EUROfusion

# SPD.2 (D005): Model development for dust production mechanisms from melting

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# Need for customized fluid solvers

Commercial CFD codes are generally not well-suited for simulations of transient PFC surface melting

- Huge disparity between plasma and metal properties
- Navier-Stokes equations are not adapted to describe plasma behaviour near boundaries
- Large range of physical scenarios and associated scales (arcing, disruptions, flow over obstacle, …) → successful recipes to use a commercial tool in one case can fail in another
- Licensing issues

# Governing equations for interface resolved 3D simulations

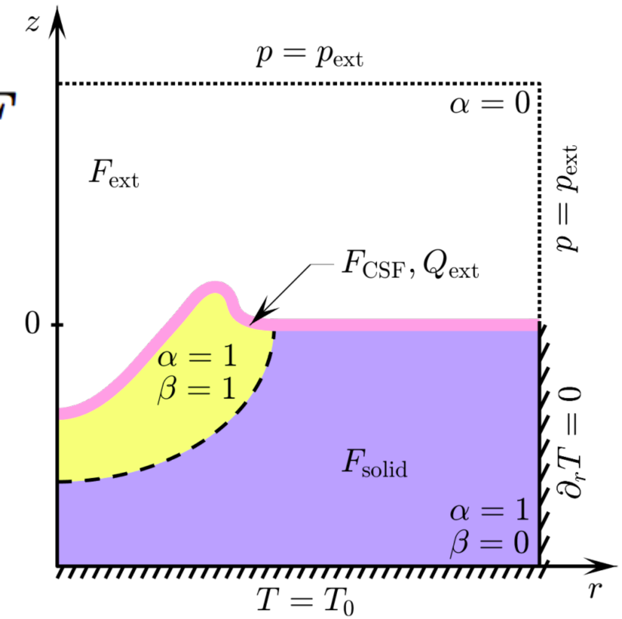
- Conservation of mass, momentum and energy
- Need to track solid-liquid interface in the metal

$$\frac{\partial}{\partial t}(\rho \boldsymbol{v})+\nabla\cdot(\rho \boldsymbol{v}\boldsymbol{v}) = -\nabla p+\nabla\cdot\left[\mu\left(\nabla \boldsymbol{v}+\nabla \boldsymbol{v}^{\mathrm{T}}\right)\right]+\boldsymbol{F}$$

$$\frac{\partial}{\partial t}(\rho h)+\nabla\cdot(\rho h \boldsymbol{v}) = \nabla\cdot(\lambda\nabla T)+Q$$

$$\nabla\cdot\boldsymbol{v}=0$$

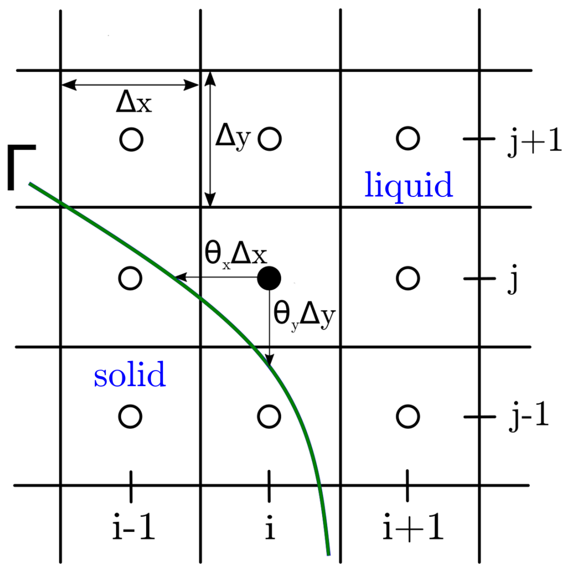
$$\frac{\partial \alpha}{\partial t}+\nabla\cdot(\alpha \boldsymbol{v})=0$$




<u>Challenge</u>: liquid-plasma flows are characterized of extremely-large difference in the material properties which make the commonly employed “one-fluid formulation approach” not adequate both from a physical and numerical point of view.

# Selected approach: impose a free-surface interface with the plasma

- Impose the “free-surface boundary condition” at the interface:
  1. continuity of the velocity normal-to-the-interface
  2. zero tangential stress
  3. pressure jump
- Impose heat/mass flux at the interface with the ghost-fluid method




$$[\mathbf{v}]_\Gamma = \mathbf{v}_1 - \mathbf{v}_2 = 0$$

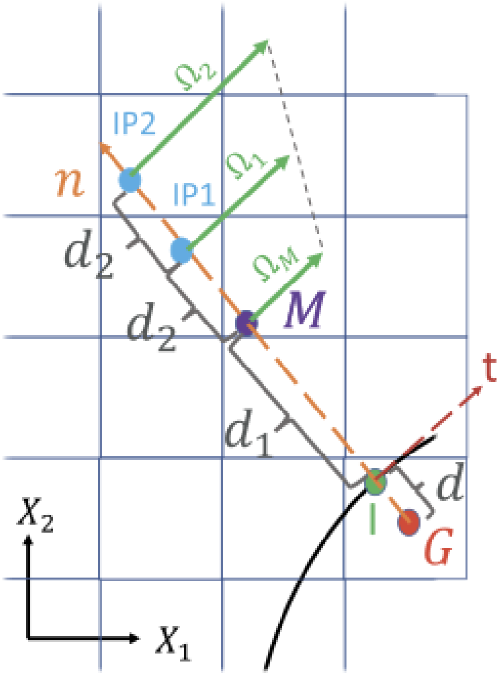
$$2\mu_l \mathbf{t} \cdot \mathbf{S} \cdot \mathbf{n}|_\Gamma = 0$$

$$p|_\Gamma = \sigma \kappa_\Gamma + 2\mu_l \left(\mathbf{n} \cdot \mathbf{S} \cdot \mathbf{n}\right)|_\Gamma$$

Scapin, N., Costa, P., & Brandt, L. (2020). A volume-of-fluid method for interface-resolved simulations of phase-changing two-fluid flows. *Journal of Computational Physics* **407** 109251.

# Selected approach: hybrid VOF-IBM

- Geometric VoF to track interface and to keep the interface within 2-3 grid cells
- Immersed Boundary method to impose the kinematic boundary conditions at the moving interface



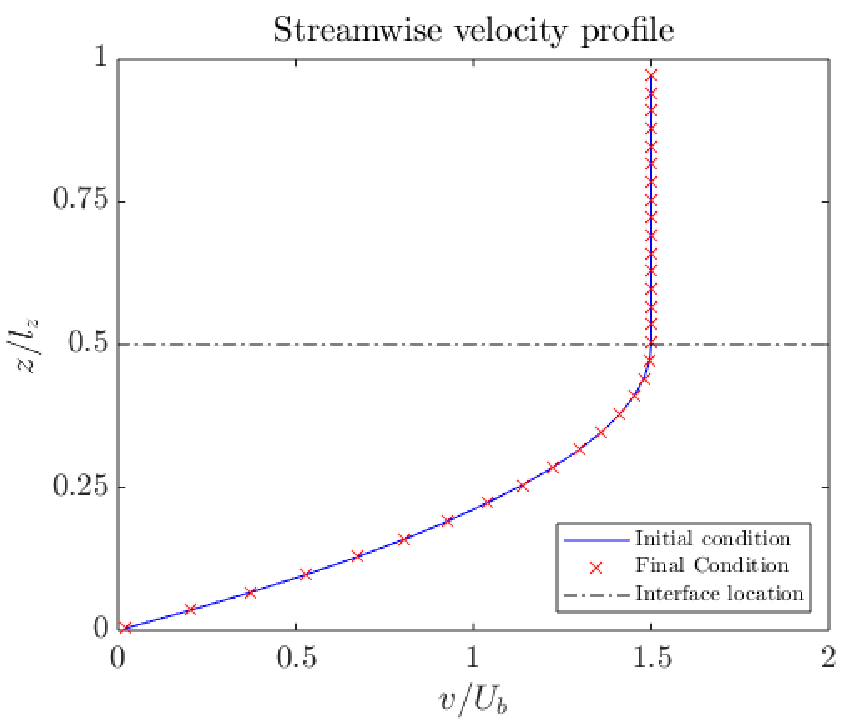

By doing so:

- The two phases are decoupled at a discrete level
- The material properties of the plasma, often difficult to predict, do not affect the fluid dynamics of the liquid metal.

Shahmardi, A., Rosti, M. E., Tammisola, O., & Brandt, L. (2021). A fully Eulerian hybrid immersed boundary-phase field model for contact line dynamics on complex geometries. *Journal of Computational Physics*, 110468.

# Preliminary validation – Test 1: flat stationary surface

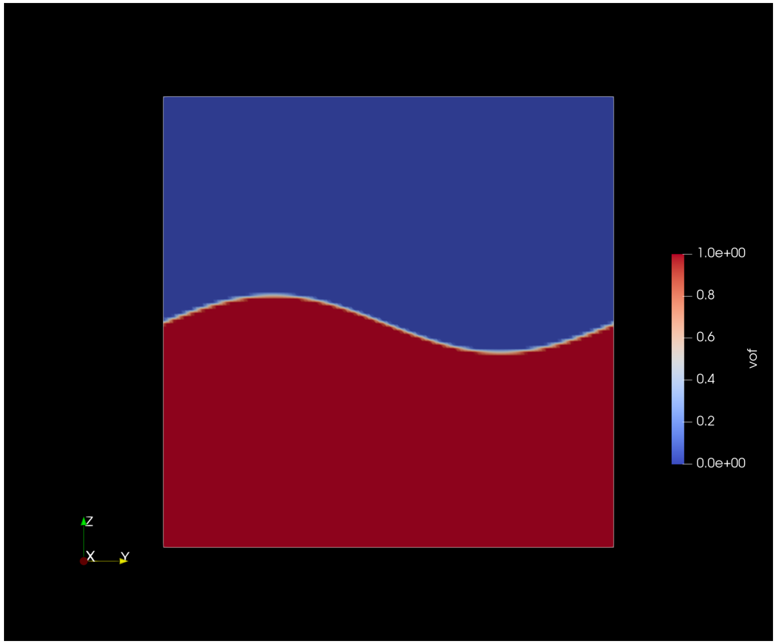
- Set-up: flat surface (at $z/l_z = 0.5$) in a 2D square box. The interface is kept fixed and the flow is kept with a prescribed mean velocity $U_b$. Wall boundary condition prescribed on the bottom ($z/l_z = 0$), free-slip on the top ($z/l_z = 1$), periodicity in the horizontal direction.

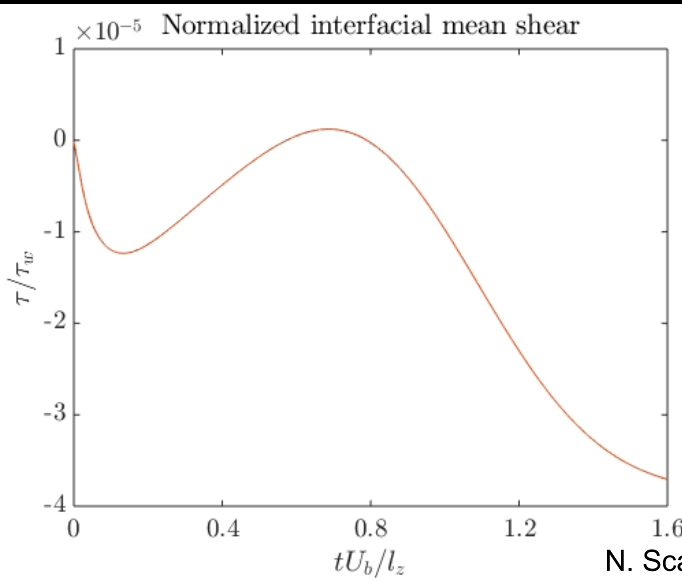



Aim: Assess the ability of the method to maintain the zero tangential boundary condition at the interface.

Outcome: as desired, the zero stress boundary condition is kept in time.

# Preliminary validation – Test 2: moving, curved interface



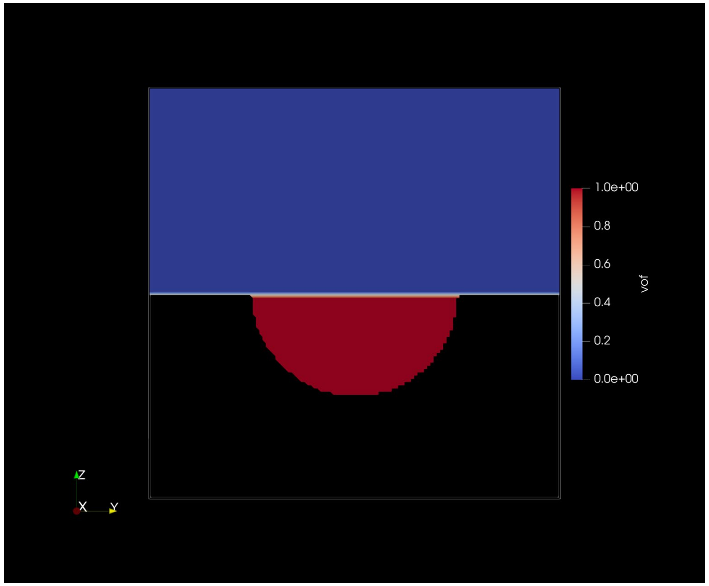



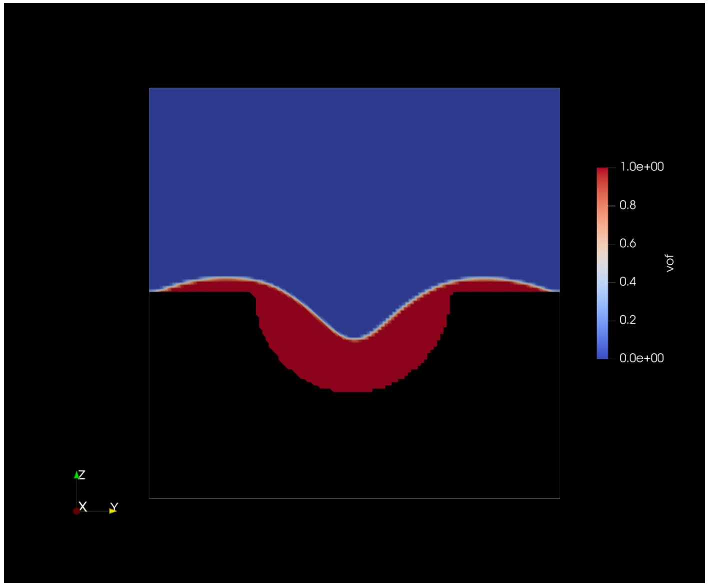

- Set-up: moving curved surface in a 2D square box. Wall boundary condition prescribed on the top, free-slip on the top, periodicity in the horizontal direction.

- Aim: assess the ability of the method to maintain the zero tangential boundary condition at the interface when this one moves.

- Outcome: as desired, the mean tangential stress at the interface is kept relatively small compared to the wall shear stress at the bottom wall.

# Preliminary validation – Test 3: Pressure driven liquid pool (on-going)




- Set-up: hemisphere of full of liquid. Wall boundary conditions at the top, zero-pressure outflow in the horizontal one, external pressure jump imposed at the interface.
- Aim: assess the ability of the method to correctly impose a zero-stress boundary condition at the interface in a more complex case.
- Outcome: the tangential interface stress remains small (0.1% of the wall stress).

# Conclusions and outlook

- The code development phase in well underway
- The imposition of free-surface boundary conditions has been tested in several benchmark cases

**Next steps**

- Implement heat transfer modelling and the associated boundary conditions
- Carry out new tests using more complex and realistic geometries