
# Comparison between DSMC and CFD for hypersonic planetary entry simulations

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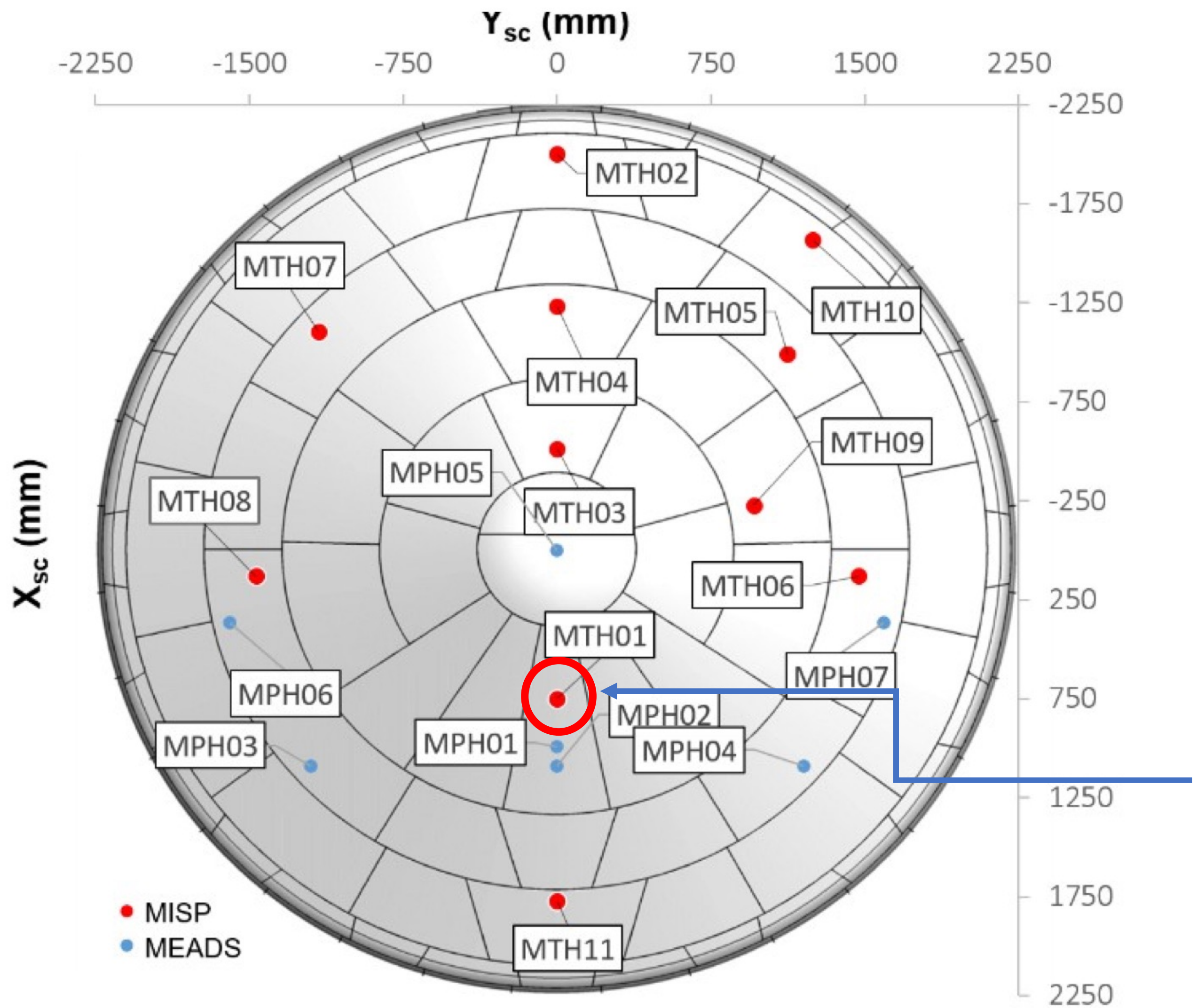
# Motivation and Objectives

- Design of thermal protection system relies on aerothermal environments predicted (and margined) using *continuum* flow solvers.
  - Flow solvers are usually applied up to $Kn_{\infty,D} \leq 0.001$, *i.e.*, altitudes well below Entry Interface {EI} altitude.
  - Pressure & heat pulses are closed at early time (from EI) *via* conservative extrapolation.
- For reconstruction of aerothermal environments post-flight, restrictive design assumptions must be dispensed with.
  - Use low-density/non-continuum flow solvers from EI up to the point where continuum flow assumption is tenable for CFD solver.
- **Key questions:**
  - **What is a possible metric to determine the appropriate altitude for a smooth hand off from a low-density flow field solver to a continuum CFD solver?**
  - **How well do non-continuum and continuum solvers compare in the region of overlap?**
- We first investigate a flow (of Ar, and $CO_2/N_2$ reacting mixture) past a hemispherical geometry, before turning our attention to Mars 2020 for which flight data are available.

# Mars 2020: MEDLI2 Sensor Locations

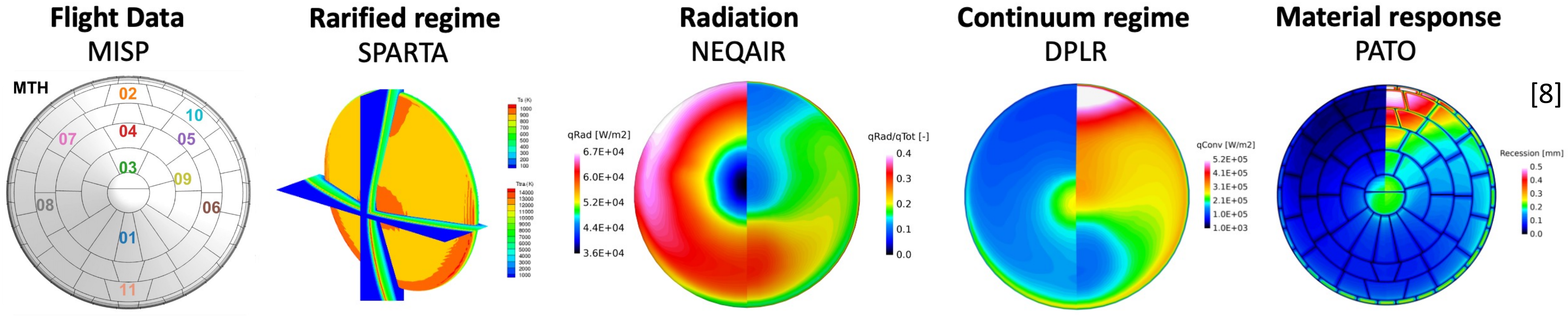



- Mars 2020 suite of flight sensors
  - Heatshield
    - Pressure sensors (MPH01-07)
    - MISP plugs with 3 T/Cs (MTH01-11)
  - Backshell
    - Pressure sensor
    - Heat flux gauge
    - Radiometer
    - MISP plugs
- MTH01 focus of present work

[1] *T. White et al. (2022), AIAA SciTech 2022 Forum, 2022-0011.*

# Analysis Tools

- Environments early in the trajectory (h > 72 km) are provided from DSMC using SPARTA[2].
- Aerothermal environment computed using DPLR[3].
- Radiative heating computed with NEQAIR[4].
- Material response of the heatshield computed using PATO[5-7].



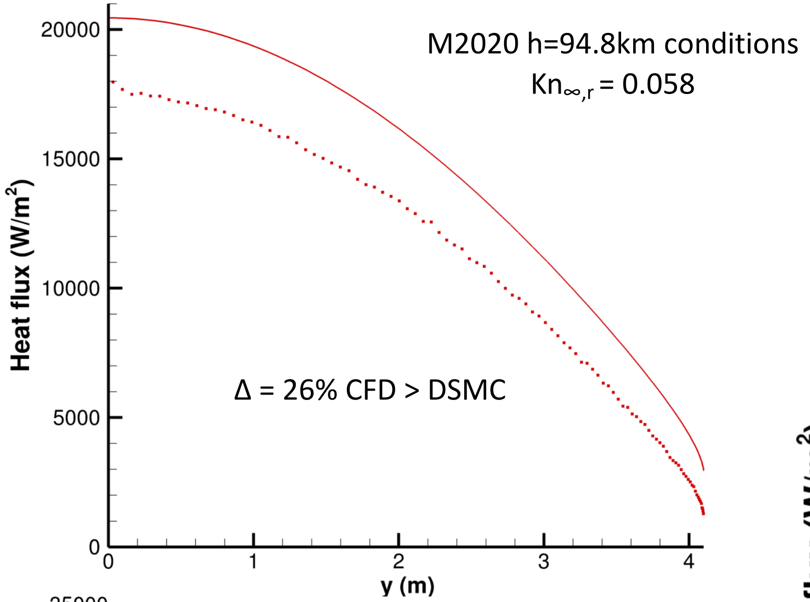


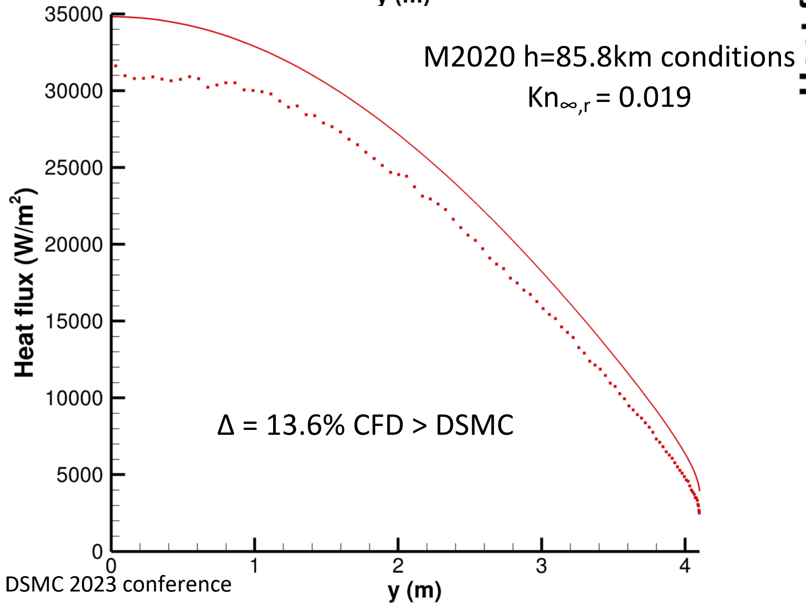
[2] *S.J. Plimpton et al. (2019), Phys. Fluids, 31(8), 086101.*
[3] *M.J. Wright et al. (2009), DPLR Code User Manual: Acadia-Version 4.01.1.*
[4] *E. Whiting et al. (1996) NASA RP-1389.*
[5] *J. Lachaud et al. (2014), J. Thermophys. Heat Tran., 28, 191–202.*
[6] *J. Lachaud et al. (2017), Int. J. Heat Mass Tran., 108, 1406–1417.*
[7] *J. B.E. Meurisse et al. (2018), Aerosp. Sci. Technol., 76, 497-511.*
[8] *J. Thornton et al. (2023), AIAA SciTech 2023 Forum, 2023-0963.*

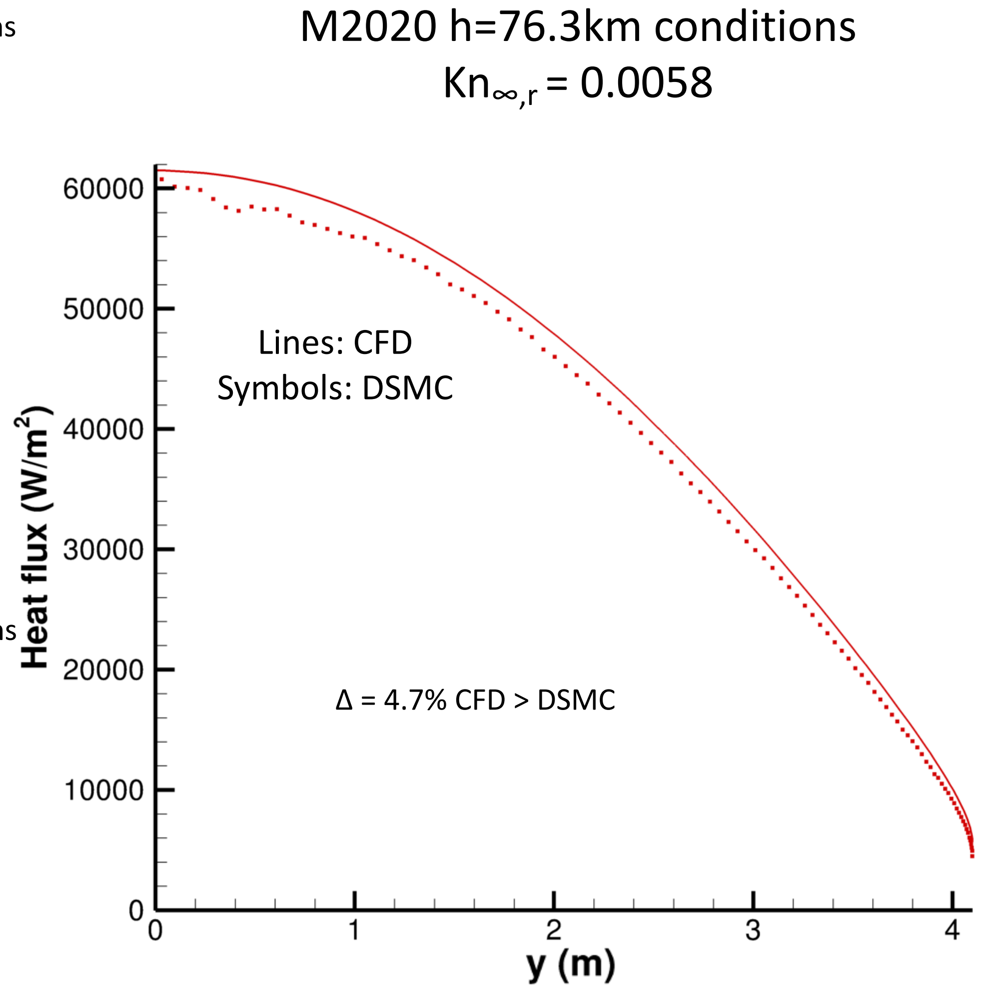
# Non-reactive Sphere Cases

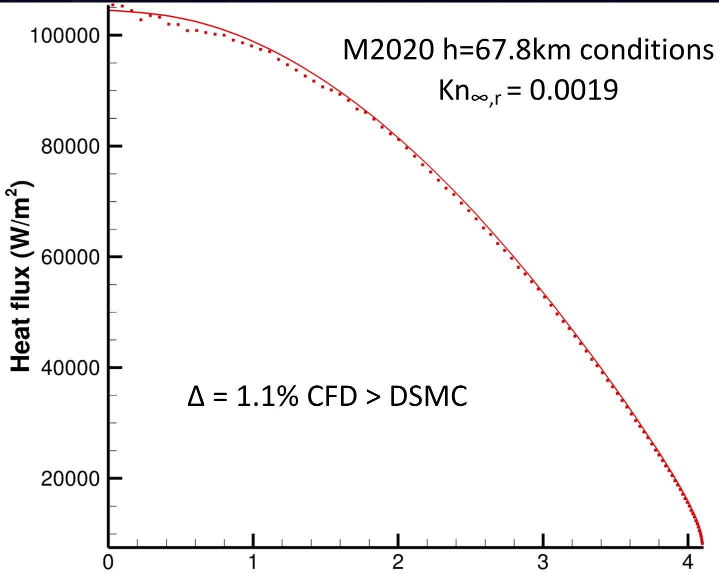
- We are only able to run one overlap case for the full M2020 3D geometry, since these are truly 3D (no symmetry in freestream flow):
  - Little confidence in CFD higher than 80 km altitude (continuum breakdown; not using slip boundary conditions here).
  - Not computationally feasible to run DSMC lower than 80 km altitude.
- Focus on 4.1 m radius hemisphere
  - Stag. point environments of this geometry best replicate the environments at MTH01 of M2020.
- Start by investigating non-reactive flows (Argon), with freestream densities representative of the M2020 trajectory between h = 94.8 km and 58.0 km altitudes.

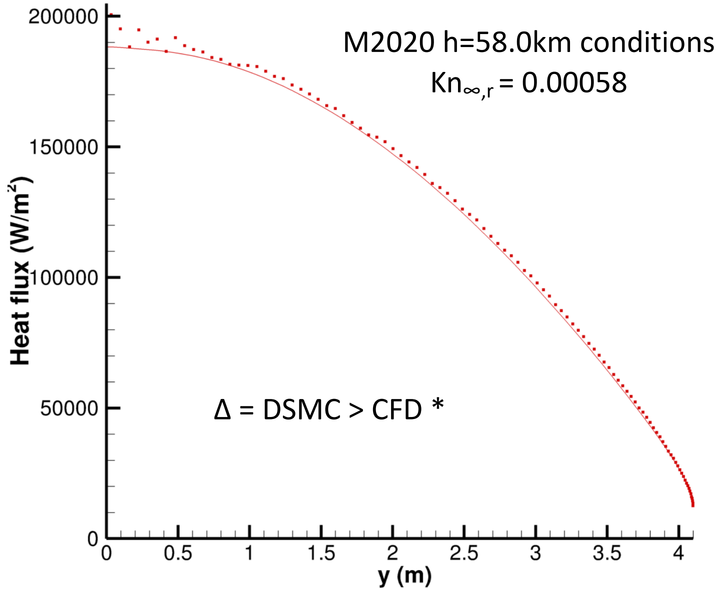
# Non-reactive Sphere Cases: Surface Heat Flux



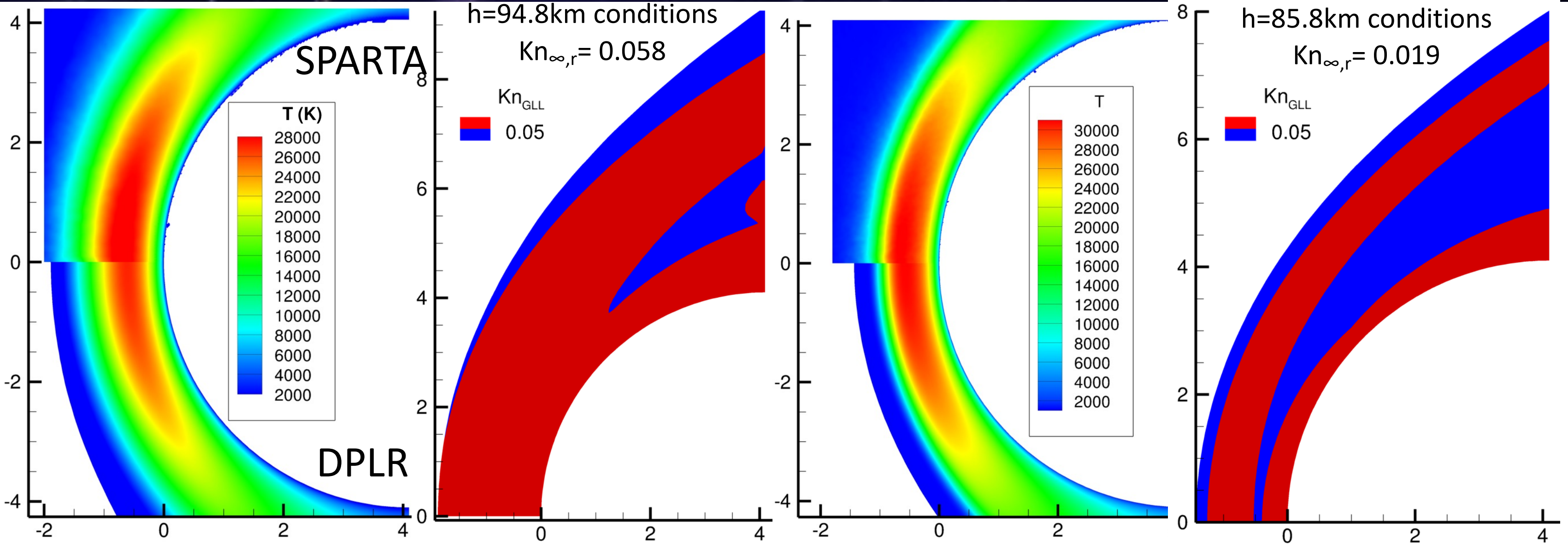

Agreement between DSMC and CFD improves with increasing density, as expected

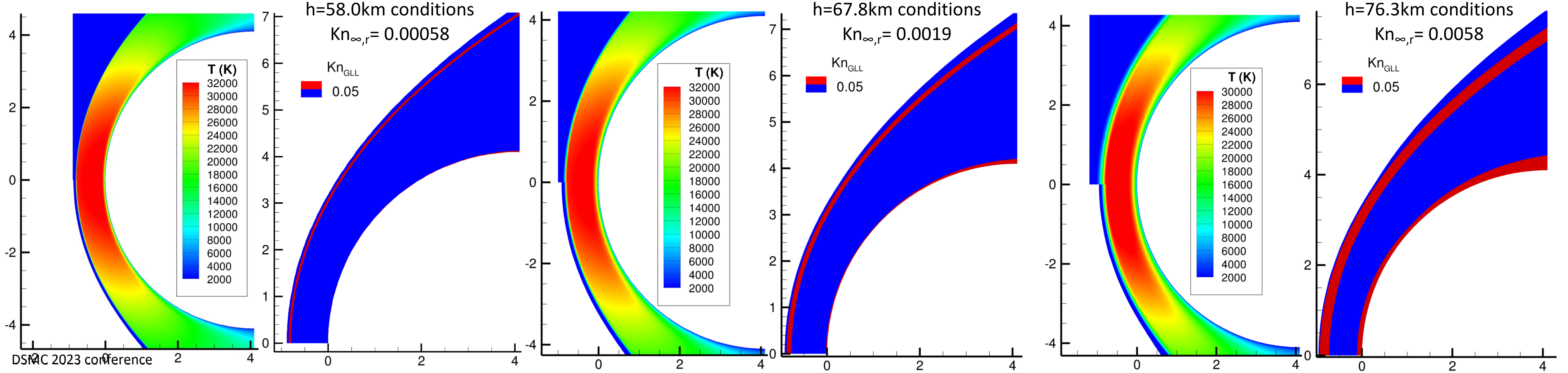
# Non-reactive Sphere Cases: Continuum Breakdown

$$Kn_{GLL} = \frac{\lambda}{Q}\left|\frac{dQ}{dl}\right|$$

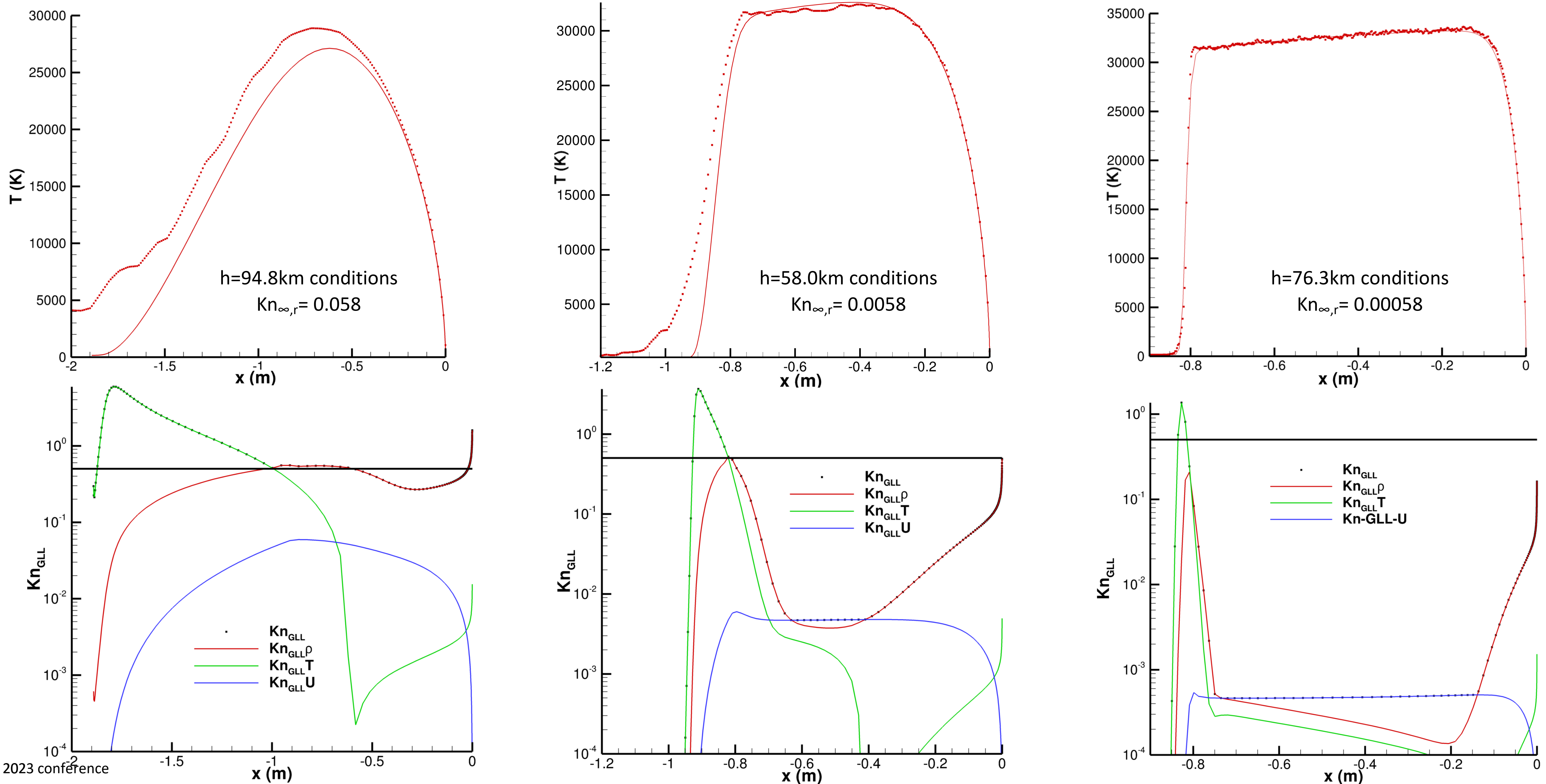
- Q = T, ρ, U (in practice, U rarely breaks down)
- $Kn_{GLL} > 0.05$ => continuum breakdown [9]
- Could use as a criterion for handoff between DSMC and CFD
- $Kn_{GLL} > 0.05$ might be too conservative

[9] *I. Boyd et al. (1995), Phys. Fluids, 7, 210-219.*



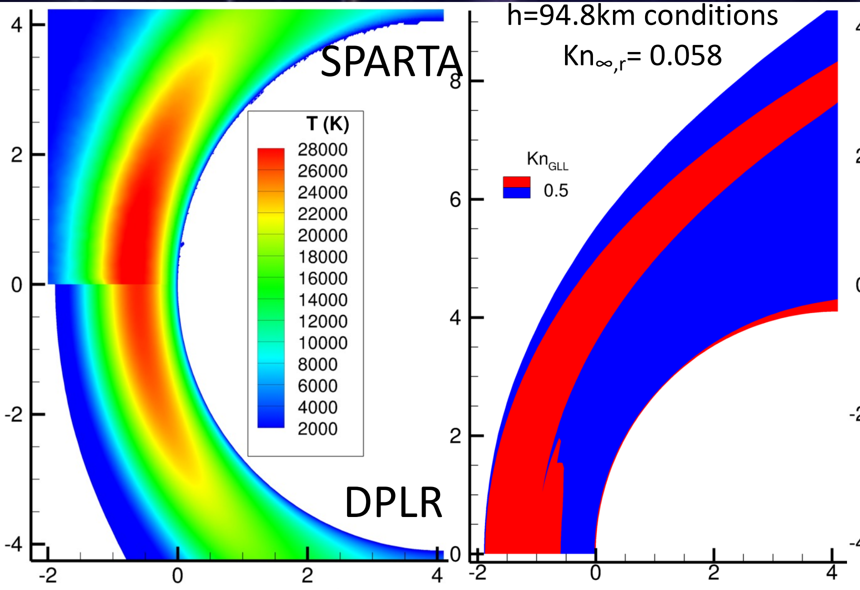



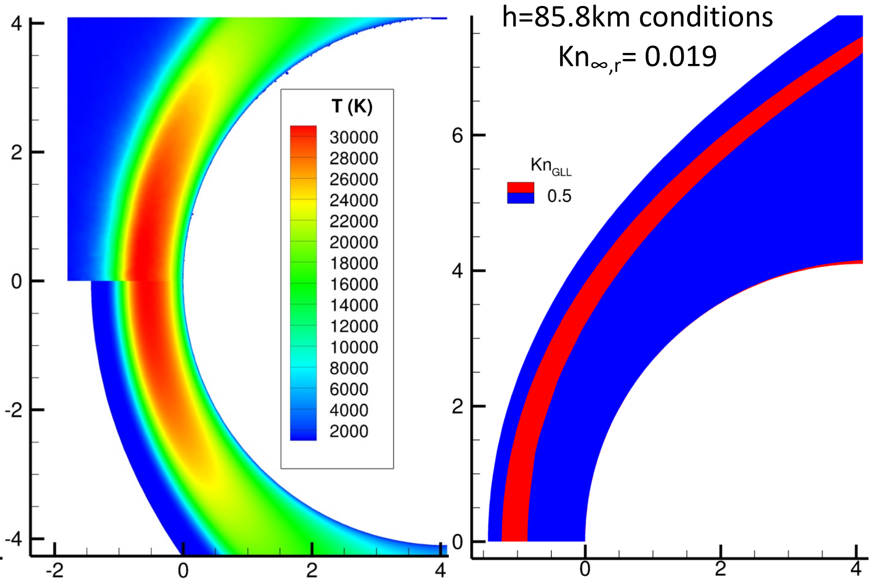
# Continuum Breakdown with Updated Criterion

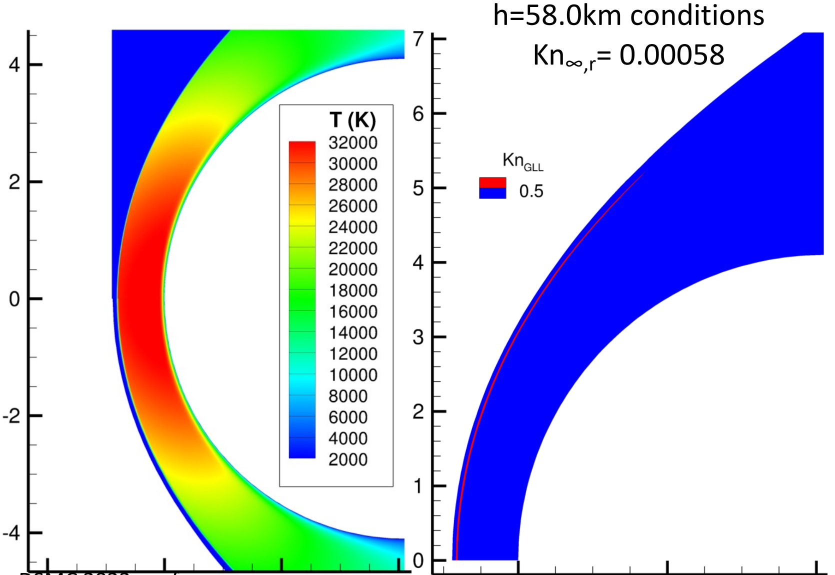


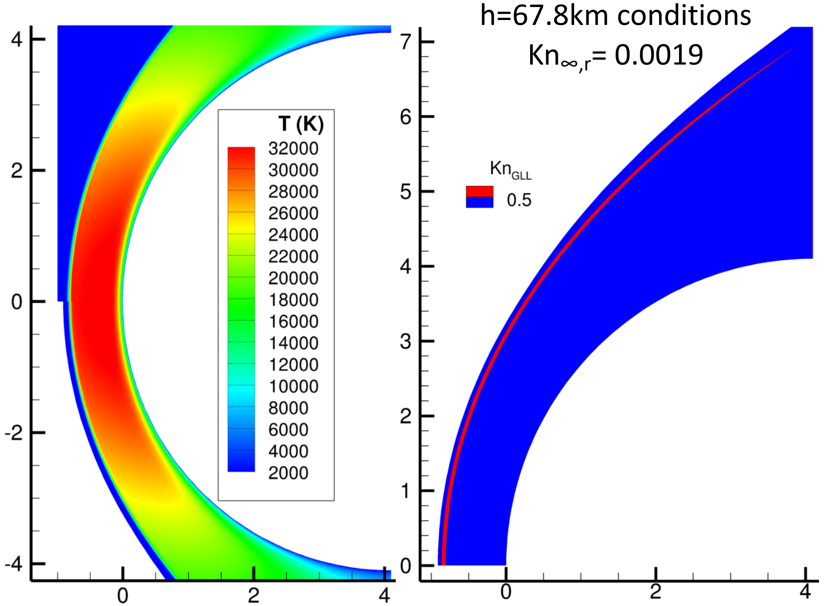
# Continuum Breakdown with Updated Criterion

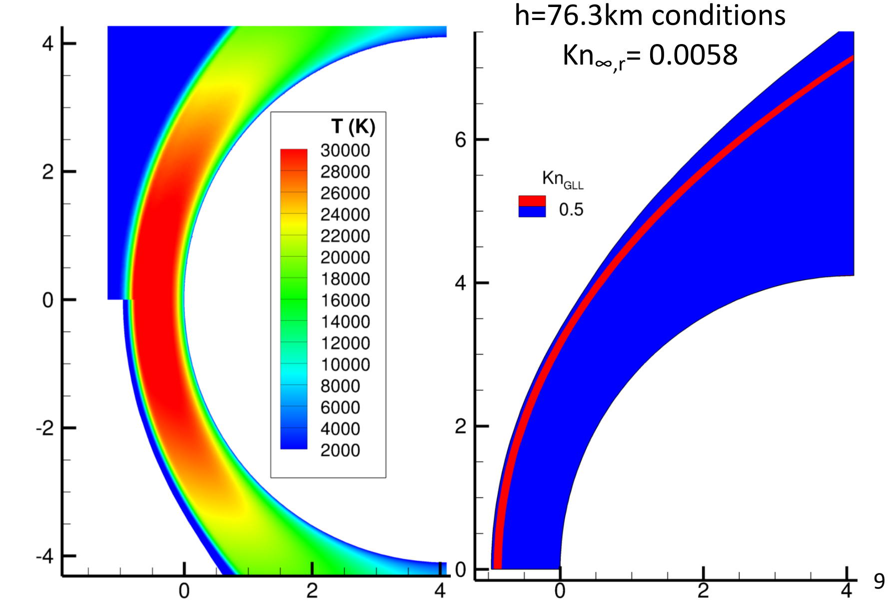
- $Kn_{GLL}$ = 0.5 appears to be a good predictor for the onset of slip in the shock front.
- We now update the $Kn_{GLL}$ contour plots with a cutoff value of 0.5.
- The onset of shock slip coincides with a deviation of surface heat flux ~ 1%.



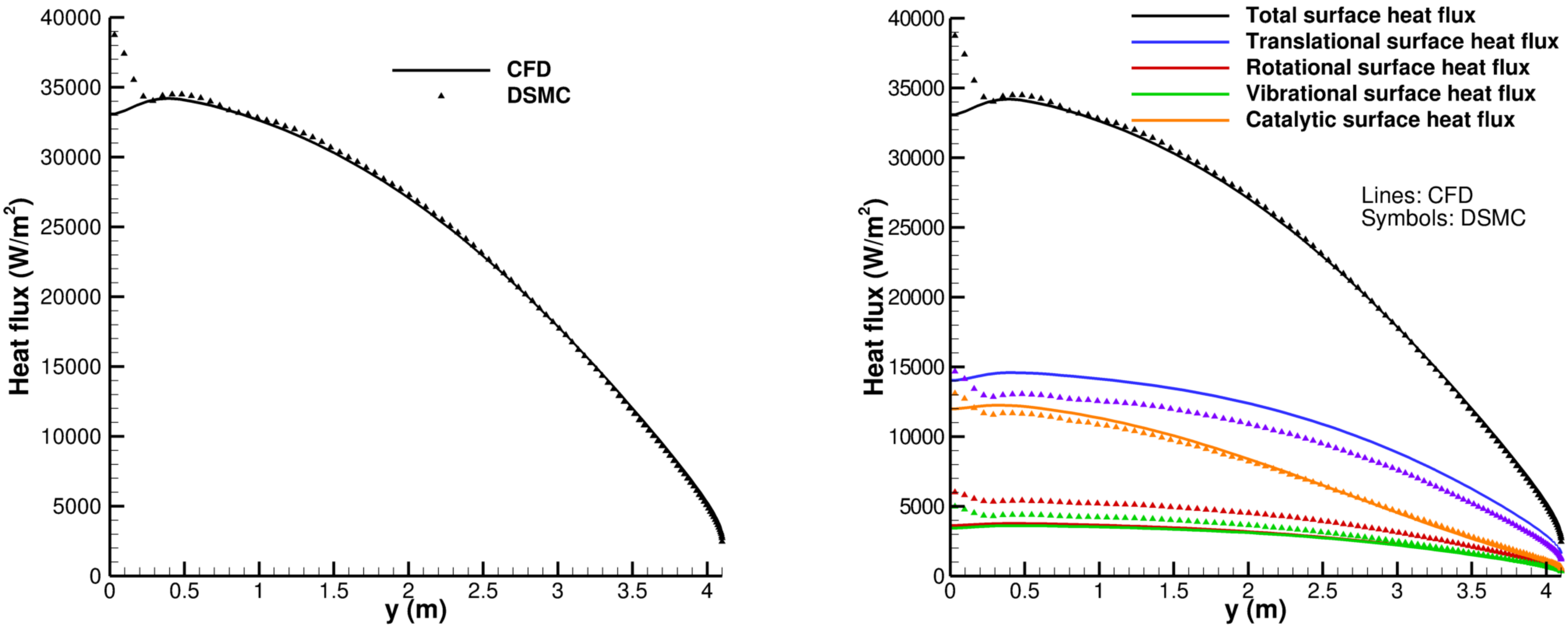



# Non-reactive Sphere Cases: Takeaways

- Investigated density conditions similar to M2020 from 94.8 to 58.0 km altitudes.
- Continuum breakdown effects as expected, although, in general, the Boyd continuum breakdown criterion $Kn_{GLL} > 0.05$ seems overly conservative.
- We propose that $Kn_{GLL} = 0.5$ might be a continuum breakdown criterion better suited for shock and surface slip.
- Surface heat flux is impacted at higher $Kn_{GLL}$ around 2.0.

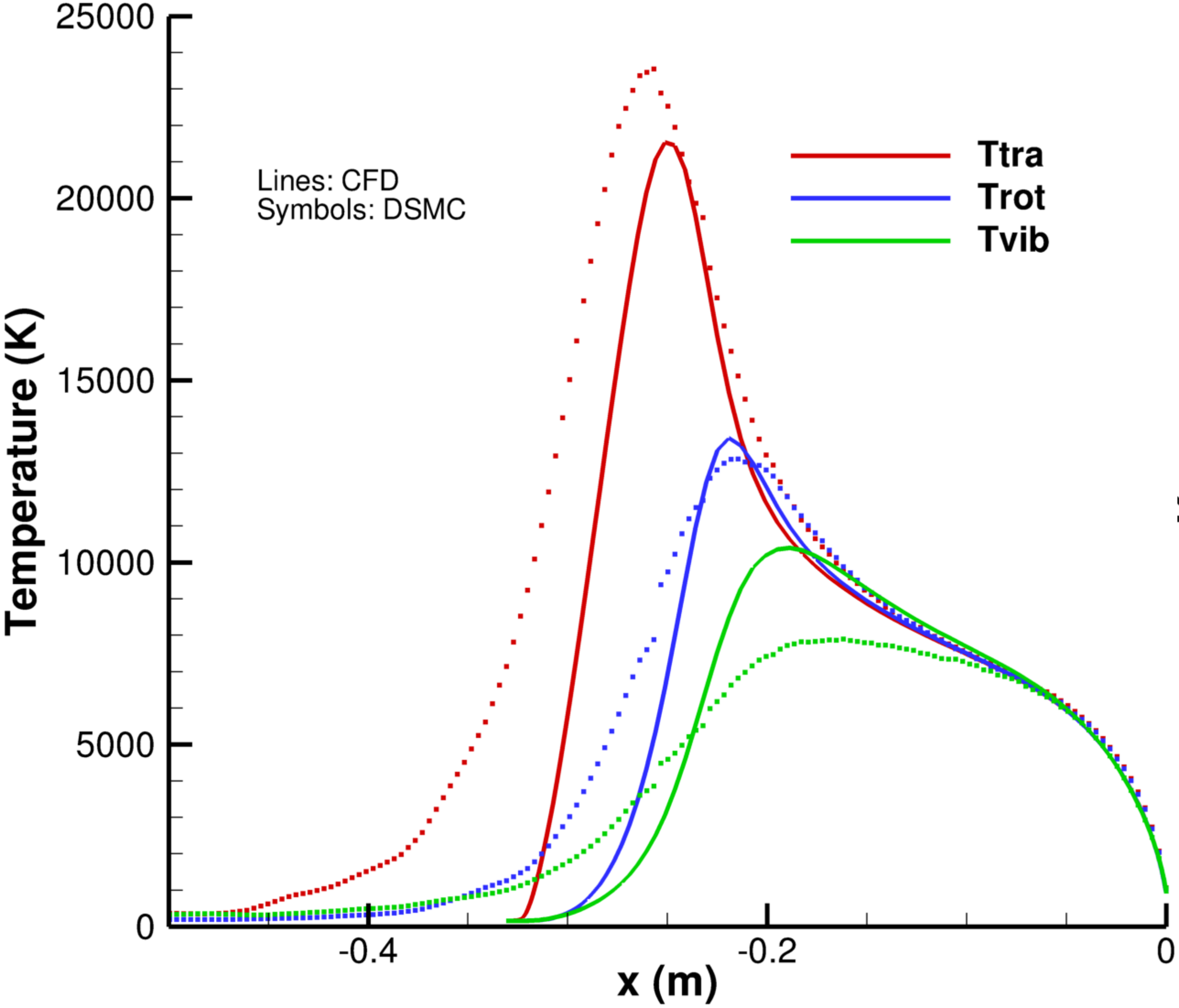
- We now return to Martian atmosphere flows ($CO_2/N_2$) but keep the 4.1 m radius sphere geometry.

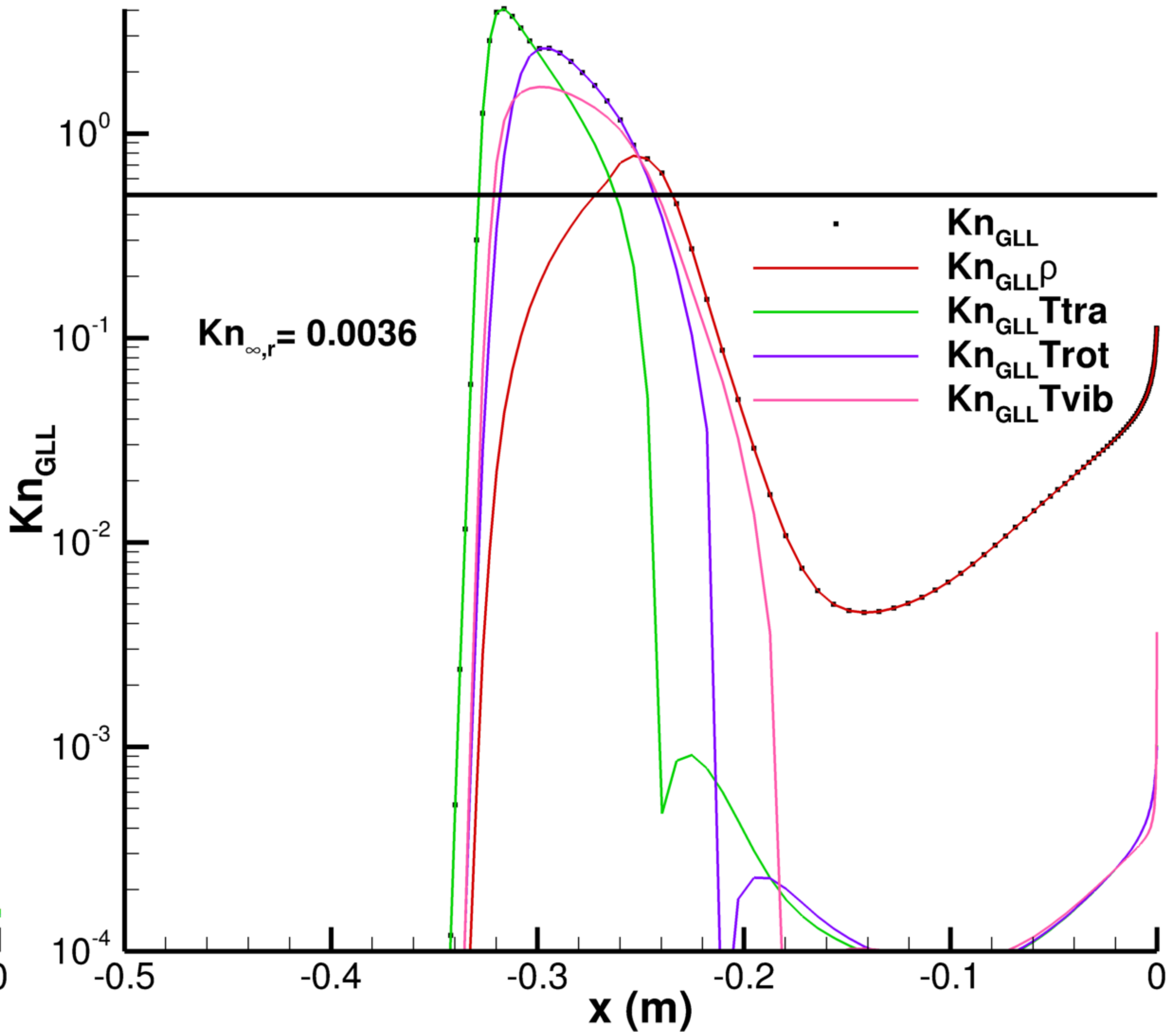
# Reactive Sphere Case at M2020 h = 80.6 km Conditions




Excellent agreement in total heat flux, despite discrepancies in each separate heat flux contribution from the various modes.

# Reactive Sphere Case at M2020 h = 80.6 km Conditions



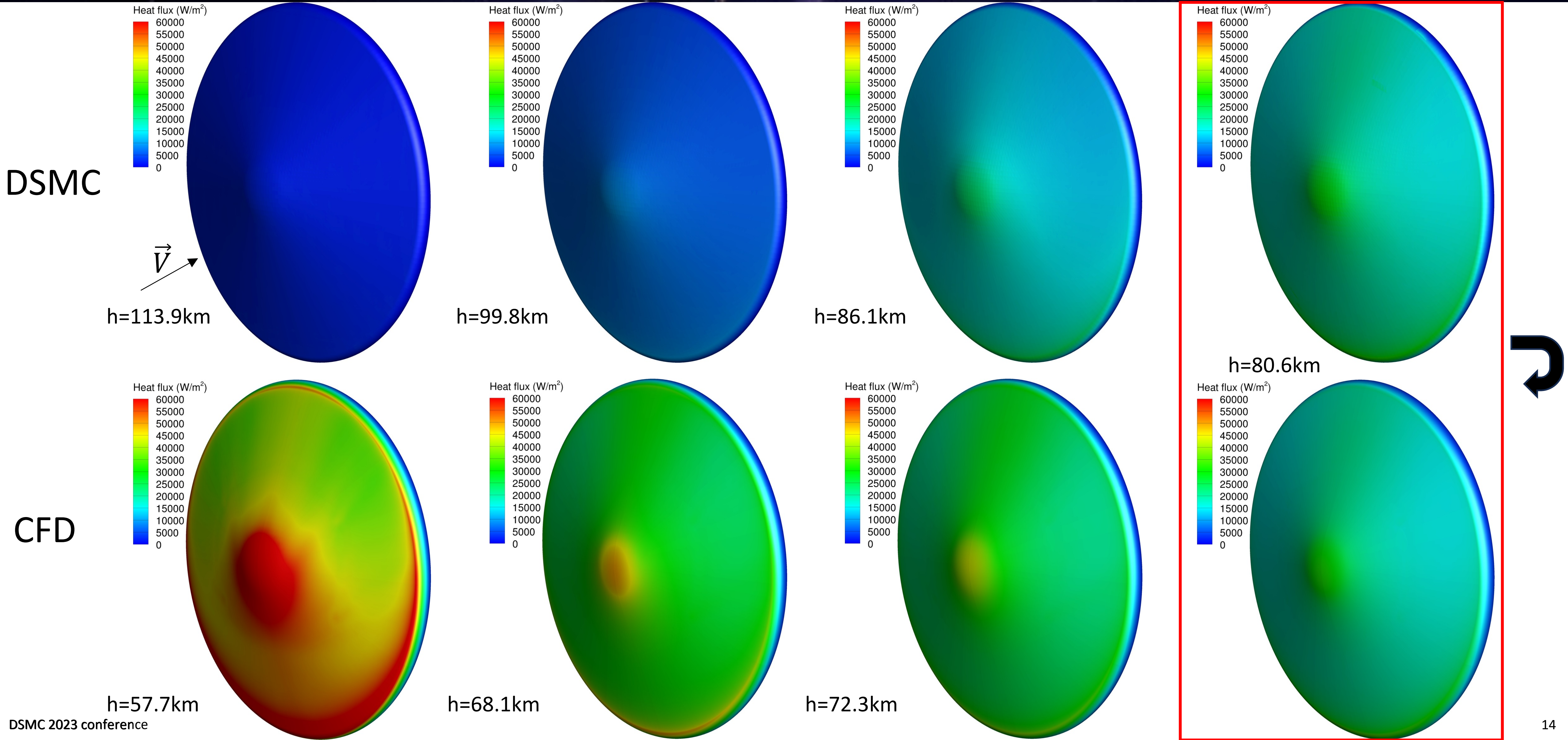

Now, each individual temperature contributes to the shock slip / breakdown -> Relaxation (and chemical) models matter!

# Reactive Sphere Case Takeaways

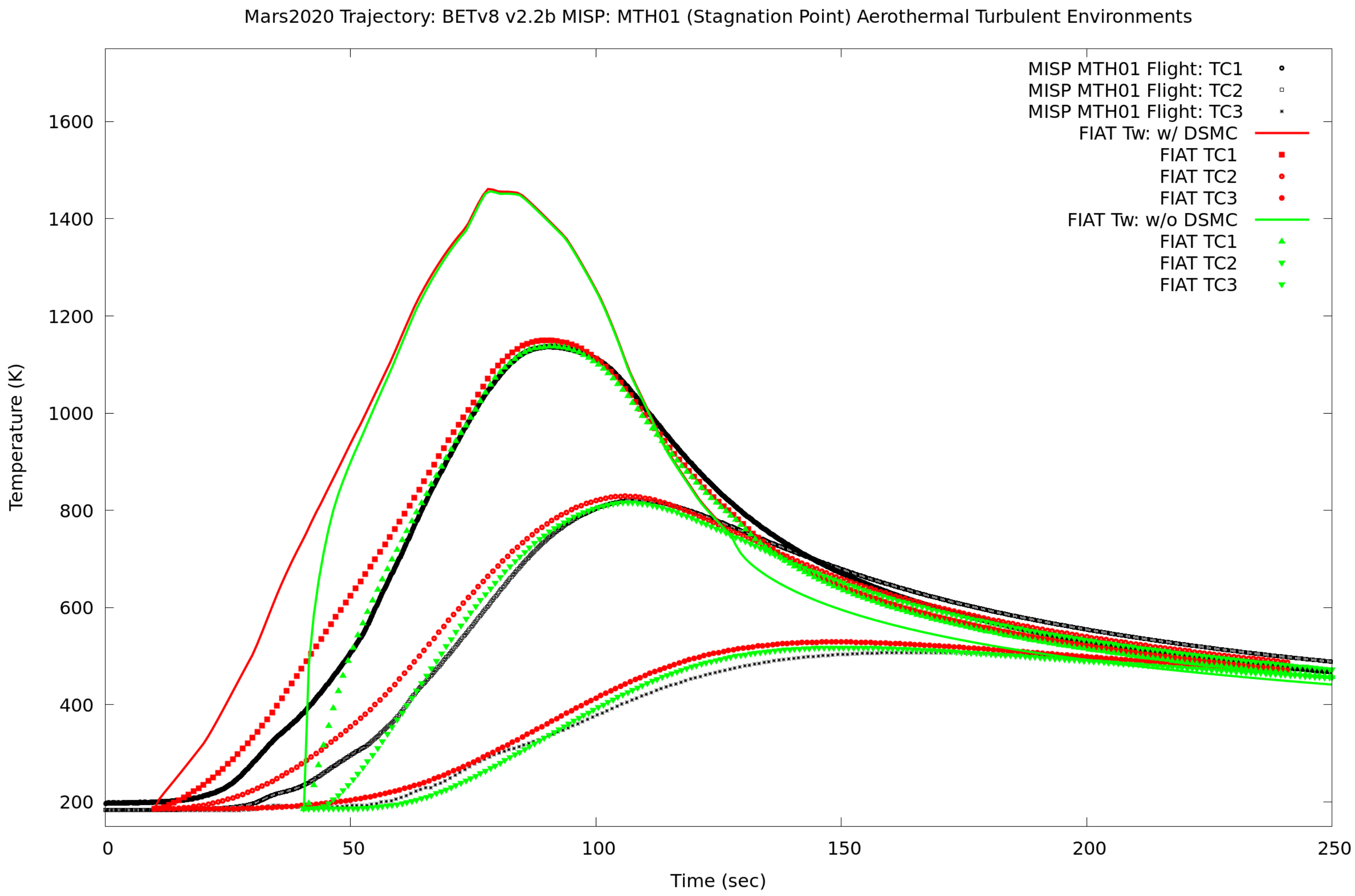
- Reactive flows show excellent agreement between SPARTA and DPLR for M2020 conditions at h = 80.6 km after EI, **for surface quantities.**
- Corresponds to $Kn_{GLL}$ larger than 2.0.
- Flow quantities still display breakdown around $Kn_{GLL}$ of 0.5.

- *Notes:*
  - *Lots of questions about accuracy of rotational relaxation rates remain.*
  - *Also not shown here, but the chemistry model has a massive impact on the results.*

# M2020 Early Time Points: 3D Heat Flux Contours



# M2020 Material Response: With and Without DSMC




Courtesy of Josh Monk (NASA/TSM)

While the additional heat load between EI and 35 s is small, it is obvious that neglecting contributions from early time points entirely affects the surface and in-depth temperature response for a long time.

# Conclusions

- A continuum breakdown occurring at $Kn_{GLL}$ = 0.5 appears more appropriate for flow quantities.
- Surface quantities are less impacted by breakdown than flow quantities.
  - $Kn_{GLL}$ of 2.0 for non-reacting and higher for reacting cases.
- Shock slip occurs before surface slip and may or may not impact surface quantity.
- Reacting flows appears more forgiving than non-reacting flows with respect to breakdown.
- Relaxation and chemical models matter!
- For post-flight reconstruction efforts, accuracy is of the utmost importance, and DSMC provided added accuracy compared to CFD for non-continuum conditions, despite the added cost.

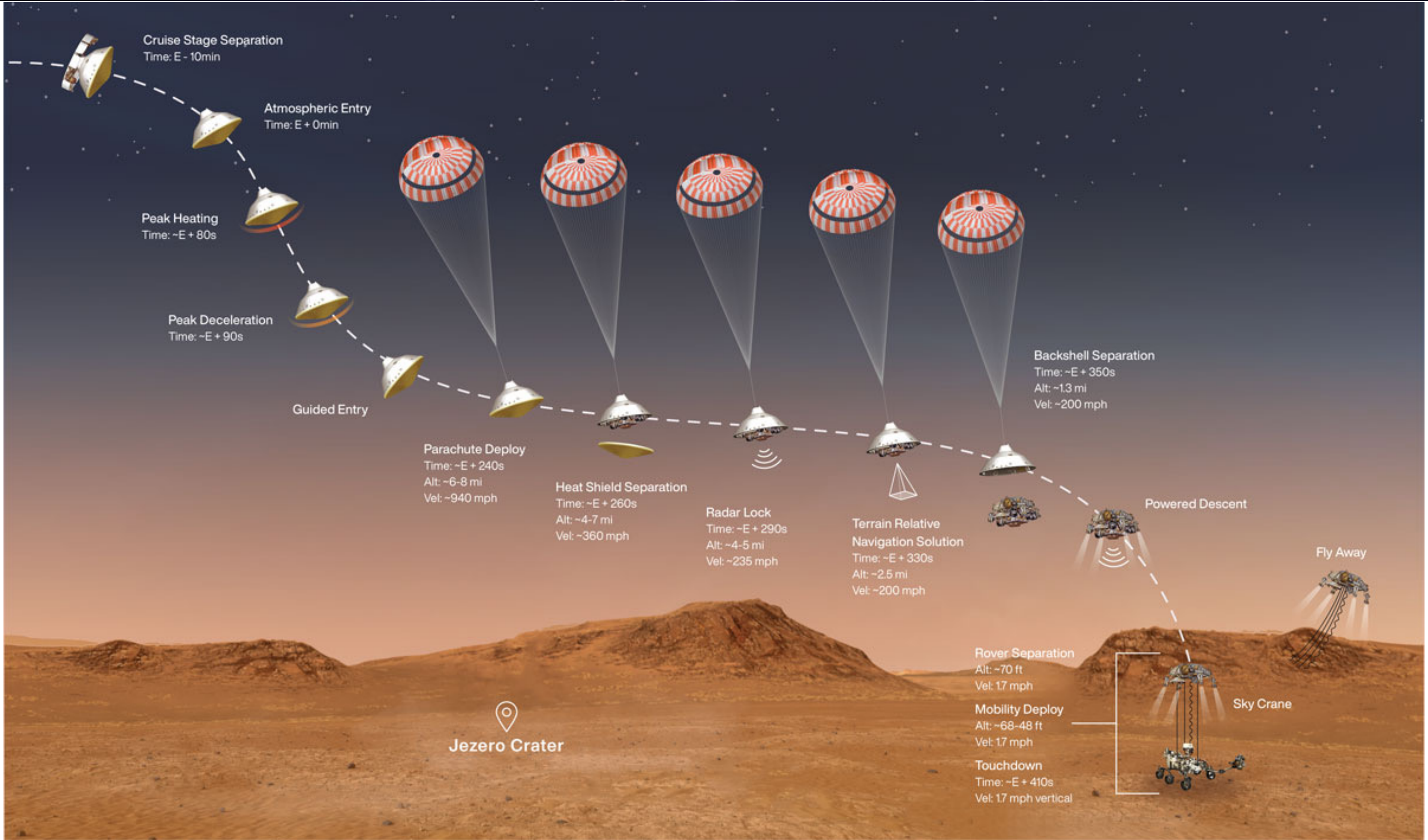
# Acknowledgments


- John Thornton, Josh Monk, Jeremie Meurisse, Georgios Bellas-Chatzigeorgis for useful discussions.
- Entry Systems Modeling project (J. Haskins PM, A. Brandis PI), as part of the NASA Game Changing Development program.
- In particular, the MEDLI2 Deep Dive task (T. West PI).

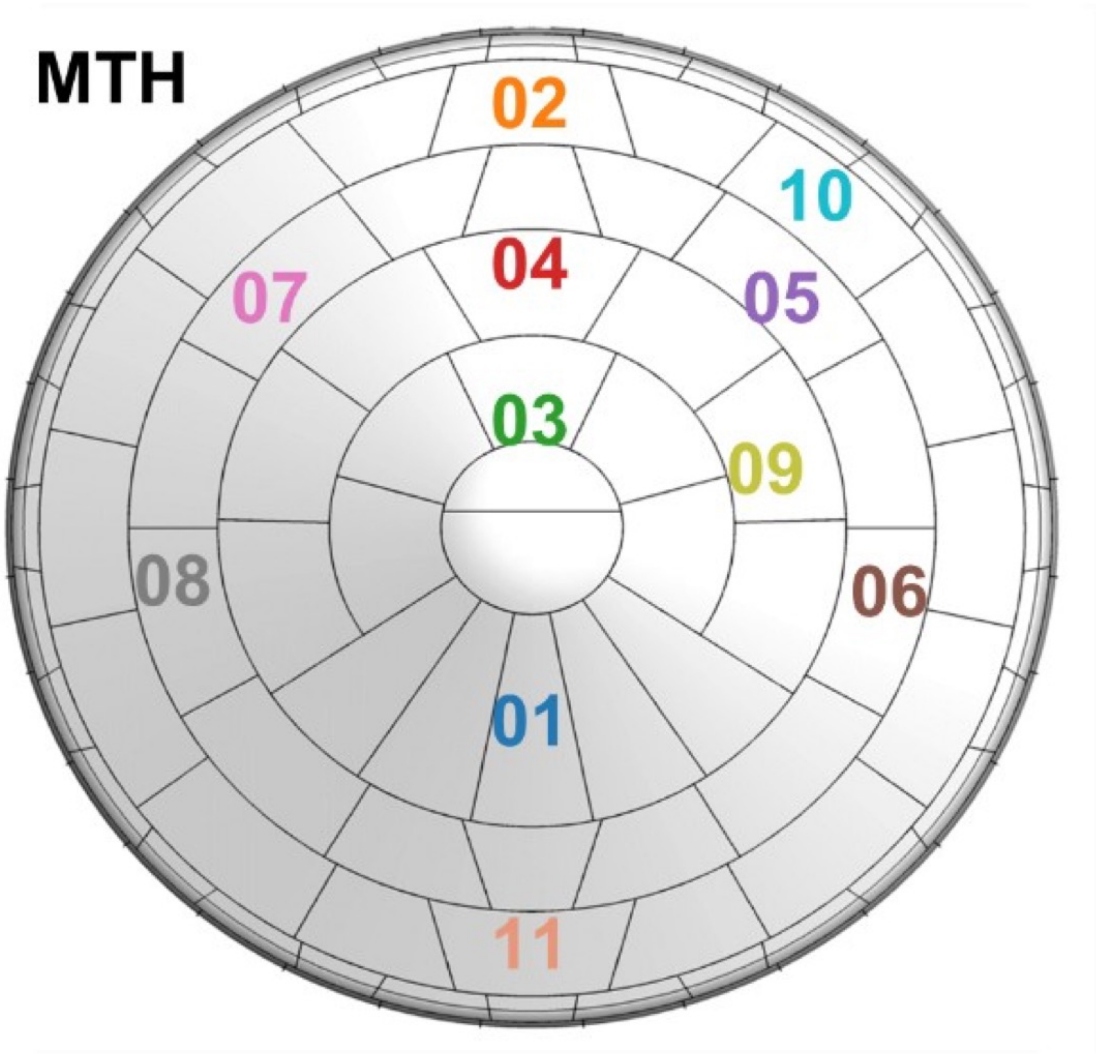

# Questions?

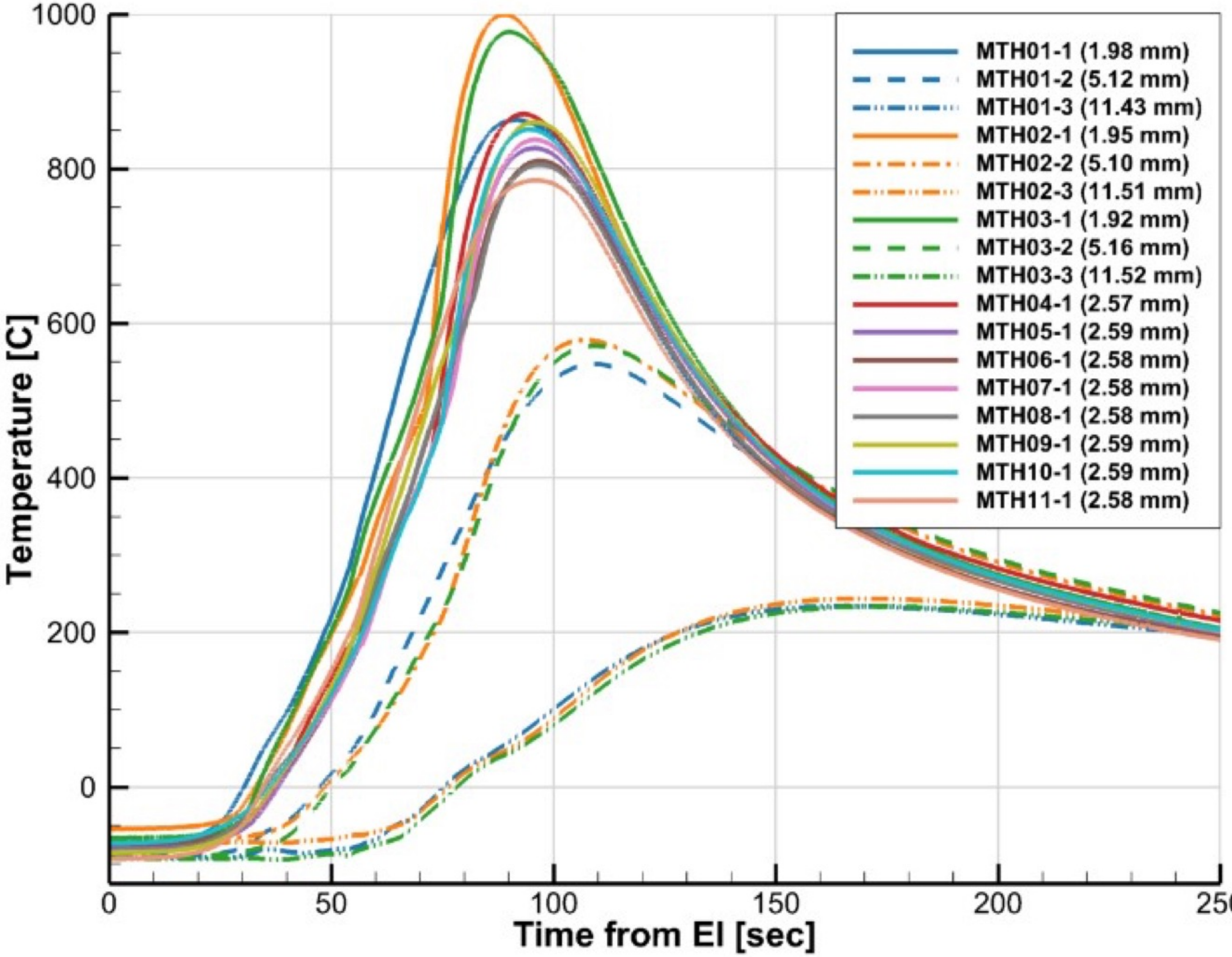
# Backup Slides

# The Mars 2020 EDL Sequence



# Heatshield Temperature History from MEDLI2





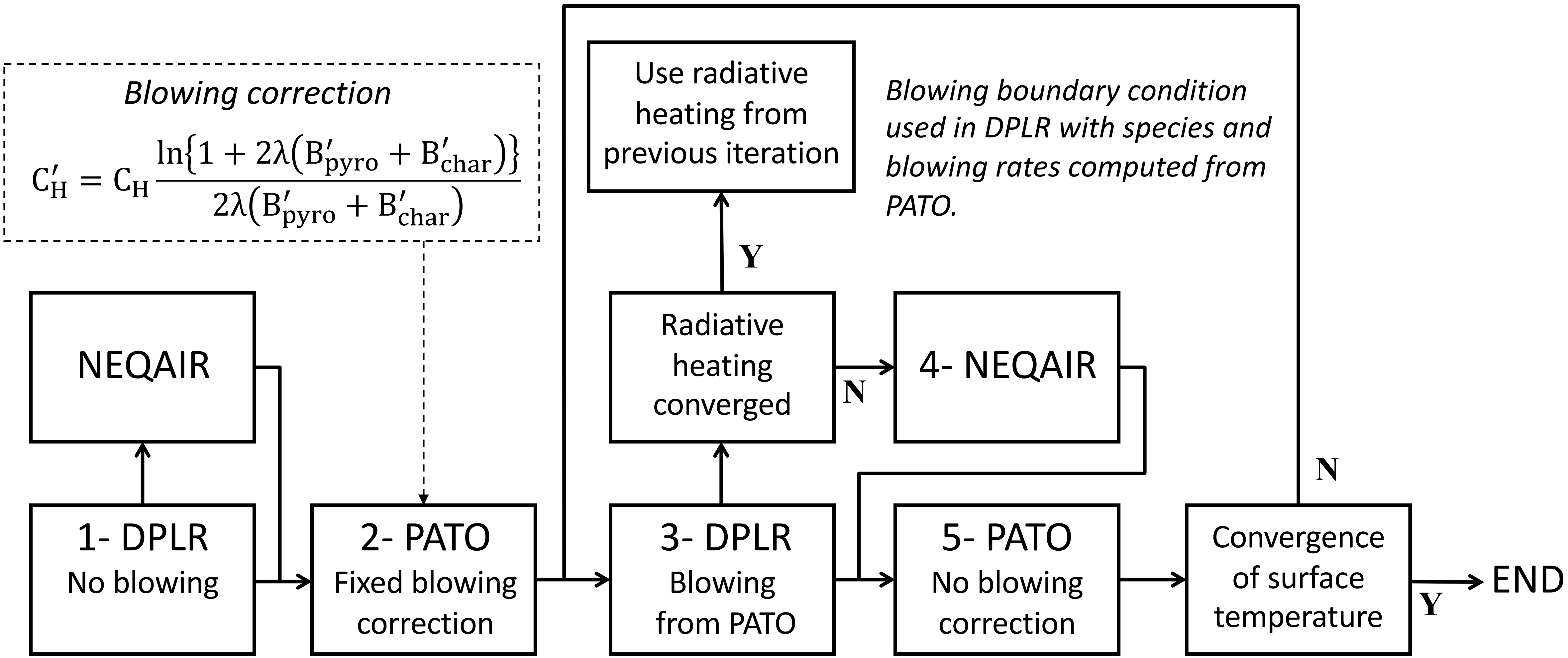
[1] *T. White et al. (2022), AIAA SciTech 2022 Forum, 2022-0011.*

# Coupling Methodology

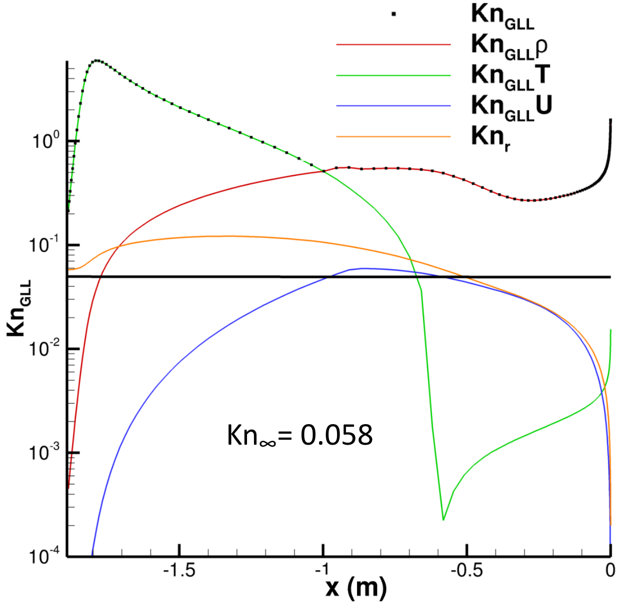
$$q_w = \varepsilon \sigma T_w^{\ 4}$$

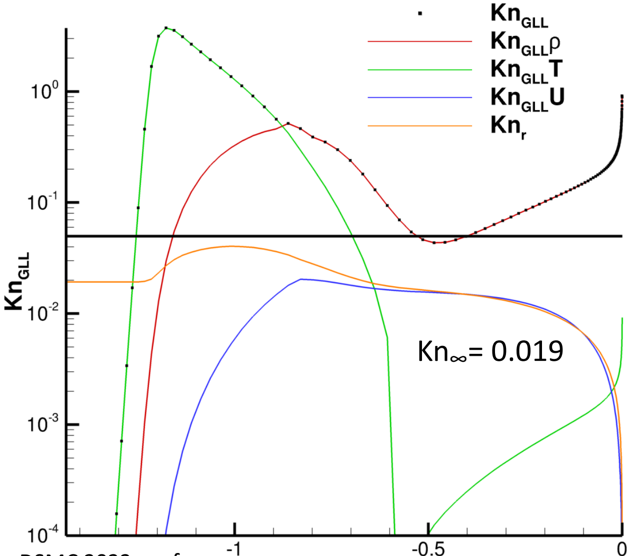
$$C_H = \frac{q_w}{\left(H_{edge} - H_{wall}\right)}$$

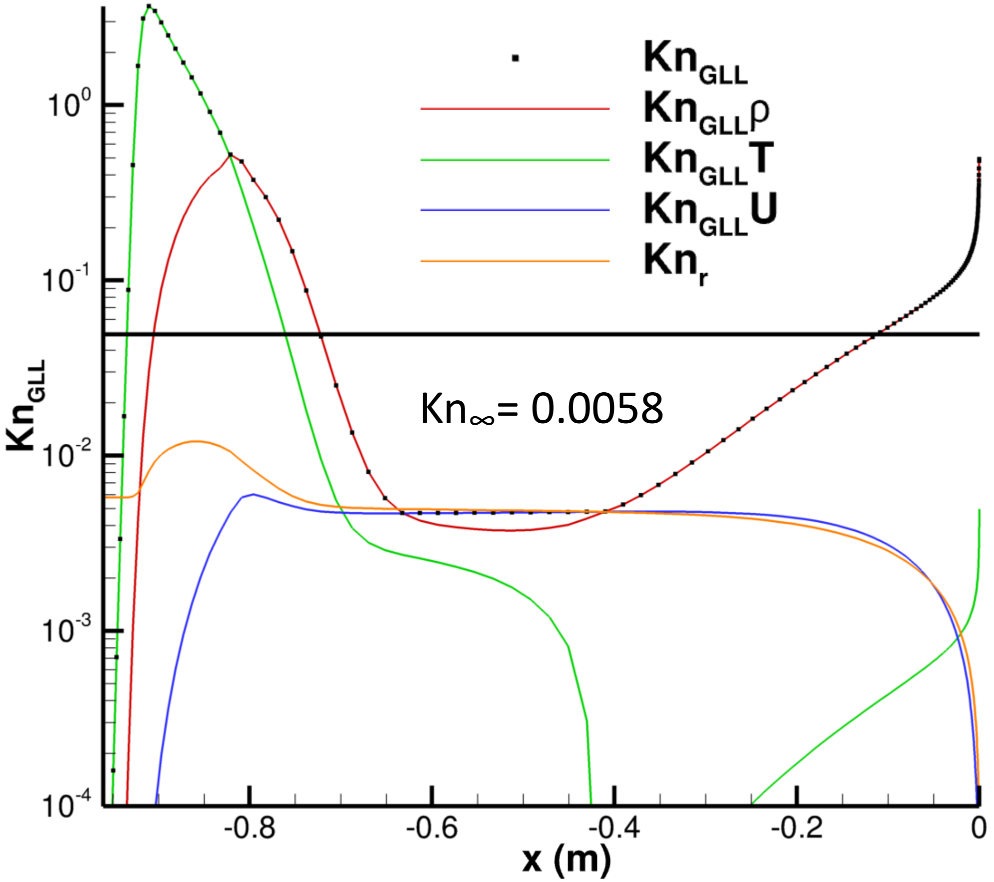
[8] *J. Thornton et al. (2023), AIAA SciTech 2023 Forum, 2023-0963.*

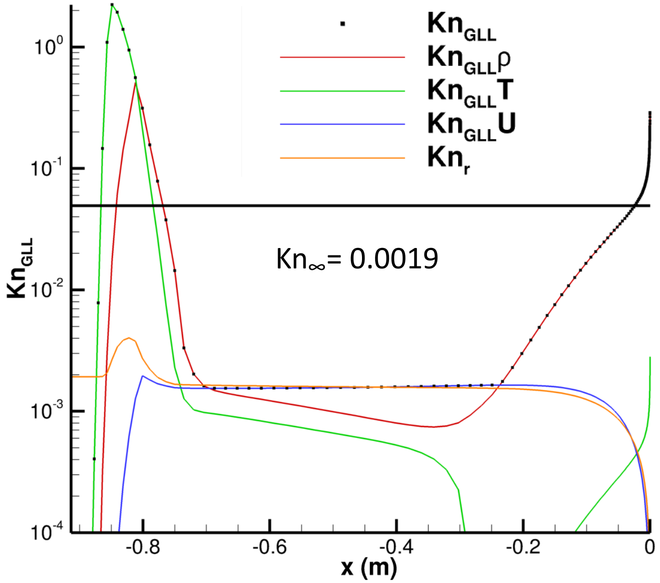


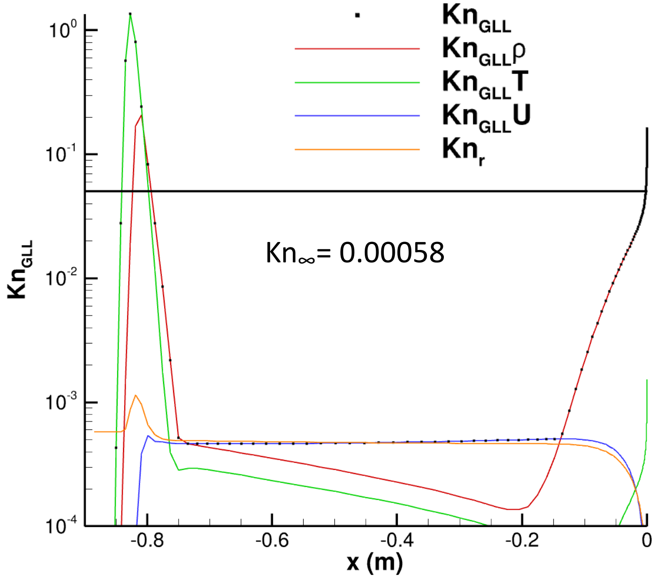
# Continuum Breakdown



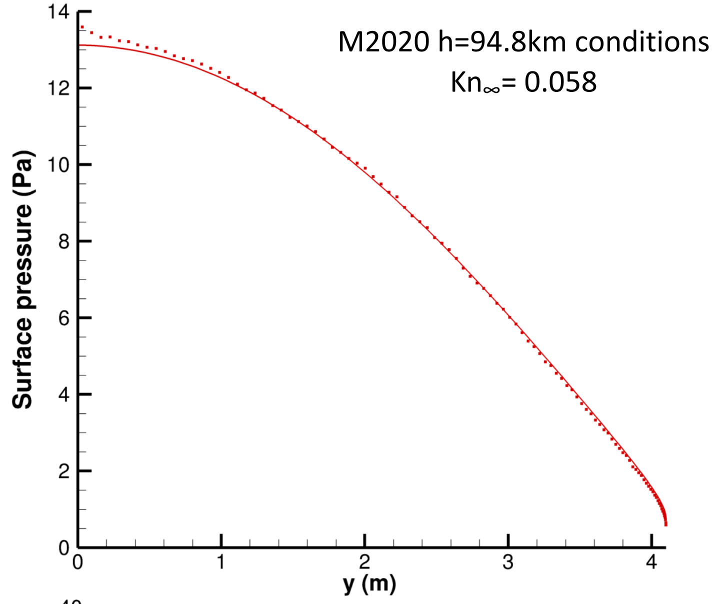



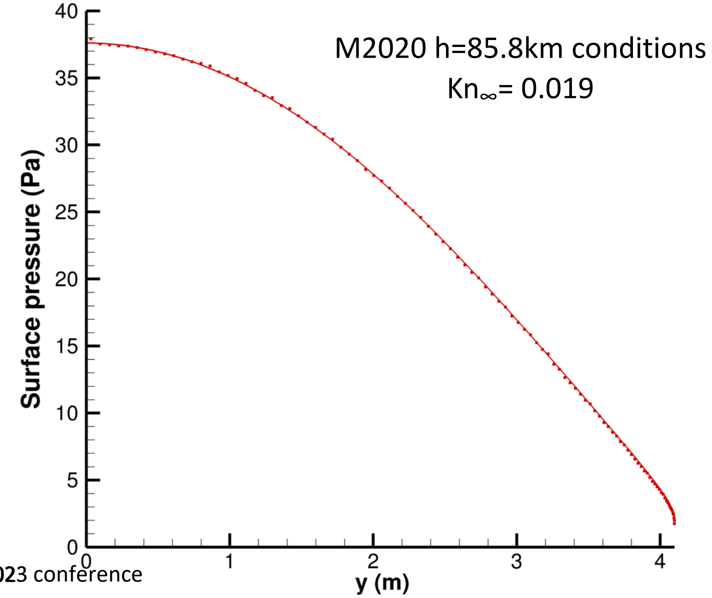



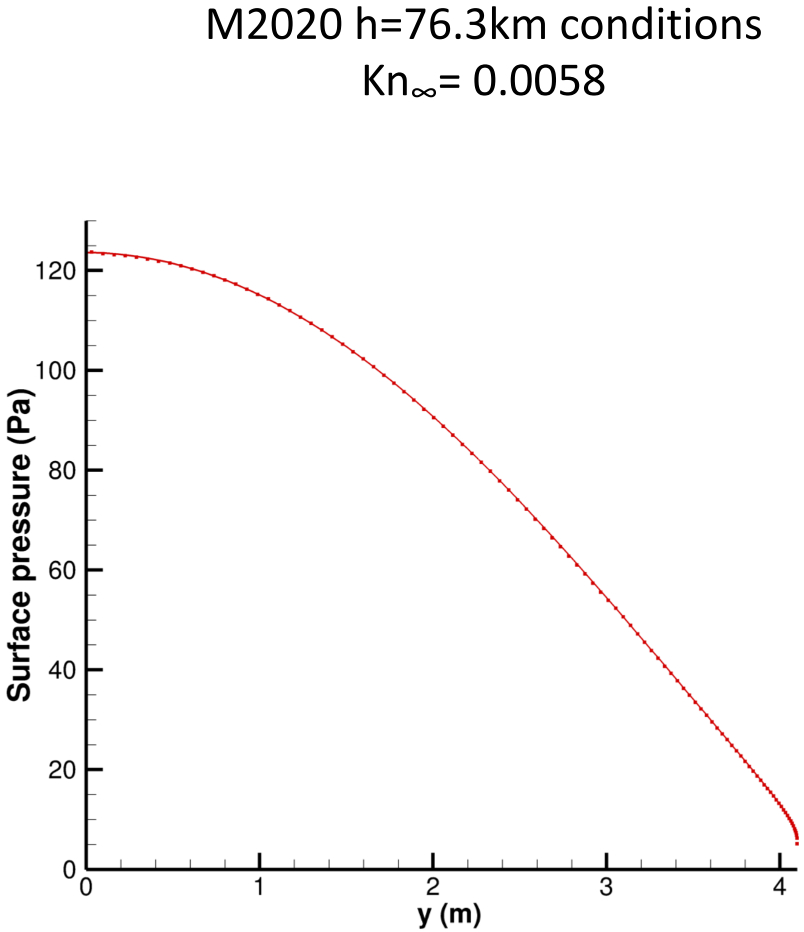



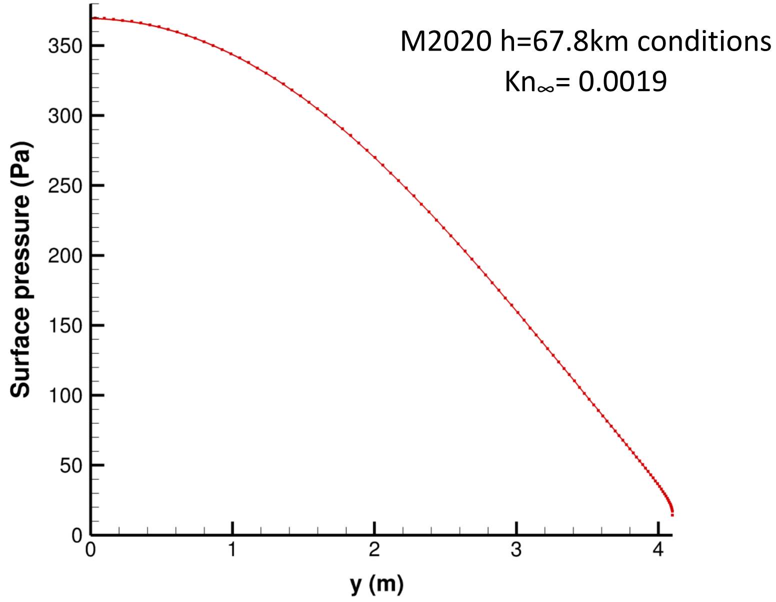



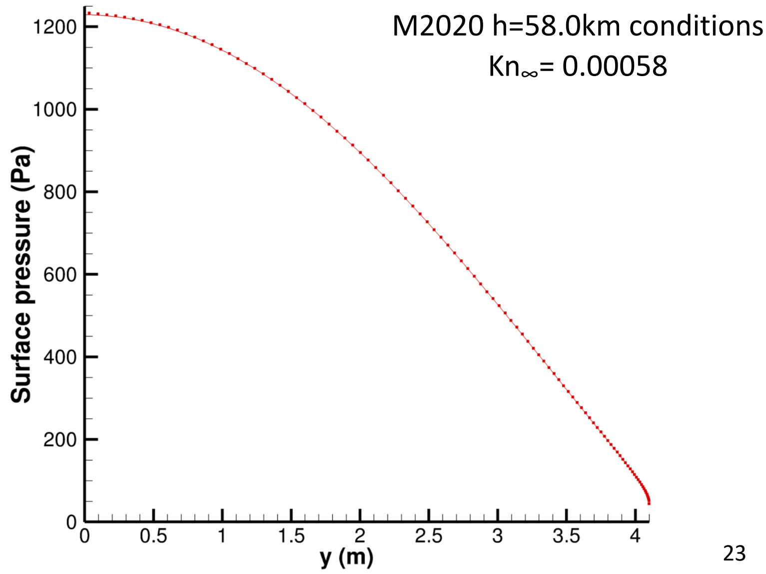
# Surface Pressure



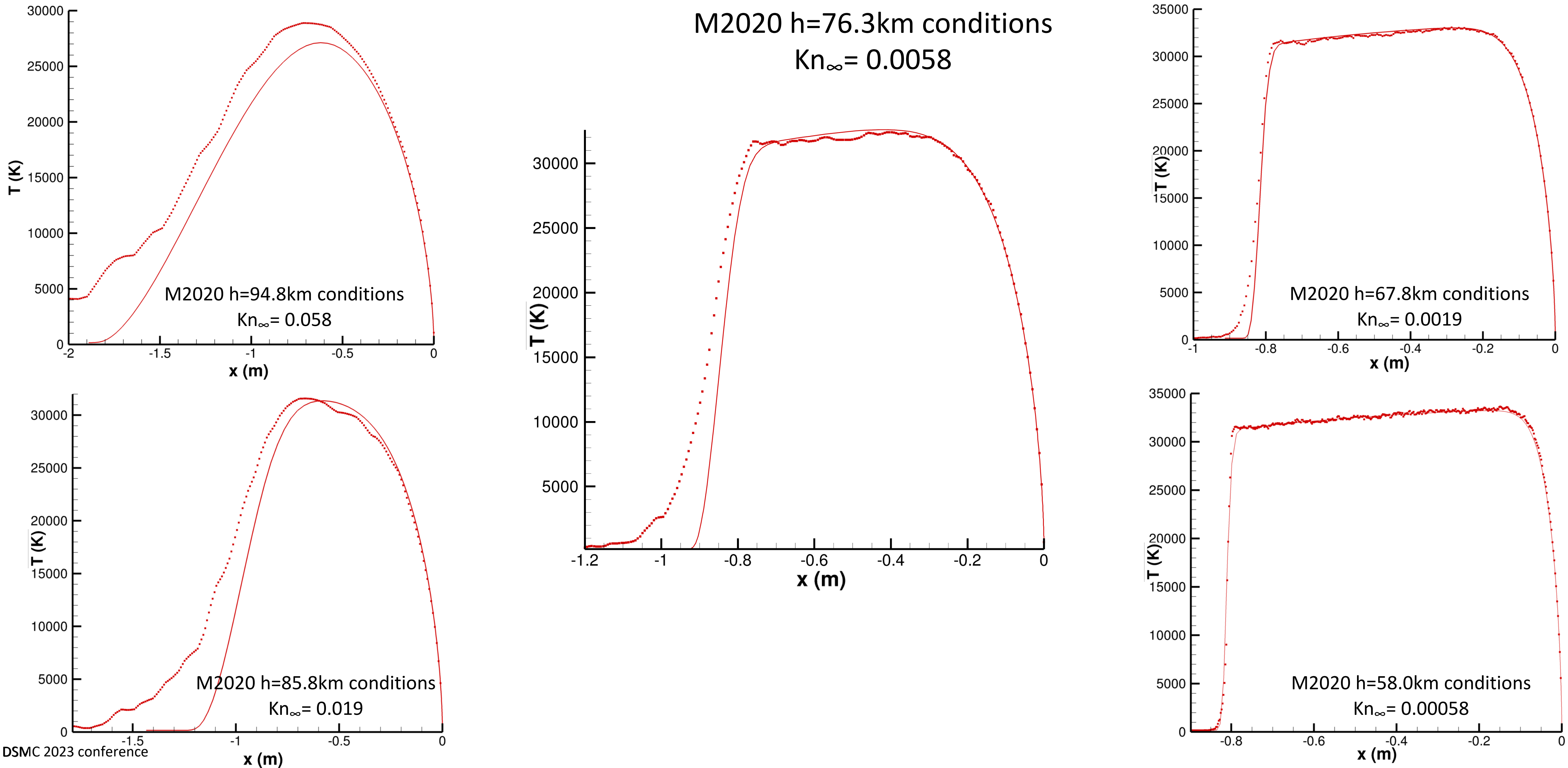



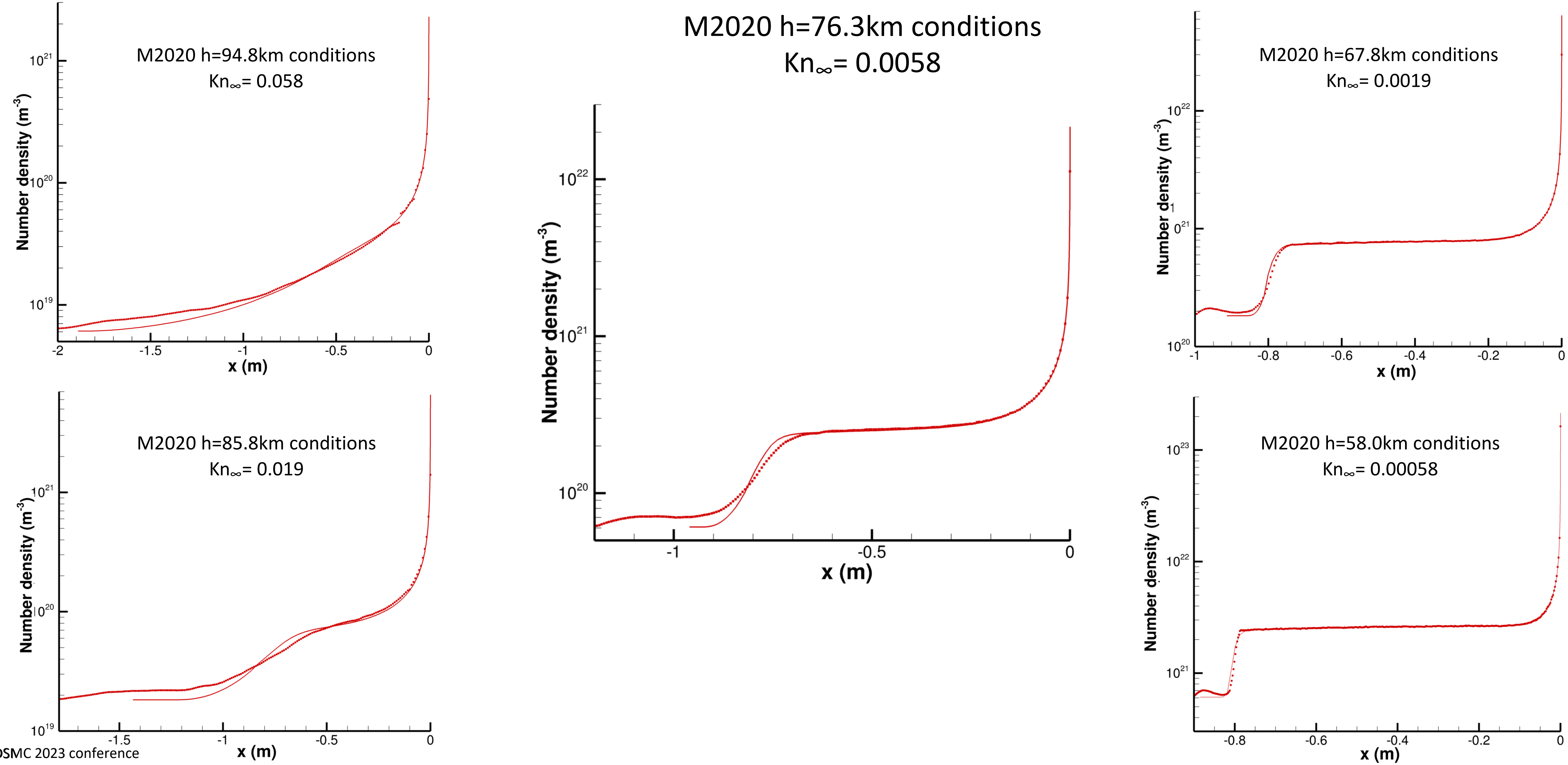



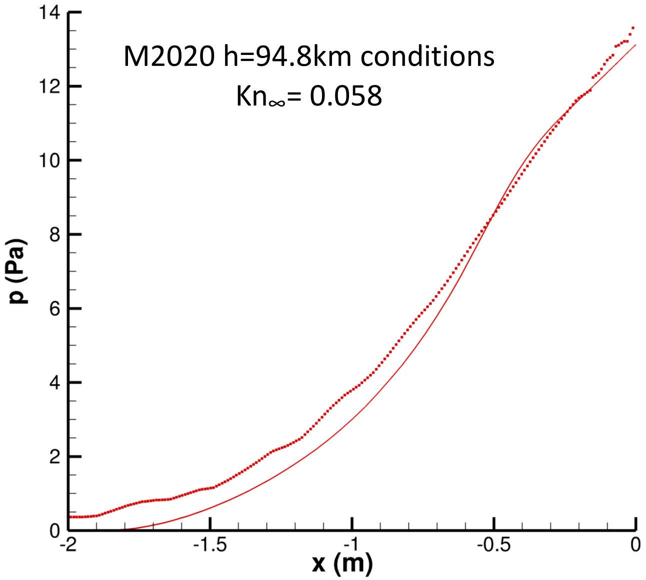
# Stagnation Line Temperature

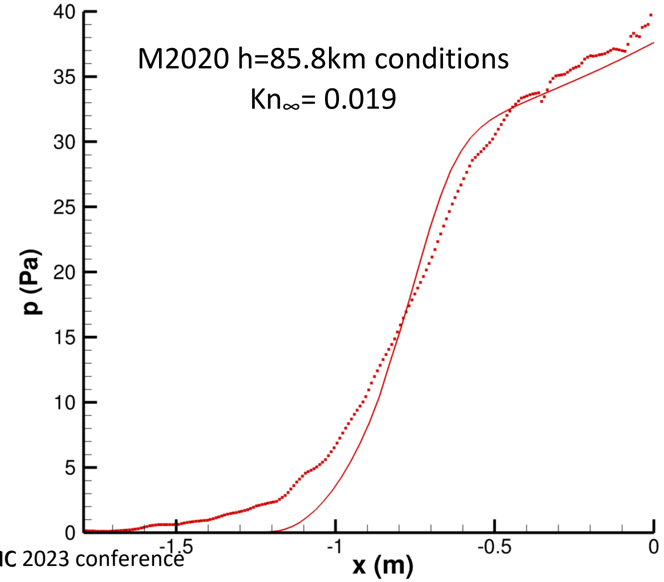


# Stagnation Line Number Density

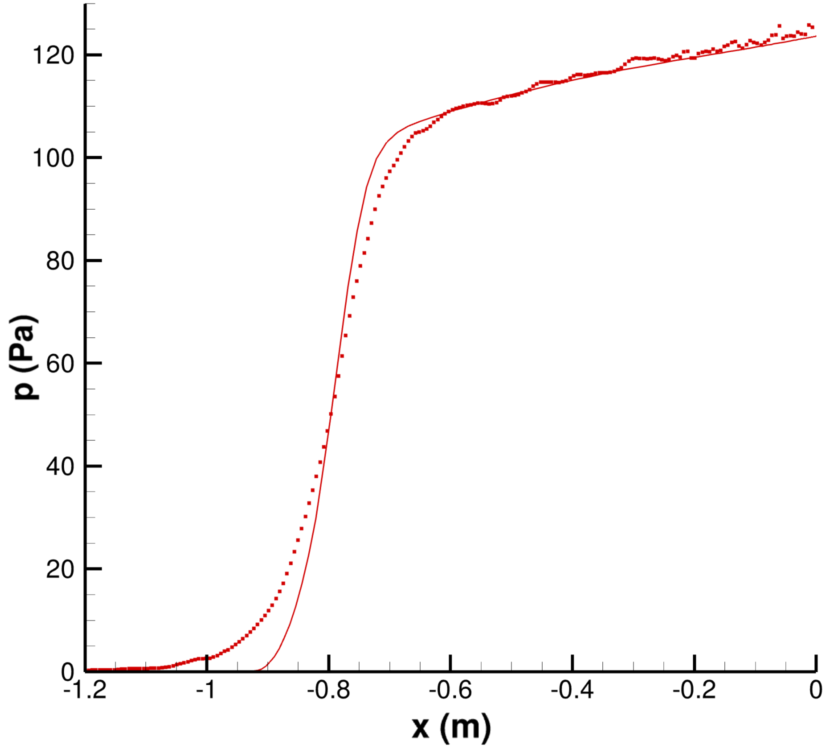


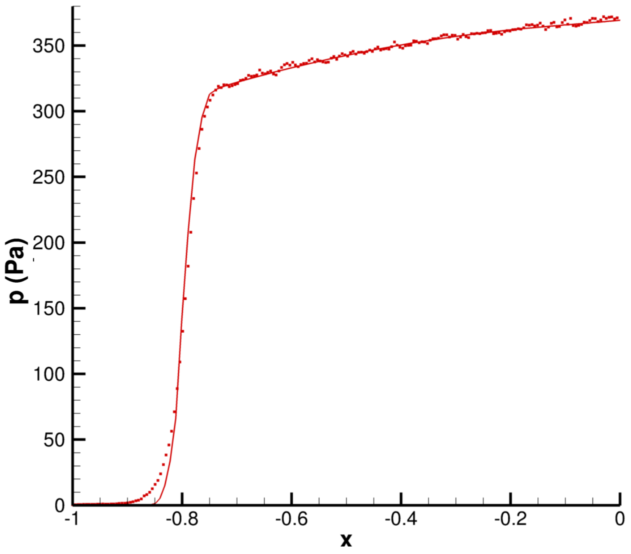
# Stagnation Line Pressure

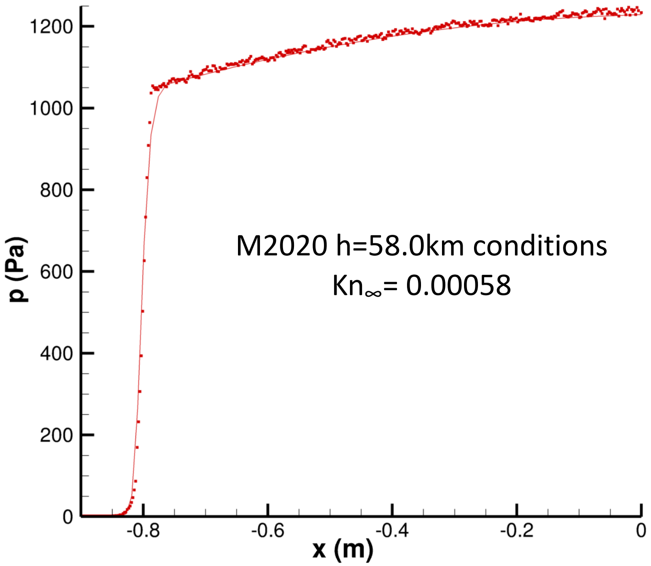



M2020 h=76.3km conditions
Kn∞= 0.0058



# Reactive Sphere Case at M2020 h = 80.6 km Conditions

Solid vs dashed lines represent 2 different chemistry models in DPLR.
Main differences are the dissociation rates of $CO_2$, CO and $O_2$, as well as additional exchange reactions.