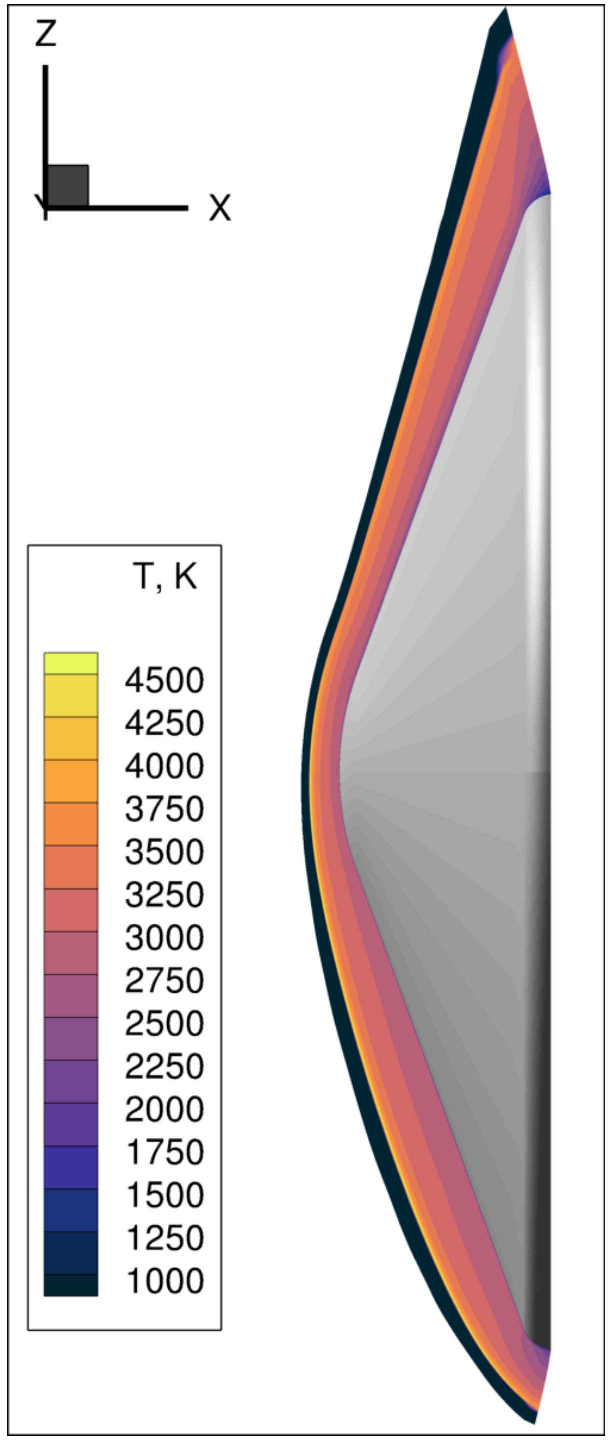


Convective heating predicted by various turbulence models on the DAVINCI heatshield at $u_\infty = 8161$ m/s. The shaded region represents $\pm 20\%$ margin on the Cebeci-Smith prediction.

Mars2020 Flight Conditions

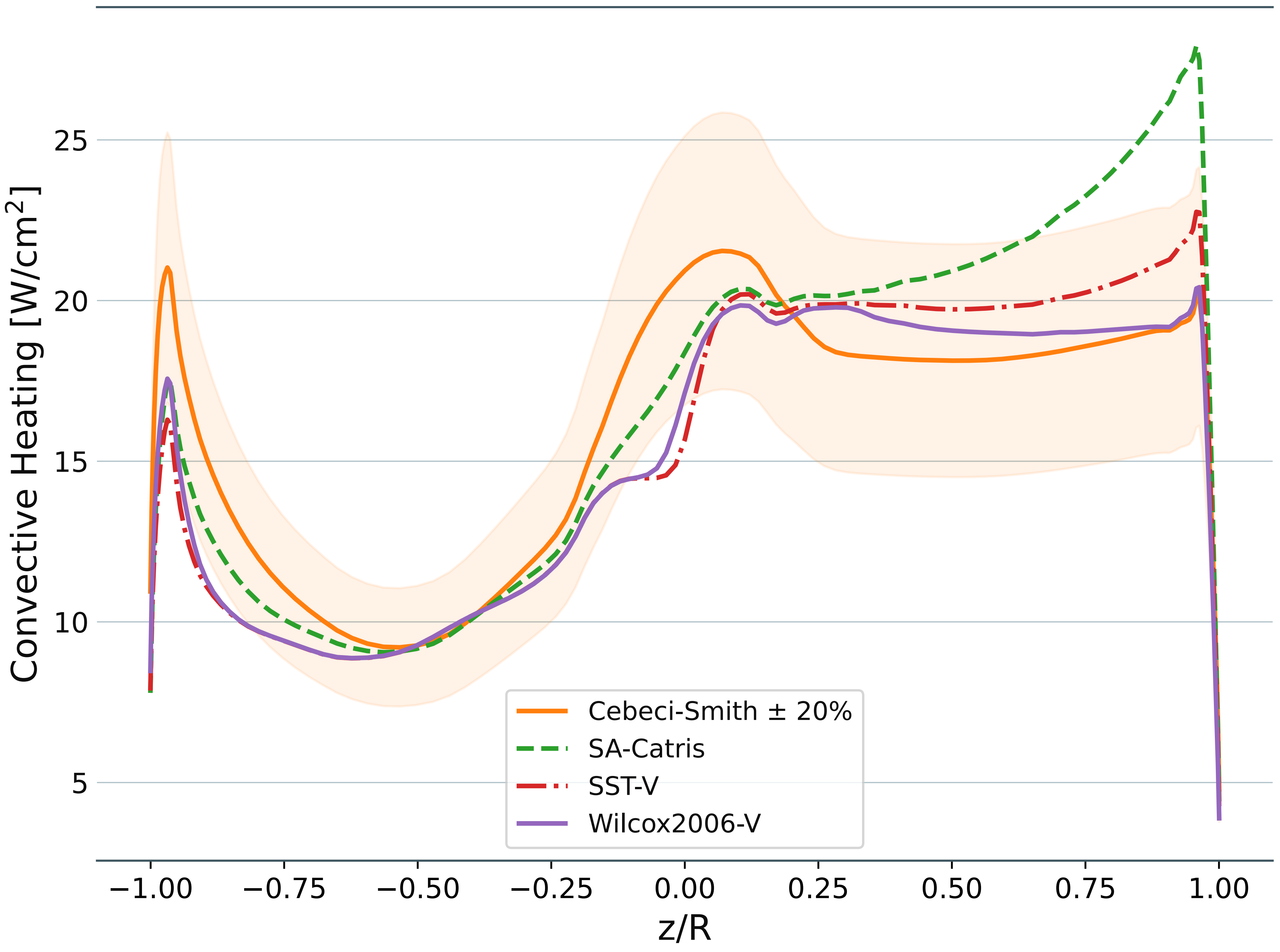
Mach	u_∞ [m/s]	α [°]	Re_D
16.8	3717	16.6	3.7 x 10^6

- Geometry
  - 70 degree sphere-cone
  - Max diameter: 4.5 m
- Conditions selected near max-Q, about 10 seconds after peak heating
- Two-temperature, 8-species model (97% CO2, 3% N2)
- Fully catalytic wall BCs
- Radiative equilibrium temperature BC
- Decoupled radiation from HARA



Contours of the temperature along a slice through the symmetry-plane of the Mars2020 flowfield at the $u_\infty = 3717$ m/s condition.

Mars2020 Flight Conditions



Convective heating predicted by various turbulence models along the symmetry plane of the Mars2020 heatshield at $u_\infty = 3717$ m/s. The shaded region represents ± 20% margin on the Cebeci-Smith prediction.

Conclusions

- Research at NASA and universities is providing improved RANS models for more accurate predictions of turbulent convective heating on blunt-body geometries.
- SA and SA-Catris give reasonable predictions for attached boundary layers, but give poor predictions for supersonic axisymmetric wakes
- Two improvements are needed to make k-ω models useful for blunt-body aeroheating:

1. The Durbin-Yin transformation greatly improves the ω equation and heating predictions
2. Production must be limited at strong shocks and stagnation regions

- With these corrections:
  - Predictions for wind tunnel conditions agree well with experiment
  - Predictions for flight conditions are similar to Cebeci-Smith

Acknowledgments

- This work would not have been possible without the advice of Chris Johnston and Prahladh Iyer.
- Funding was provided by the Entry Modeling & Instrumentation (EM&I) project under the Research and Technology Mission Directorate.
- Computing resources supporting this work were provided through the NASA K-Cluster at NASA Langley Research Center.

Backup

Differences in models?

- Note that for incompressible cases, the skin friction predicted by BSL is the highest, followed by SST, followed by Wilcox2006. They differ by about 1%.

Mars2020 Conditions

Chemistry

1. CO_2 0.97
2. N_2 0.03
3. CO
4. NO
5. O_2
6. C
7. N
8. O

Other specs:

- Altitude: 22.03 km
- Max diameter: 4.5 m

DAVINCI Conditions

Chemistry

1. CO_2 0.974
2. CO
3. N_2 0.026
4. O_2
5. NO
6. C_2
7. CN
8. C
9. N
10. O
11. CO^+
12. N_2^+
13. O_2^+
14. NO^+
15. CN^+

What is Omega?

Given a 1D shear flow, such as a zero-pressure-gradient boundary layer, we can derive an eddy viscosity as:

$$\mu_t = \frac{-\overline{\rho u_i'' u_j''}}{\partial \bar{u} / \partial y}$$

We can also find the turbulent kinetic energy. Given an eddy-viscosity relationship:

$$\mu_t = \frac{\rho k}{\omega}$$

we can find an empirical definition of ω as:

$$\omega = \frac{\rho k}{\mu_t} = \frac{\rho k}{-\overline{\rho u_i'' u_j''}} \frac{\partial \bar{u}}{\partial y}$$

Problem: Strong Shocks

For 1D flow passing a strong shock, a k-ω models production as:

$$P = 4/3\mu_t(\nabla \cdot u)^2 - 2/3\rho k(\nabla \cdot u)$$

As the velocity jump across the shock increases, the TKE amplification increases without bound. This jump in TKE is problematic for wind tunnel conditions and completely derails a simulation for planetary entry velocities.

But direct numerical simulations and theory show that kinetic energy amplification is bounded by $k_2/k_1 < 2$, even as the incoming Mach number approaches infinity. The buildup of TKE at a shock is unphysical.

Common Solutions

1. Use a shock-unsteadiness model[1]
2. Replace the entire production model with $P = \mu_t|\Omega|^2$.

Both terms (the μ_t term and the ρk term) contribute, and limiting only one of them is insufficient.

1. Sinha and Candler, AIAA Paper 2003-1265, doi:10.2514/6.2003-1265

Problem: Stagnation Regions

Consider an incompressible, stagnation region with a plane strain, where $\tilde{u} = -Ax$, $\tilde{v} = Ay$, and A is a constant. The strain-rate magnitude is $|S| = 2A$ and the vorticity magnitude is $|\Omega| = 0$.

The production of TKE for an unlimited k-ω model is:

$$P = 4\mu_t A^2$$

However, for large strain rates the true production scales as $P \propto A$, not A^2. The anisotropy of the eddy-viscosity model aka Boussinesq hypothesis is the root of the error.

Common Solutions

1. Limit the eddy viscosity for large strains so that $\mu_t \propto \rho k / |S|$.
2. Replace the entire production model with $P = \mu_t |\Omega|^2$.

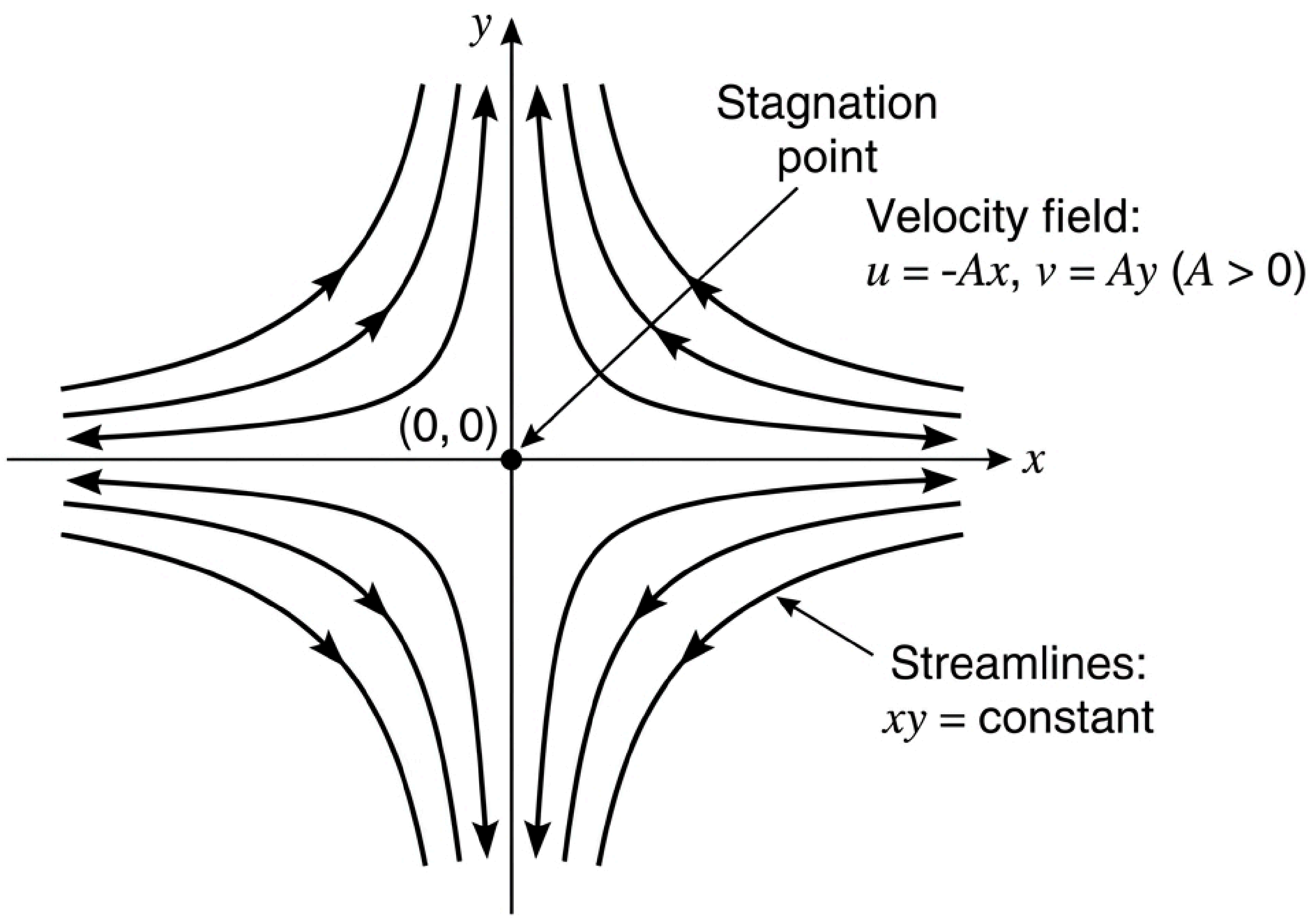


Diagram of streamlines for an idealized stagnation point flow

An aside on the vorticity and production model

The approximation $P = \mu_t |\Omega|^2$ is a pragmatic workaround for deficiencies in linear eddy-viscosity models:

- Production is close to zero at a strong shock (where $|\Omega| << |\nabla \cdot u|$)
- Production is zero for idealized stagnation-point flows

Note that this is a pragmatic fix, but goes against the key physics:

- Production is not actually zero across shocks or stagnation point flows.
- Violating energy conservation. The production term is a sink in the equation for mean kinetic energy and a source in the equation for turbulent kinetic energy. It represents the transfer of energy between the two forms of kinetic energy. Changing the model in an ad hoc way means small errors will be present in the total energy.

What about the stress limit in SST?

In SST, the eddy-viscosity is limited as:

$$\mu_t = \frac{\rho k}{\min(\omega, F_2|\Omega|/a_1)}$$

There are several issue that make this limit of little use for blunt-body aeroheating:

1. The F_2 blending turns off the limit outside of near-wall regions. No limiting at shocks or stangation regions.
2. $|\Omega| << |S|$ for strong shocks and stangation regions, so the limit is essentially inactive.

Without a large scale overhaul, the only way to get SST to work reliably for blunt-body predictions is to use the SST-V model, where production is approximated as $P = \mu_t|\Omega|^2$.

Fixing turbulence modeling issues in the SST is difficult. To improve the model, one should instead build on the foundation of BSL (SST without a stress limiter) or the more recent GEKO model[1].

1. Menter and Matyushenko, "Generalized k–ω (GEKO) Two-Equation Turbulence Model", 2025, doi:10.2514/1.J065393