Electric arc / weldpool coupling : application to GTAW welding

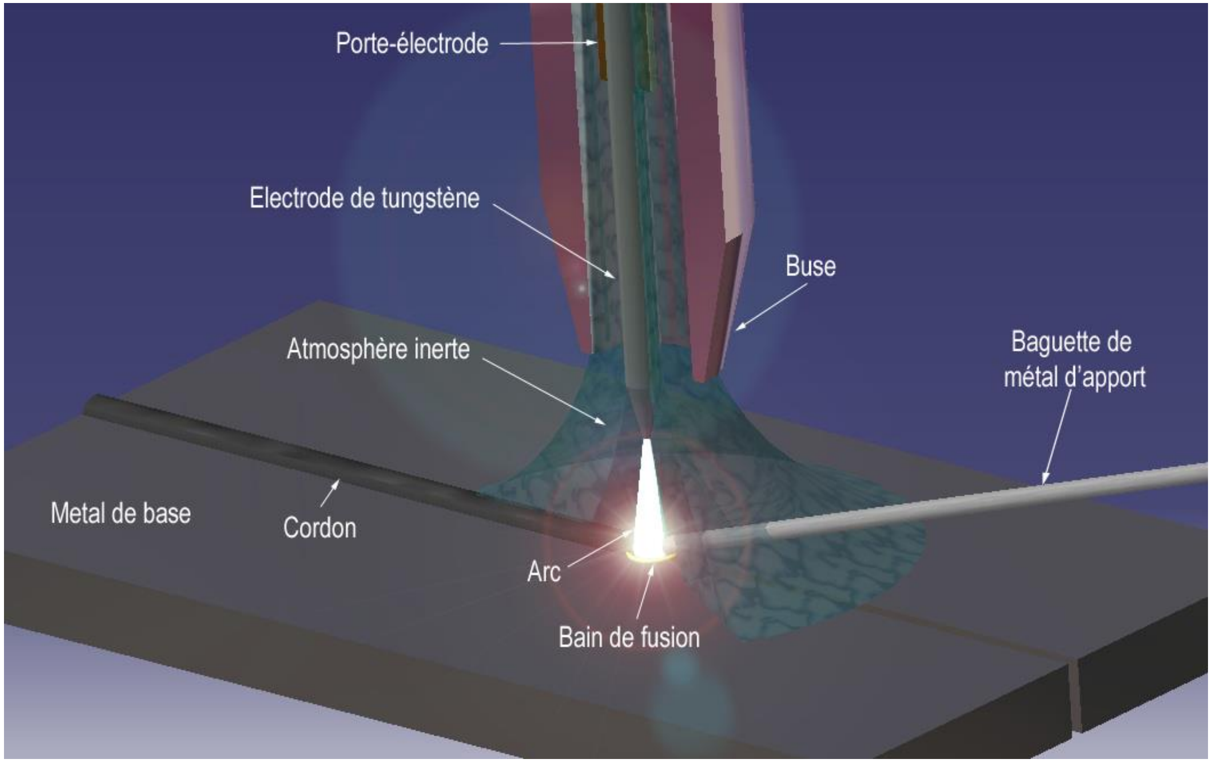
Damien BOREL

Code_Saturne user meeting

02/04/2015, EDF Lab Chatou

Global context

GTA Welding



- Electrode (cathode): Tungsten

- Metal (anode): Stainless steel 304L

- Shielding Gas : Argon

- I = 200A

Modelling welding process :

- Prediction of the weld comportment in function of welding operating parameters with low cost and less time

- Best understanding of the phenomena

Global context

Goal of this work

Modeling of the whole process :

Include electric arc in weld pool simulations (instead of having only an equivalent thermal source)

Industrial issues

- Prediction of weld defects such as lack of fusion (mass transfer)
- Better prediction of residual stress (heat transfer)

Electric arc modeling (heat flux as a function of operating parameters)

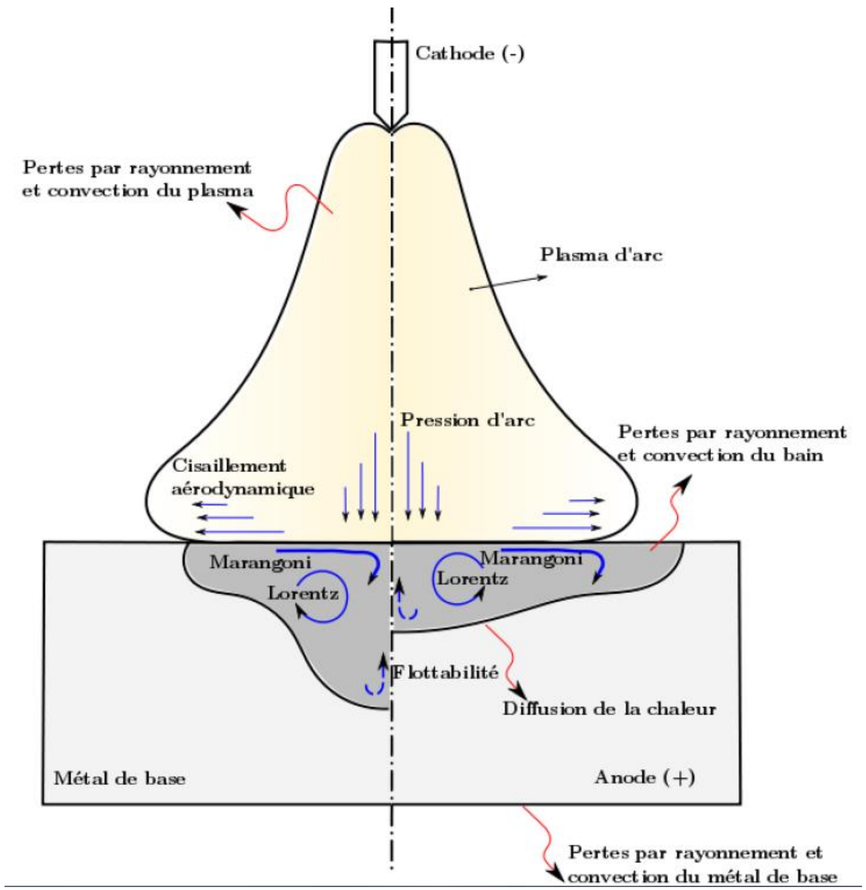
Modeling of weld pool (shape of weldpool)

COUPLING

Weld pool shape as a function of operating parameters

Global context

- Coupling of « plasma » and « weldpool » calculations

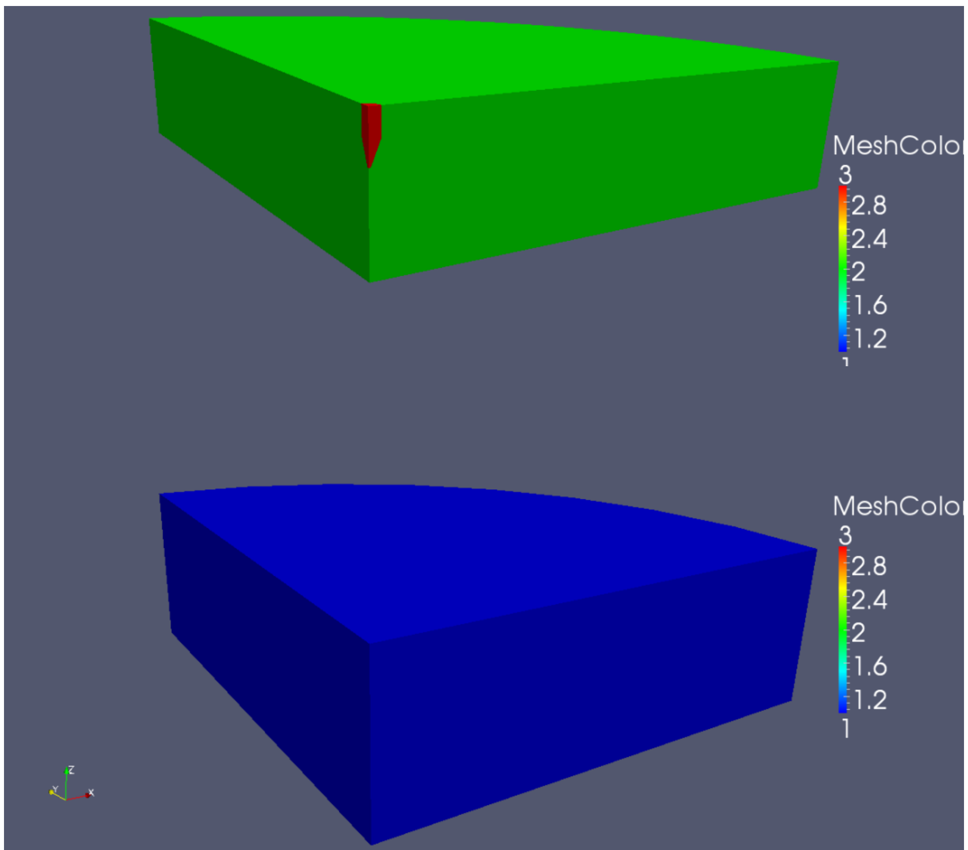


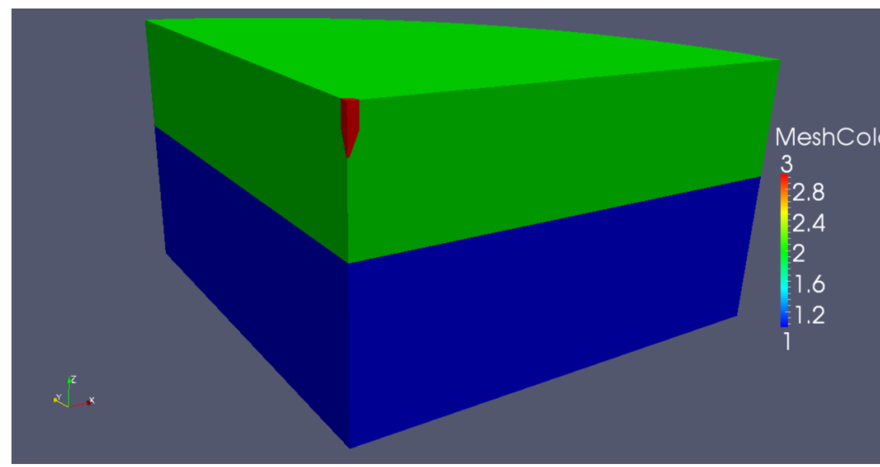
Calculations arc coupled via:

- Thermal, electrical, magnetic fluxes continuity
- Aerodynamic shear on weldpool surface
- Free surface (deformable)

Code_Saturne / Code_Saturne coupling

- Geometry:
  - arc + electrode
  - Base metal (weld pool)
- Mesh:
  - 2.10^6 cells
  - 2.10^6 cells





Global modelling

- **Plasma:** LTE arc column (magnetohydrodynamics)
- **Weldpool**: Newtonian fluid

Navier-Stokes

$$div(\rho\vec{U}) = 0$$

$$\frac{\partial(\rho\vec{U})}{\partial t} + \rho\left(\vec{U}.\vec{\nabla}\right)\vec{U} = -\vec{\nabla}P + div\left(\vec{\tau}\right) + \vec{j}\wedge\vec{B} + \rho\vec{g} + \vec{T}S_{qdm}$$

$$\frac{\partial(\rho h)}{\partial t} + \rho\left(\vec{U}.\vec{\nabla}\right)h = div\left(\frac{\lambda}{C_p}\vec{\nabla}h\right) + \vec{j}.\vec{E} - S_{rad} + TS_h$$

Maxwell

$$\vec{\nabla}.(\sigma\vec{\nabla}V) = 0$$

$$\Delta\vec{A} = -\mu_0\vec{j}$$

With:

$$\vec{j} = \sigma\vec{E}$$

$$\vec{E} = -\vec{\nabla}V$$

$$\vec{B} = rot\left(\vec{A}\right)$$

- **Solids:** penalization source term

$$\vec{T}S_{qdm} = -\frac{\rho}{C}\left(\vec{u} - \vec{u}_0\right)$$

Cathode: $\vec{u}_0 = \vec{0}$

Anode: $\vec{u}_0 = \vec{U}_{weld} = \vec{0}$

$$\vec{T}S_{qdm} = \underbrace{-\frac{\rho}{C}\frac{\left(1-f_l\right)}{f_l^{\,3}+b}\left(\vec{u}-\vec{u}_0\right)}_{\text{Weld pool}} - \underbrace{\vec{\nabla}T\frac{\partial\gamma}{\partial T}\frac{f_l}{\Delta z}}_{\text{Marangoni (surface)}}$$

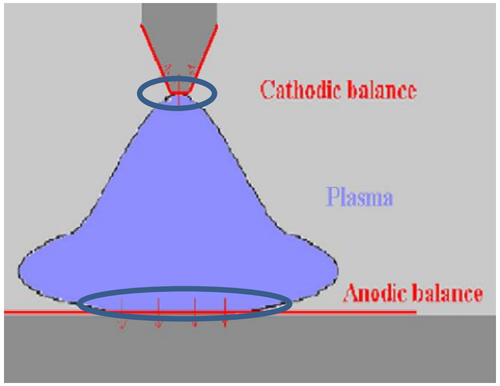
Marangoni: (S only) $\frac{\partial\gamma}{\partial T}\left(10^{-3}N.m^{-1}.K^{-1}\right) = -0.4 - 0.056\left(\frac{28798\left(1-B\right)}{BT} + \ln B\right)$ with $B = 1 + \left(0.68C_S\right)e^{\left(\frac{28798}{T} - 8.5647\right)}$

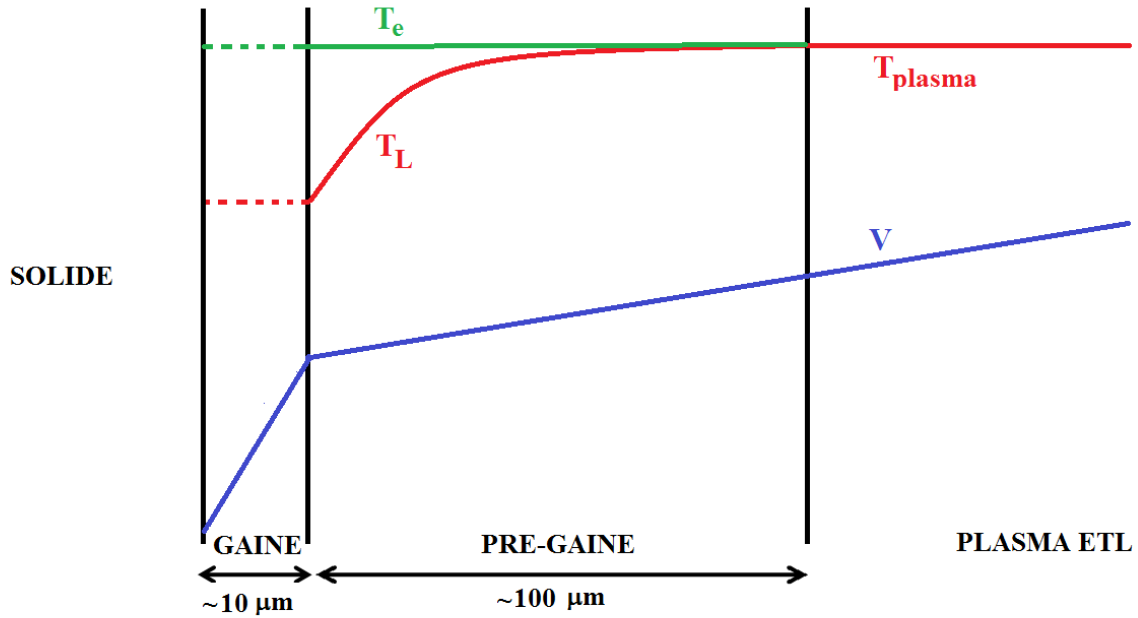
- **Plasma / solid interfaces:** Cathodic and anodic sheath modelling with an enthalpic source term

Cathode: $TS_h = TS_K$

Anode: $TS_h = TS_A$

Plasma / solid interfaces modelling





<u>Issues:</u>

- Modelling of anodic and cathodic layers (complex non-LTE phenomena and small spatial scale 0.1mm)

- We don't resolve them but we model their effetcs on the interface thermal balance

$$-\lambda_{sol}\vec{\nabla}T_{sol}.\vec{n} = -\lambda_{pla}\vec{\nabla}T_{pla}.\vec{n} + \underbrace{Q(j_e) + Q(j_i)}_{TS_h}$$

Interfaces solide/plasma modelling

- **Anodic (arc / weld pool)** balance :
  - Anodic thermal transfer is (heating):

$$Q(j_e) = j_e\left(\frac{5k_B}{2e}(T_{Plasma} - T_a) + W_a + \Delta V_a\right)$$

$$Q(j_i) = 0$$

- **Cathodic (arc / electrode)** balance :
  - Cathodic thermal transfer is (cooling + heating):

$$Q(j_e) + Q(j_i) = -j_e\left(\frac{2k_B}{e}T_{Wall} + W_c\right) + j_i\left(\frac{5k_B}{2e}T_{Wall} + \Delta V_c + V_i\right)$$

Electron emission (cooling)

$$j_e = A_r T^2 \exp\left(-\frac{eW_{eff}}{k_b T_{Paroi}}\right)$$

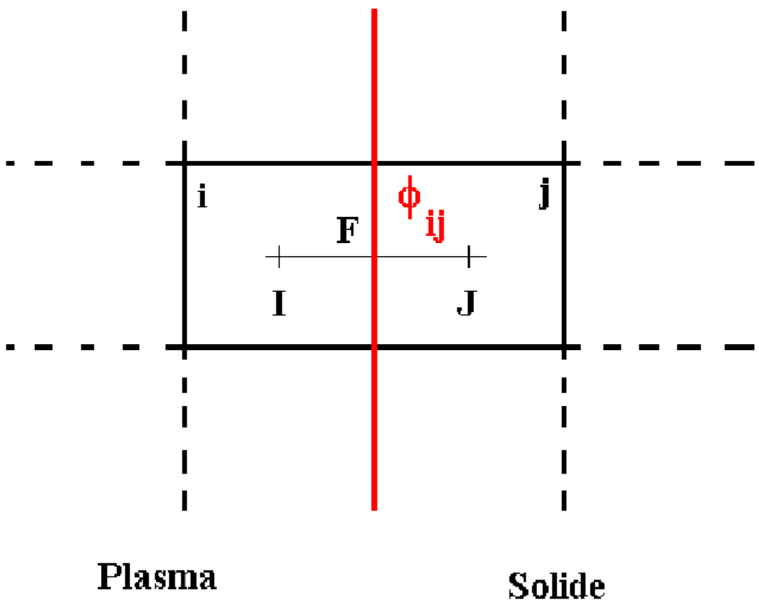
Ionic heating

$$j_i = j - j_e$$

Δv_a and Δv_c are parameters taken from litterature

Coupling faces

- 2 calculations are coupled via arc domain bottom face and weld pool domain top face



Thermal and electrical fluxes continuity

+

Aerodynamic shear

$$\phi_{ij} = \frac{\sigma_j IF}{\sigma_j IF + \sigma_i JF}\phi_j + \frac{\sigma_i JF}{\sigma_j IF + \sigma_i JF}\phi_i$$

Magnetic flux continuity

$$\phi_{ij} = \frac{IF}{IF + JF}\phi_j + \frac{JF}{IF + JF}\phi_i$$

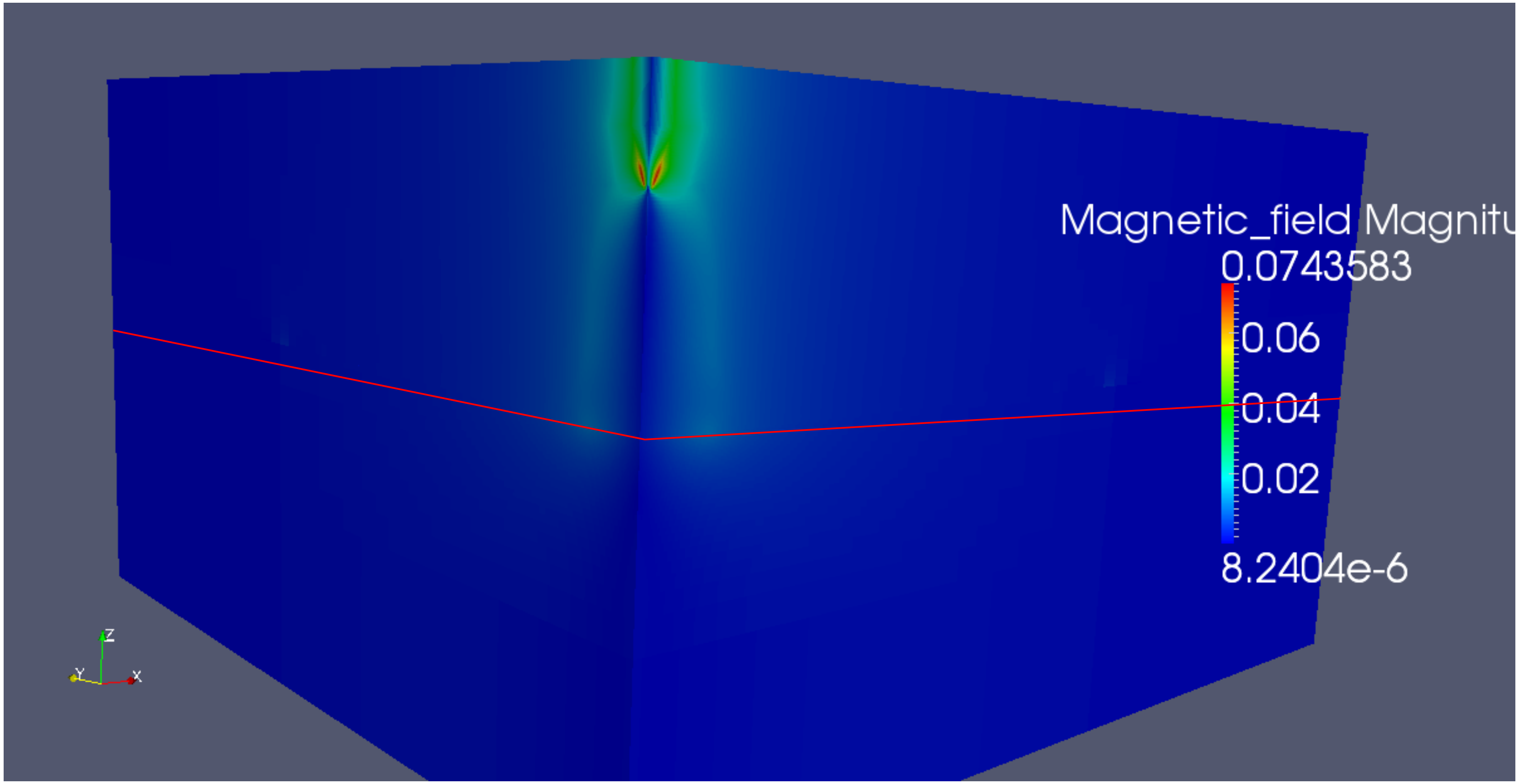
- Flux of h, V, A trough coupling faces?

→ Apply these relations with semi-implicit B.C. (Robin) on plasma and weldpool side

→ Routines csc2cl, cscfbr, cscpfb

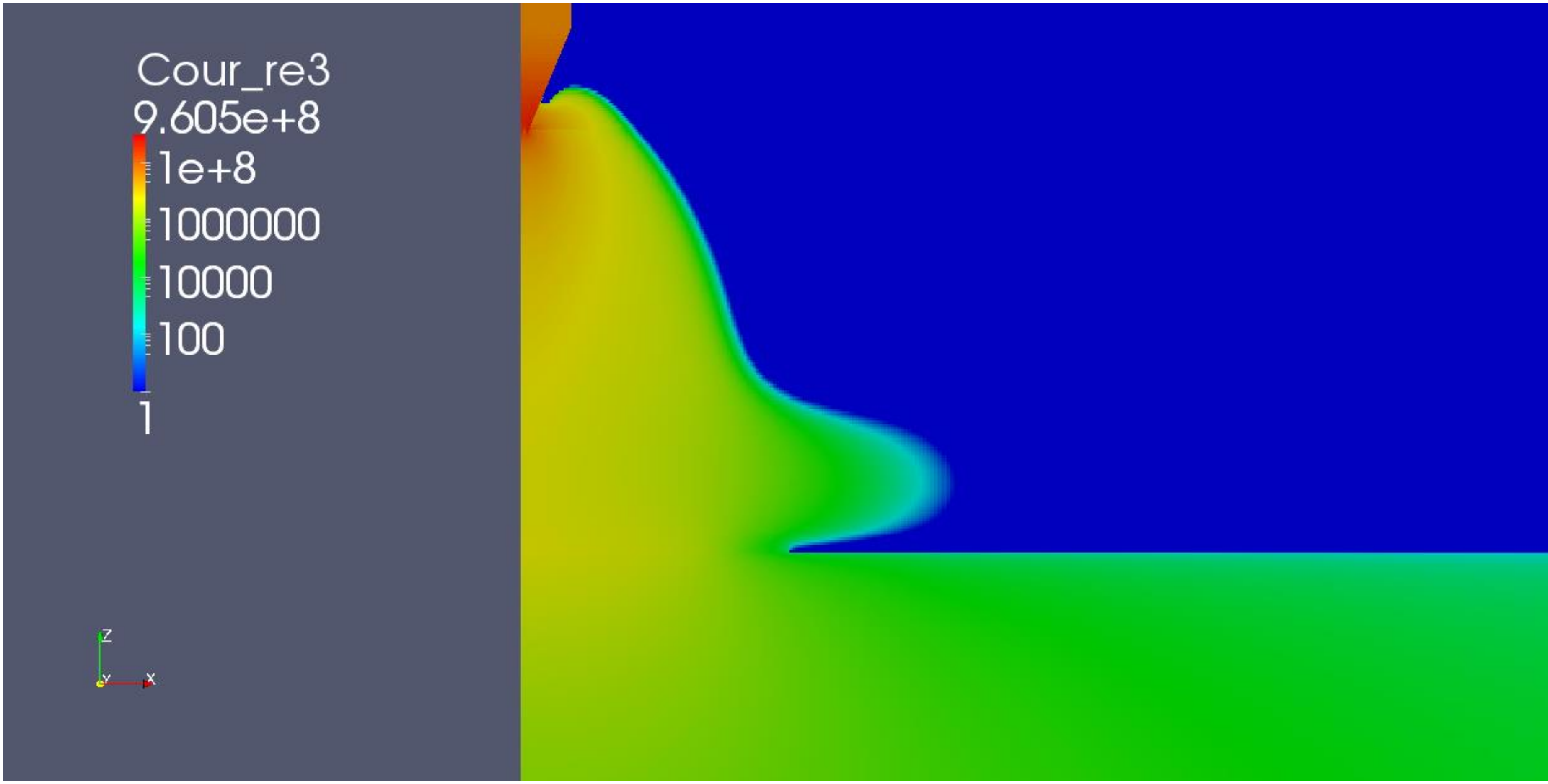
Results of the coupling

- Magnetic flux continuity



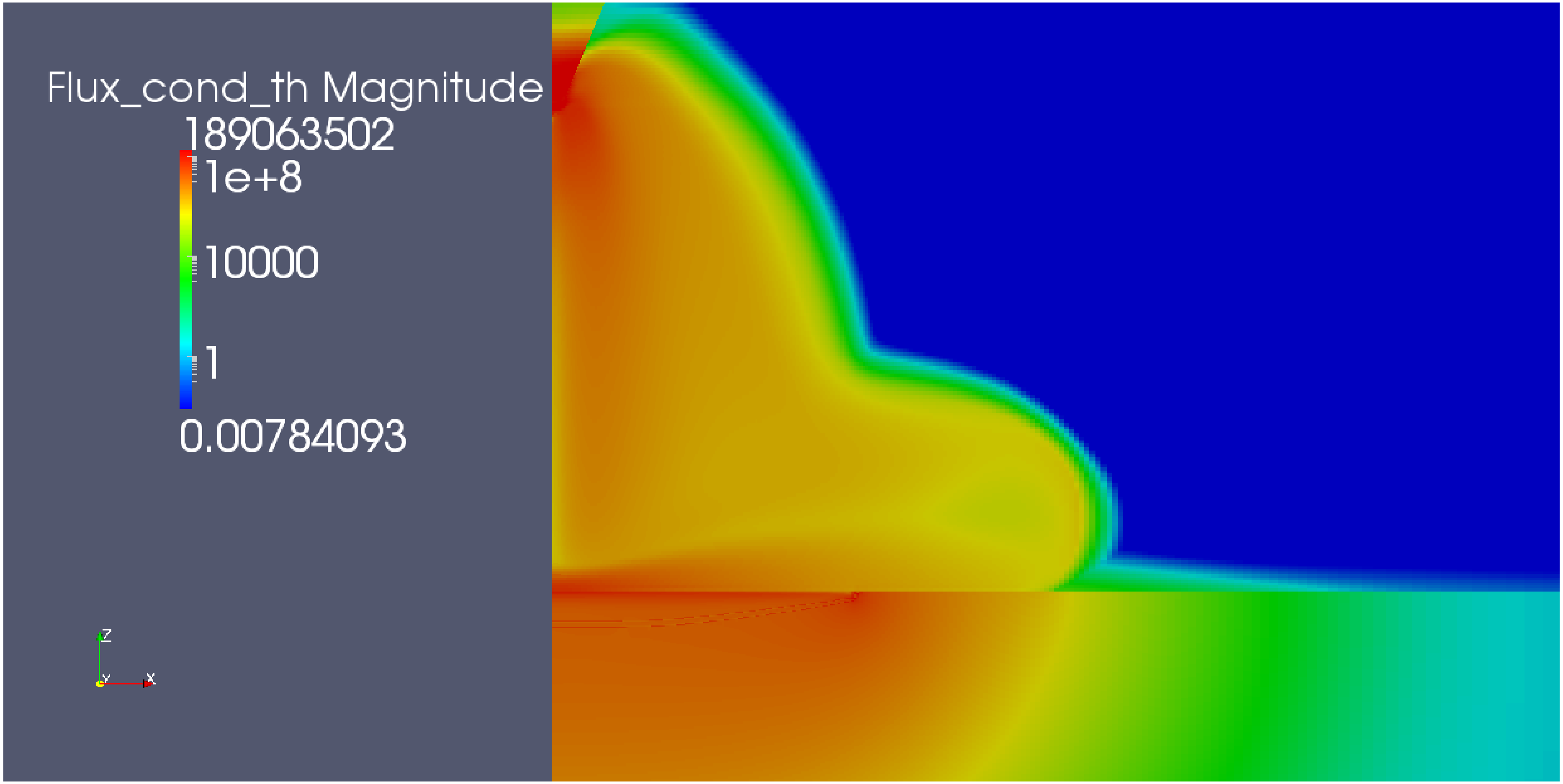
Results of the coupling

- Electrical flux continuity



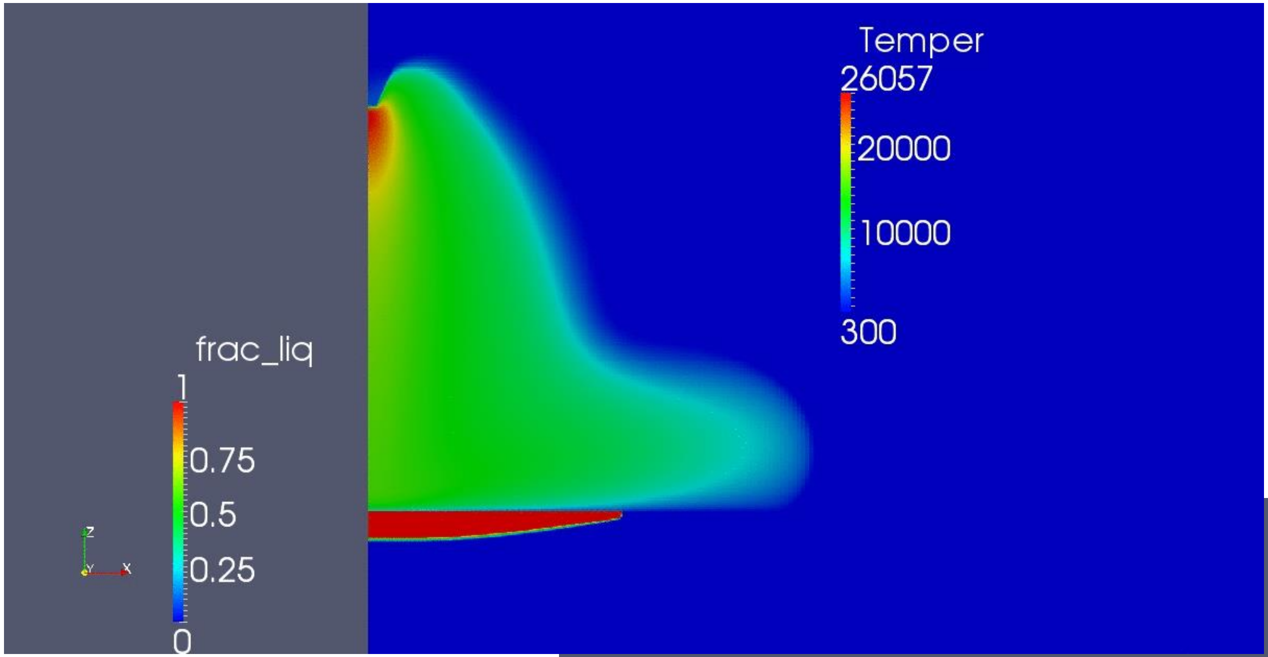
Results of the coupling

- Thermal flux continuity



Not exactly continuous because of TS_K and TS_A

Results of the coupling

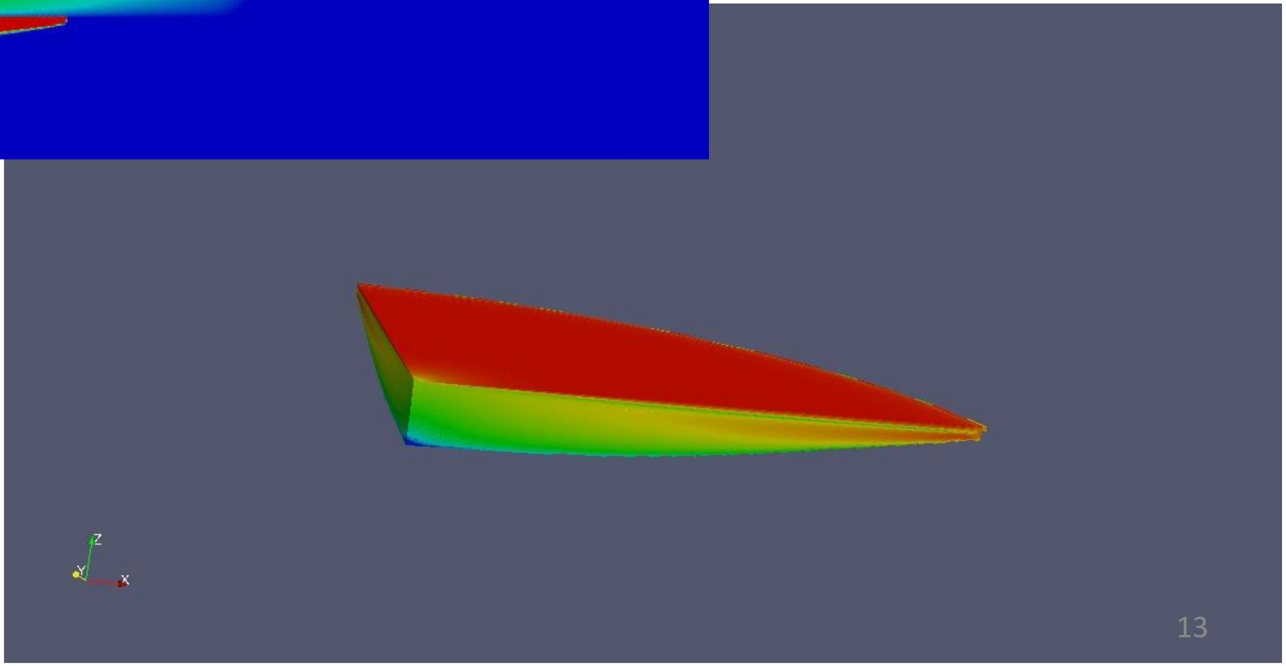


$$dt_{arc} = 2.10^{-7}\,s$$

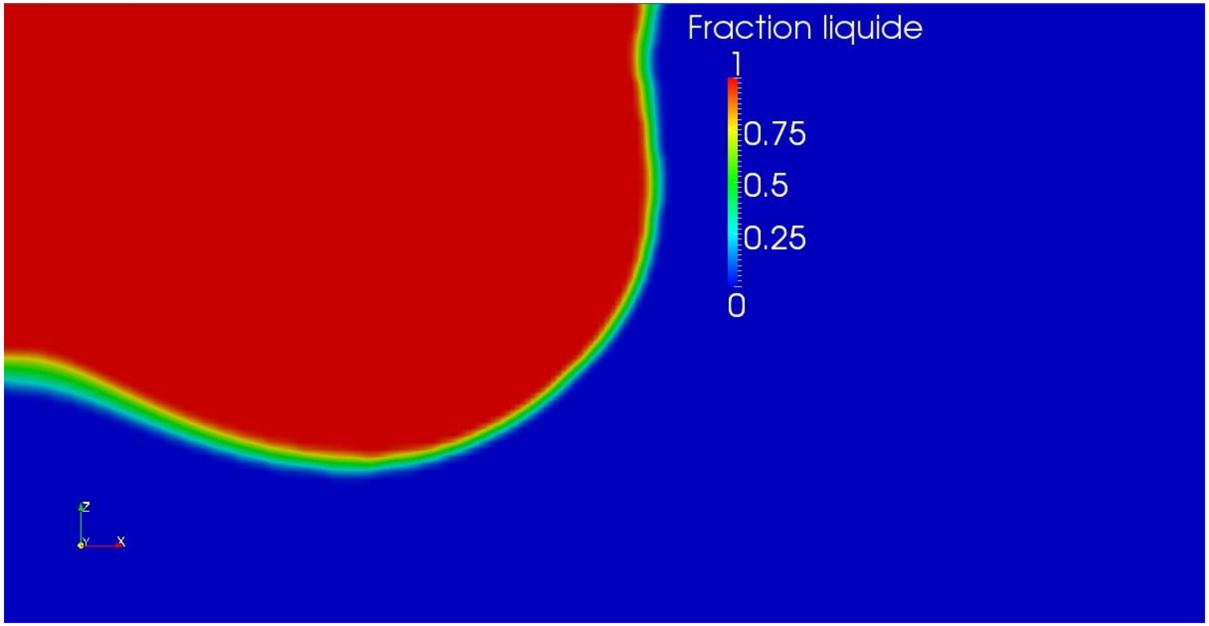
$$dt_{bain} = 2.10^{-4}\,s$$

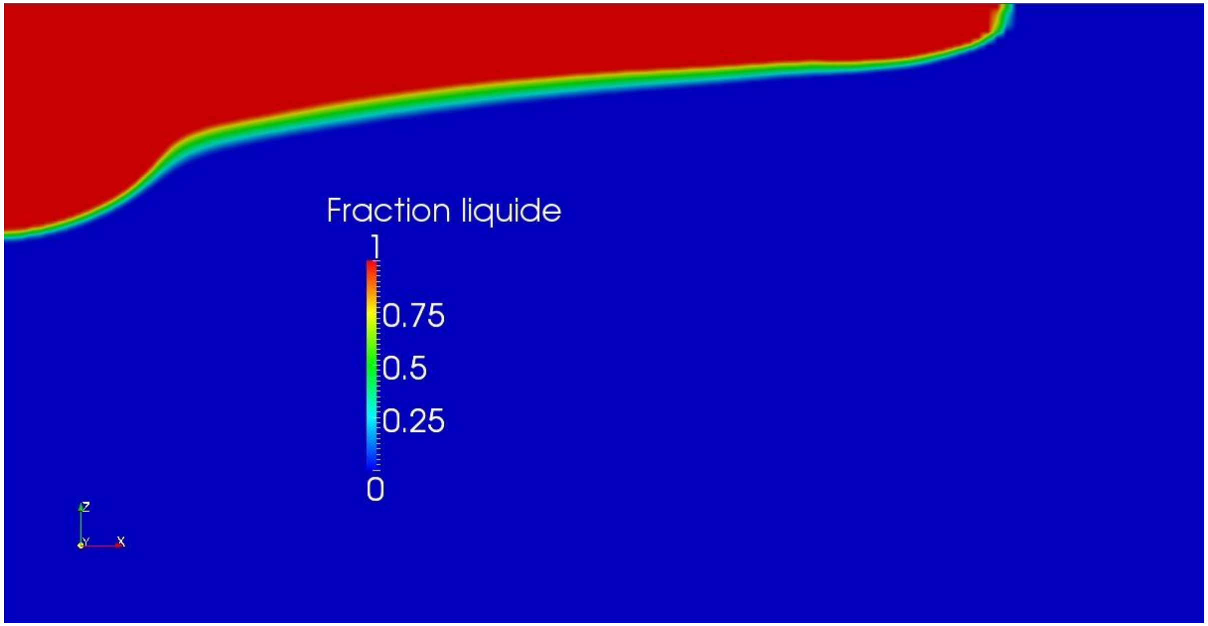
$$C_S = 20\,ppm$$

$$T_{\max} \approx 2500K$$



Results: influence of c_s





High Sulfur concentration:

$$C_S = 280\,ppm$$

$$t = 8s$$

→ High depth and small radial extension

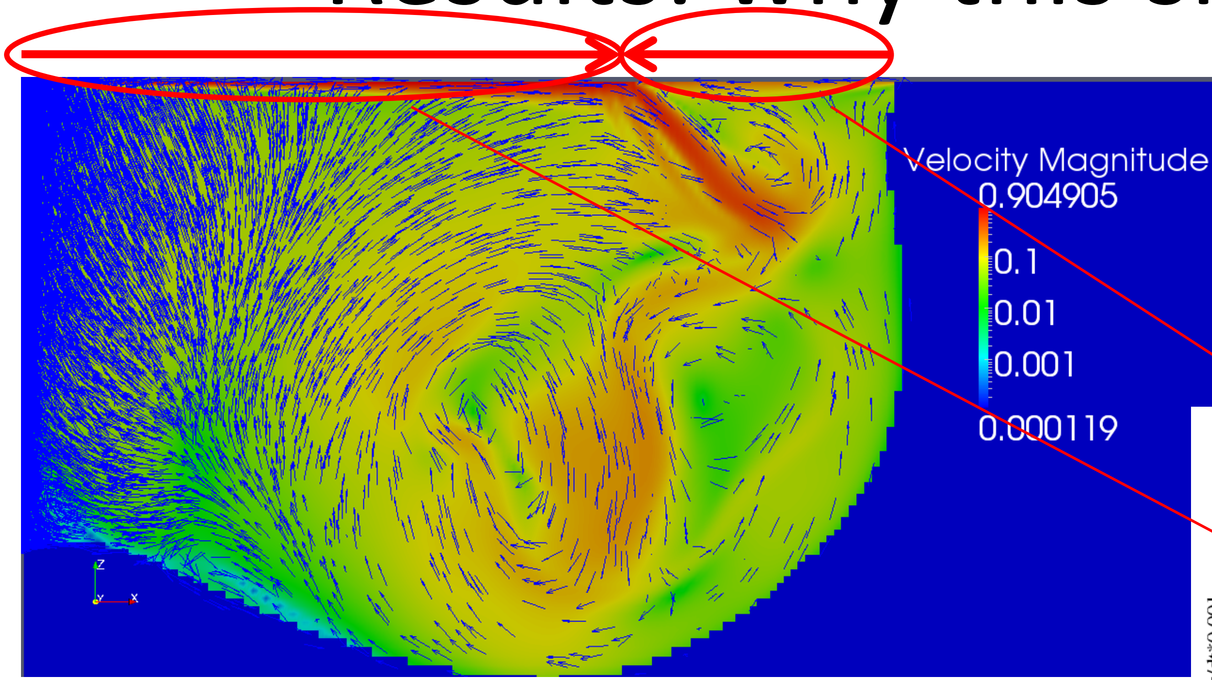
Low Sulfur concentration :

$$C_S = 10\,ppm$$

$$t = 8s$$

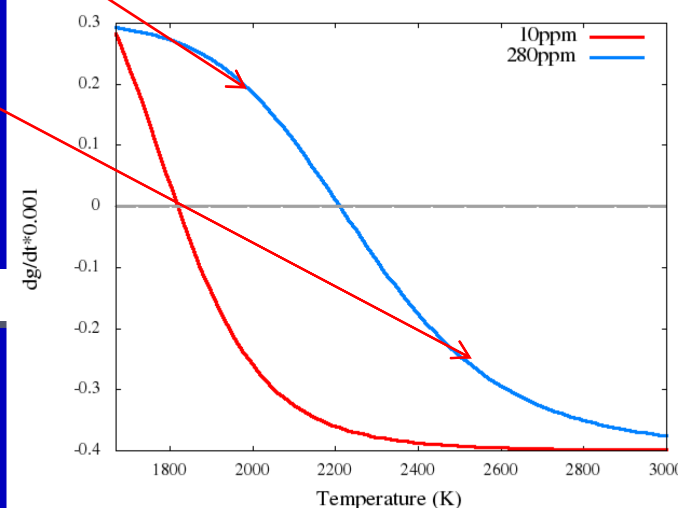
→ High radial extension and small depth

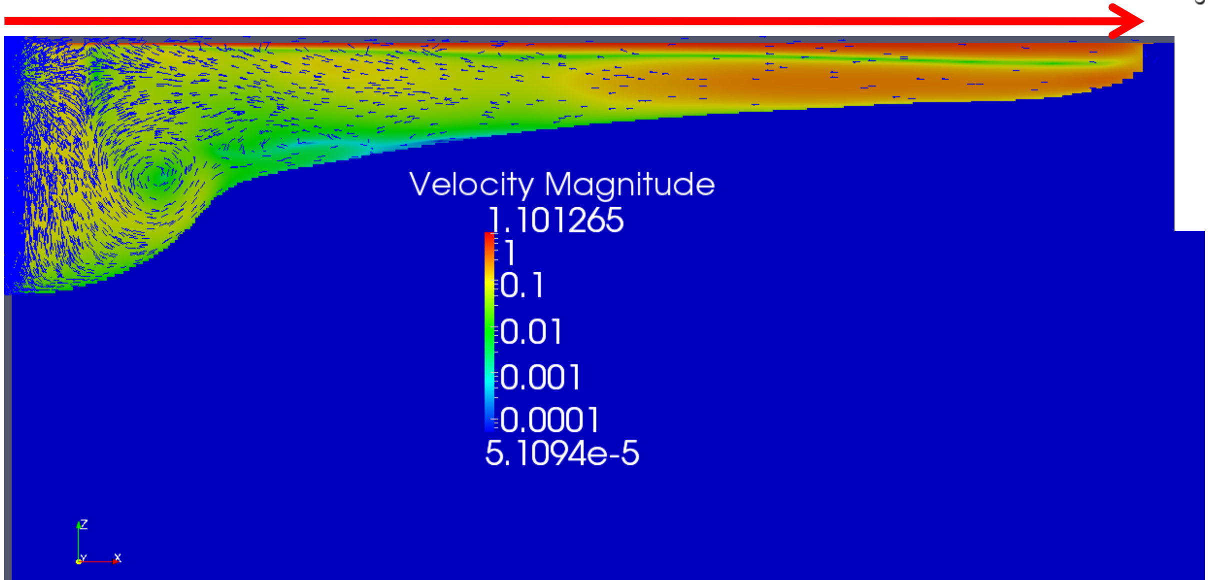
Results: why this shape?



$C_S = 280\,ppm$

$t = 8s$





$C_S = 10\,ppm$

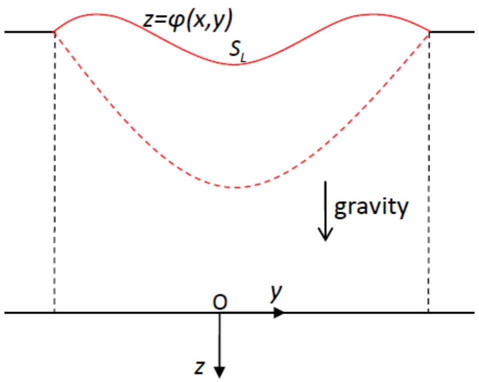
$t = 8s$

Conclusions

- We perform GTAW electric arc – weldpool coupling
- We are able to predict the shape of weldpool as a function of operating parameters, without equivalent thermal source

Future work

- Free surface of weld pool



- Enhance plasma model to compute potential drops in electrostatic sheaths
- Take into account chemistry (S+Mn→MnS)

Thank you for your attention