Reentry flow and aerothermal characteristics of a retro-propulsive booster

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Background

Retro-propulsion and reusability

- Recent development
  - Vertical Takeoff, Vertical Landing (VTVL) launchers
    - SpaceX: Falcon 9, Starship
    - Blue Origin: New Shepard, New Glenn
- Themis demonstrator project
  - GKN contributes to developing the prometheus engine

Objectives

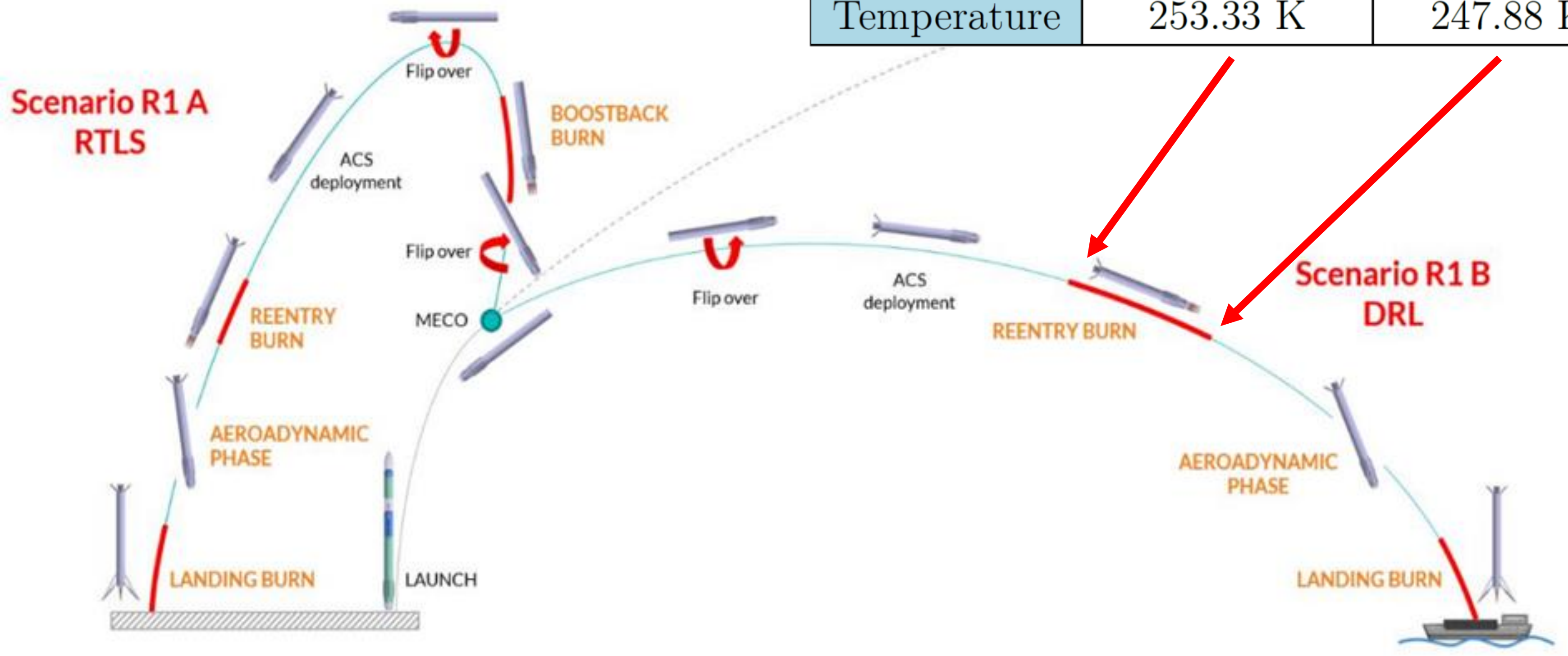
Investigate the aerothermal loads on the rocket nozzles during reentry with and without retro-propulsion:

- > What is the flow behavior around the nozzles during reentry, with and without retro-propulsion.
- > What is the **temperature**, **heat transfer coefficient** and **heat flux** during reentry.
- > How can a CFD model be set up in order to investigate thermal loads on the nozzles, and what simplifications can be made

Theory: Flight trajectory

	Start of burn	End of burn
Mach	7.14	5.35
Altitude	57.66 km	39.06 km
Pressure	30.02 Pa	327.6 Pa
Temperature	253.33 K	247.88 K

VTVL launch trajectories



*Ansgar Marwege and Ali Gülhan. "Unsteady Aerodynamics of the Retro-propulsion Reentry Burn of Vertically Landing Launchers". In: Journal of Spacecraft and Rockets 60.6 (2023), pp. 1939–1953

Theory: Chemical models

Non-reacting flow

Calorically perfect gas

- Constant γ
- Constant C_p

Frozen chemistry

- Thermally perfect gas
- γ = f(T)
- C_p = f(T)

Reacting flow

Chemical equilibrium

- γ = f(T,p)
- C_p = f(T,p)
- R = f(T,p)

Chemical non-equilibrium

- γ = f(T,p,t)
- C_p = f(T,p,t)
- R = f(T,p,t)

Model	Temperature
Calorically perfect gas	< 800 K
Thermally perfect gas	< 2000 K
Chemical reactions	> 2000 K

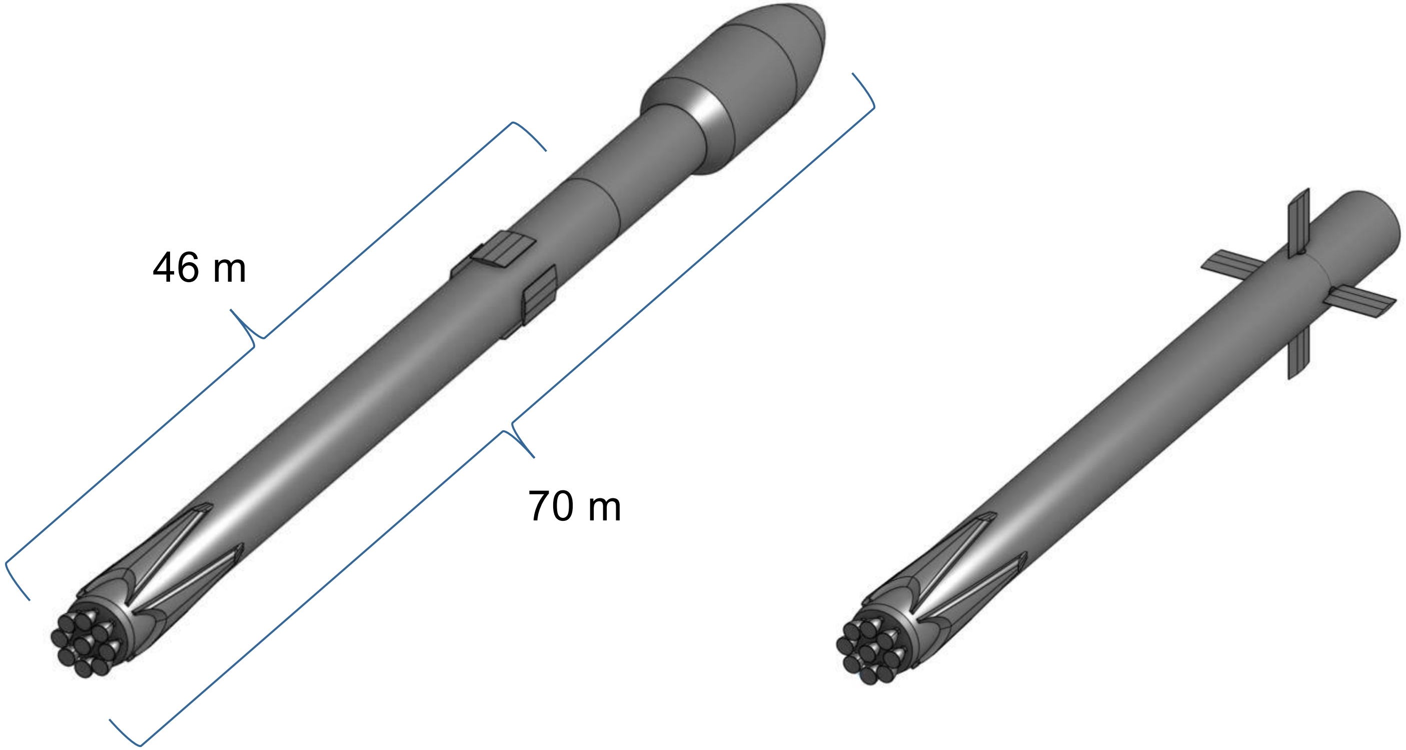
Method: Standard rocket model

EU project to investigate retro-propulsion

- Developed by German Aerospace Center (DLR) as an EU project
- CAD model: based on Falcon 9
- Flight data: DRL of Falcon 9
- Engine data: Methane/LOx

Ascent configuration:

Descent configuration:



*Tamas Bykerk. “A standard model for the investigation of aerodynamic andaerothermal loads on a re-usable launch vehicle”. In: July 2023

Method: Modification to standard rocket model

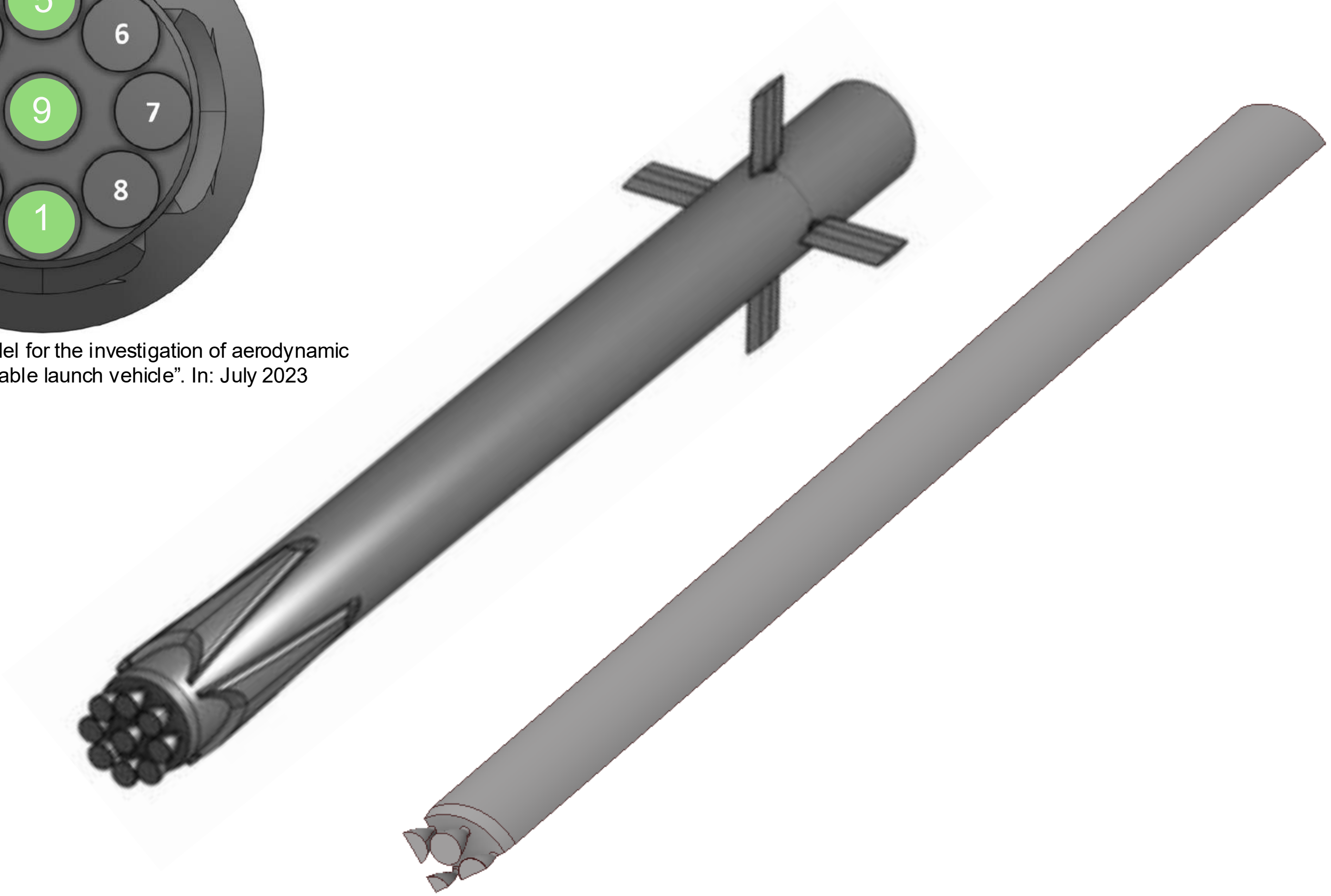
Engines

- Ascent: 9 engines
- Reentry burn: 3 engines (1-9-5)

*Tamas Bykerk. “A standard model for the investigation of aerodynamic andaerothermal loads on a re-usable launch vehicle”. In: July 2023

Simplifications

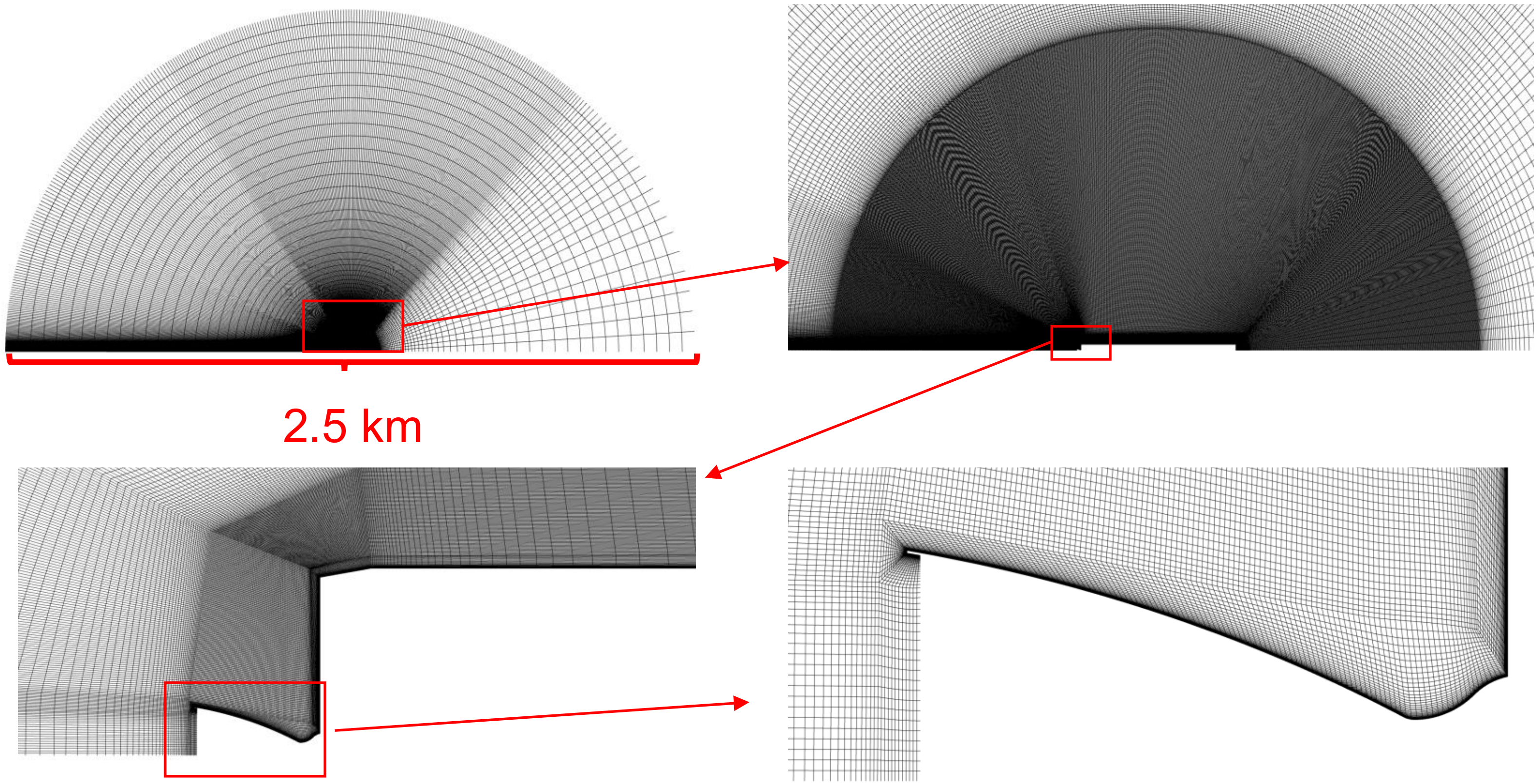
- Removed: Fins and landing legs
- Quarter symmetry



2D prestudy

Prestudy 2D - axisymmetric

- Only 1 engine
- ICEM for meshing
- Effects of chemistry models



3D main study

3D simulations

> All engines

Main goal

> Adiabatic simulations

> Heat transfer coefficient

> Heat flux

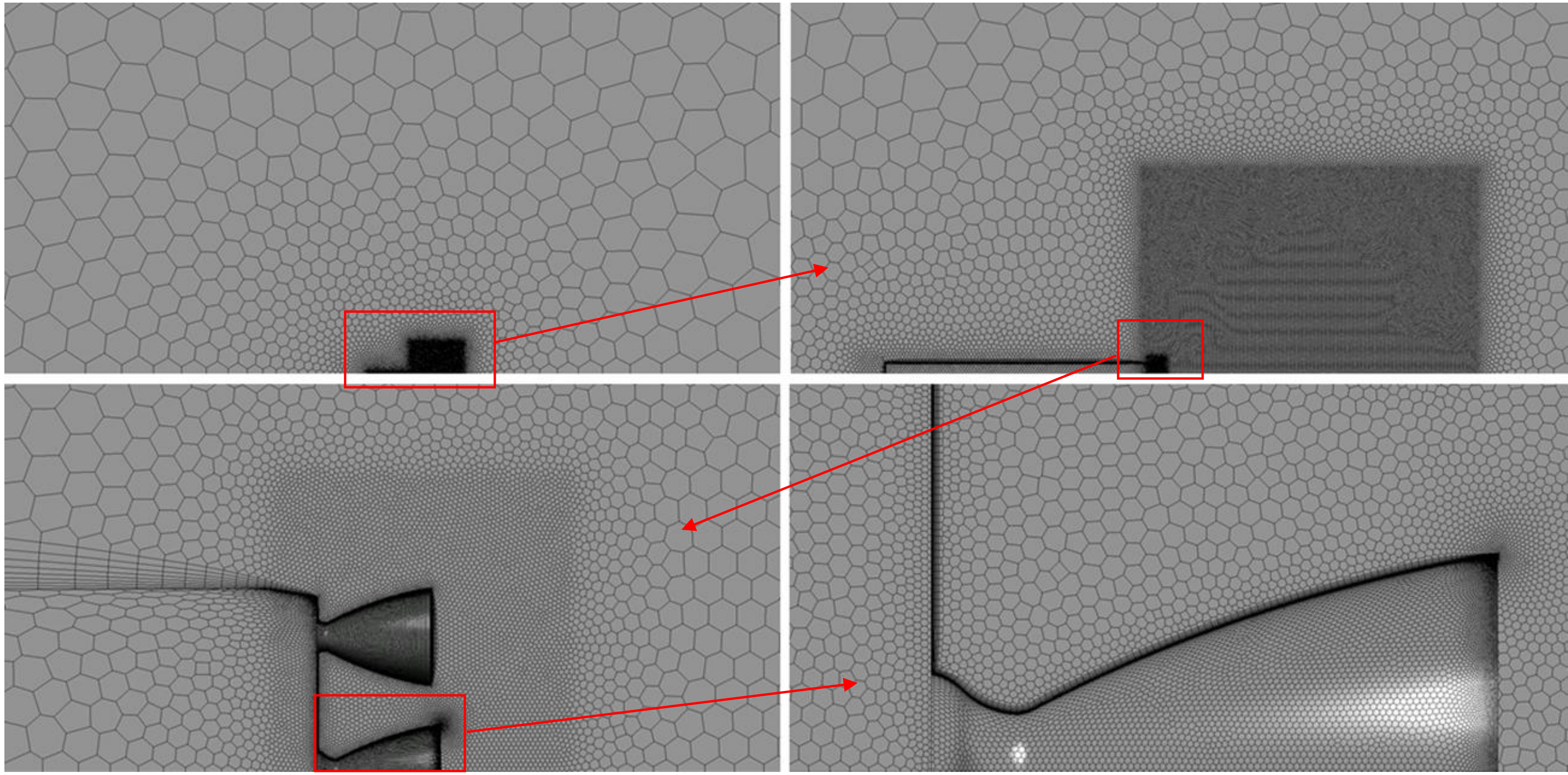
> Investigate flow behaviour

Steady state RANS

> Implicit density based solver

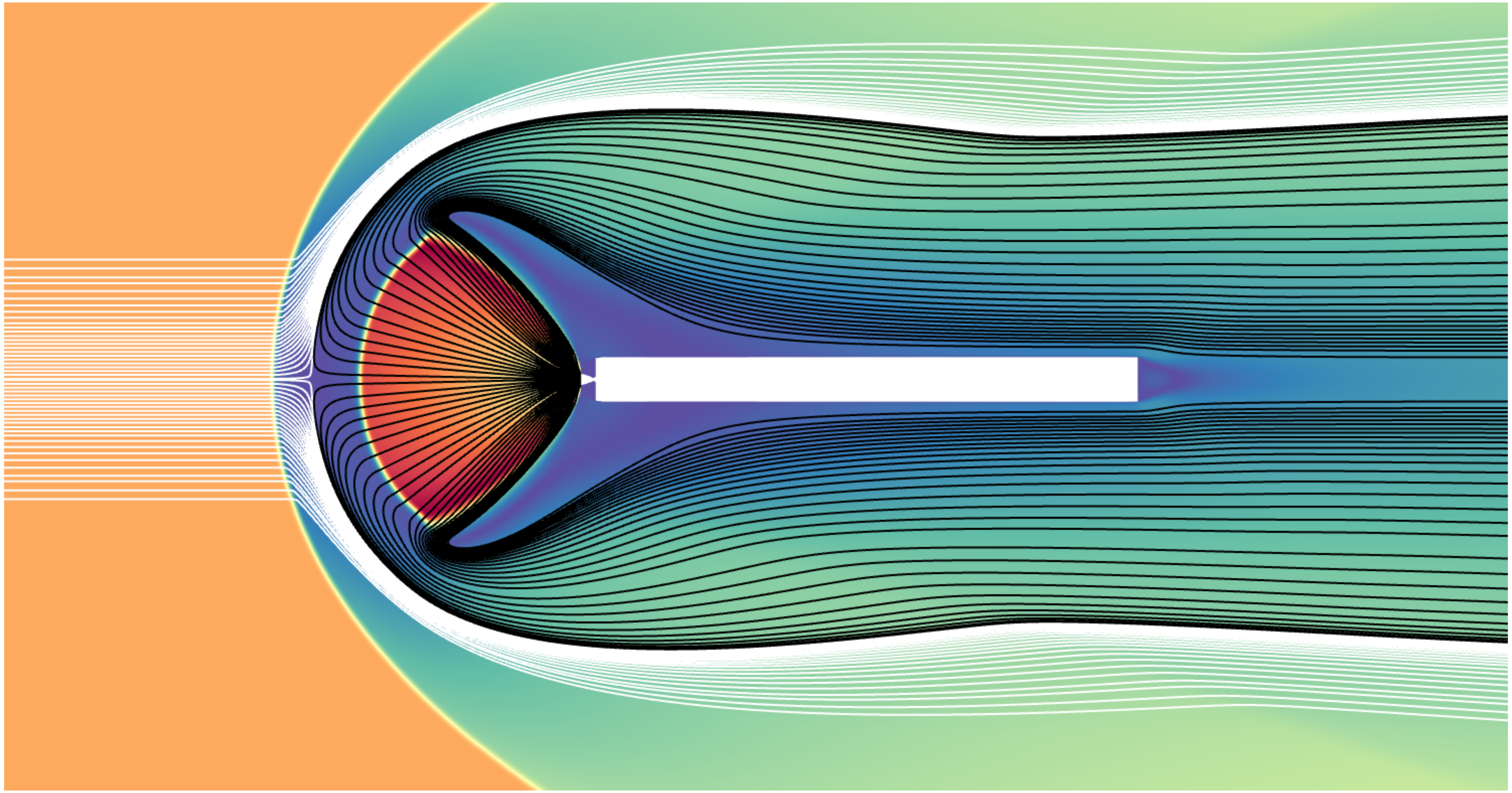
> $k - \omega \ SST$

> 2^{nd} order scheme



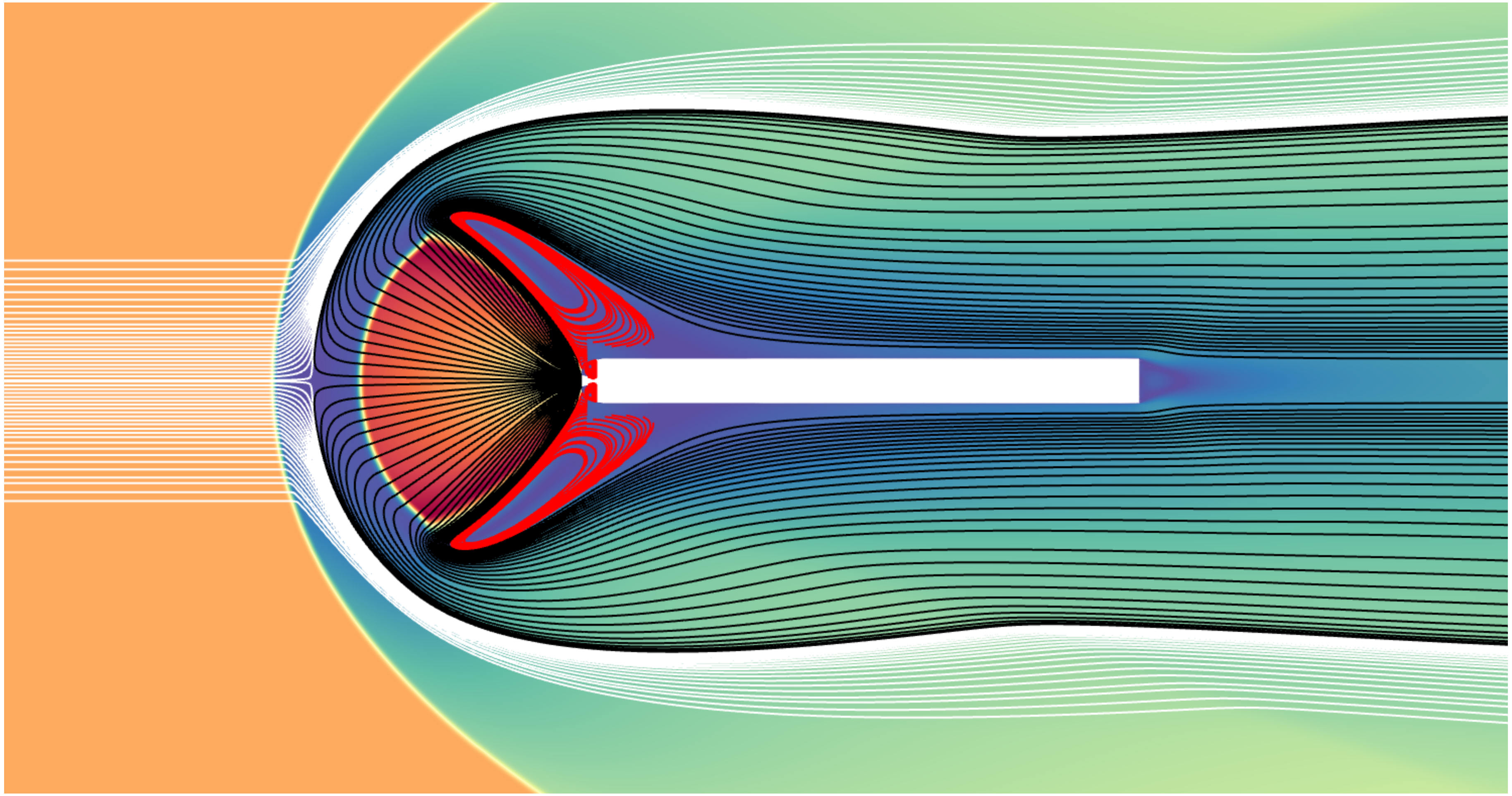
2D results: Flow behaviour

Direction of flight

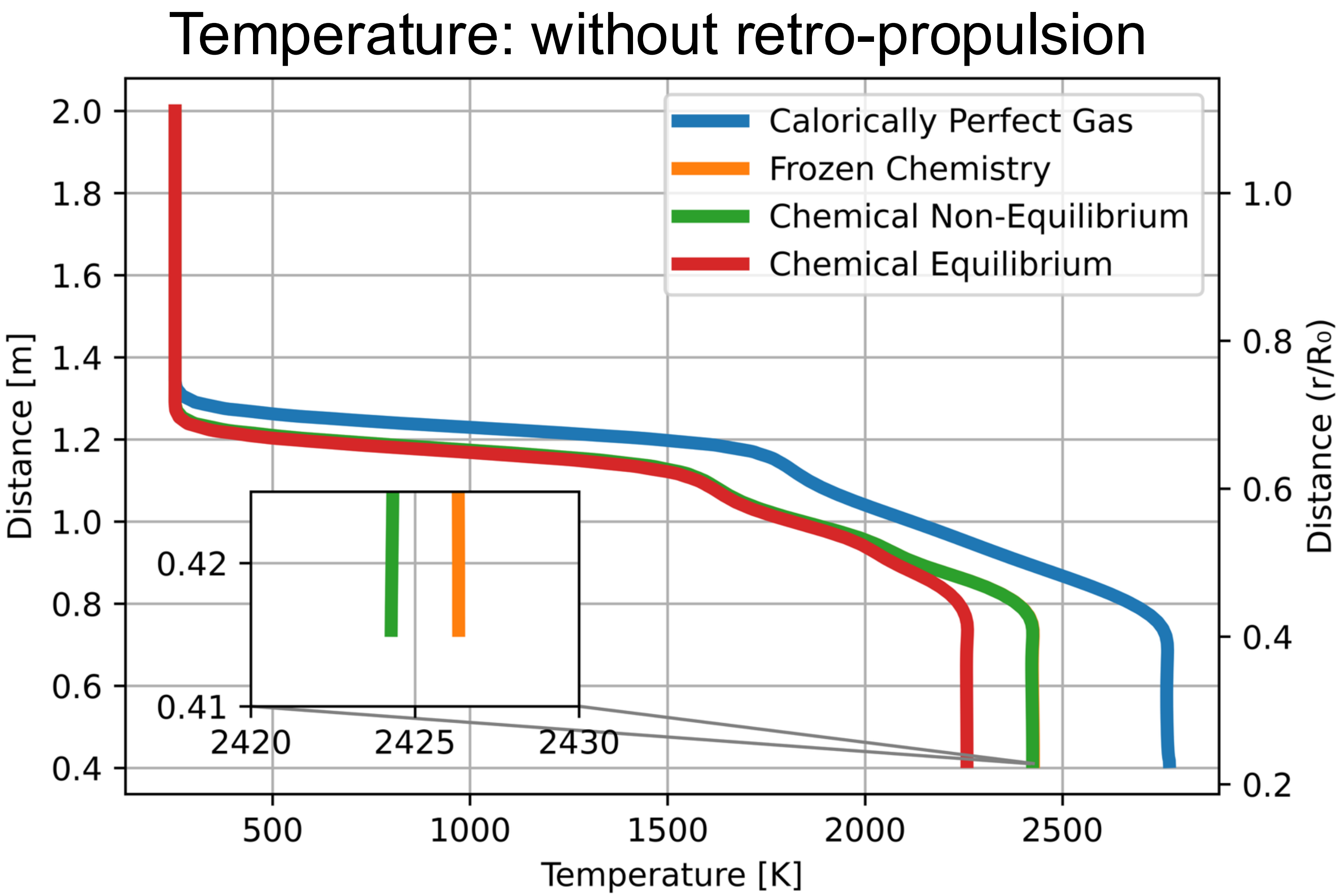


2D results: Flow behaviour

Direction of flight

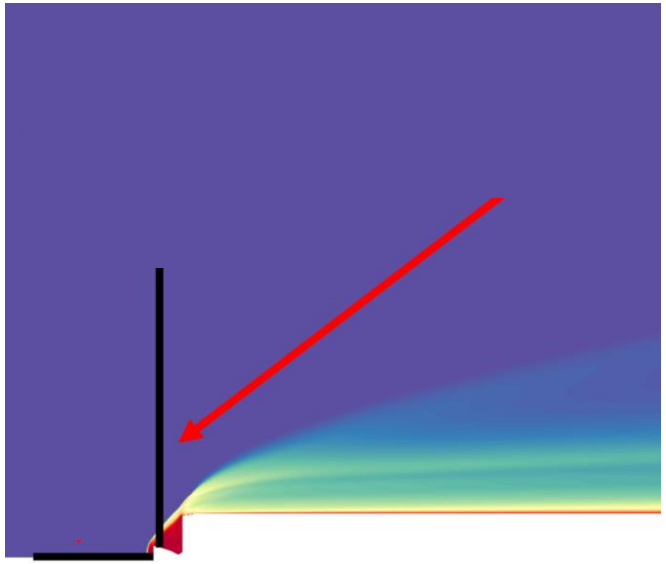


2D Prestudy: Chemistry model investigation 2D



Conclusion

- Frozen chemistry is a good model



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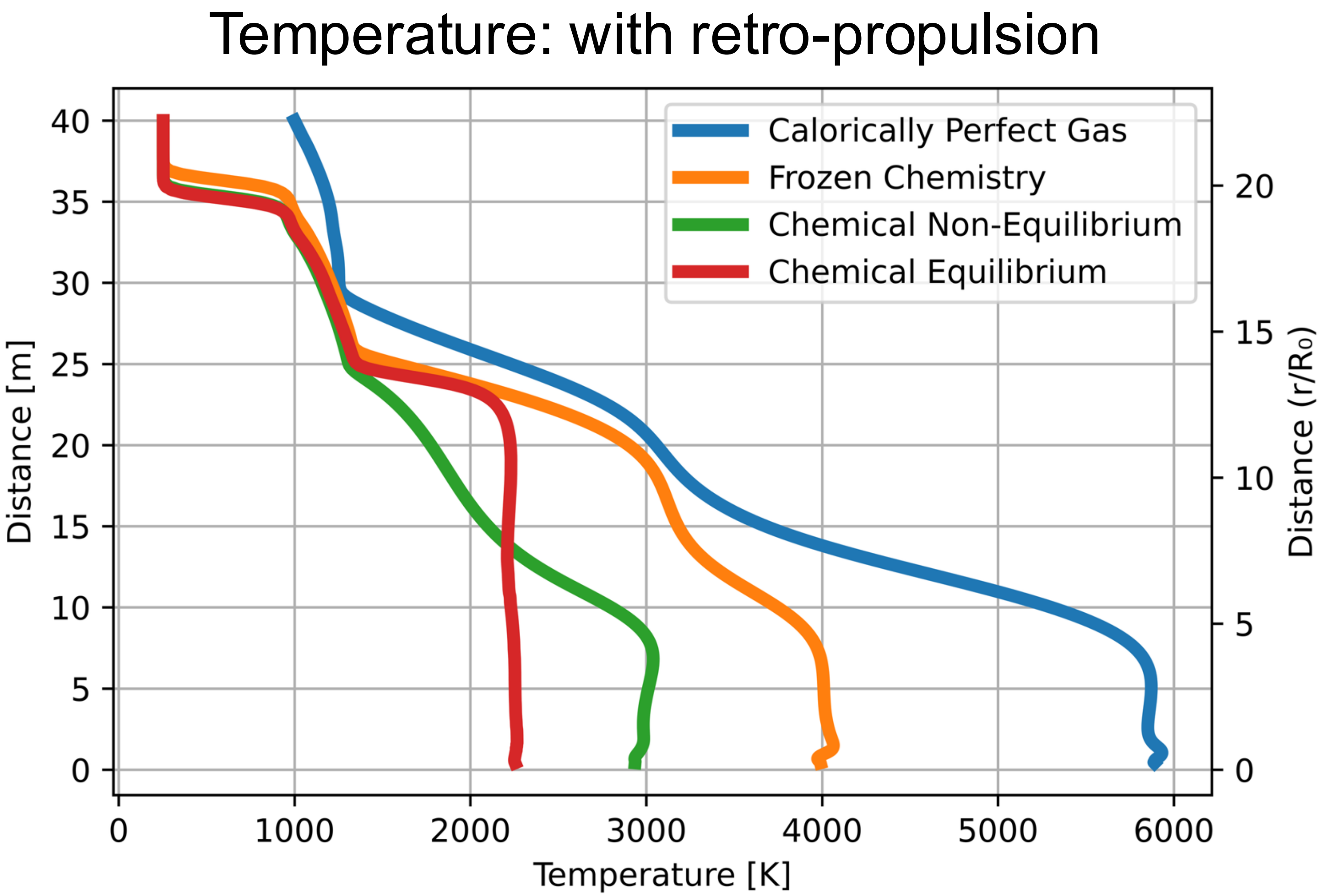
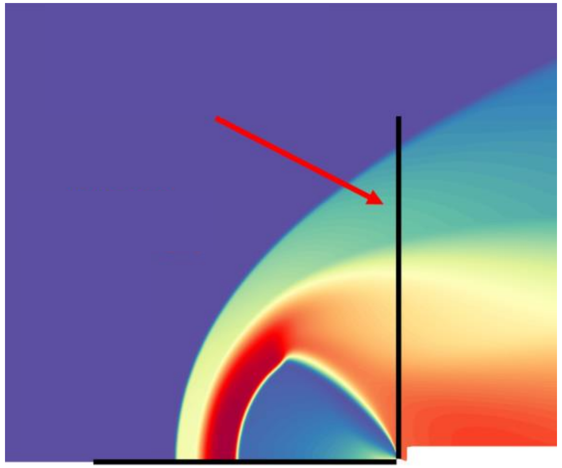


Conclusion

- Non-equilibrium is a necessary model

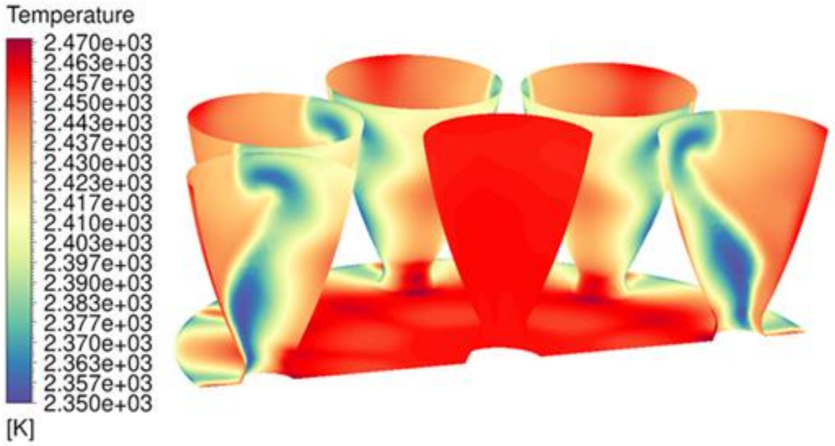


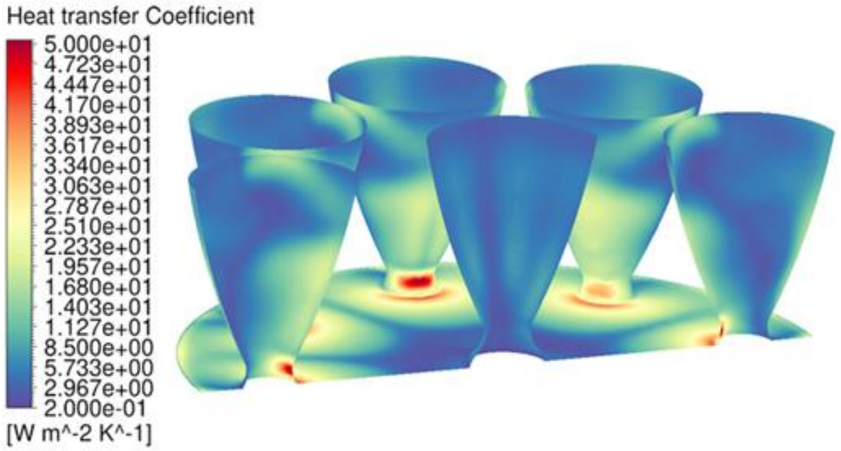
3D without Retro-propulsion: Temperature and HTC

Adiabatic temperature and Heat Transfer Coefficient (HTC)

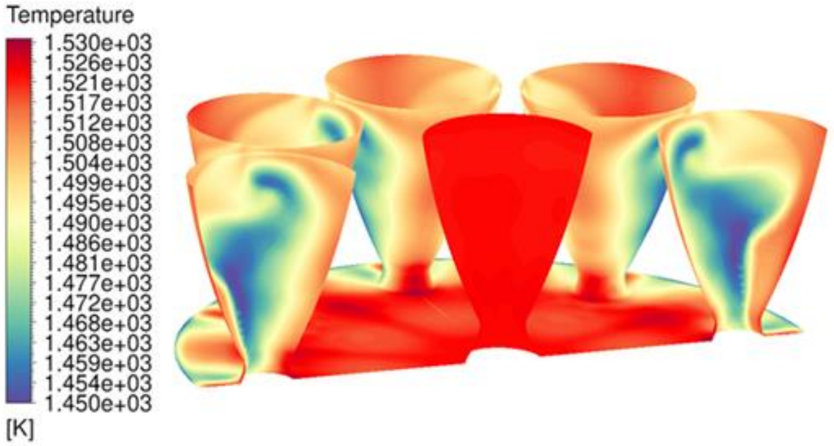
- Small range in temperature, highest temperature around the throat/root of nozzle with fairly constant temperature at the center nozzle
- Heat transfer coefficient (HTC) is the highest near the throat

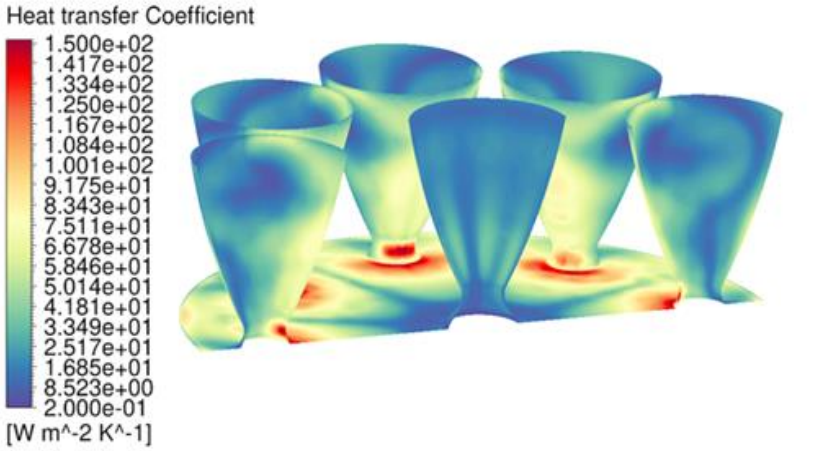
Start burn





End burn



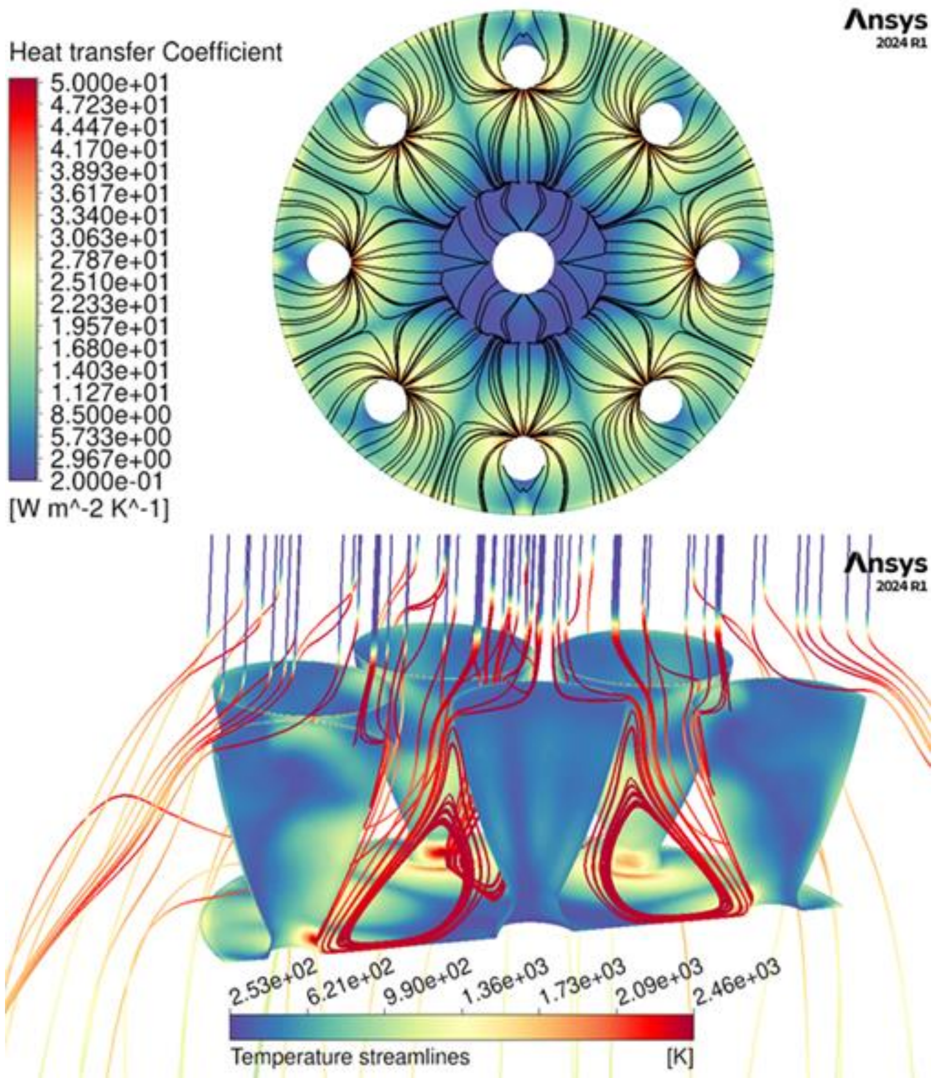


3D without Retro-propulsion: Streamlines

Start burn

Streamlines

- Highest HTC near the throat and root of the nozzle
- A lot of recirculation occurs and the flow stagnates near the throat of the nozzle

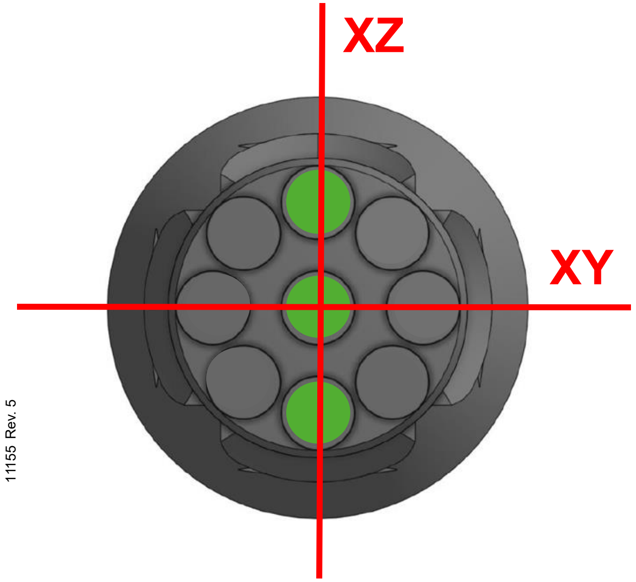


3D Retro-propulsion: Flow behaviour

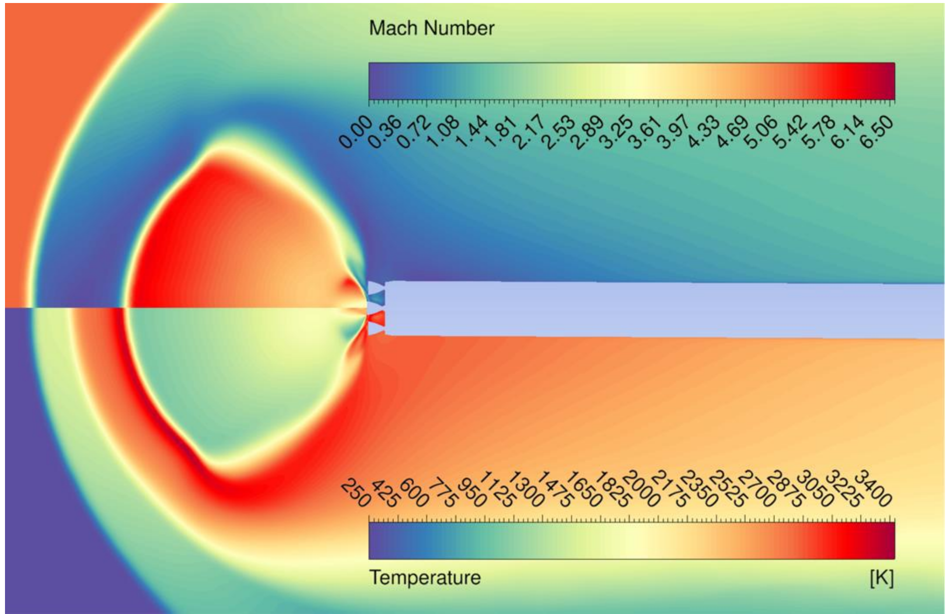
Mach number and temperature

> Mach and temperature plot during retro-propulsion at the end of the burn

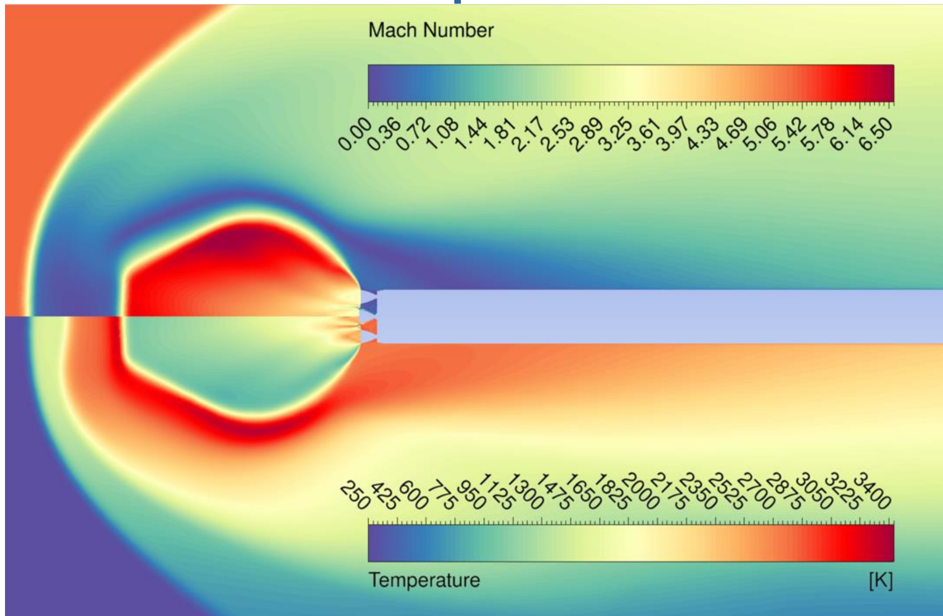
> Engine 1, 5 and 9 is on and showcased in the XZ plane while the rest are off



XY-plane



XZ-plane

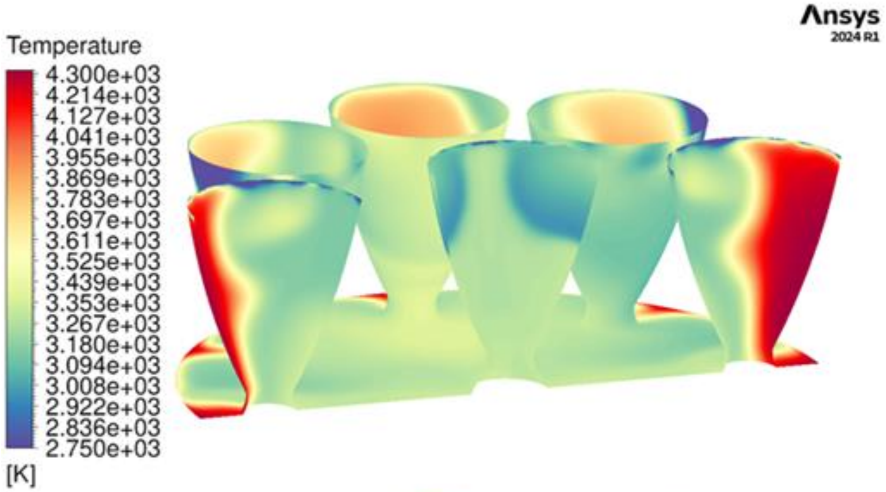


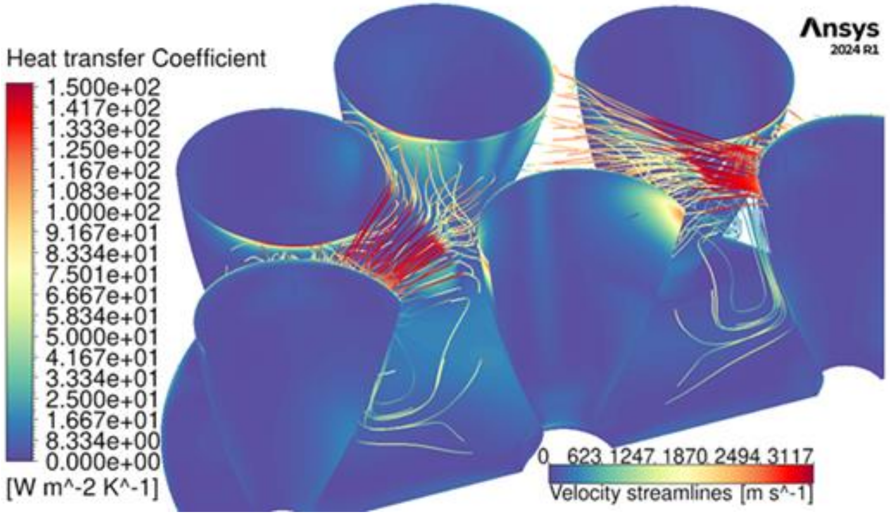
3D Retro-propulsion: Heat transfer coefficient

Heat transfer coefficient: Frozen chemistry

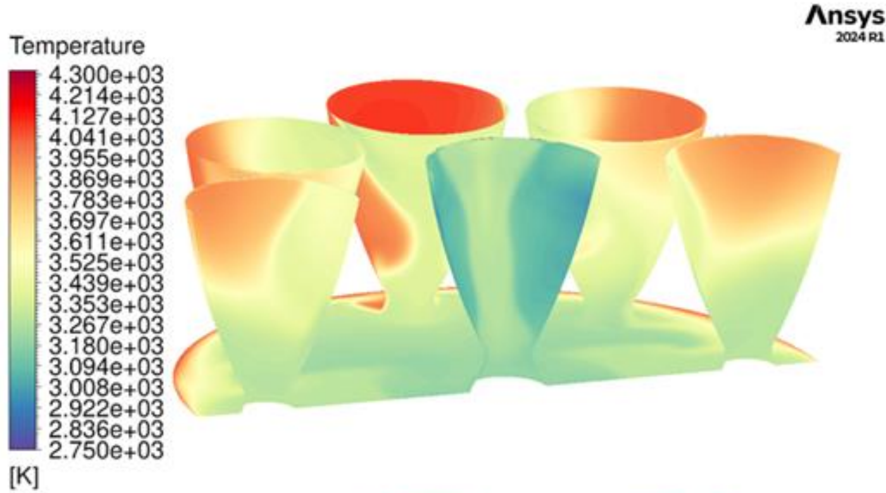
- Similar HTC at both altitudes
- The exhaust expands into the other nozzles resulting in a high HTC specially near the top edges of the nozzles.

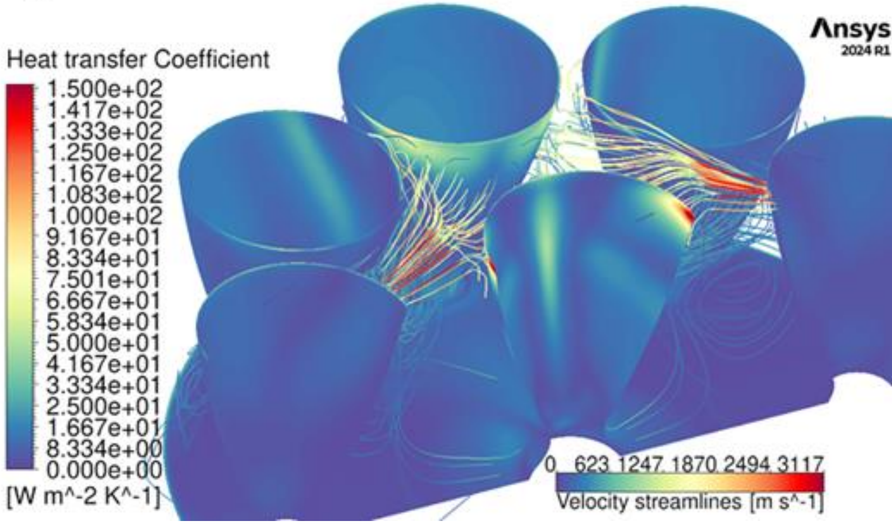
Start burn





End burn

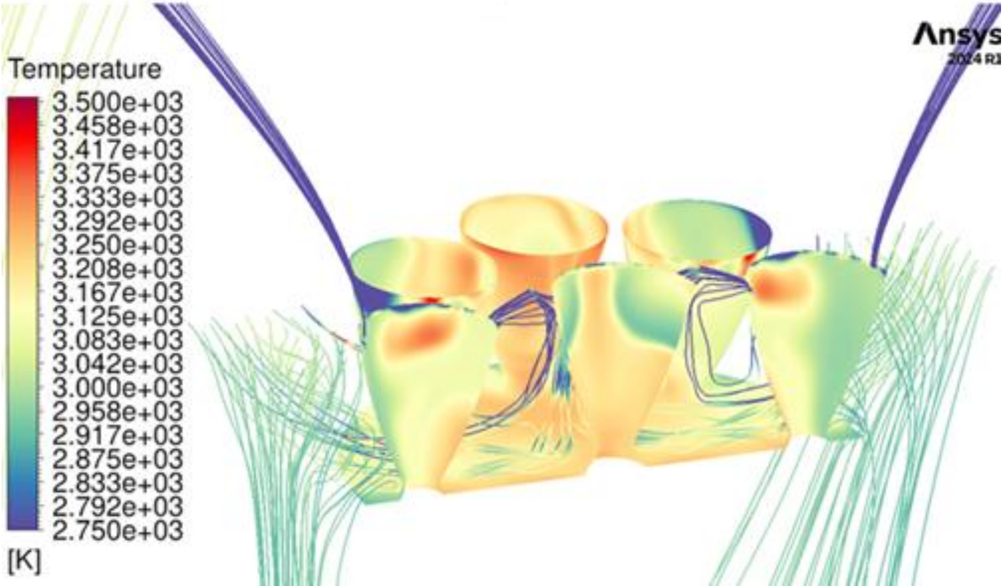




3D Retro-propulsion: Chemical model temperature

Temperature start burn: Chemical non-equilibrium

> The highest temperatures are found at the outside of the activated nozzles



Conclusion

Model reduction

- Frozen chemistry
  - Without retro-propulsion
- Chemical non-equilibrium
  - With retro-propulsion

Thermal loads

- Without retro-propulsion
  - Highest near throat of nozzle
  - HTC highest at end burn
- With retro-propulsion
  - Highest loads from direct recirculation of exhaust
  - HTC similar magnitude at both operating points

Thermal comparison

- Internal loading
  - q ~ 1-10 MW/m^2
- External loading
  - Max 0.5 MW/m^2
  - Very local
  - Short duration