Study of a Hypersonic Scramjet under thermochemical equilibrium and non-equilibrium conditions

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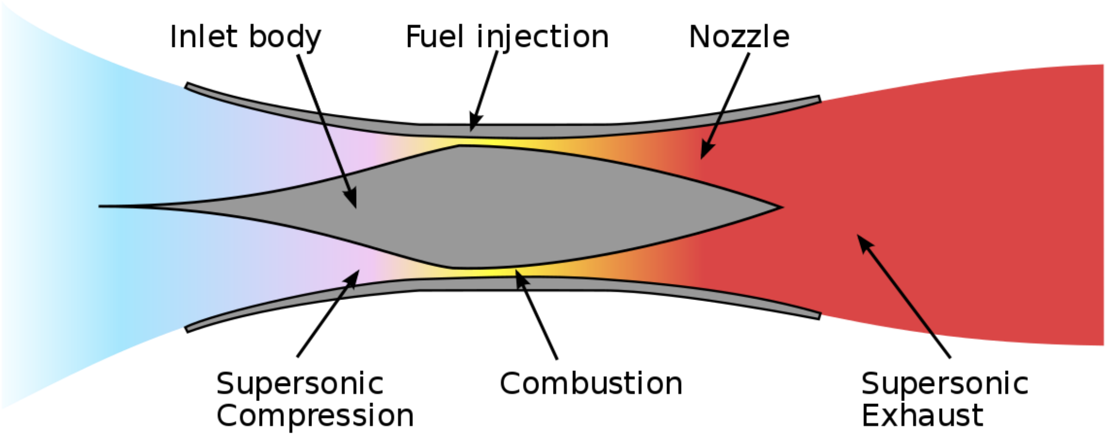
BACKGROUND

Boeing X-51 A prototype

- Initial Project: Study of a waverider.
- Weak shocks didn't produce enough temperature jump to activate finite rate chemical reactions
- Diamond shape to further increase temperature



Scramjet's interior

OPERATING CONDITIONS

	COLD	HOT
Inlet Mach	5, 10, 15	5, 10, 15
Inlet Tr [K]	386.8	800
Inlet Pressure [Pa]	1177	2553.14
Outlet Pressure [Pa]	1090.2	1090.2

Bibliographic reference for cold case. Hot case done to mimic combustion

Initial Composition : 77% N_2 , 23% O_2, 0% NO, 0% N, 0% O

For thermochemical nonequilibrium: Tv = 1179.6 K

Geometry : L = 9m ; H_Inlet = 2 m ; H_Outlet = 4 m ; L_diamond = 4 ;
H_diamond = 0.5 m

GOVERNING EQUATIONS

Field Variables: $\rho, \mathbf{u}, T^{(rt)}, T^{(ev)}$,Ys

Mass Balance:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0$$

$$\frac{\partial \rho Y_s}{\partial t} + \nabla \cdot (\rho Y_s \mathbf{u}) = \dot{\omega}_s$$

Momentum Balance:

$$\frac{\partial \rho \mathbf{u}}{\partial t} + \nabla \cdot (\rho \mathbf{u}\mathbf{u} + p\hat{\mathbf{I}}) = \mathbf{0}$$

Energy Balance:

$$\frac{\partial}{\partial t}\left[\rho\left(\frac{1}{2}\mathbf{u}^2 + e\right)\right] + \nabla \cdot \left\{\rho \mathbf{u}\left(\frac{1}{2}\mathbf{u}^2 + e\right) + p\mathbf{u}\right\} = 0$$

Vibrational Energy Balance:

$$\frac{dE^{(v)}}{dt} = \frac{E^*(T^{(rt)}) - E^{(v)}}{\tau_v(n, T^{(rt)})}$$

SOLVER SETUP

- Software : SU2Nemo
- Solver : Nemo Euler
- Fluid Model : Mutation++
- Mixture : Air5 species
- Meshing software : Gmsh
- Convective Numerical Method : AUSM
- Slope Limiter : Venkatakrishnan Wang
- Time Discretization : Explicit
- CFL : 0.8
- Park's Two Temperature model

SU2 code

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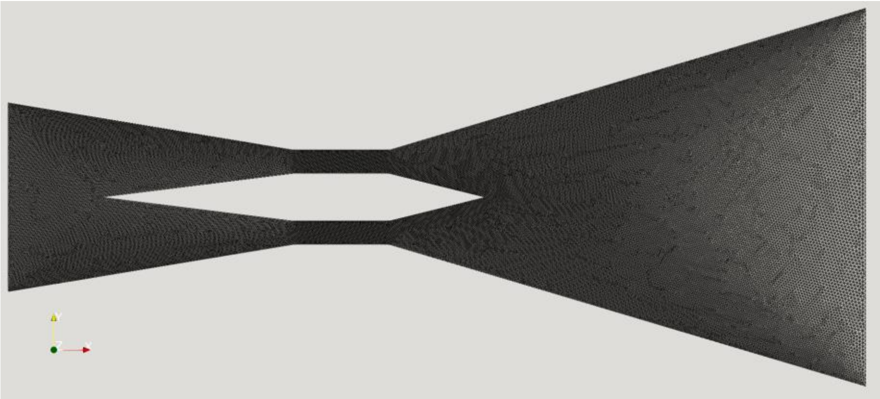
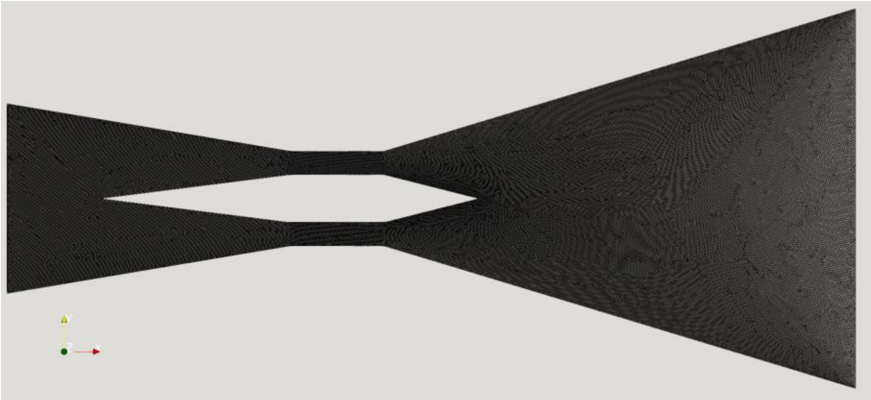
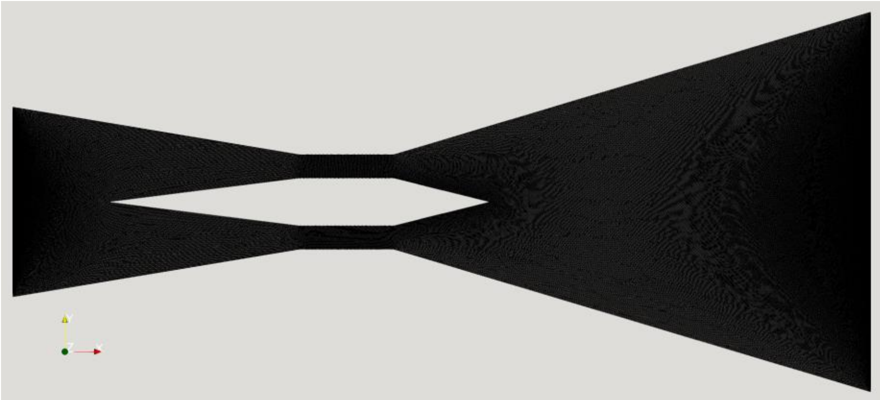
MESH INDEPENDENCE TEST



Coarse



Medium



Fine

Mesh type	Relative error
Coarse	2.007%
Medium	0.382%

Performed for Ma = 15 and Tr = Tv = 800 K

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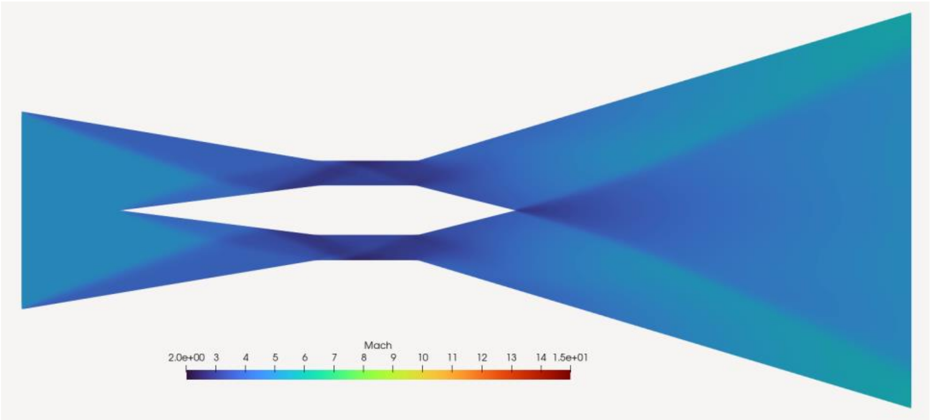
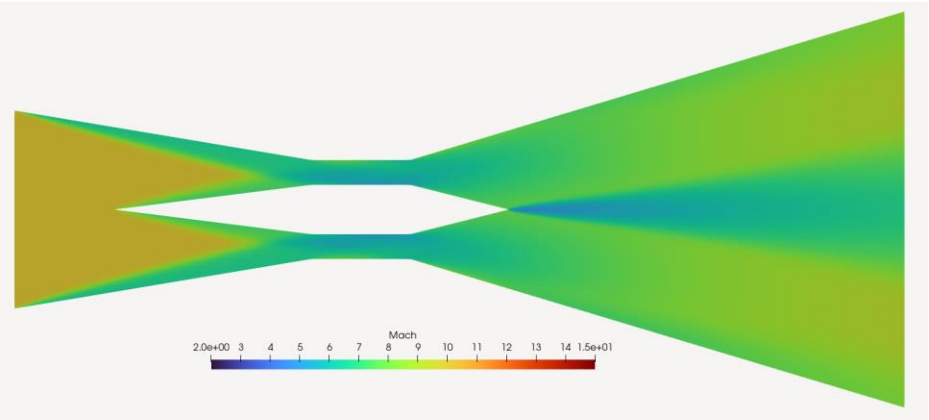
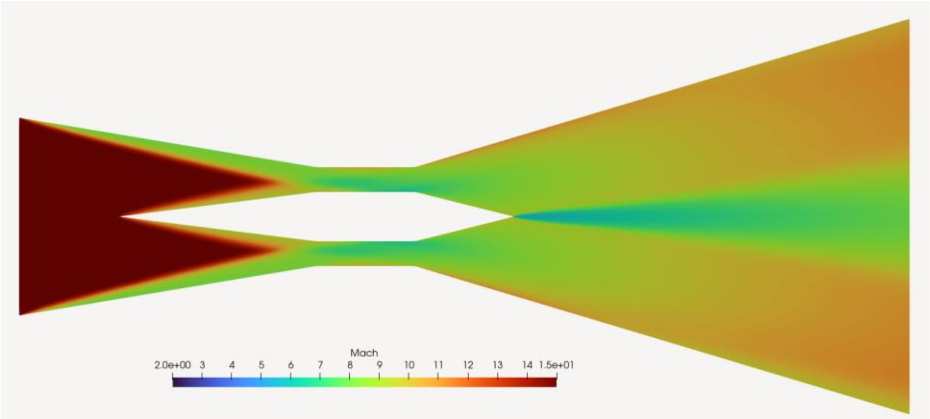
THERMOCHEMICAL EQUILIBRIUM



Ma = 5 Tr = Tv = 386.8K



Ma = 10 Tr = Tv = 386.8 K



Ma = 15 Tr = Tv = 386.8K

- Shock angle decreases as Ma increases
- Shock intensity after the diamond is larger as freestream Ma increases
- Lower Ma always after diamond

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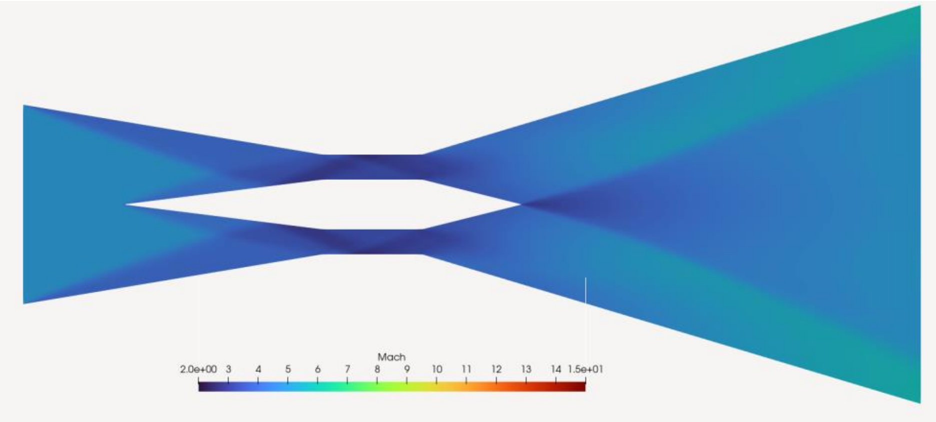
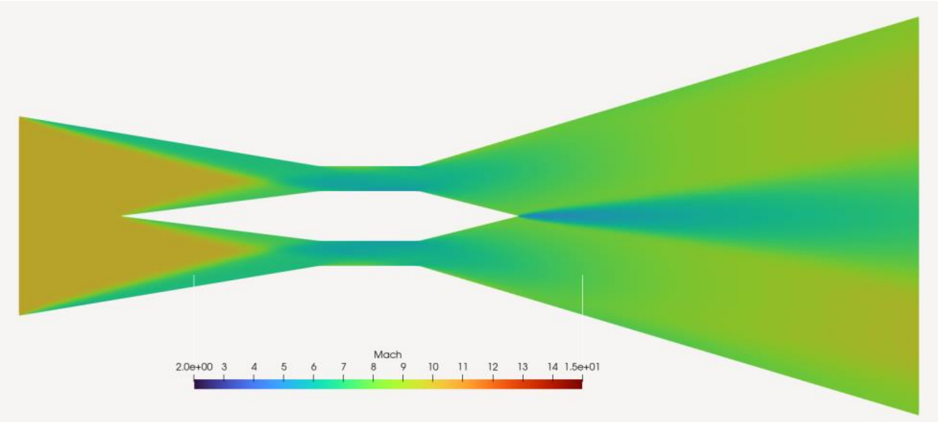
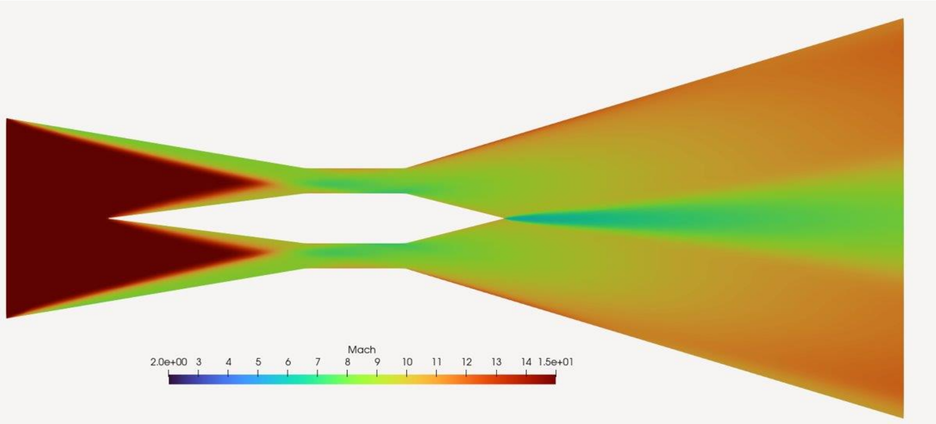
THERMOCHEMICAL EQUILIBRIUM



Ma = 5   Tr = Tv = 800K



Ma = 10   Tr = Tv = 800K



Ma = 15   Tr = Tv = 800K

- Almost no difference between cold and hot for Ma = 5.
- Large freestream T produces larger Ma at the divergent section for the same freestream Ma

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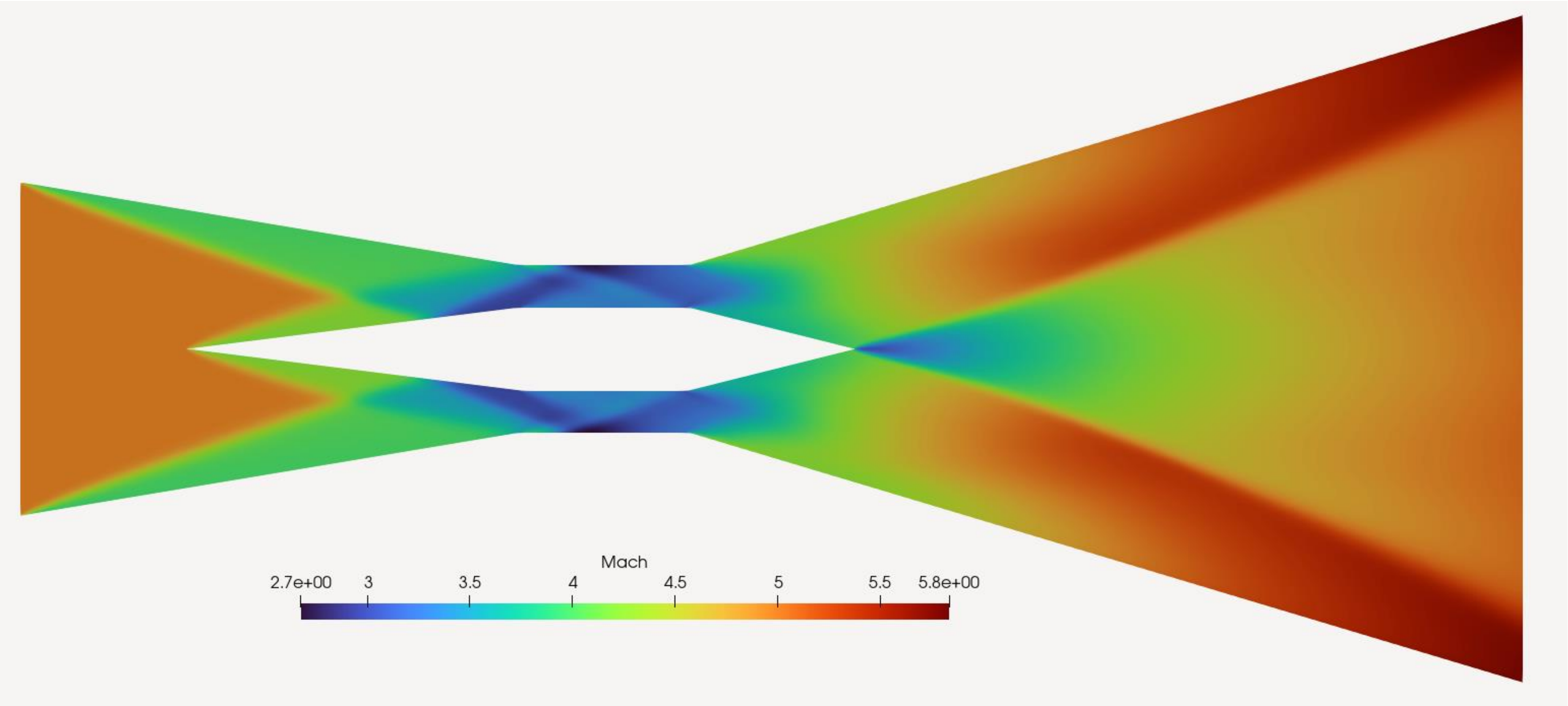
THERMOCHEMICAL EQUILIBRIUM

Reflections in central region are better captured as Ma reduces



Ma = 5   Tr = Tv = 800K

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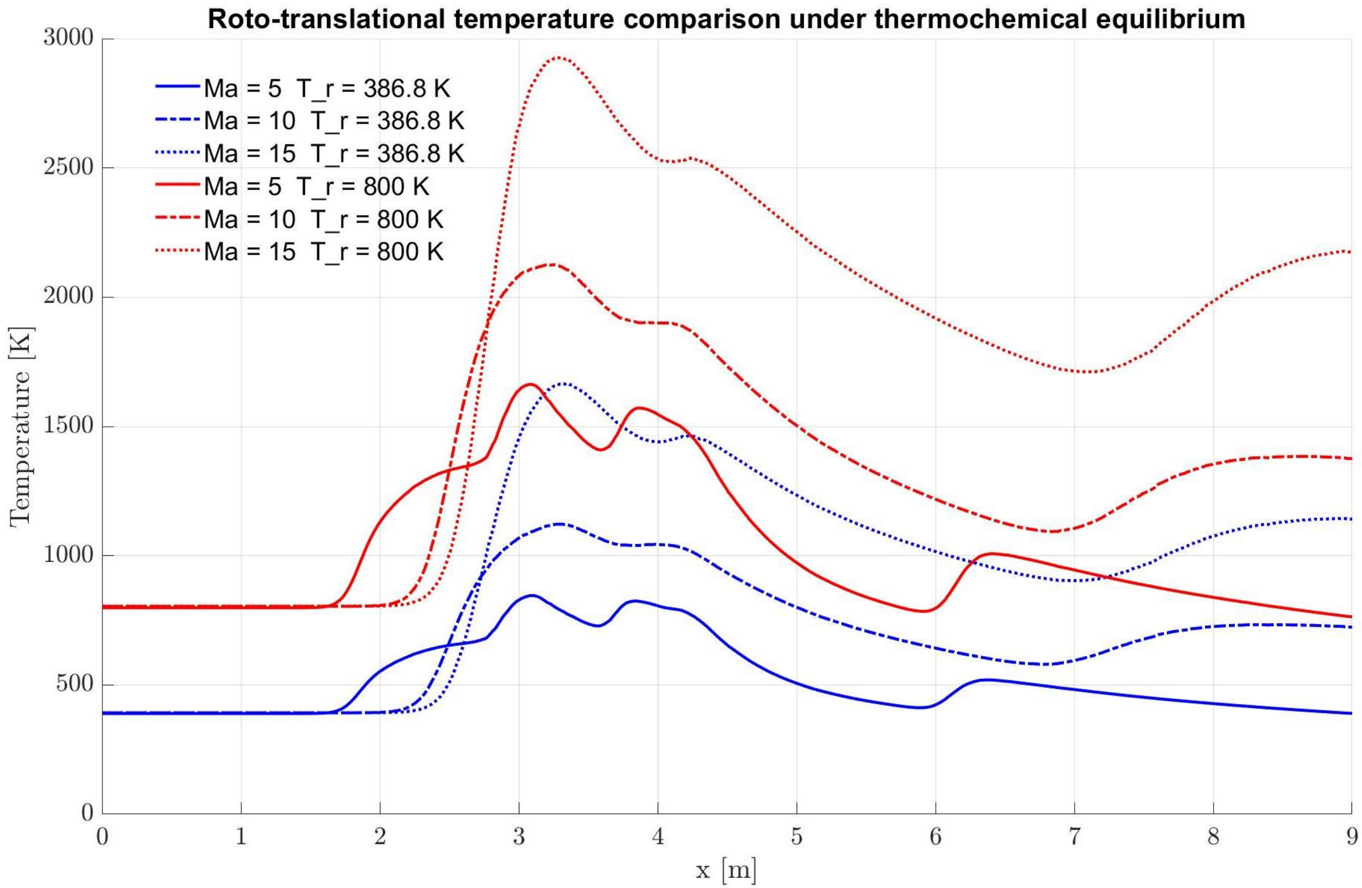
THERMOCHEMICAL EQUILIBRIUM



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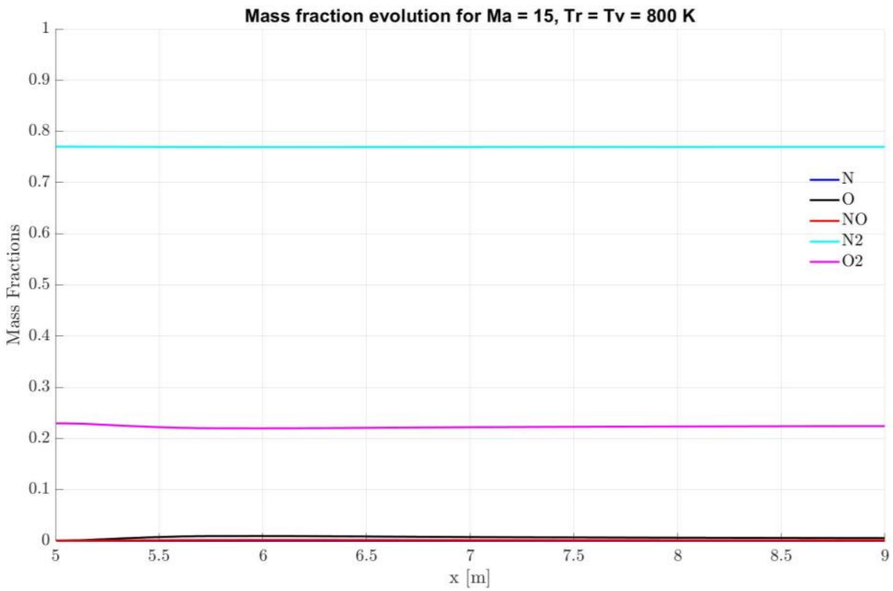
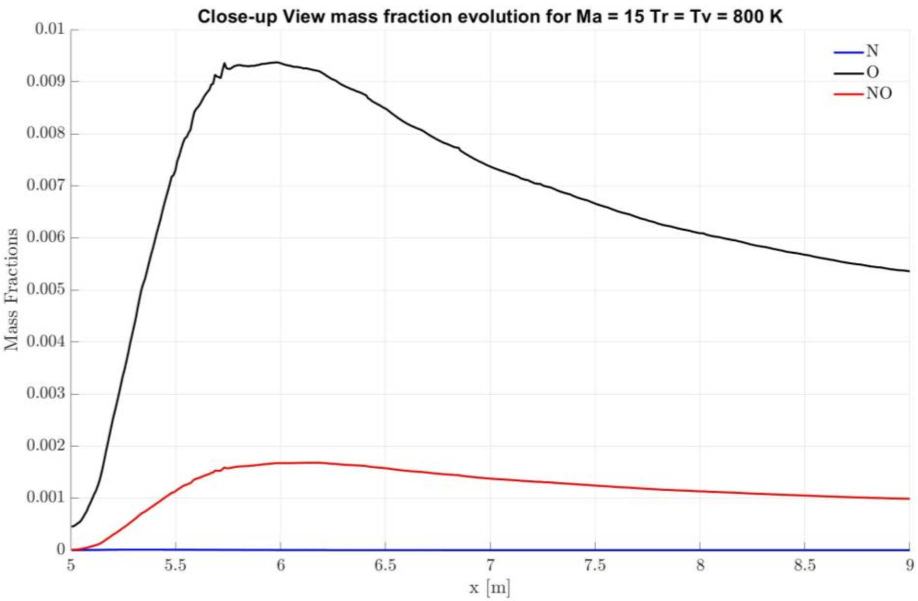
CHEMICAL NON-EQUILIBRIUM

	Ma=5 (C)	Ma=10 (C)	Ma=15 (C)	Ma=5 (H)	Ma=10 (H)	Ma=15 (H)
N2	0.77	0.77	0.77	0.77	0.77	0,7699
O2	0.23	0.23	0.23	0.23	0.23	0.2280
NO	0	2.8e-31	1.91e-14	9.45e-17	1.06e-10	3.03 e-4
N	0	1.91e-42	5.28e-24	4.66e-33	1.30e-18	6.06e-10
O	1.64e-34	1.14e-21	3.22e-10	4.05e-12	3.20e-7	0.0019

- For all Ma in cold condition, mass fractions of NO, N, O are extremely low
- Mass fractions of O, N, NO increase with Ma
- For the hot condition, at Ma=15 we can see the effect of diatomic oxygen dissociation in the resulting mass fraction of O2

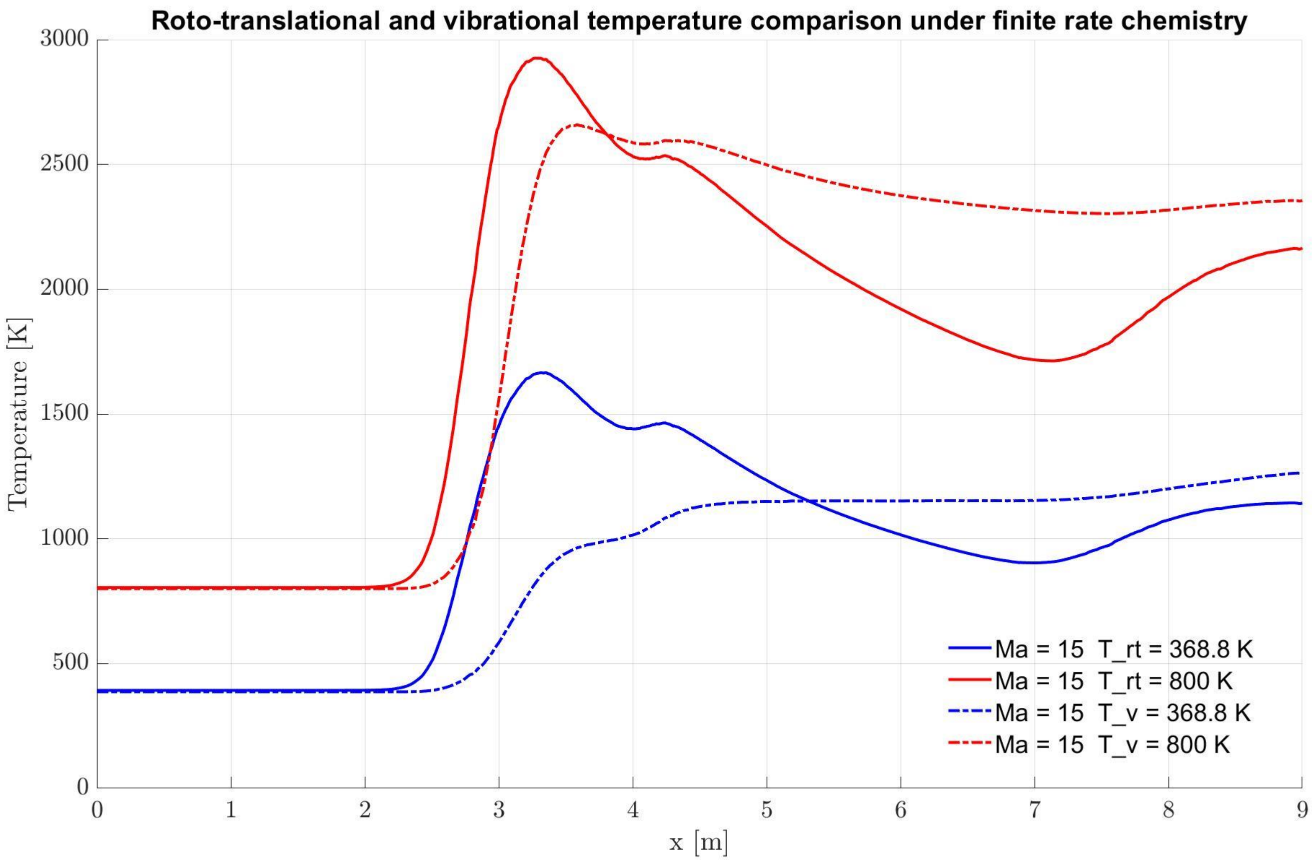
CHEMICAL NON-EQUILIBRIUM





- Finite rate chemical reaction concentrated in the post-diamond region
- Increase of O close to the diamond edge because of O_2 dissociation
- Formation of O reduced after x = 6 m due to recombination (NO formation)
- Very low N mass fraction. Higher temperature required to dissociate N_2

CHEMICAL NON-EQUILIBRIUM



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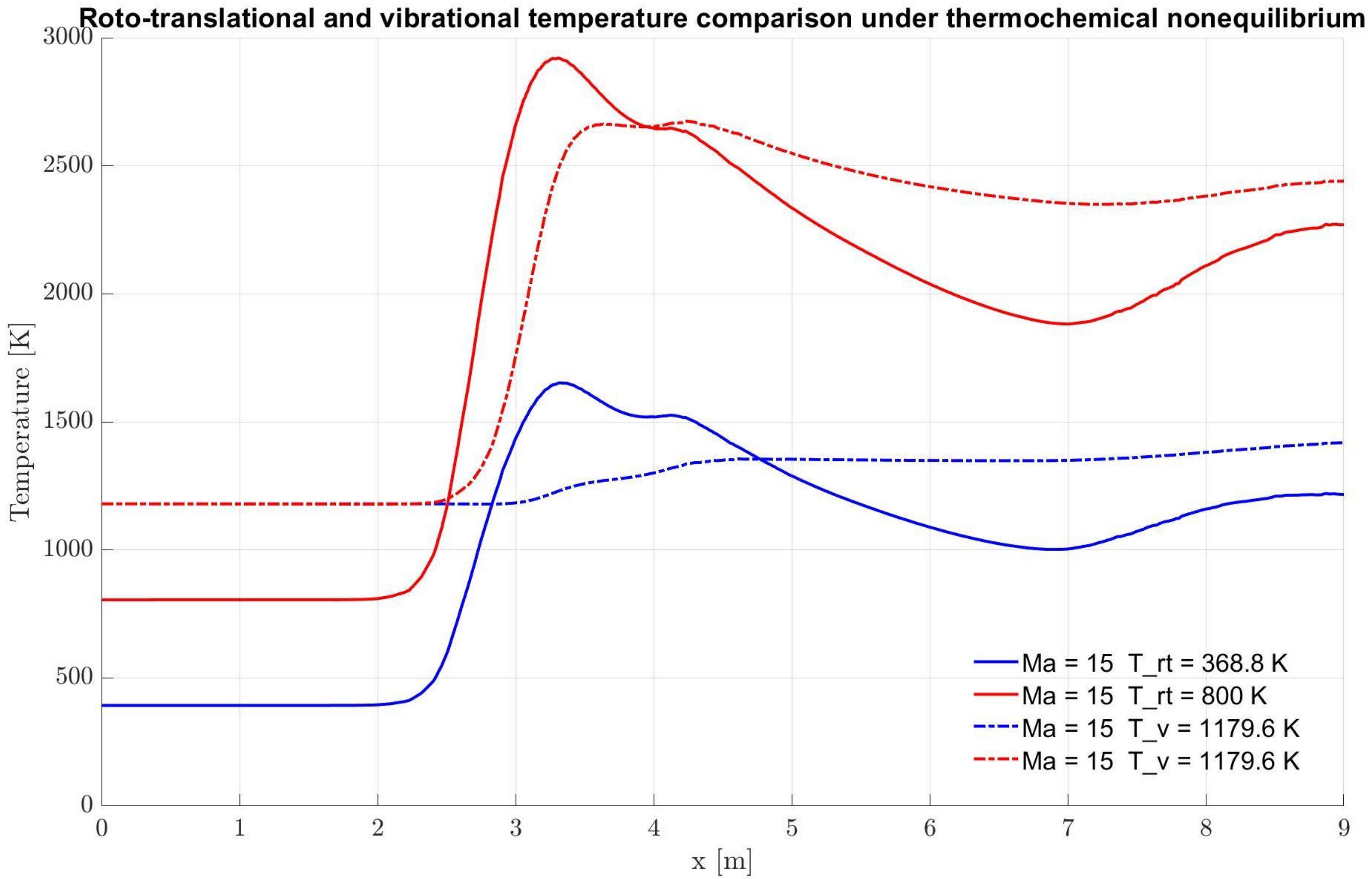
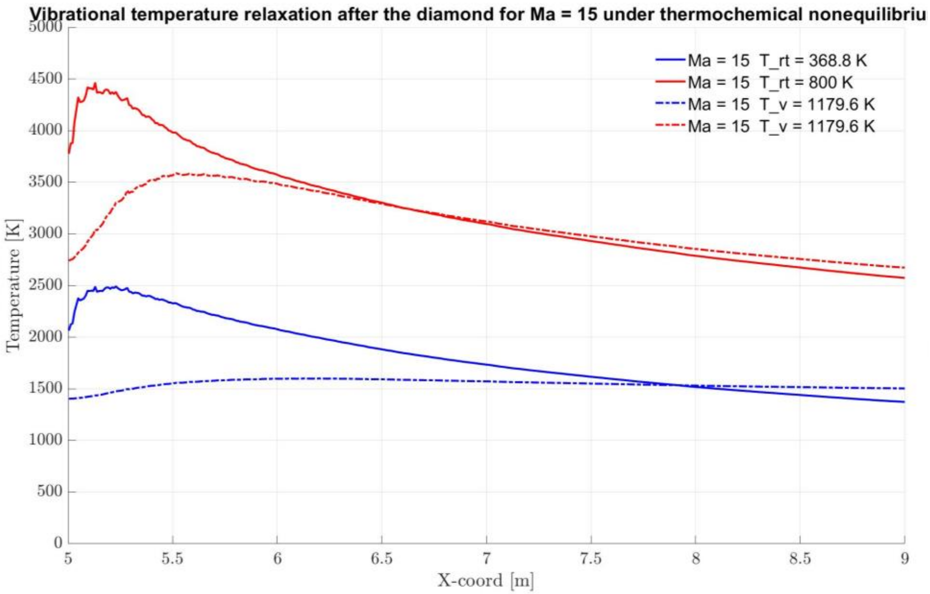
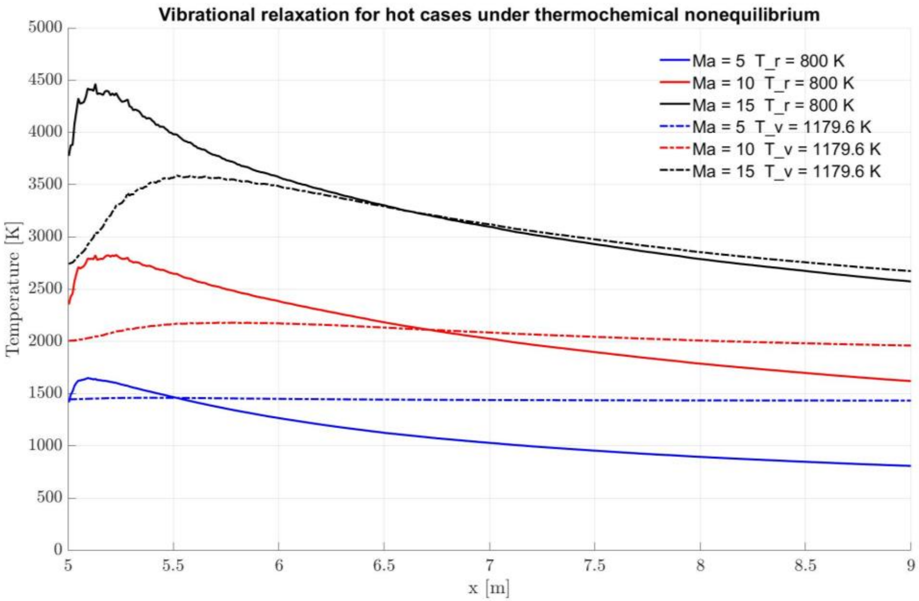


THERMOCHEMICAL NON-EQUILIBRIUM





Larger vibrational excitation with hot gas

Shorter relaxation time as Ma increases

At the scramjet's outlet, there's still thermal nonequilibrium

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CONCLUSIONS

- Similar shock patterns for the same Ma under different thermal conditions
- Stronger shock localized at the post-diamond region
- Temperature reached across the domain should be larger to better appreciate finite rate chemical reactions
- Chemical reactions observed are in accordance with the theory
- Relaxation time higher for higher Mach number
- Thermochemical non equilibrium persists throughout the geometry

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THANK YOU