Ioffe Physical-Technical Institute of the Russian Academy of Sciences

MHD re-entry flow control: OpenFOAM simulation

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Atmospheric reentry phenomena

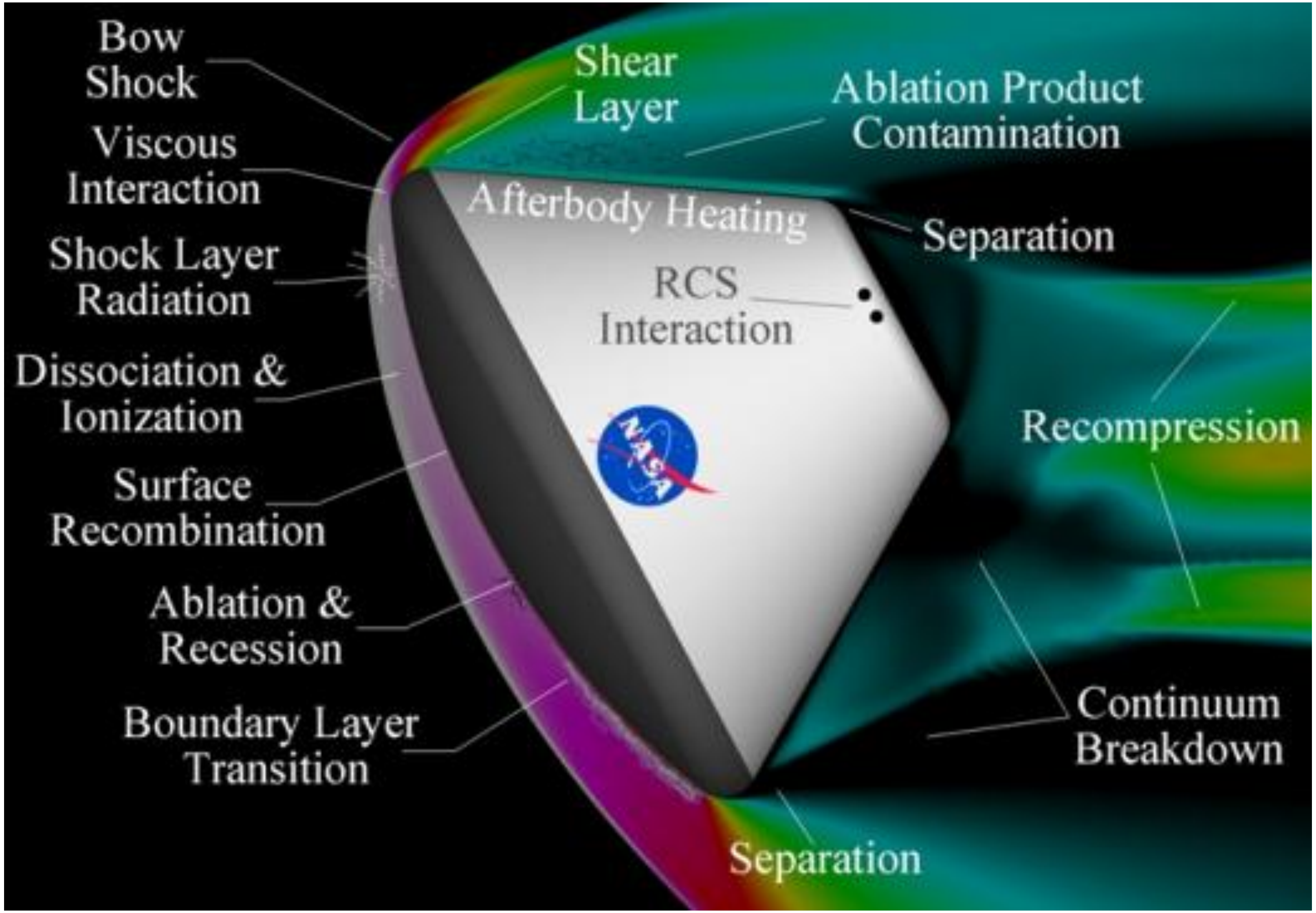


Image Taken from : http://www.ices.utexas.edu/centers/pecos/

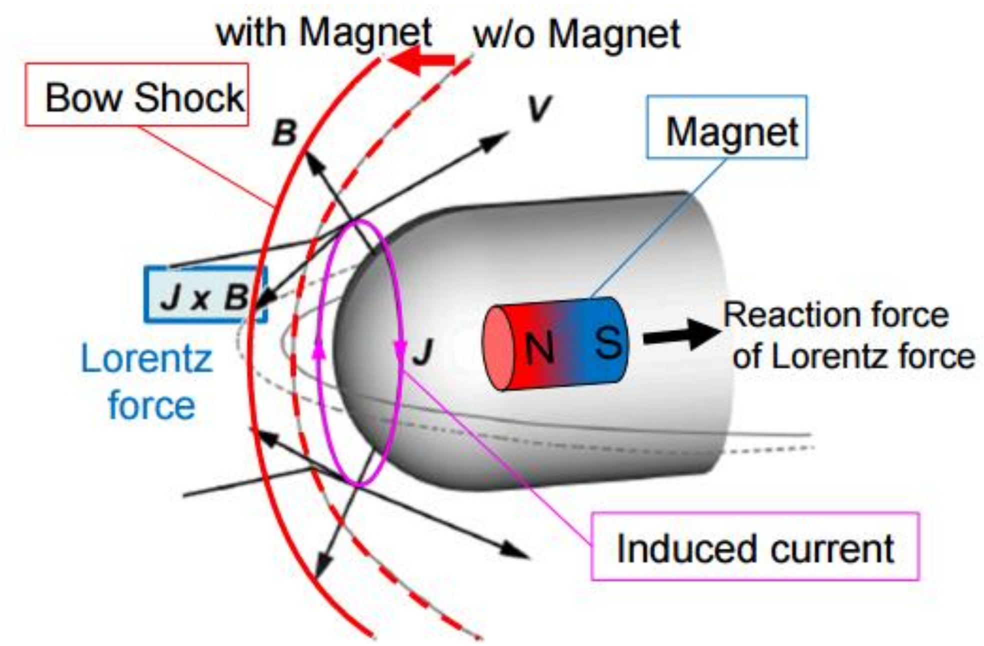
MHD flow control

Magnetic field interacts with weakly ionized plasma between the bow shock and the body:

- *Lorentz force*
- *Joule heating*

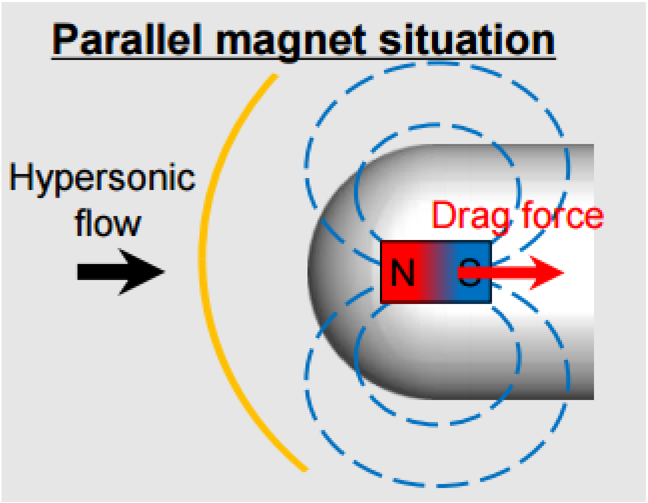
Effects:

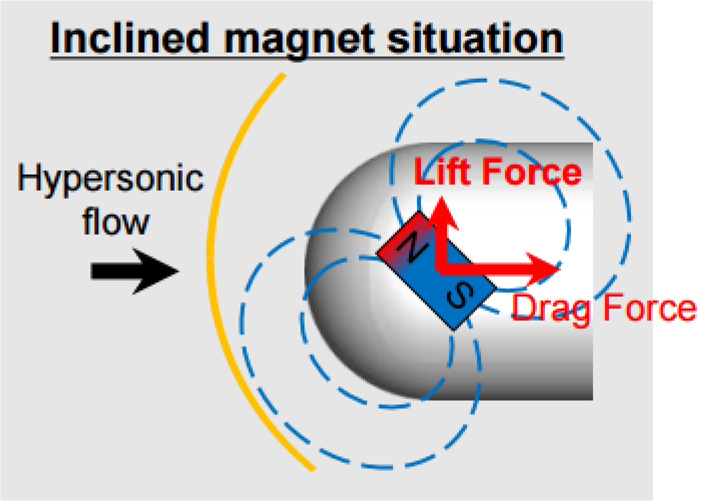
- *Reduction of aerodynamic heating*
- *Enhancement of drag force*
- *Widening of shock layer*



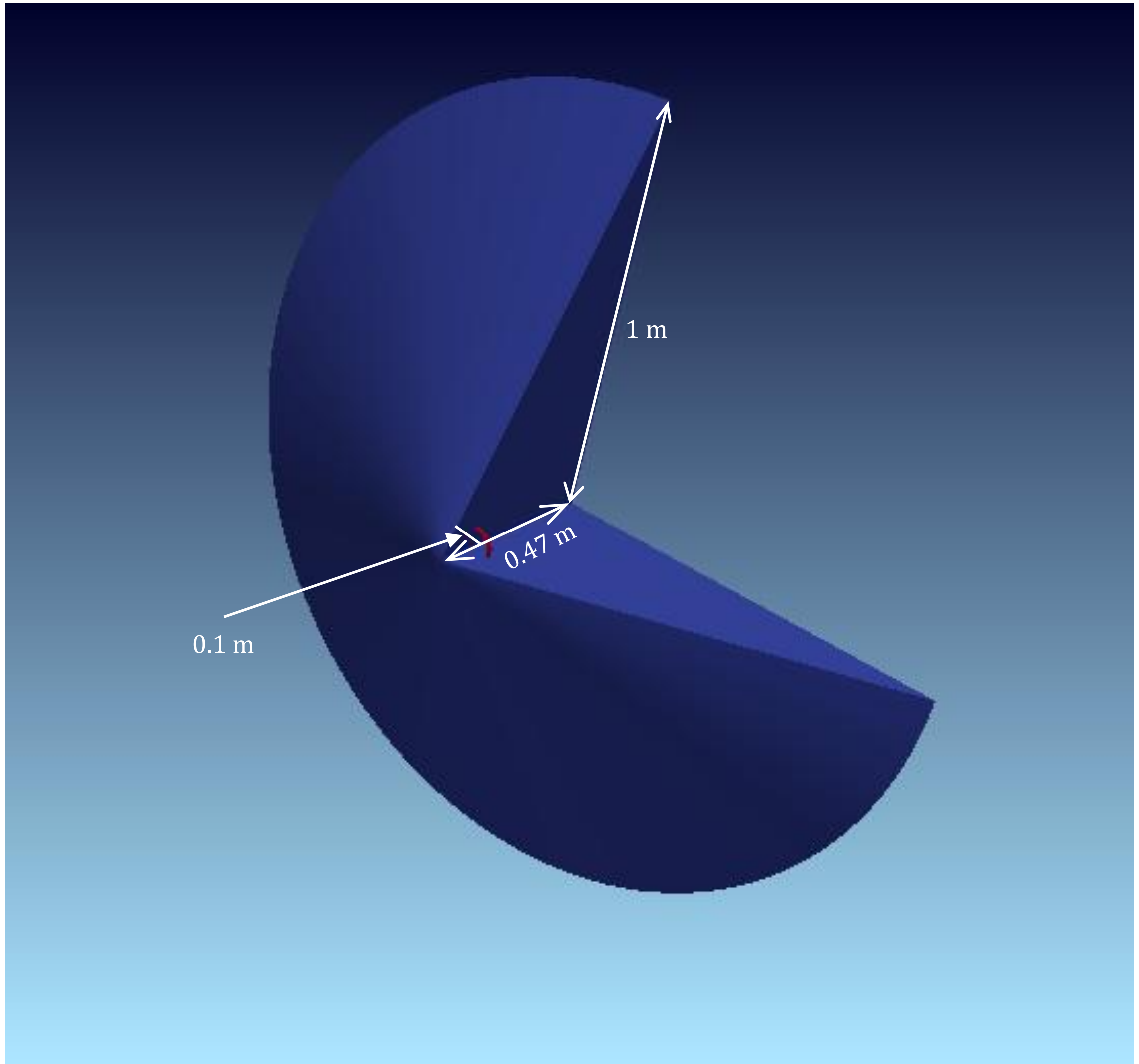
*Y Nagata, K Yamada, T Abe

Controlling reentry flight trajectory

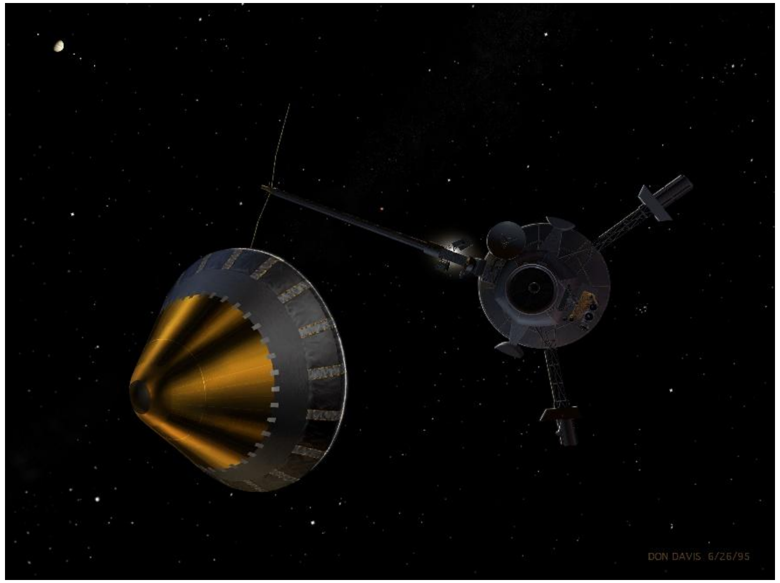




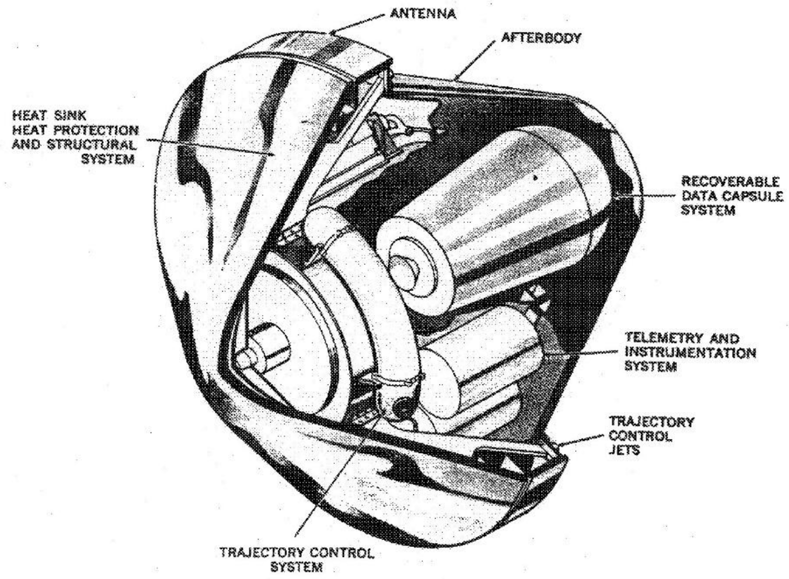
Model geometry



coil



Galileo probe leaving orbiter



Mk2 reentry vehicle schematics

Flow parameters

$$N = \frac{\sigma L_c B^2}{\rho v} \sim 0.1$$ - Stuart number

$$Re_{mag} = \frac{uL}{\eta_m} \sim 0.1$$ - Magnetic Reynolds number

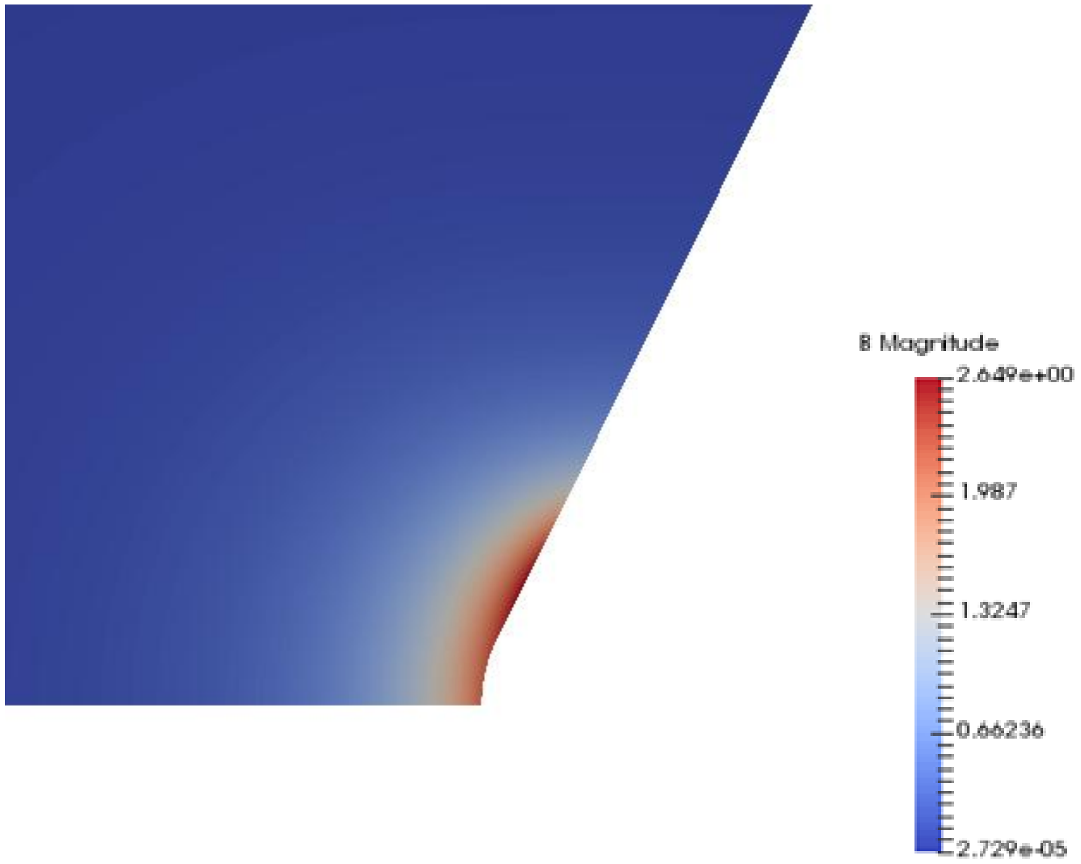
$$Ha = B L_c \sqrt{\frac{\sigma}{\eta}} \sim 100$$ - Hartmann number

$$Kn = \frac{k_B T}{\sqrt{2}\pi d^2 p l} \sim 10^{-3} - 10^{-5}$$ - Knudsen number

$$\boldsymbol{j} = \sigma(\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B})$$

$$\boldsymbol{F} = \boldsymbol{j} \times \boldsymbol{B}$$

$$\boldsymbol{Q} = \boldsymbol{j} \cdot \boldsymbol{E}$$



MHD equations

Basic form ($Re_{mag} \ll 1$)

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

$$\rho \left(\frac{\partial \mathbf{v}}{\partial t} + \mathbf{v} \cdot \nabla \mathbf{v} \right) + \nabla p - \frac{1}{\mu_0} (\nabla \times \mathbf{B}) \times \mathbf{B} = 0,$$

$$\frac{\partial e}{\partial t} + \nabla \cdot \left[\left(\frac{\gamma}{\gamma - 1} p + \frac{1}{2} \rho v^2 \right) \vec{v} - (\vec{v} \times \vec{B}) \times \vec{B} \right] = 0.$$

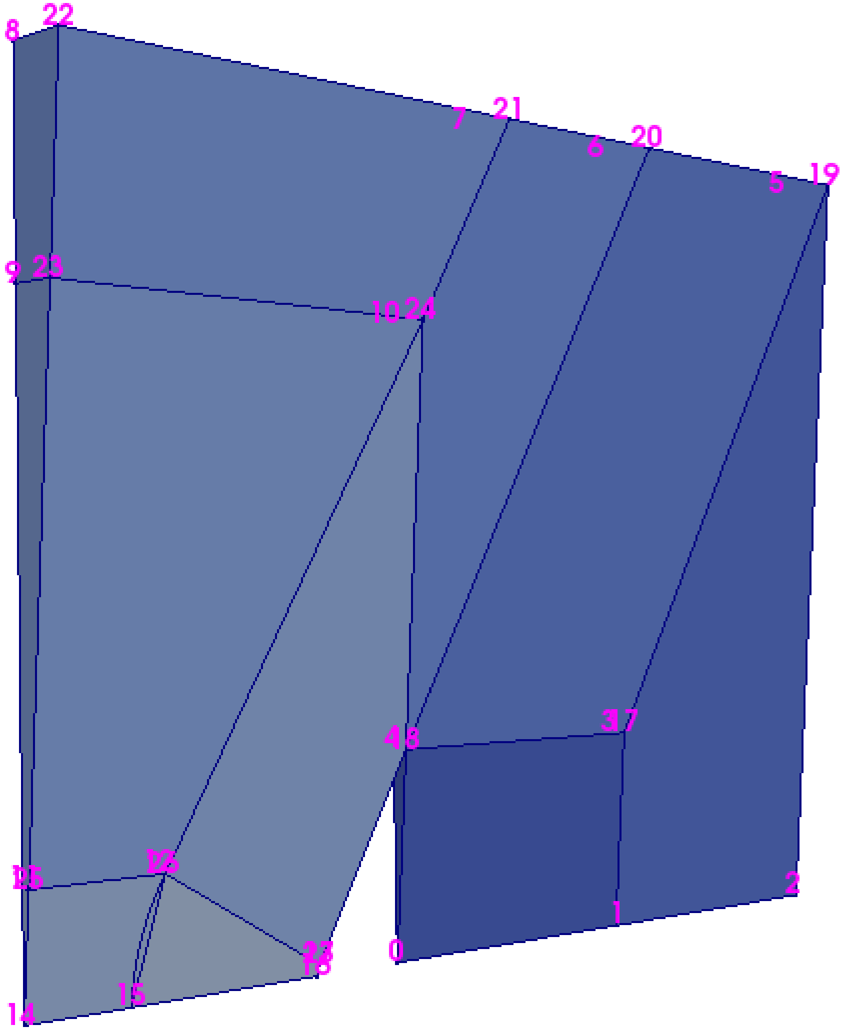
Conservative form:

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

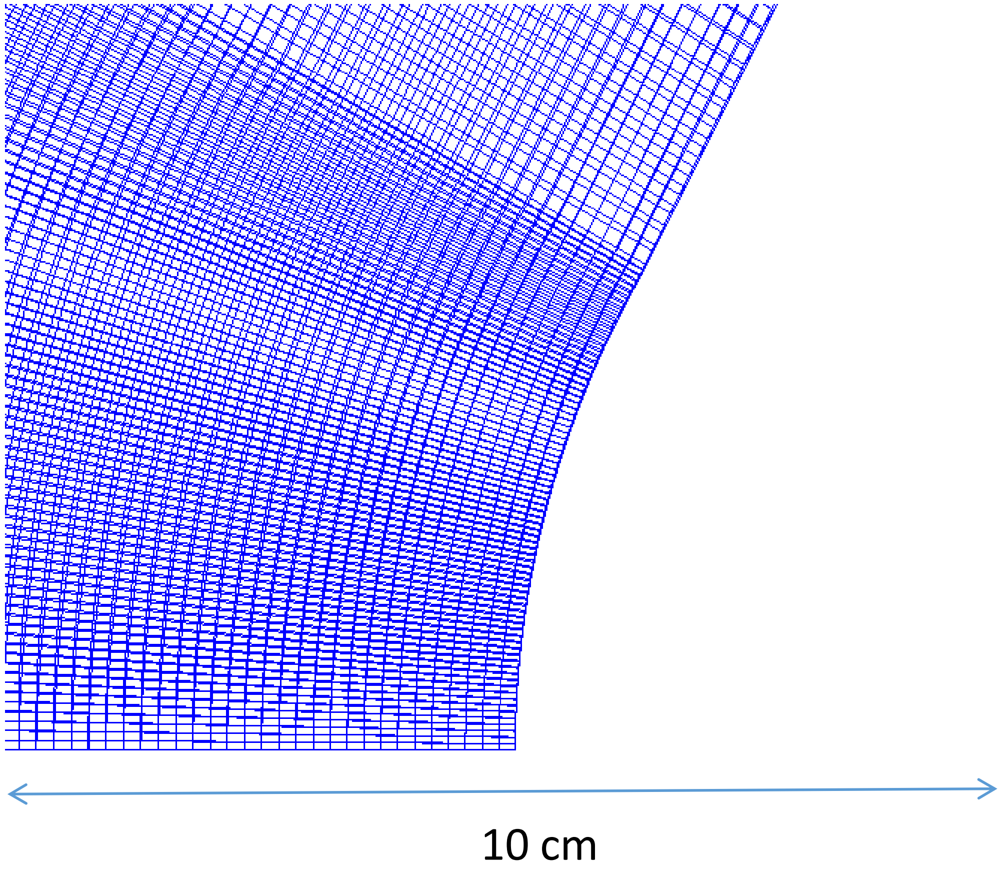
$$\frac{\partial}{\partial t} (\rho \mathbf{v}) + \nabla \cdot \left[\rho \mathbf{v} \mathbf{v} + \left(p + \frac{1}{2} B^2 \right) I_{3\times 3} - \mathbf{B} \mathbf{B} \right] = 0$$

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

Computational domain

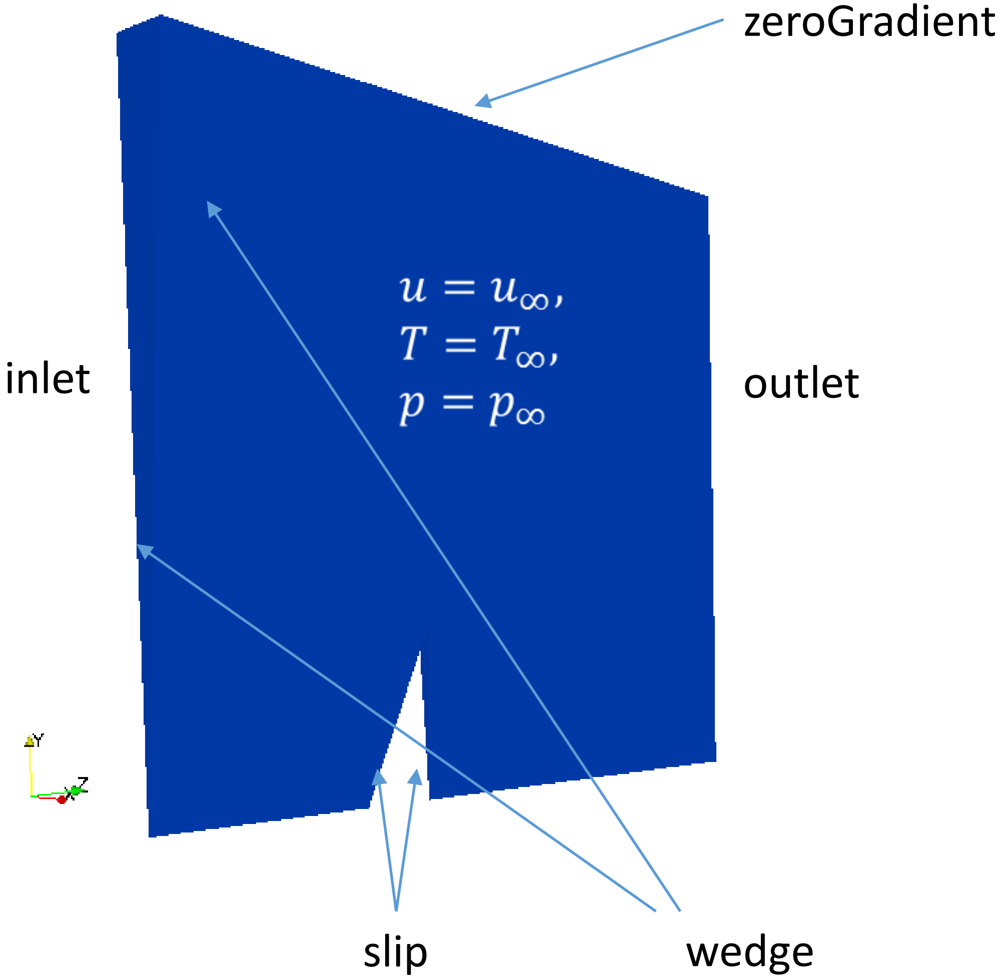


Block structure



Mesh resolution

Initial and boundary conditions



Thermophysical properties

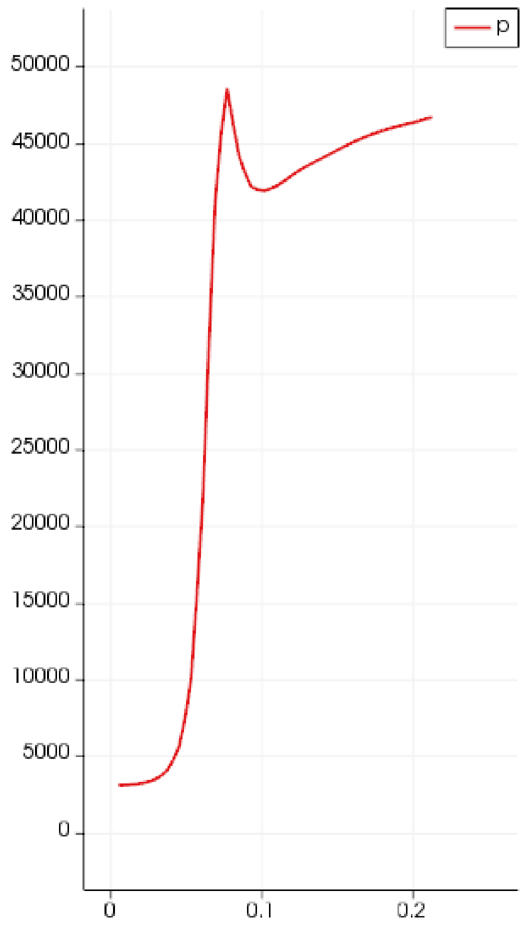
	Earth	Mars*
Gas	Air	CO_2
Molar weight (g/mol)	28.97	44.01
p_∞ (Pa)	3000	30
T_∞ (K)	216.5	190
$Mach\big\|_{u=1000}$	3.37	4.46

*Forget F. et al. Density and temperatures of the upper Martian atmosphere measured by stellar occultations with Mars Express SPICAM //Journal of Geophysical Research: Planets (1991–2012). – 2009. – T. 114. – №. E1.

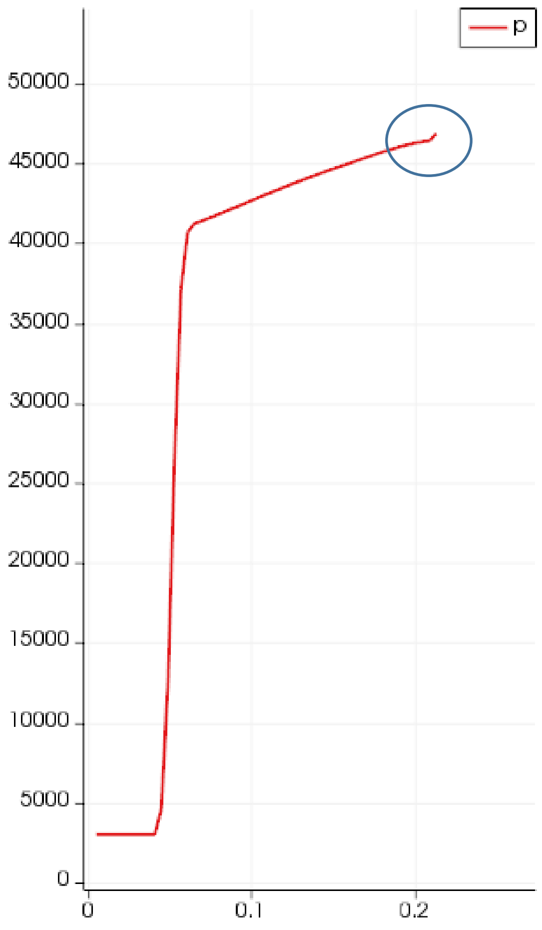
$$\eta = \frac{A_S\sqrt{T}}{1+\frac{T_S}{T}},$$ - Sutherland model

Hypersonic flow simulation

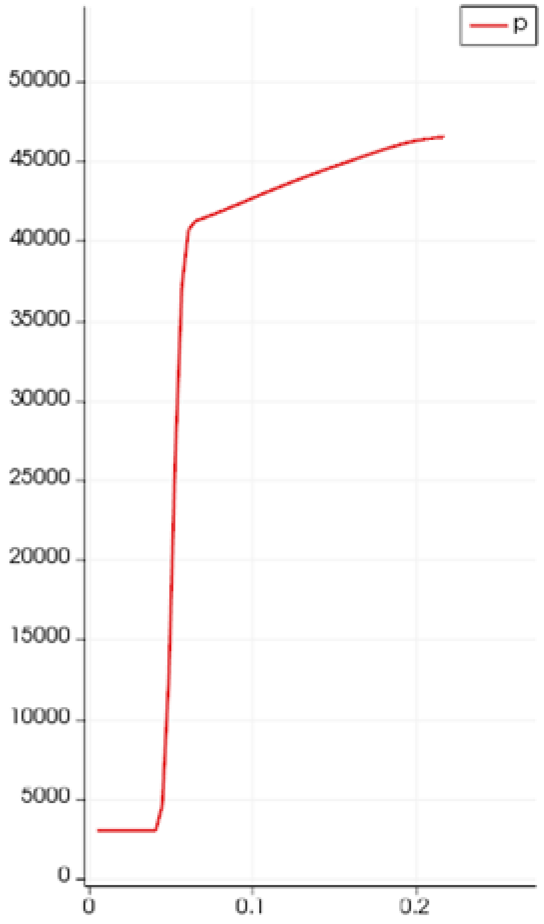
sonicFoam
(pressure-based)



rhoCentralFoam
(shock layer <30 cells)



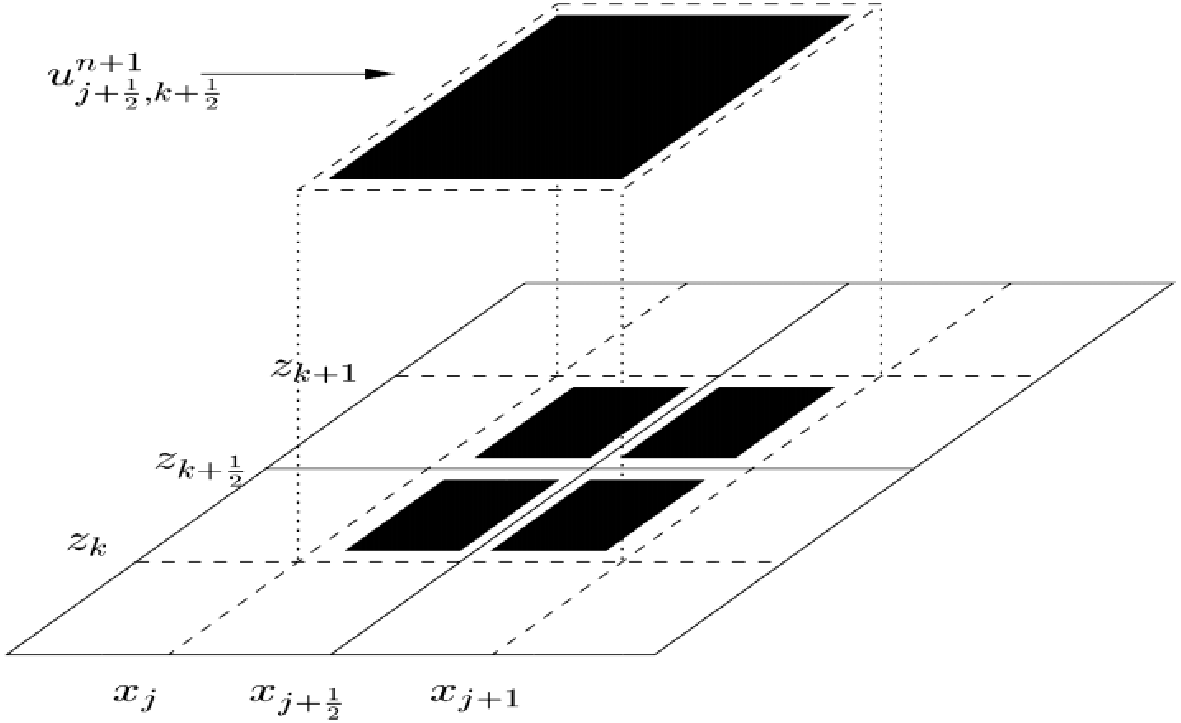
rhoCentralFoam
(shock layer >30 cells)



Tadmor schemes

Nessyahu, Tadmor, 1990 → Kurganov, Tadmor, 2000 → Balbas, Tadmor, 2004 (MHD)*

*Balbás J., Tadmor E., Wu C. C. Non-oscillatory central schemes for one-and two-dimensional MHD equations: I //Journal of Computational Physics. – 2004. – T. 201. – №. 1. – C. 261-285.



$$\frac{du}{dt} + \nabla \cdot F(u) = 0$$

$$u_t + f(u)_x + g(u)_z = 0,$$

$$u_t(x,z,t) + \frac{1}{\Delta x \Delta z}\int_{z-\frac{\Delta z}{2}}^{z+\frac{\Delta z}{2}}\left[f\left(u\left(x+\frac{\Delta x}{2},\eta,t\right)\right) - f\left(u\left(x-\frac{\Delta x}{2},\eta,t\right)\right)\right]d\eta +$$

$$+\frac{1}{\Delta x \Delta z}\int_{x-\frac{\Delta x}{2}}^{x+\frac{\Delta x}{2}}\left[g\left(u\left(z+\frac{\Delta z}{2},\xi,t\right)\right) - g\left(u\left(z-\frac{\Delta z}{2},\xi,t\right)\right)\right]d\xi = 0.$$

OpenFOAM solver development

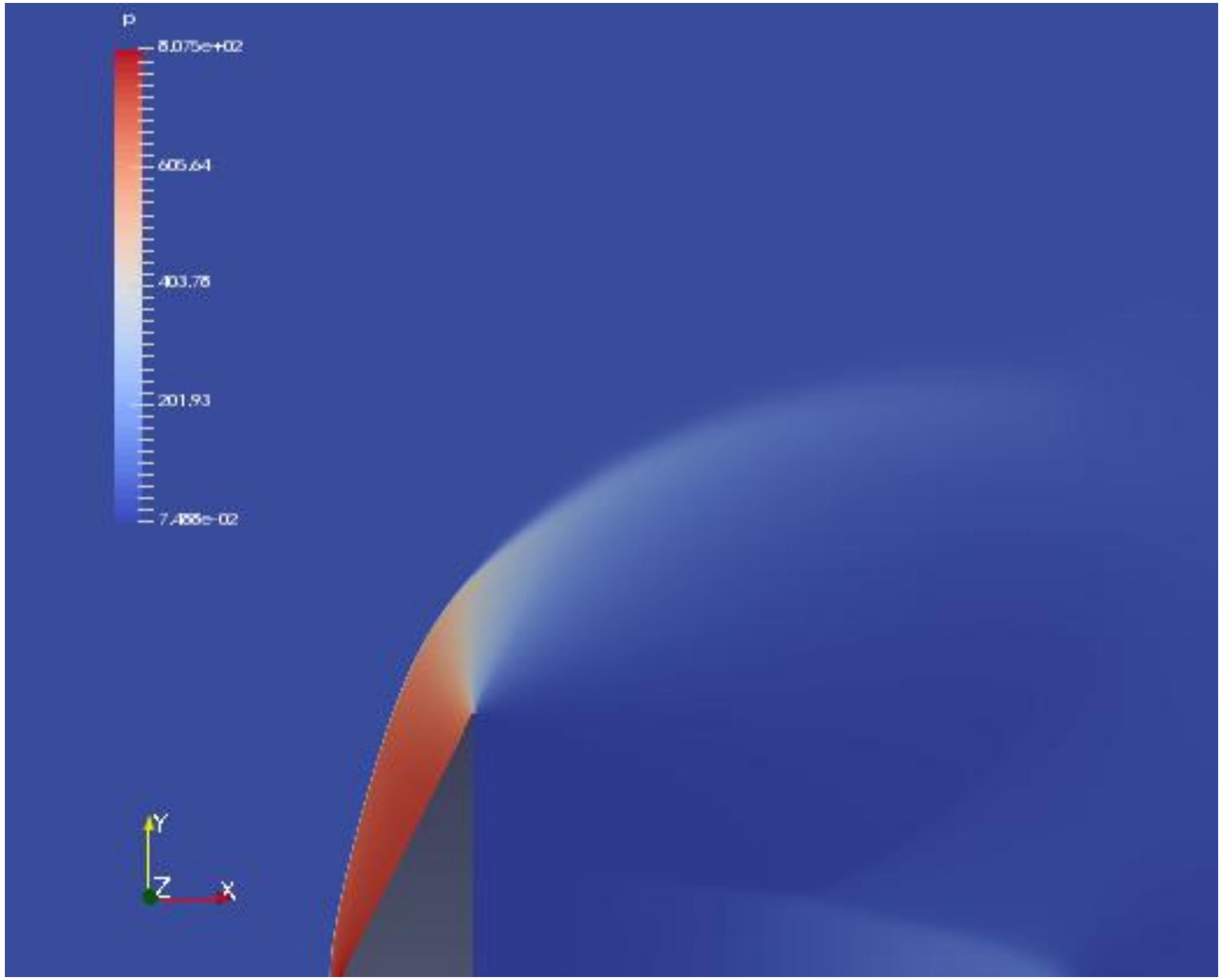
```
surfaceScalarField p_pos("p_pos", rho_pos*rPsi_pos);
surfaceScalarField p_neg("p_neg", rho_neg*rPsi_neg);
surfaceScalarField pf_pos("pMag_pos", 0.5*muR*magSqr(B_pos));
surfaceScalarField pf_neg("pMag_neg", 0.5*muR*magSqr(B_neg));
surfaceScalarField phiv_pos("phiv_pos", U_pos & mesh.Sf());
surfaceScalarField phiv_neg("phiv_neg", U_neg & mesh.Sf());
surfaceScalarField phiB_pos = ("phiB_pos", B_pos & mesh.Sf());
surfaceScalarField phiB_neg = ("phiB_neg", B_neg & mesh.Sf());
```

```
// --- Solve momentum
       solve(fvm::ddt(rhoU) +
fvc::div(phiUp) -
fvc::div(phiB,muR*B));
```

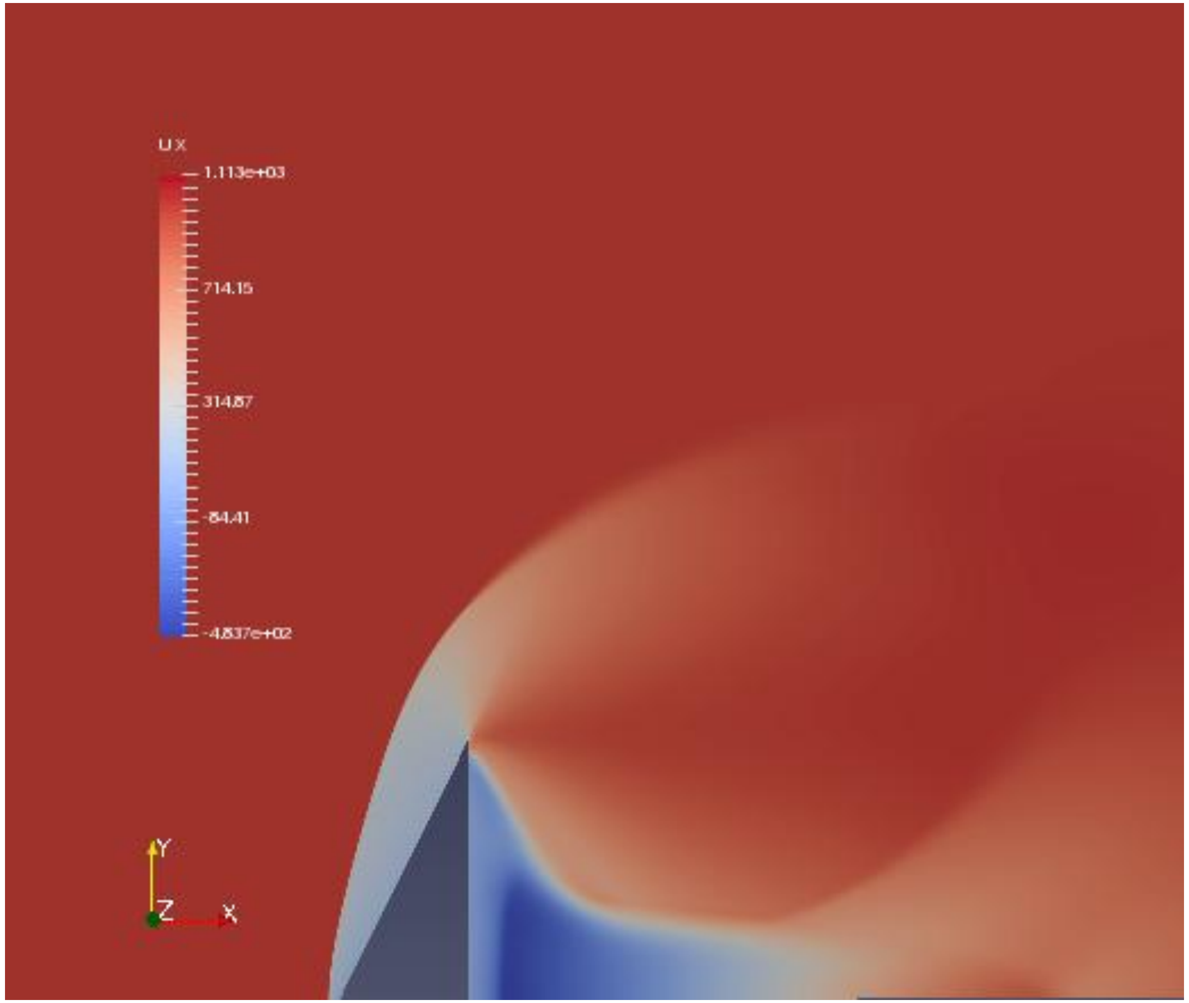
```
// --- Solve energy
solve (fvm::ddt(rhoE) +
 fvc::div(phiEp)-
 fvc::div(sigmaDotU)-
 fvc::div(phiUB,muR*B));
```

Results

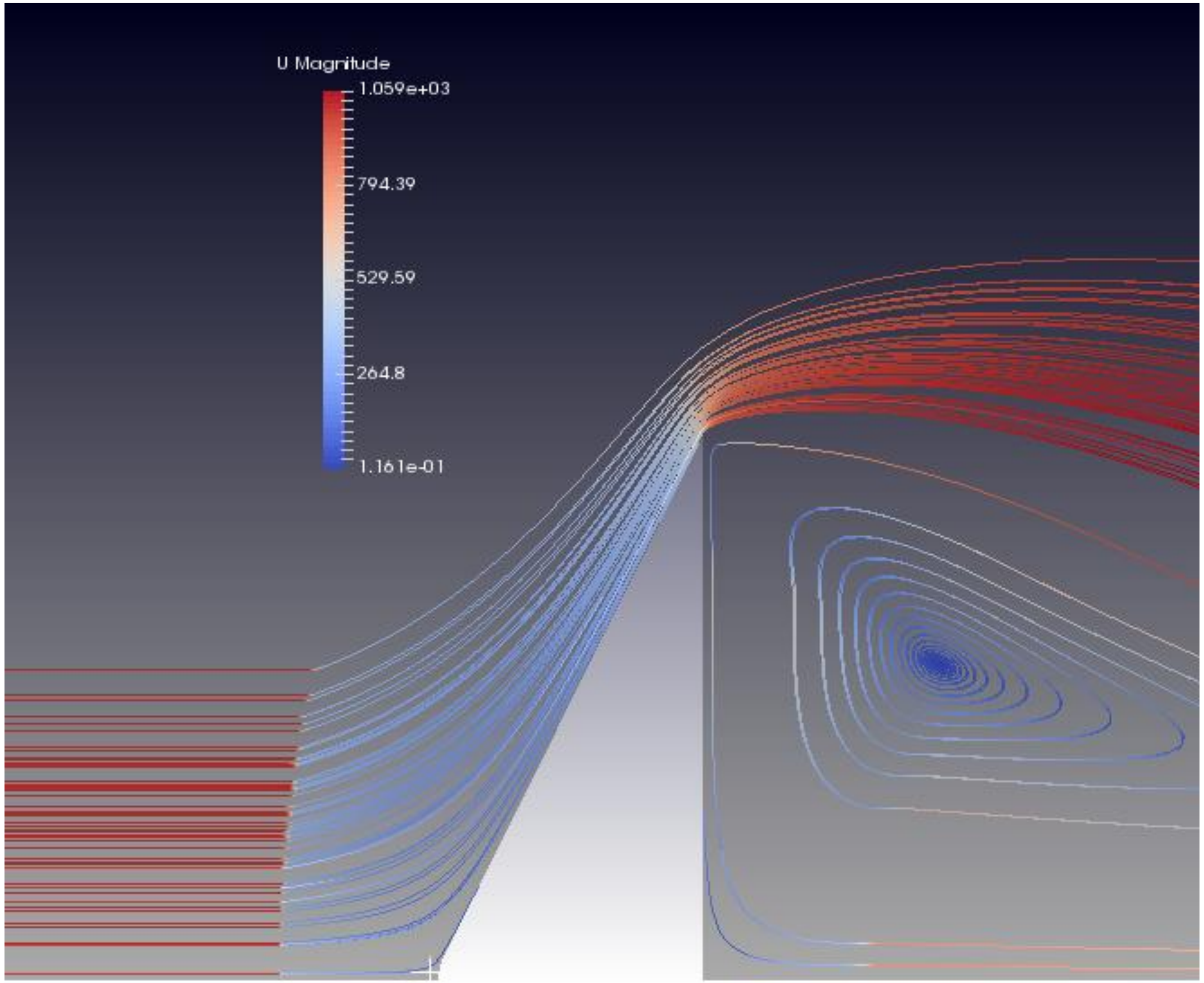
Pressure

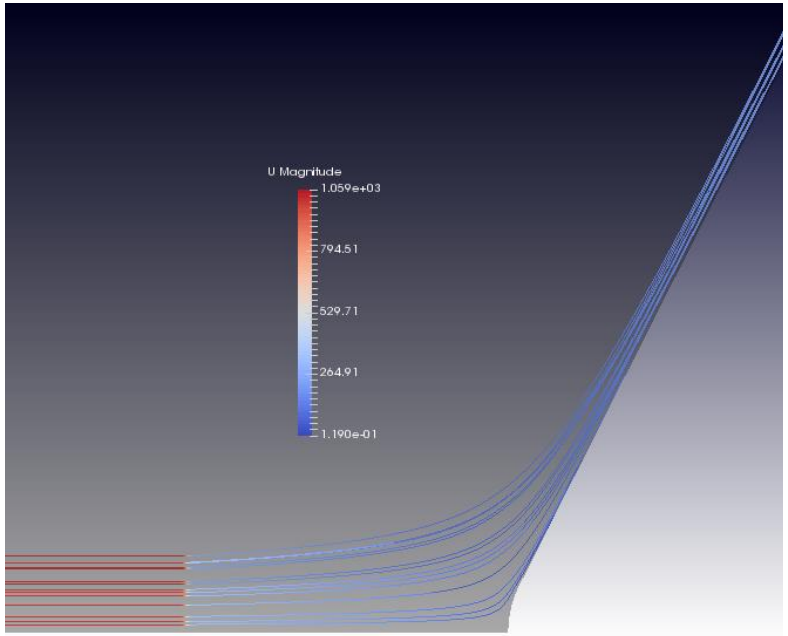


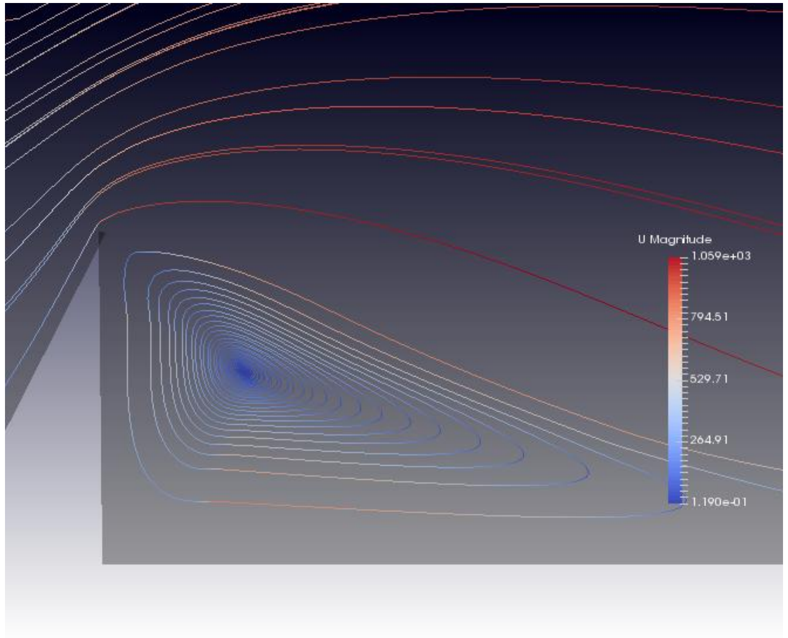
Longitudinal velocity



Results: stream traces

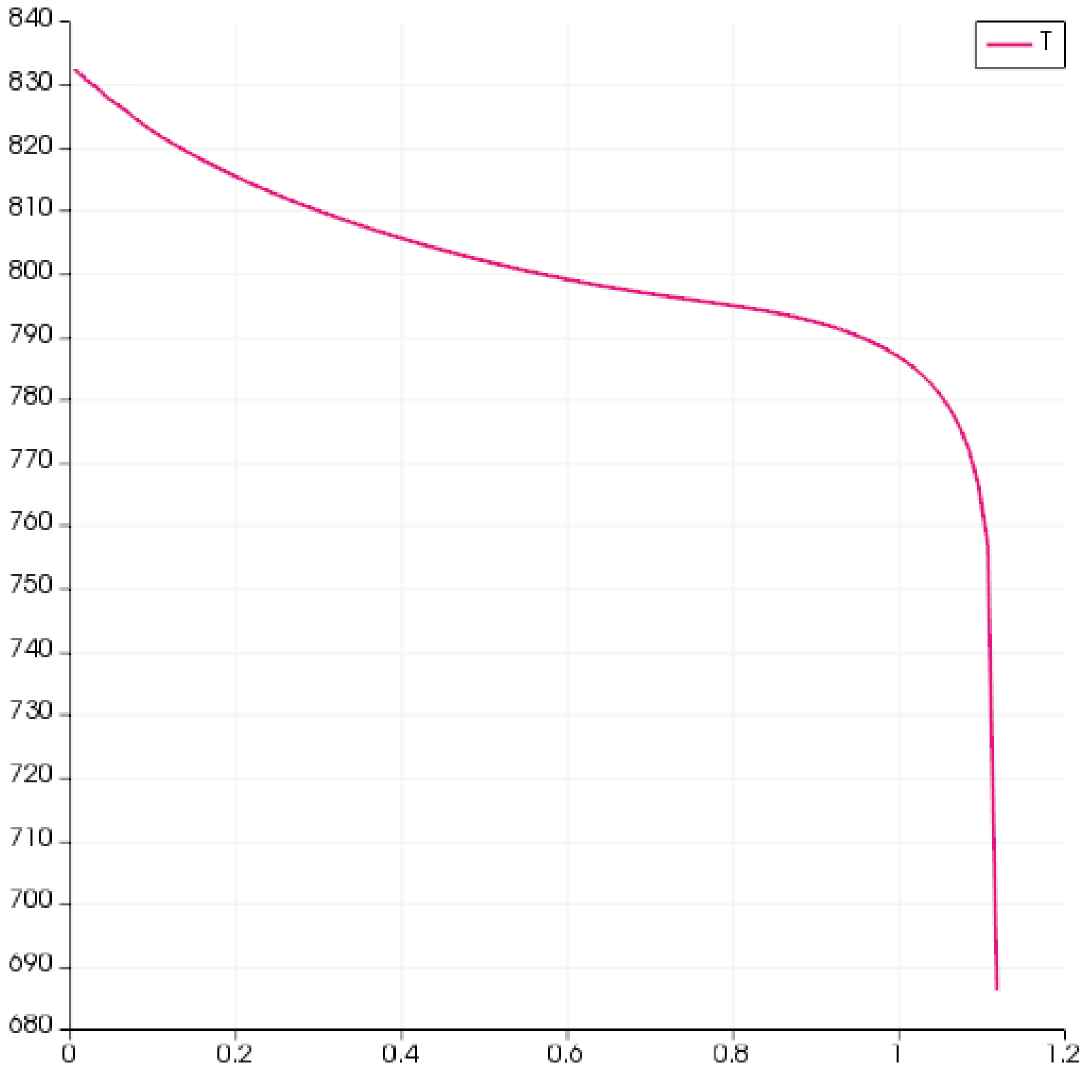




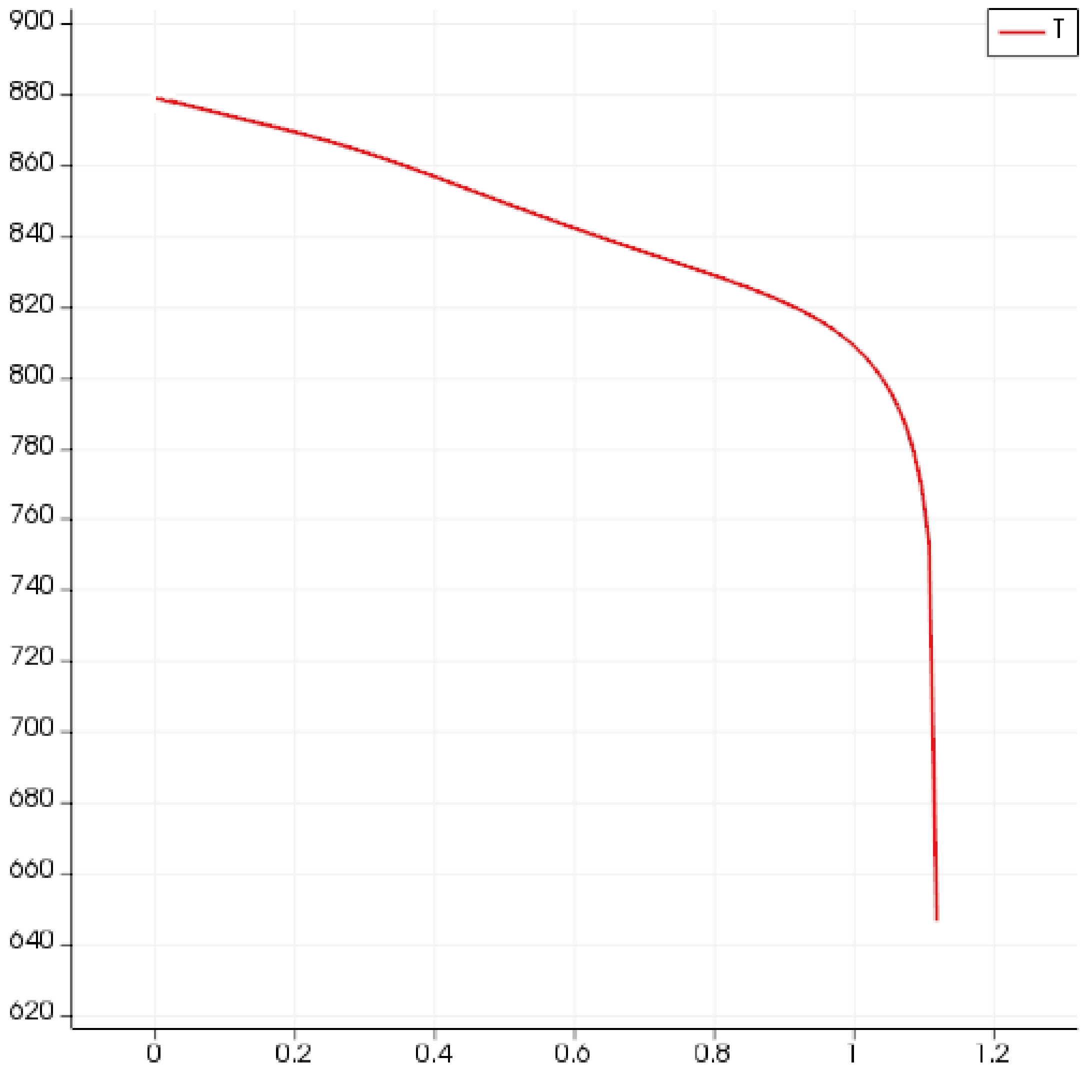


Results: surface temperature

MHD

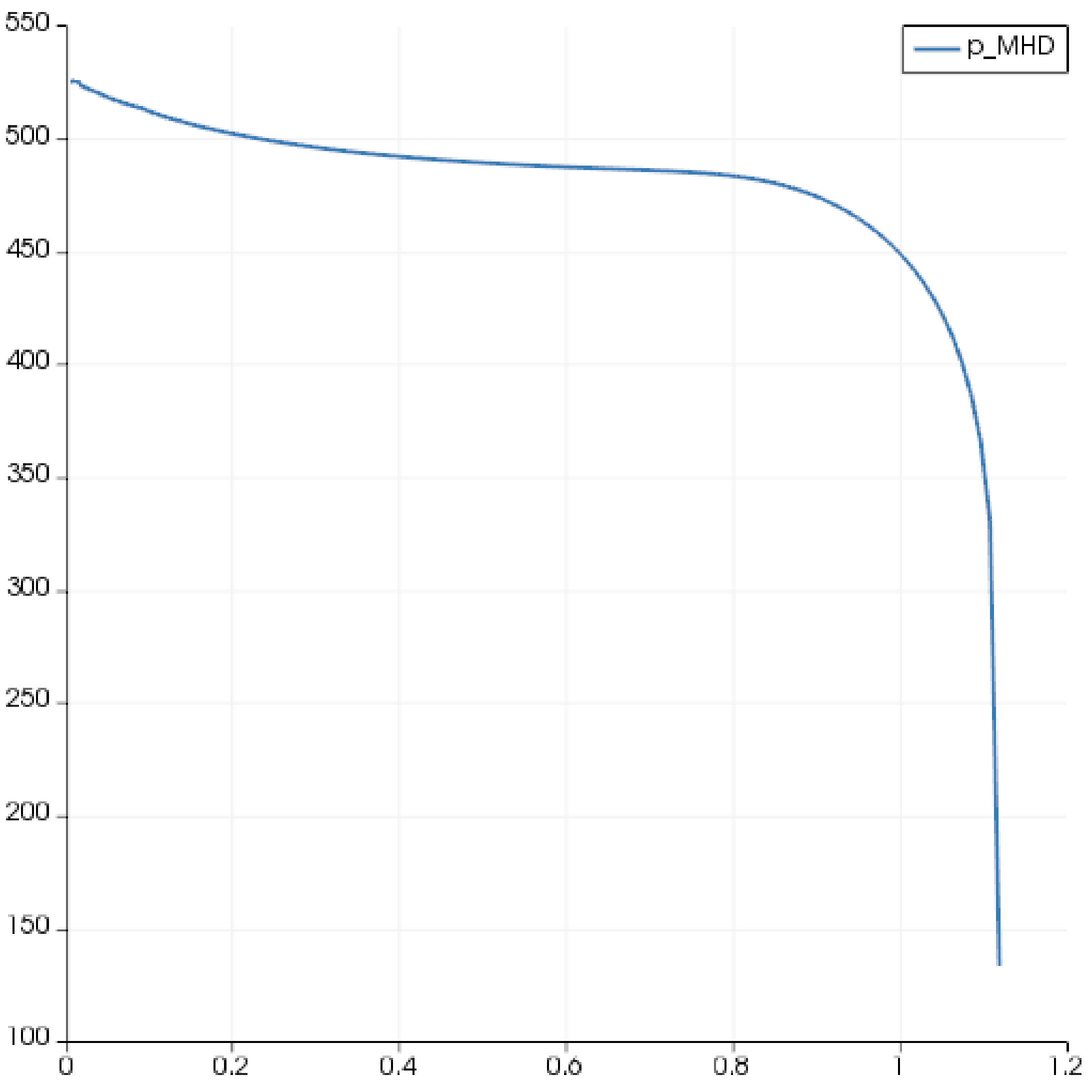


No MHD

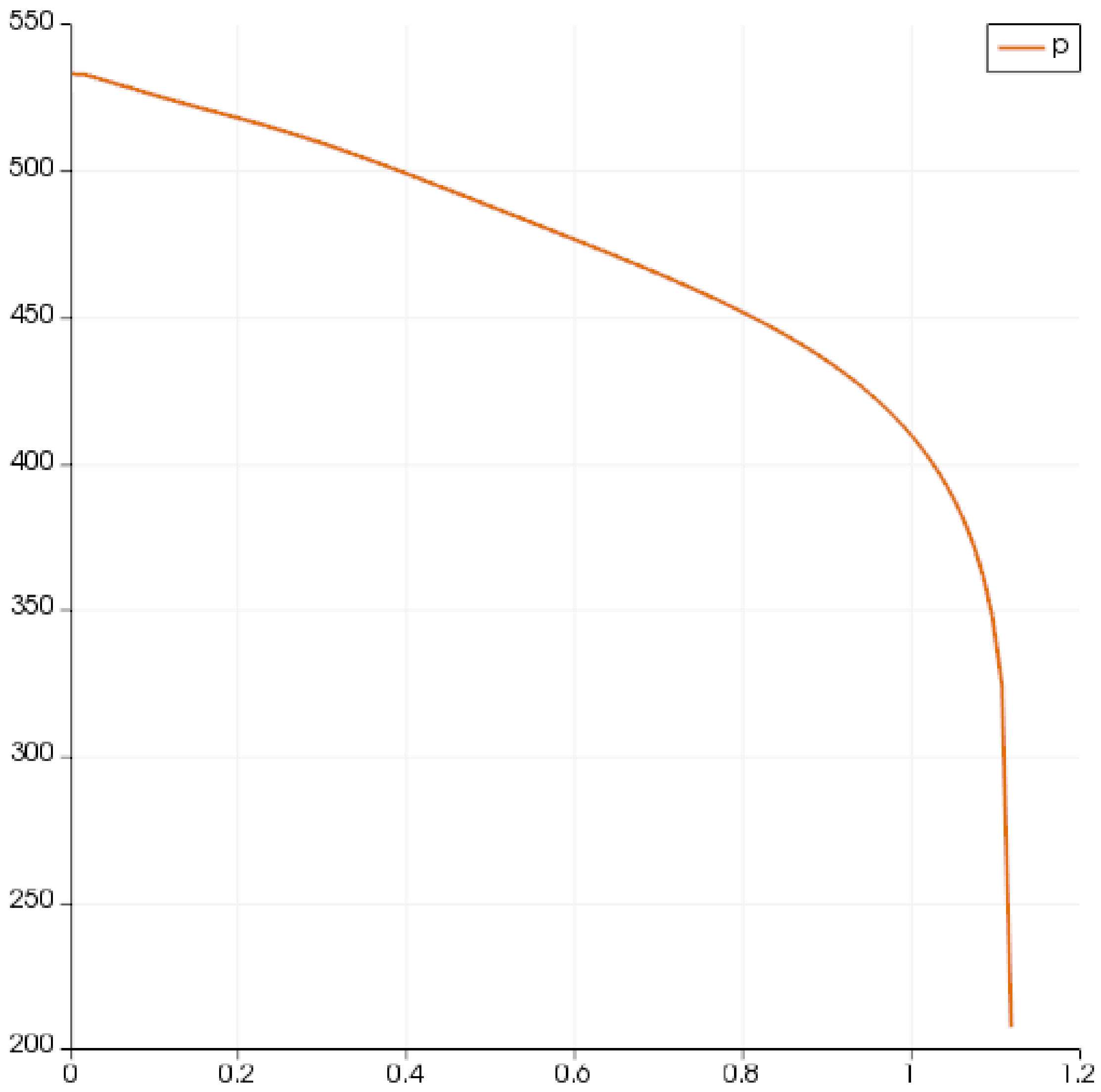


Results: front surface pressure

MHD



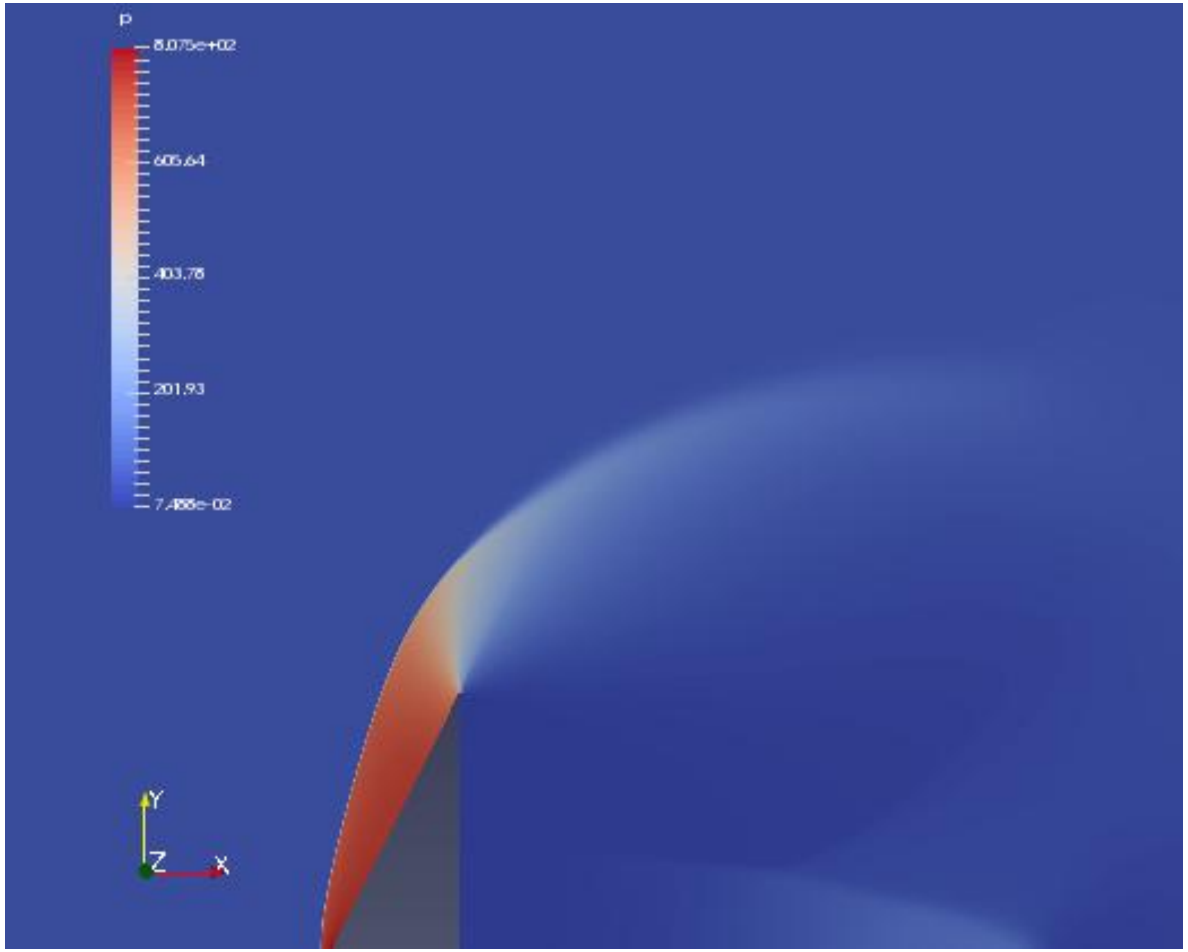
No MHD



Results: shock distance

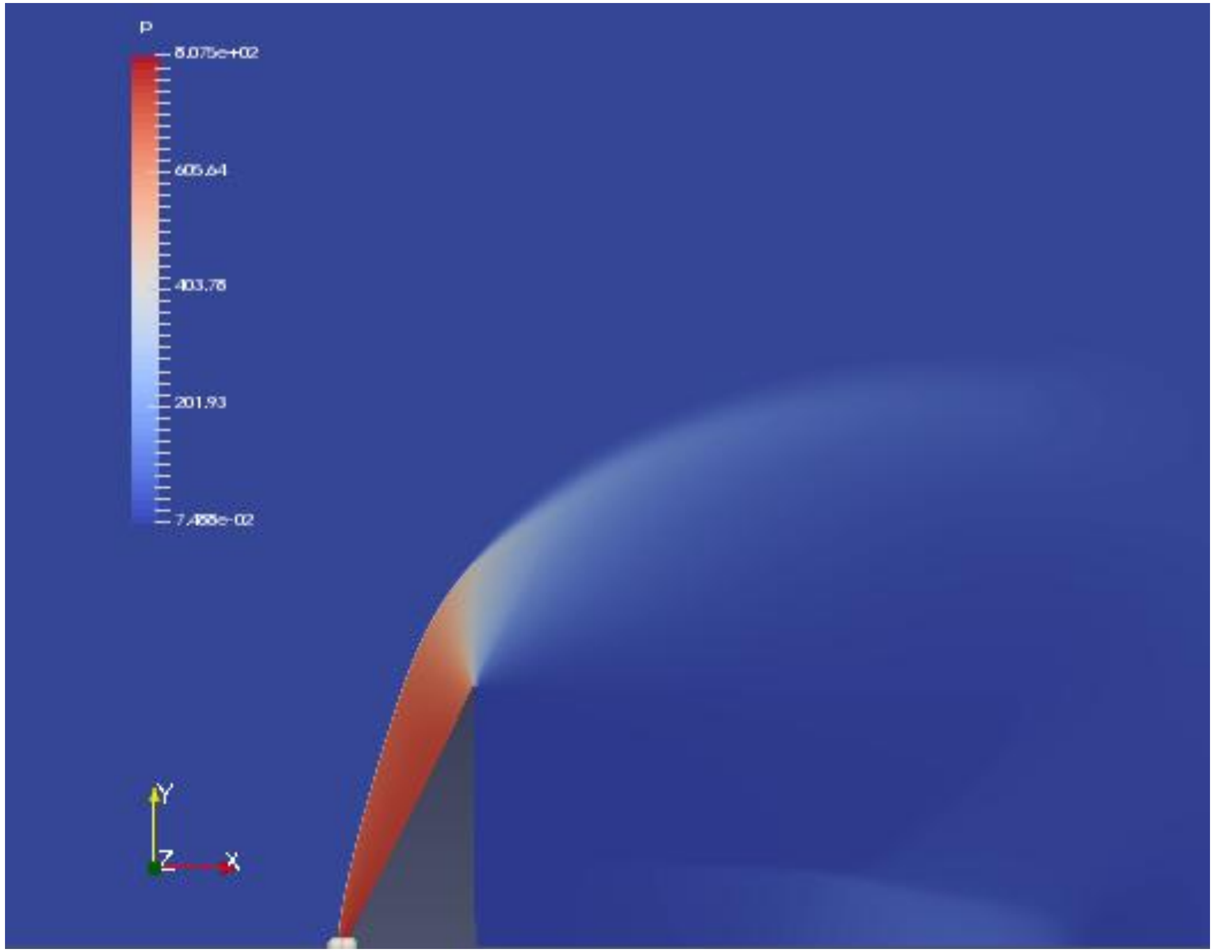
Shock standoff distances (Mach = 4.46)

MHD



L = 0.057m

No MHD



L = 0.038m

Conclusion

- The capabilities of OpenFOAM standard tools in resolving bow shock were investigated
- OpenFOAM transient solver for hypersonic compressible MHD (Stuart number <= 0.2) flow was developed
- The possibility of MHD flow control under certain assumptions was demonstrated
- The effectiveness of Balbas-Tadmor scheme was demonstated

Prospective research may include:

- Mathematical model enhancement, i.e. inclusion of conductivity model
- Further development of the OpenFOAM solver in order to adapt it to a wider range of problems
- Investigation into different solution approach (Godunov-type schemes)
- Development of comprehensive ionized gas thermophysical model in OpenFOAM

Results: MHD interaction effect

Stream traces