Around-Casting Simulations with OpenFOAM: Verification and Application of Models

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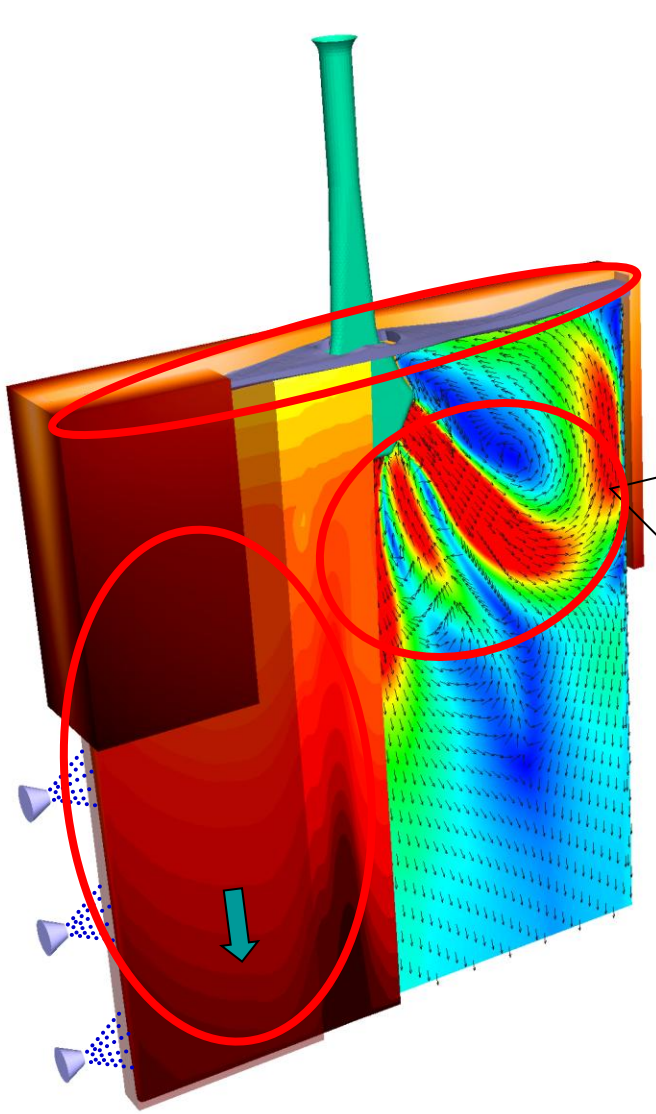
RHI: G. Nitzl, Y. Tang, G. Hackl

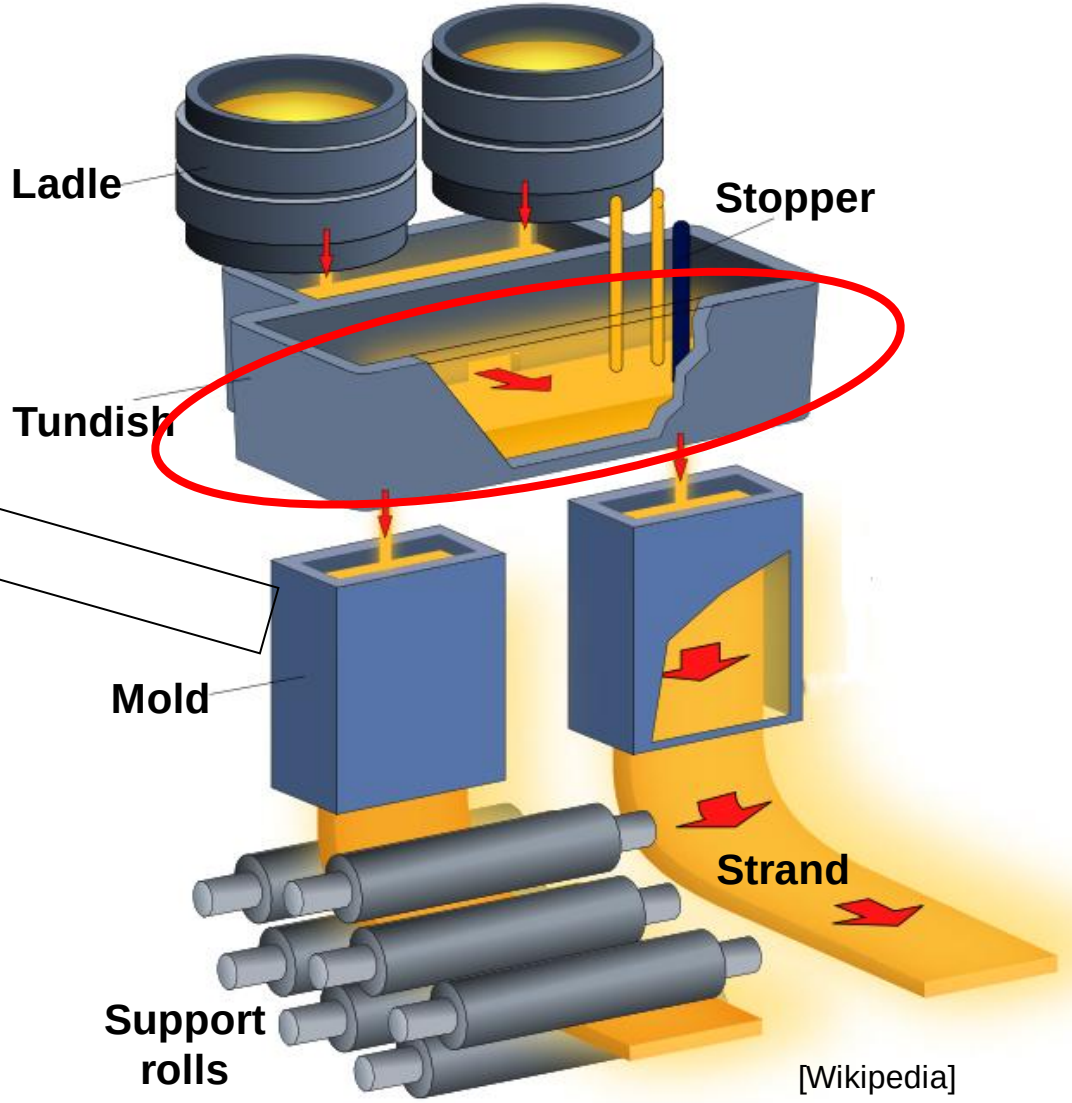
29.06.2016 | Centro Cultural Vila Flor | S4

Outline

- **Motivation** √
- **Verifying solidification model**
- **Free surface simulation**
- **Lagrangian particle tracking**
- **Turbulence & meshing**
- **Conclusions**

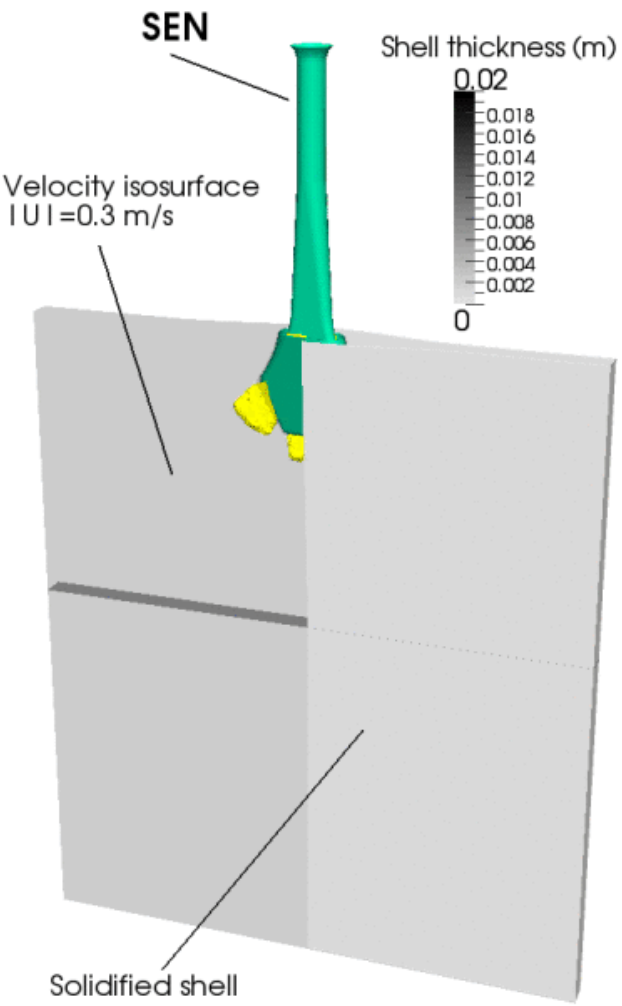
Processes to simulate: continuous casting



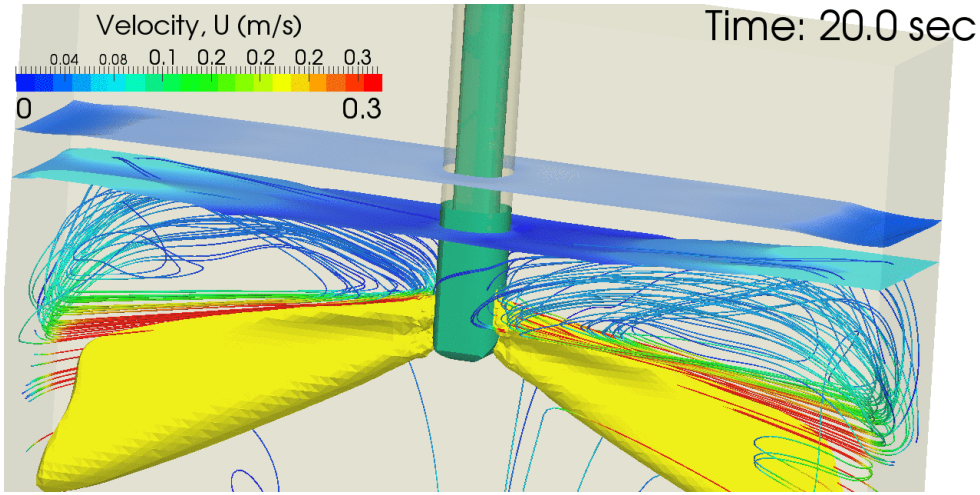


[Wikipedia]

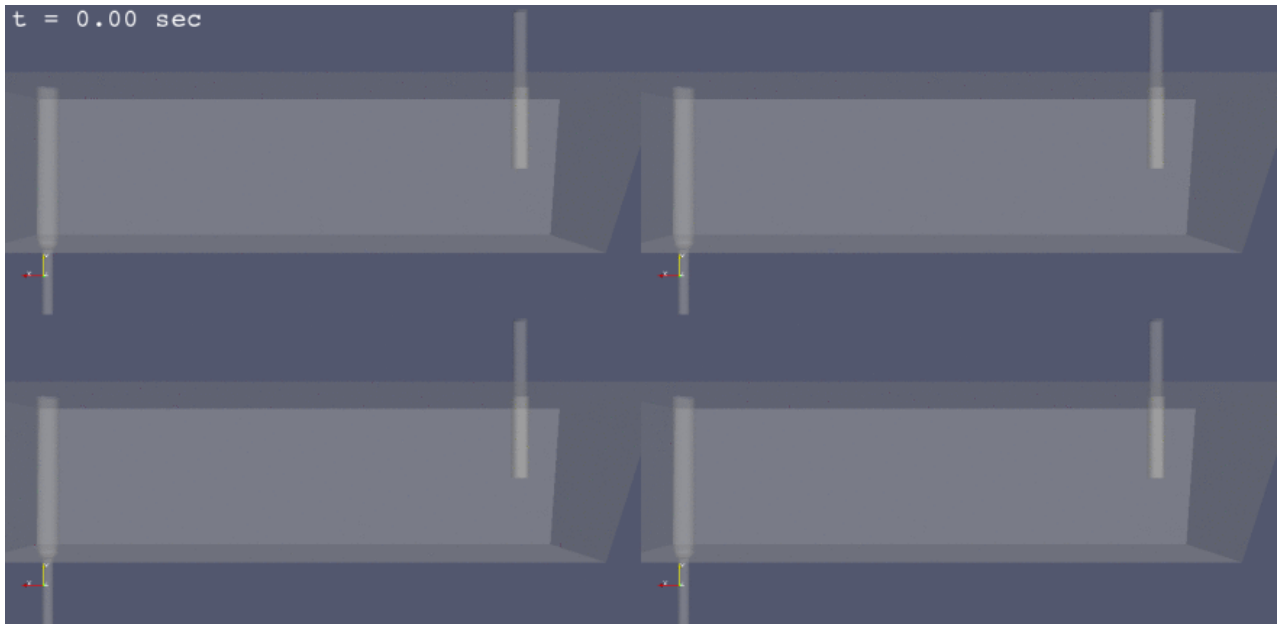
#4 Multiphase processes a continuous casting



Solidification simulation



Free surface modelling



Lagrangian particles simulation (50 ~ 600 μm)

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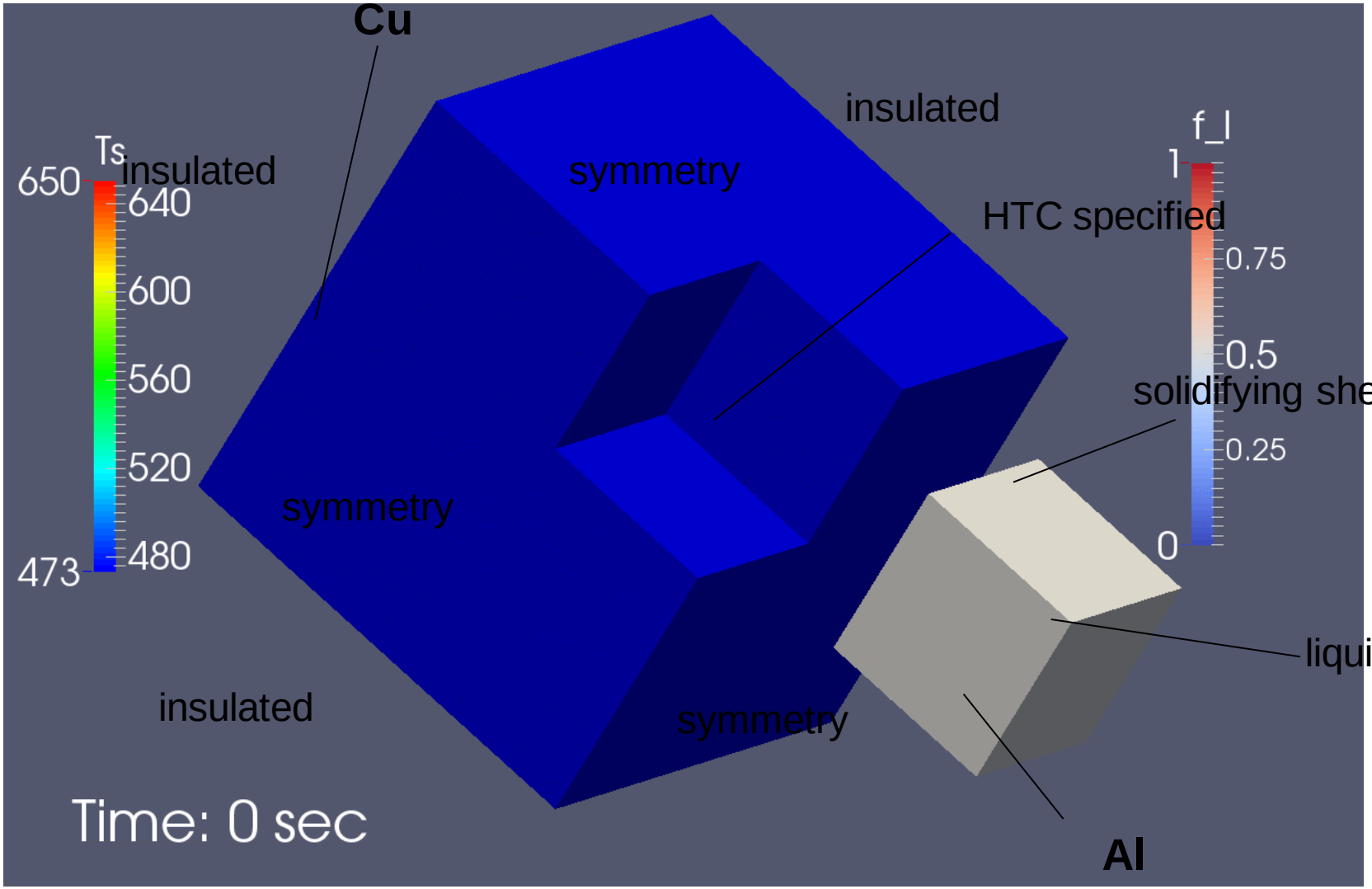
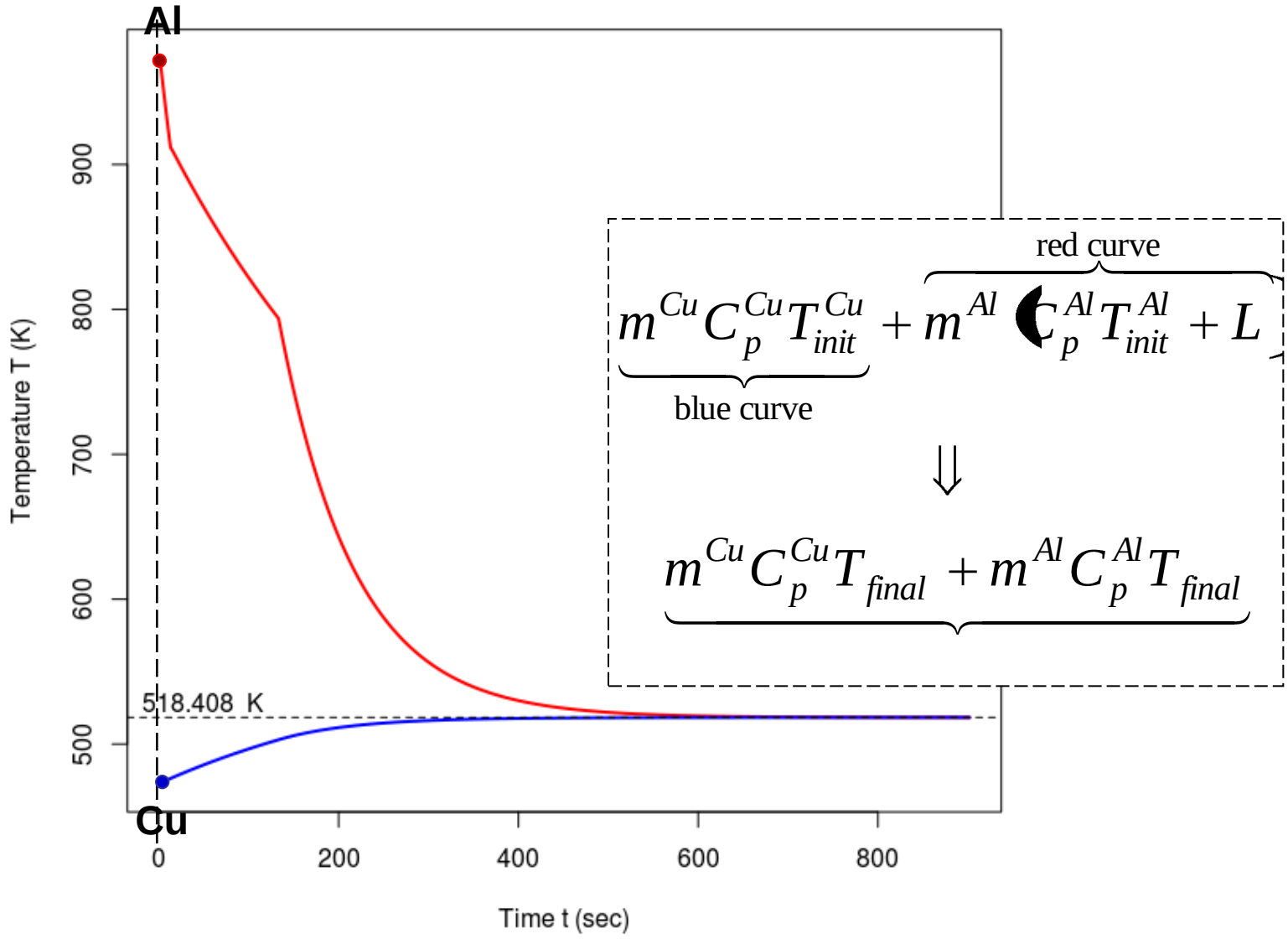
ÖGI solidification benchmark



ÖGI solidification benchmark



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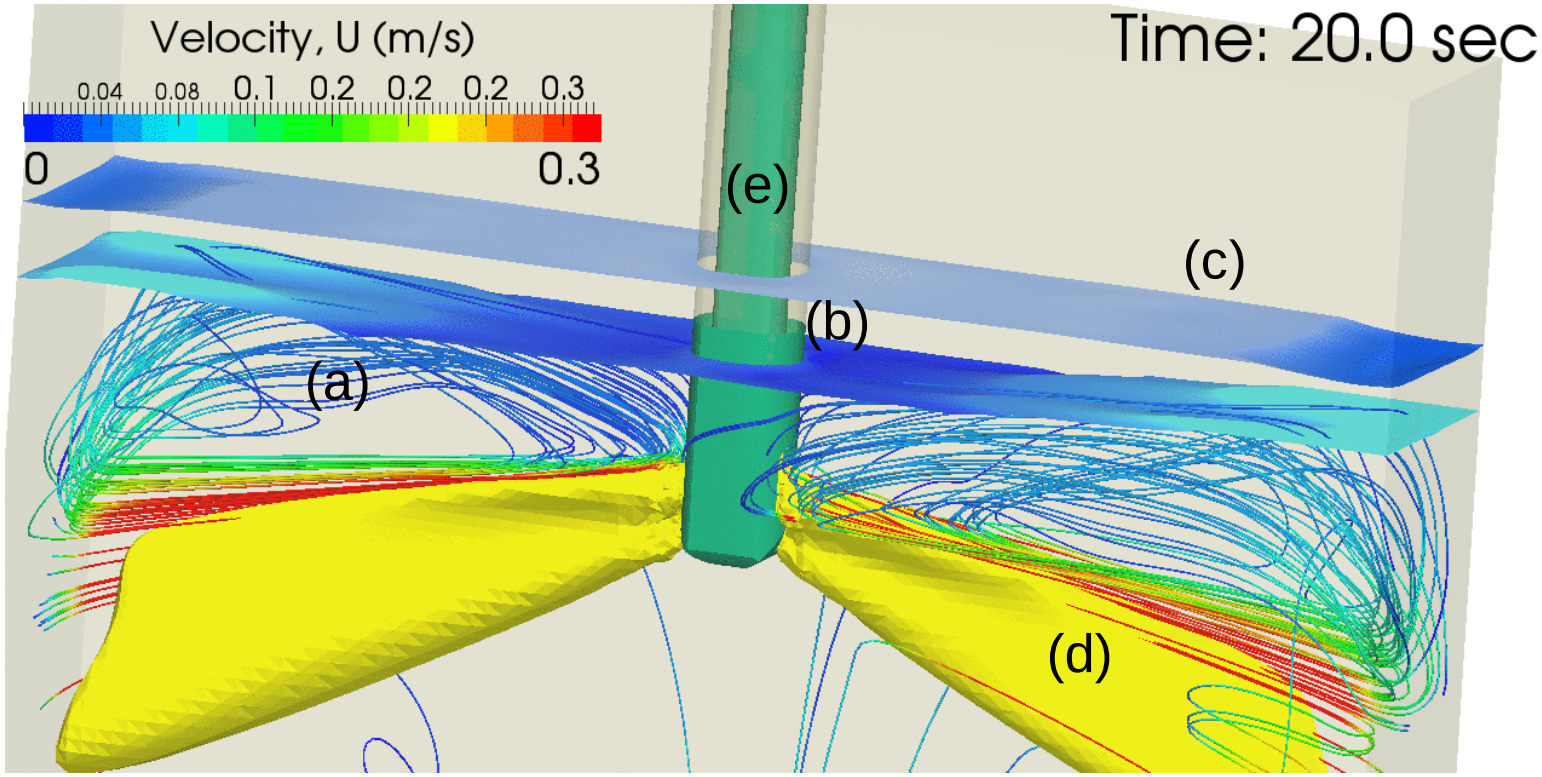
Motivation: focus on the SEN region



(a) mechanisms of slag entrapment

(b) SEN refractory erosion kinetics

(c) free surface oscillation/waves

(d) patterns of turbulent jet flow

(e) sensitivity of all phenomena to SEN design

Modifying numerical model equations

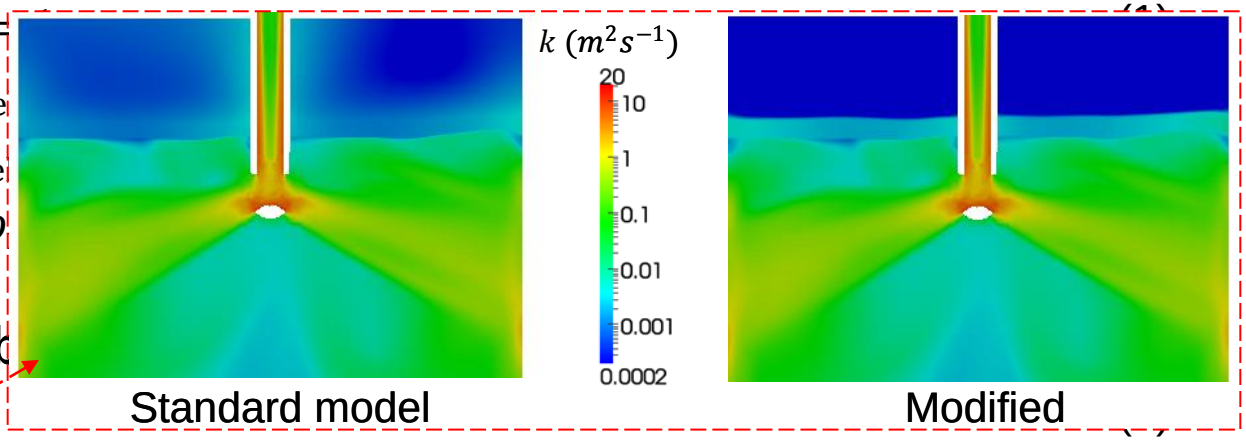
Mixture properties:

$$\alpha_{\text{melt}} + \alpha_{\text{slag}} + \alpha_{\text{air}} =$$

$$\rho_{\text{mixture}} = \alpha_{\text{melt}} \cdot \rho_{\text{me}}$$

$$\mu_{\text{mixture}} = \alpha_{\text{melt}} \cdot \rho_{\text{me}}$$

$$\eta_{\text{mixture}} = \mu_{\text{mixture}} / \rho$$



Incompressible turb

$$\nabla \cdot \vec{u} = 0$$

$$\frac{\partial \rho \vec{u}}{\partial t} + \nabla \cdot (\rho \vec{u} \otimes \vec{u}) = -\nabla p + \nabla \cdot (2\mu_{\text{eff}} \mathbf{D}) + \rho \vec{g} + \vec{S}_{\text{surf}} \quad (6)$$

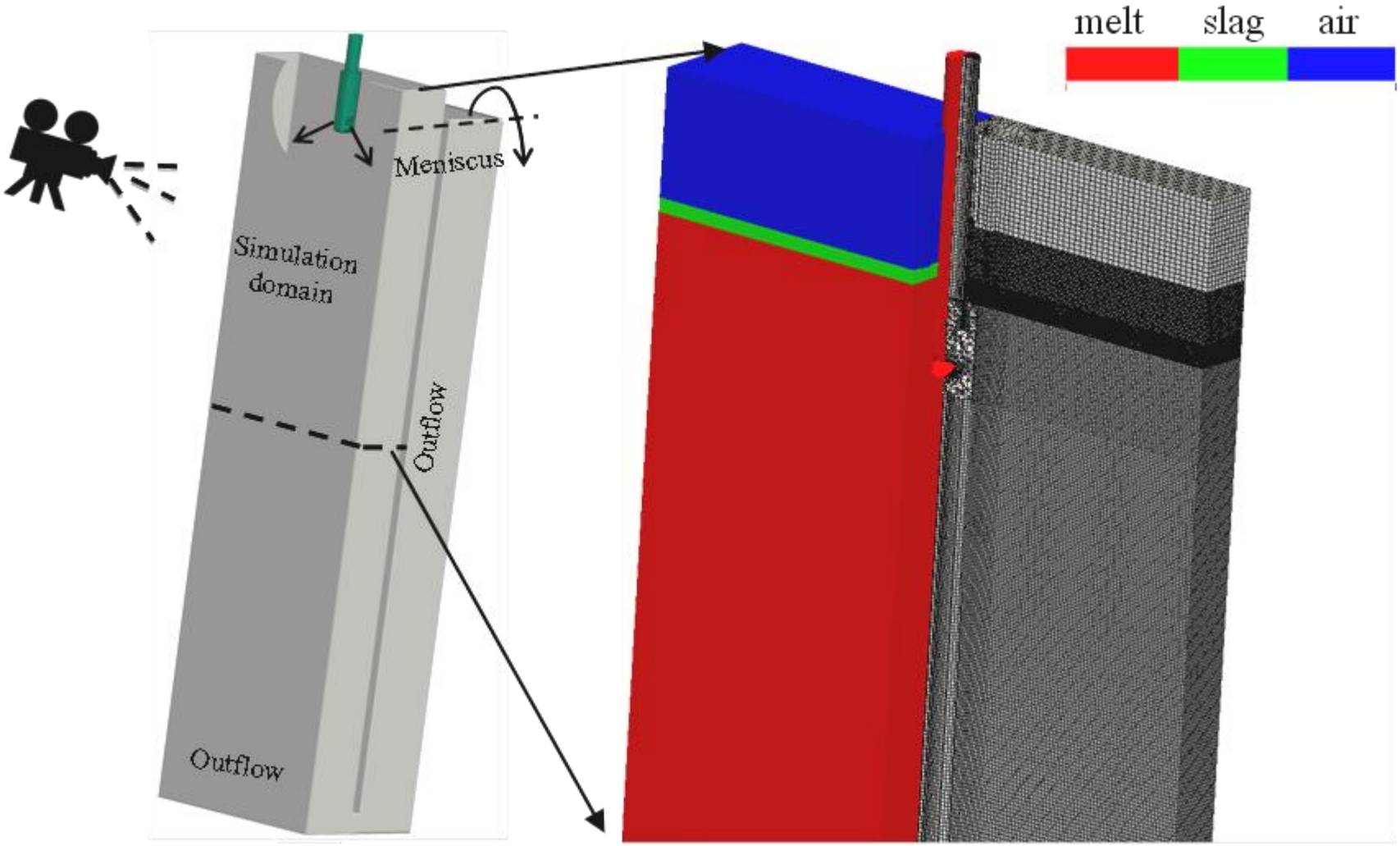
$$\vec{S}_{\text{surf}} = \sum_{i,j} \sigma_{ij} \kappa_{ij} \left(\alpha_j \nabla \alpha_i - \alpha_i \nabla \alpha_j\right) \quad \text{where} \quad \kappa_{ij} = -\nabla \cdot \frac{\left(\alpha_j \nabla \alpha_i - \alpha_i \nabla \alpha_j\right)}{\left|\alpha_j \nabla \alpha_i - \alpha_i \nabla \alpha_j\right|} \quad (7)$$

$$\frac{\partial \rho k}{\partial t} + \nabla \cdot (\rho \vec{u} k) = \nabla \cdot \left(\left(\mu + \frac{\mu_{\text{t}}}{Pr_{\text{t,k}}} \nabla k\right)\right) + G - \rho \epsilon \quad (8)$$

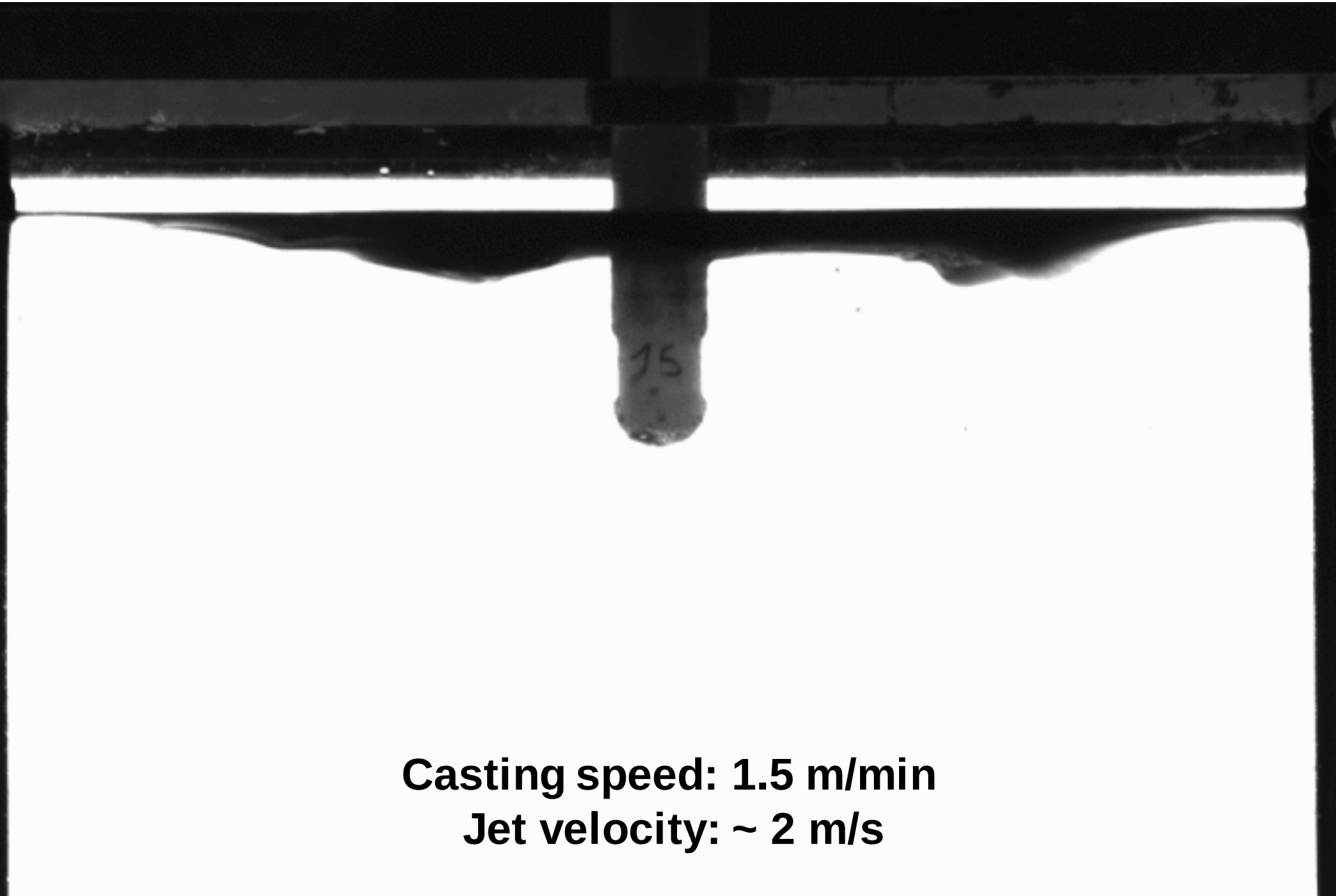
$$\frac{\partial \rho \epsilon}{\partial t} + \nabla \cdot (\rho \vec{u} \epsilon) = \nabla \cdot \left(\left(\mu + \frac{\mu_{\text{t}}}{Pr_{\text{t},\epsilon}} \nabla \epsilon\right)\right) + \rho C_{1\epsilon} \epsilon - C_{2\epsilon} \rho \frac{\epsilon^2}{\sqrt{Sk}} \quad (9)$$

Scalar transport of volume fraction: $\frac{\partial \alpha_i}{\partial t} + \nabla \cdot (\vec{u} \alpha_i) = 0$ (10)

Experimental setup and simulation domain



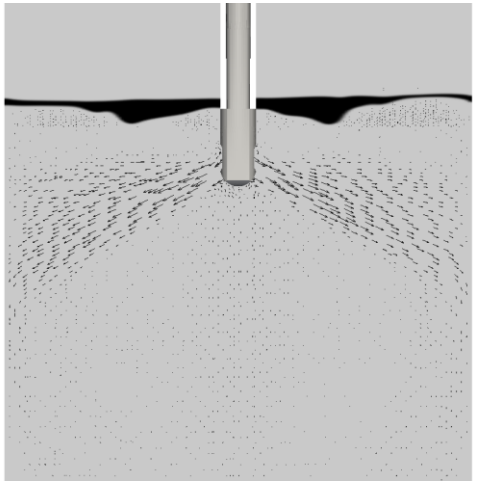
Water modelling results



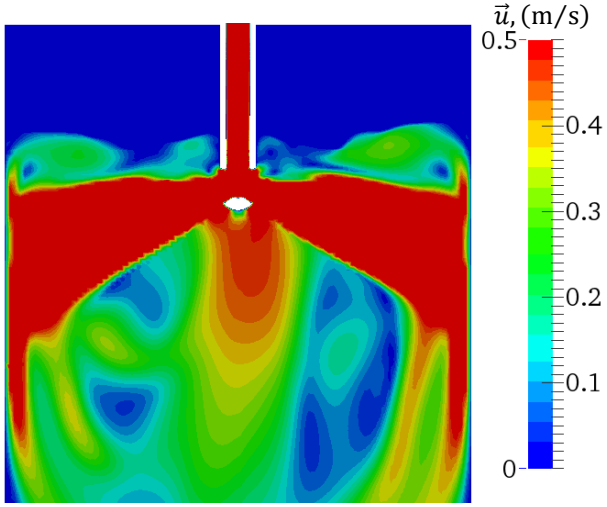
Casting speed: 1.5 m/min
Jet velocity: ~ 2 m/s

Simulation results / comparison with experiment

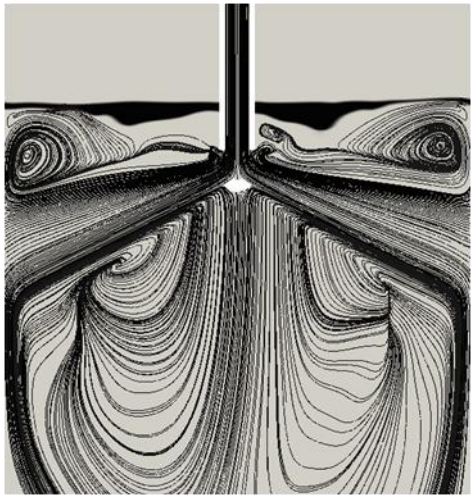
Flow simulation:



Slag position / velocity vectors

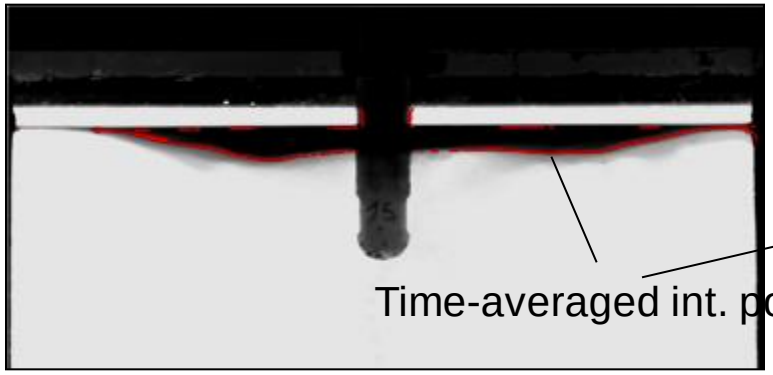


Velocity magnitude



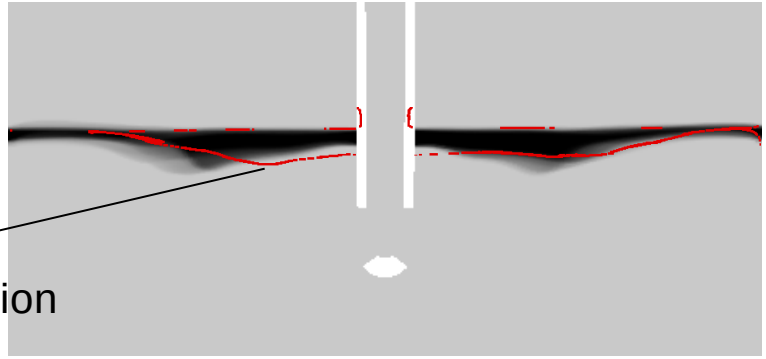
Stream-lines

Comparison with the water modelling results:



Time-averaged int. position

Experiment



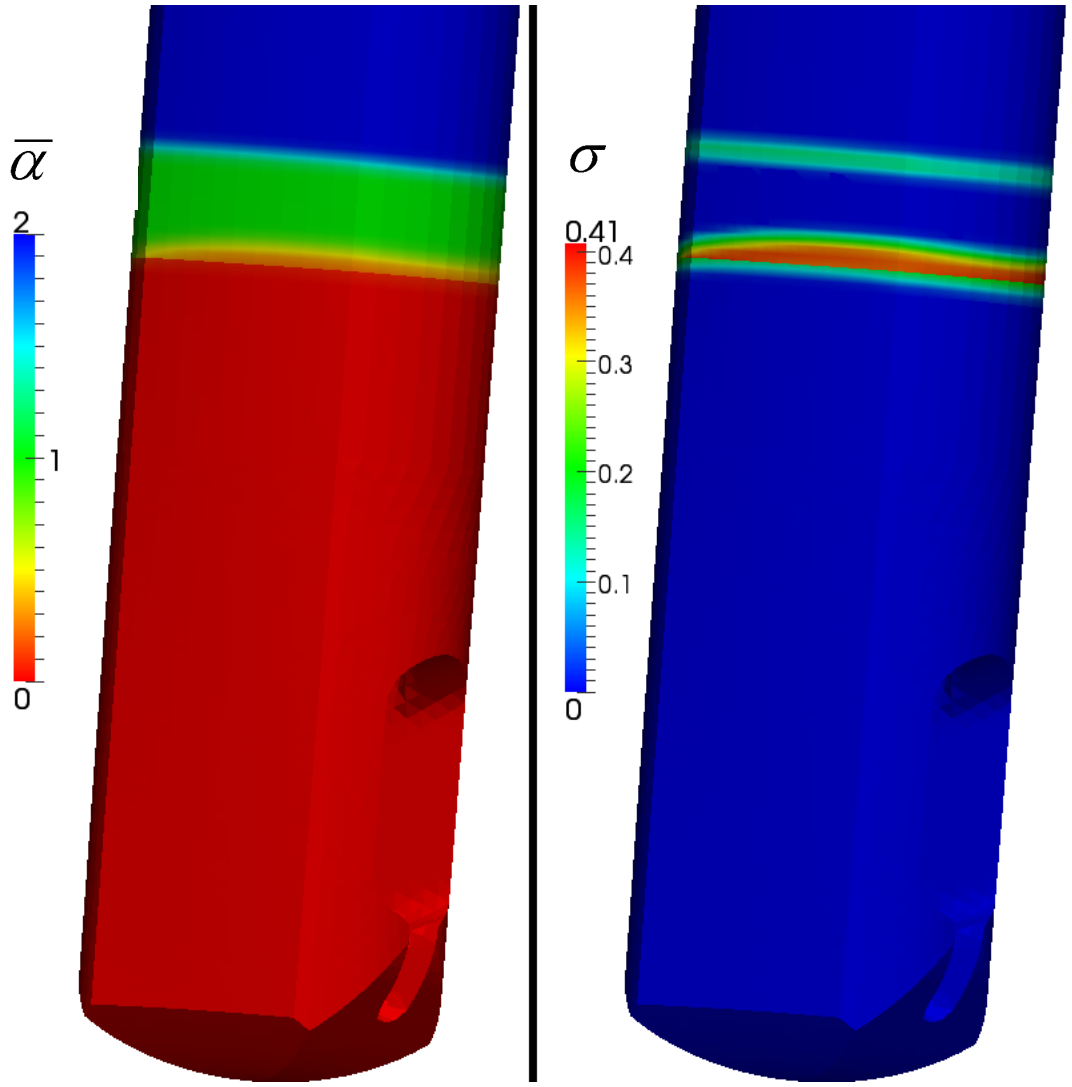
Simulation

Application: SEN erosion kinetics

Air

Slag

Melt



Areas with the most change in phase contacting SEN

$$\overline{\alpha} = \frac{1}{N}\sum_{t=t_1}^{t_N}\alpha_t$$

$$\sigma = \sqrt{\frac{1}{N}\sum_{t=t_1}^{t_N}\left(\alpha_t - \overline{\alpha}\right)^2}$$

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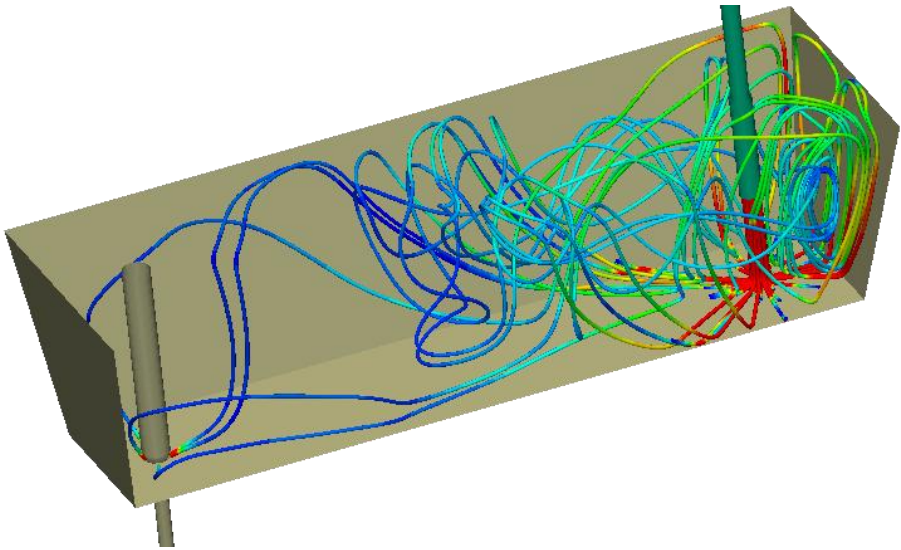
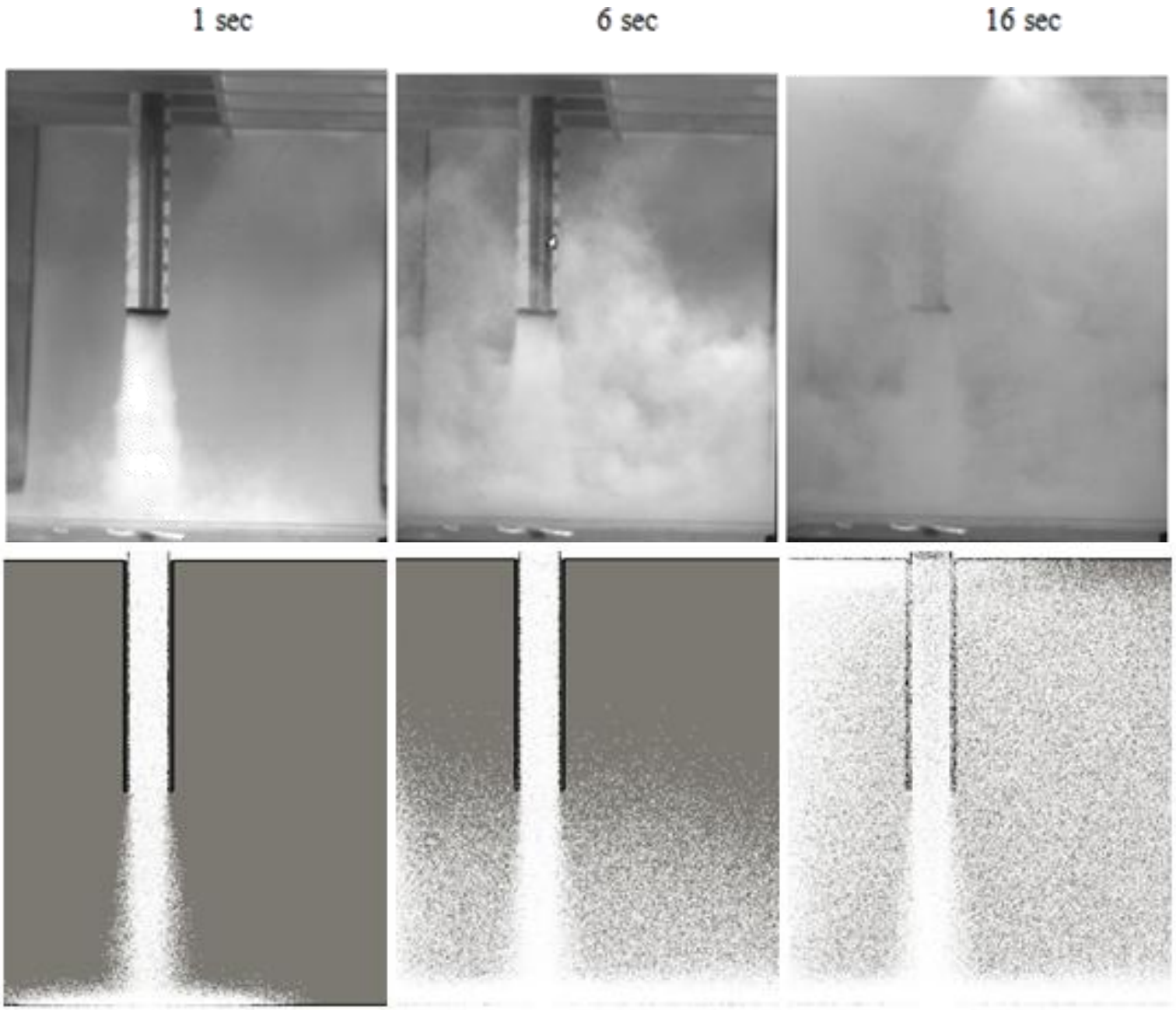
Water Modelling: voestalpine Stahl lab (Linz)



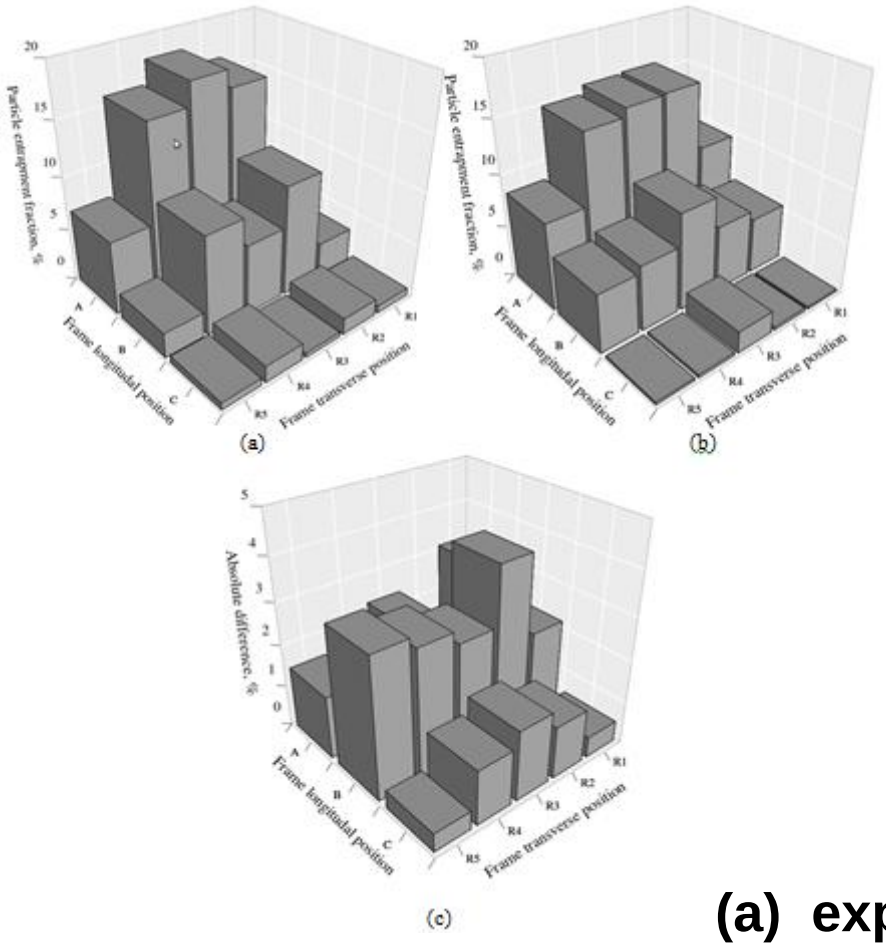
One strand slab casting tundish

Experiment vs simulation: first look

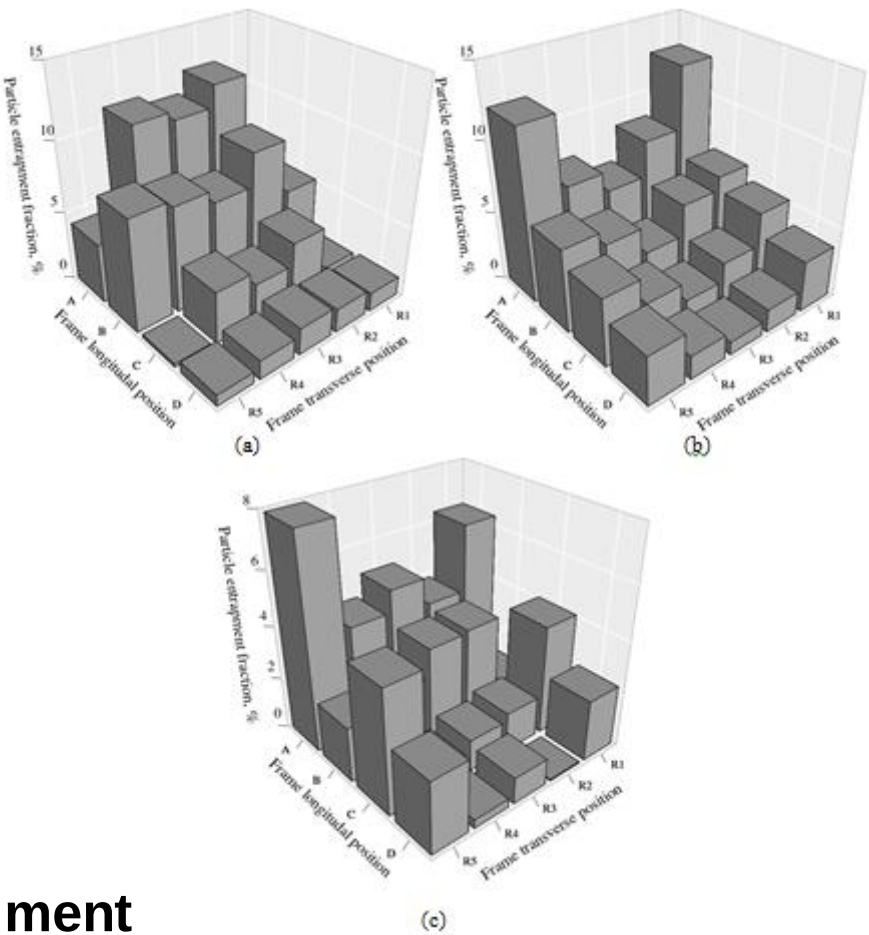


Experiment vs simulation: in details

D_p = 3.5 mm



D_p = 0.285 mm



(a) experiment

(b) simulation

(c) error

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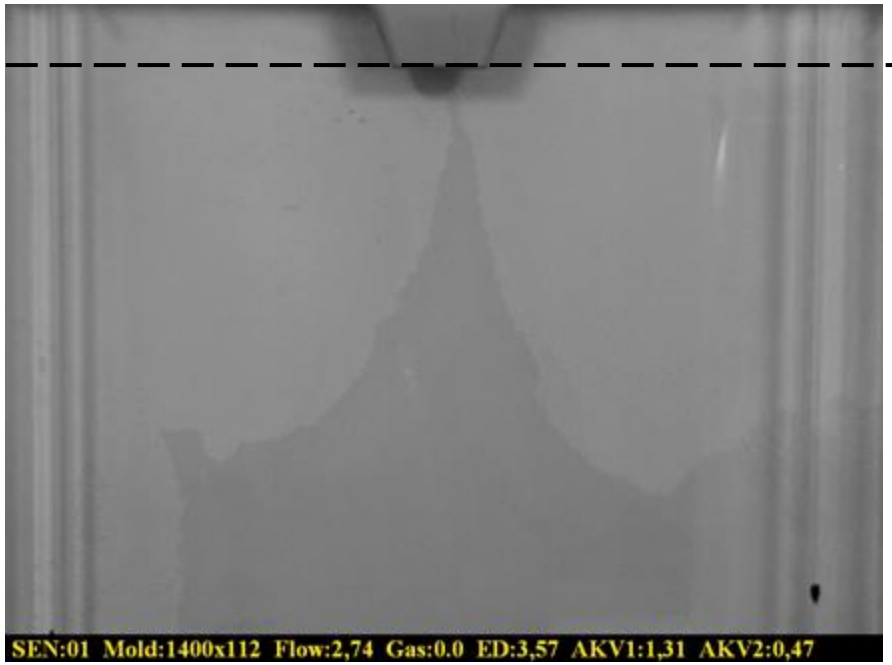
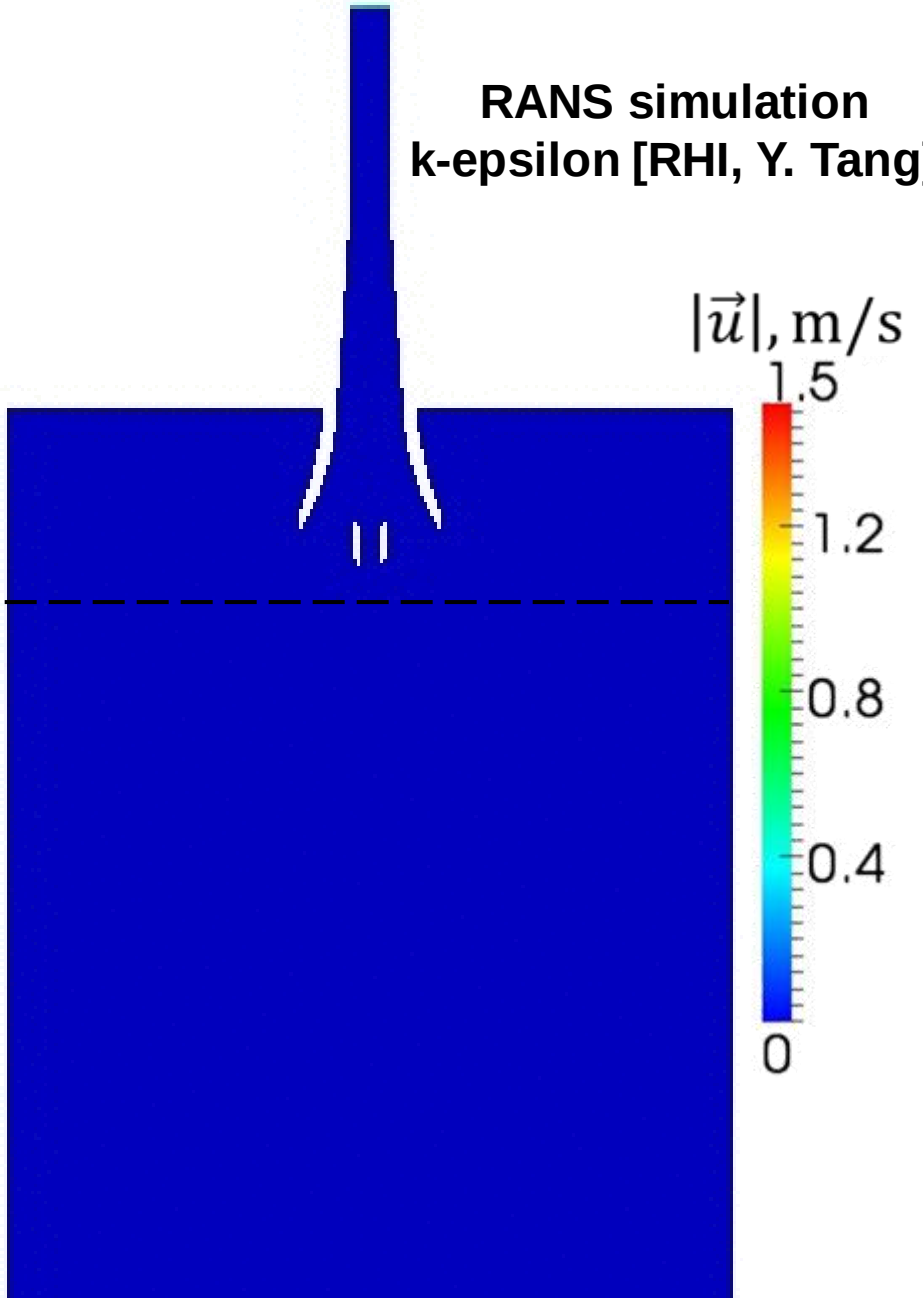
Motivation: experiment vs RANS simulation

For very special SEN designs!

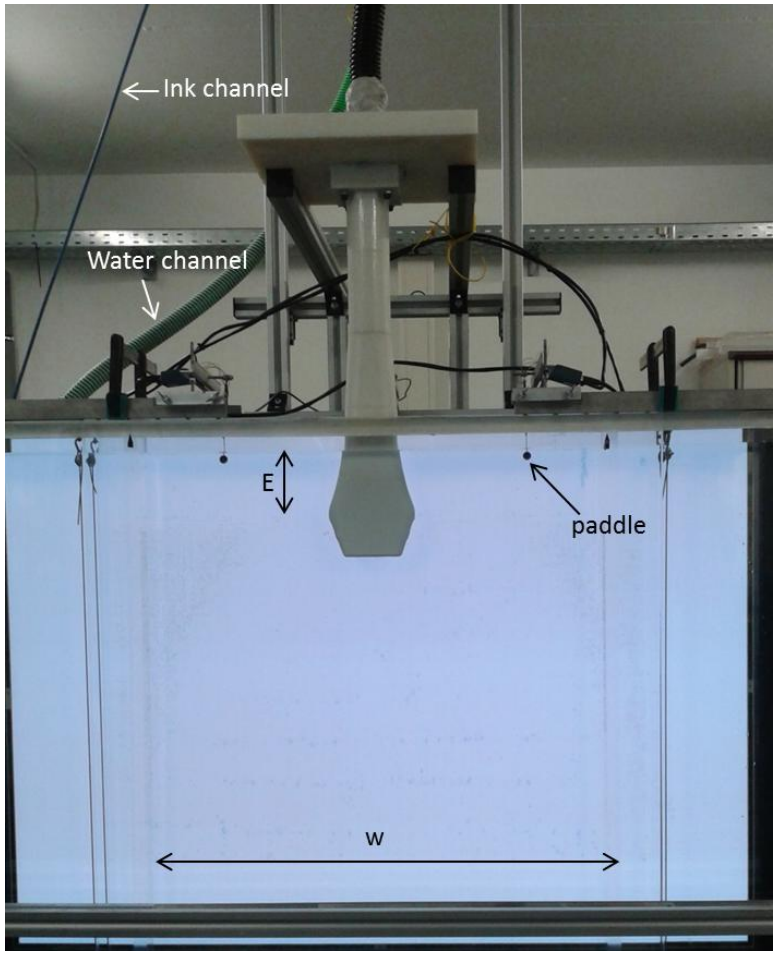


water experiment

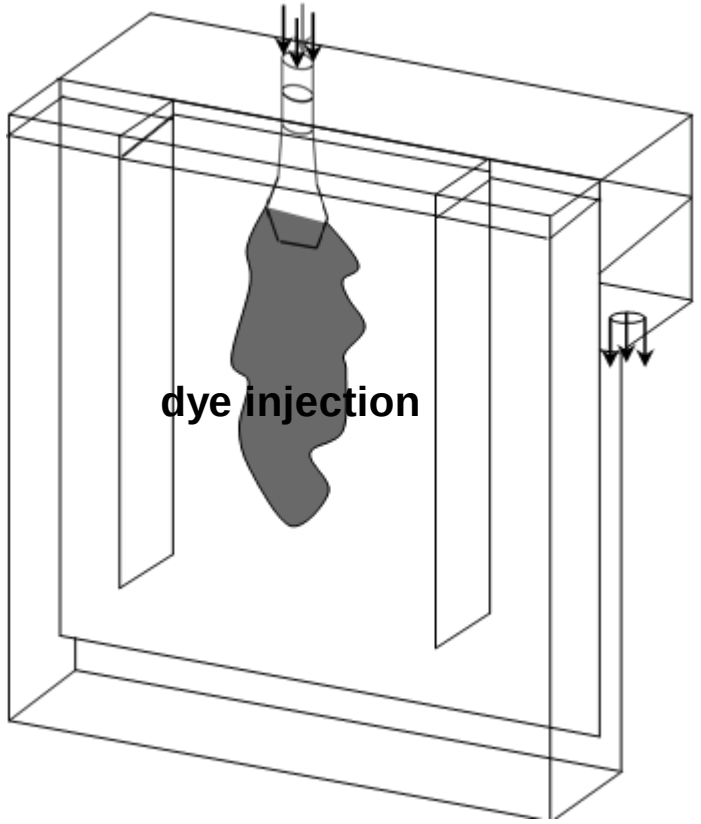
RANS simulation
k-epsilon [RHI, Y. Tang]



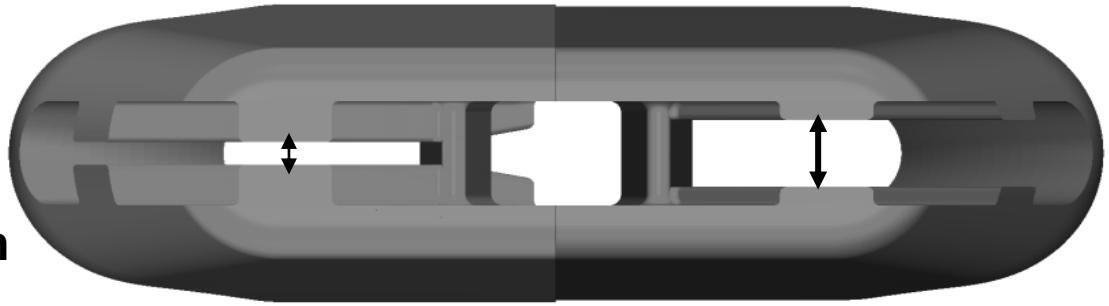
Water model experiment setup



front view of the setup



sketch of the mold and SEN



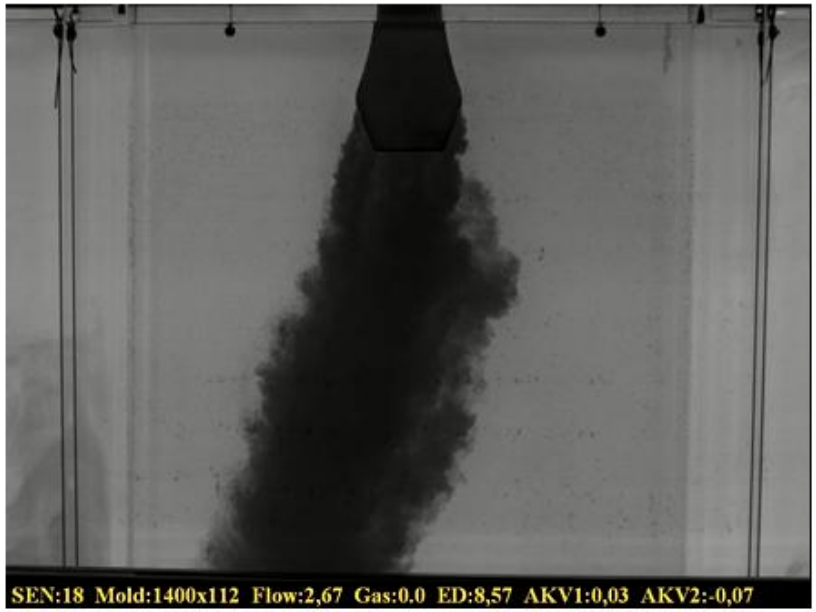
SEN gap variation

#22

Comparison of the different gap size SENs

small

middle

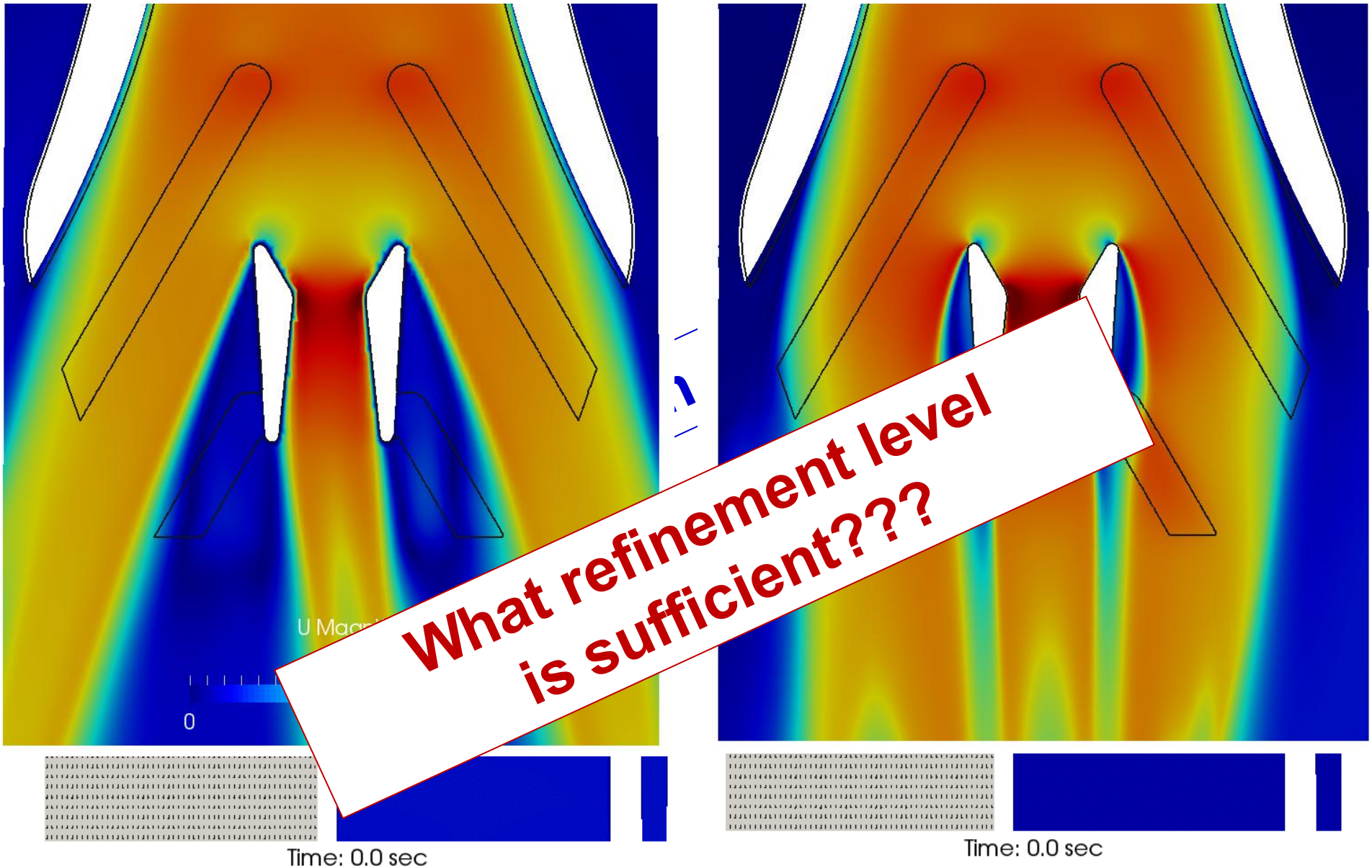


big

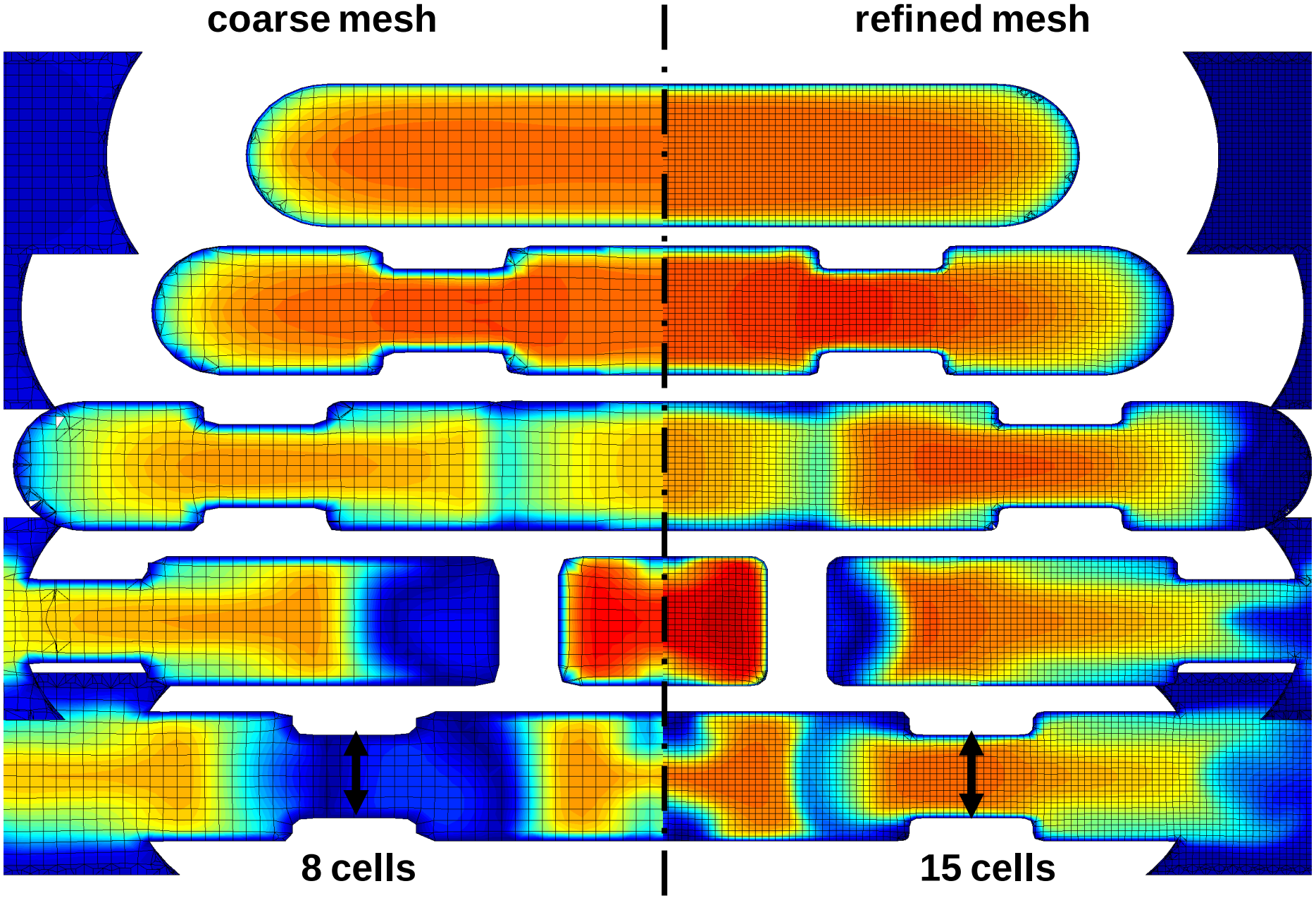
Simulation results: coarse vs. fine grid

coarse mesh, 800K cells, dt=0.01 sec

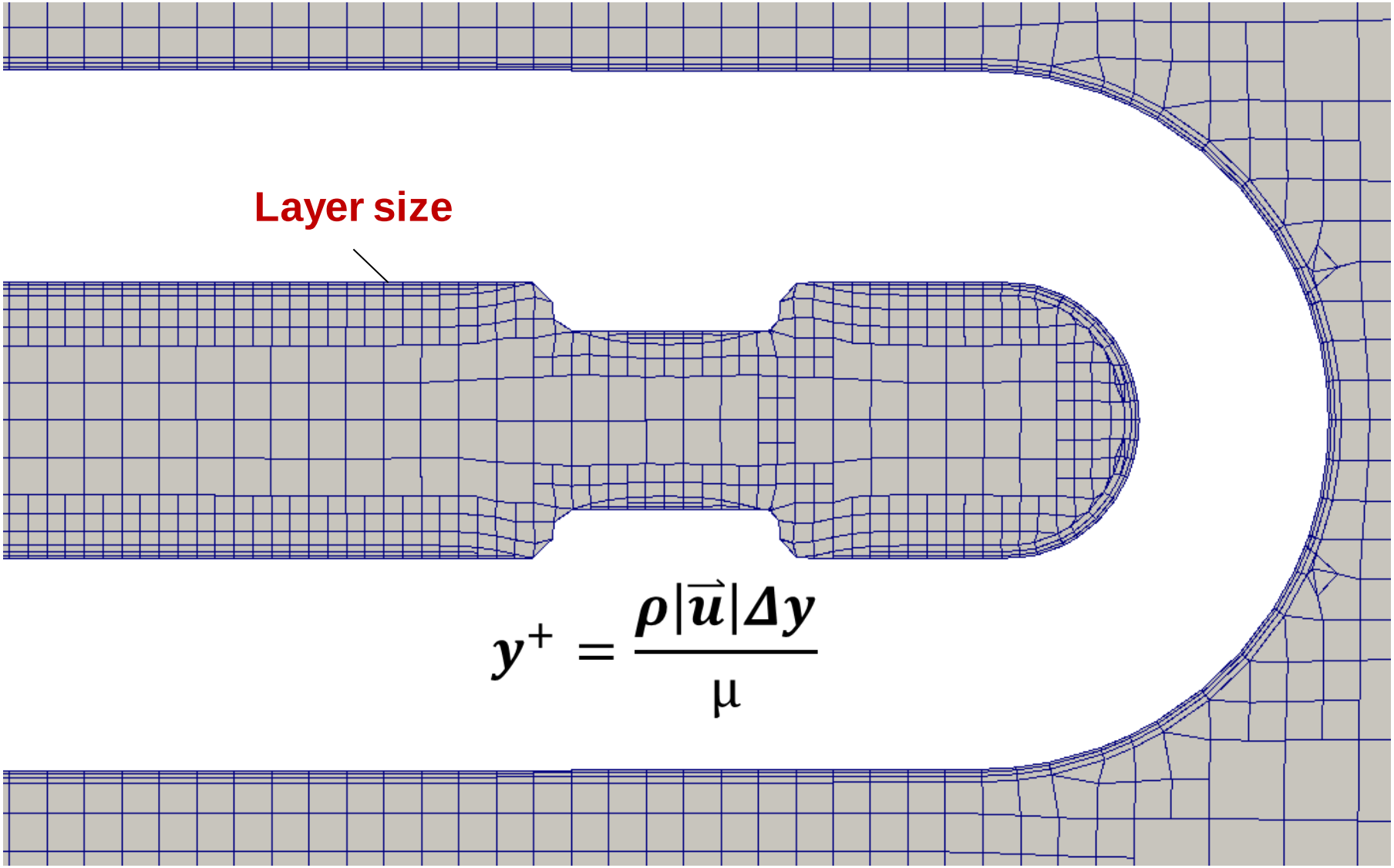
refined mesh, 6M cells, dt=0.0005



Mesh resolution

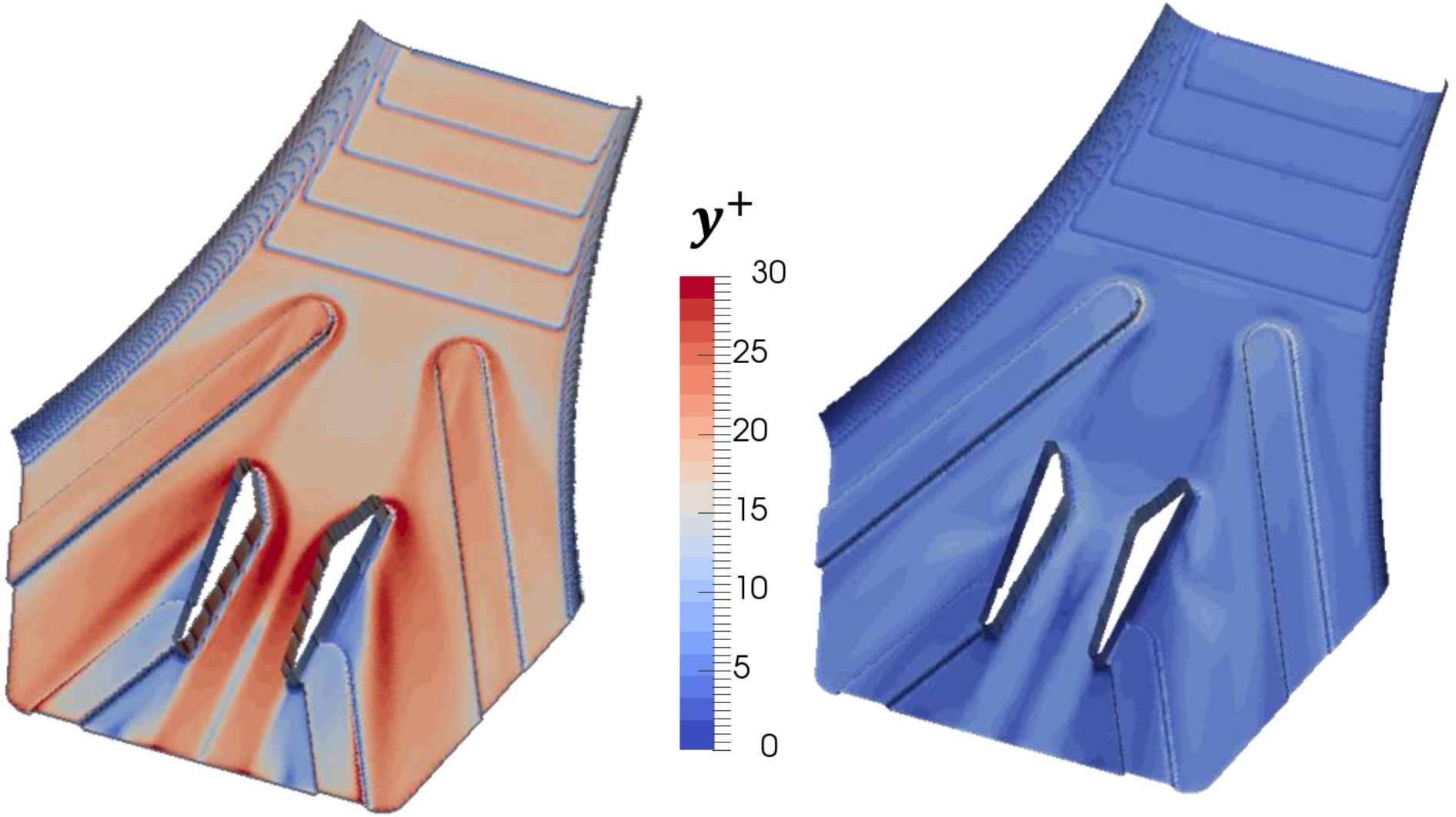


y+ wall criterion (< 30): mesh layers



$$y^+ = \frac{\rho |\vec{u}| \Delta y}{\mu}$$

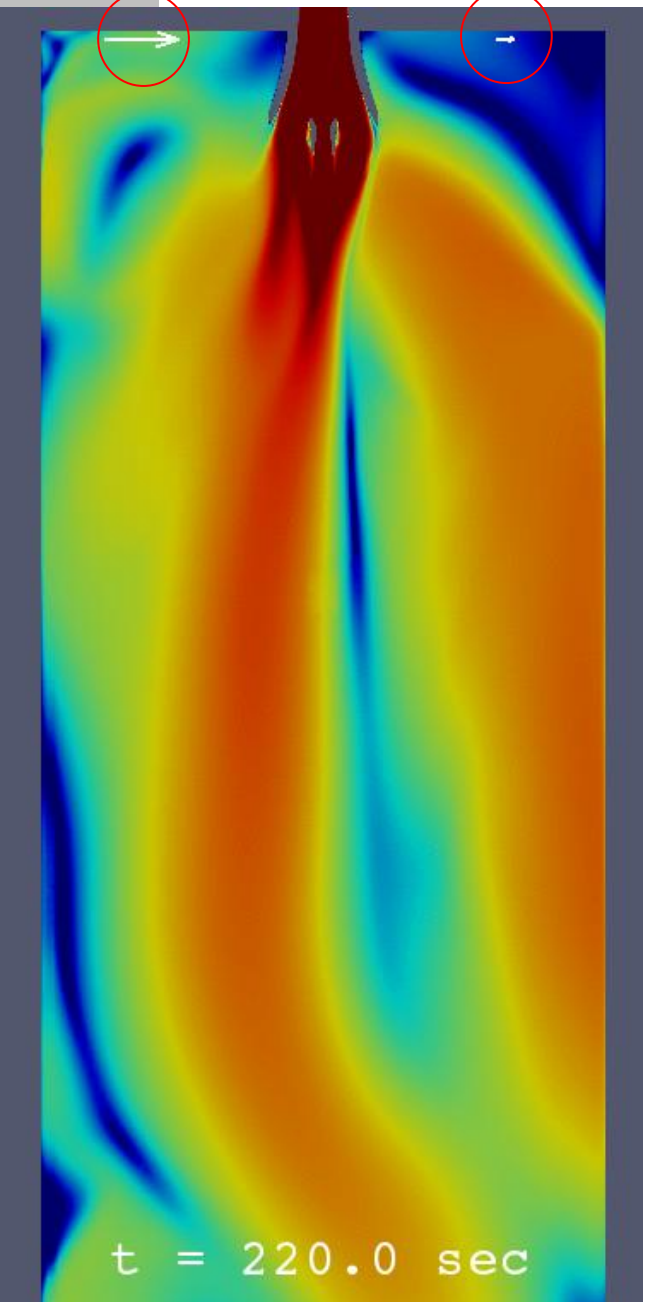
Mesh refinement: no layers vs. fine layers

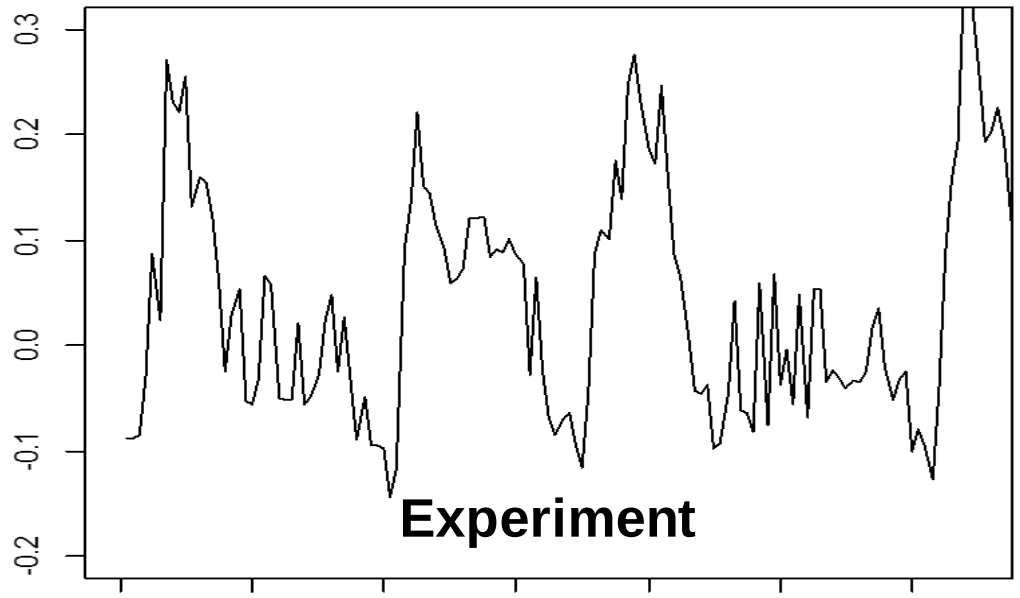


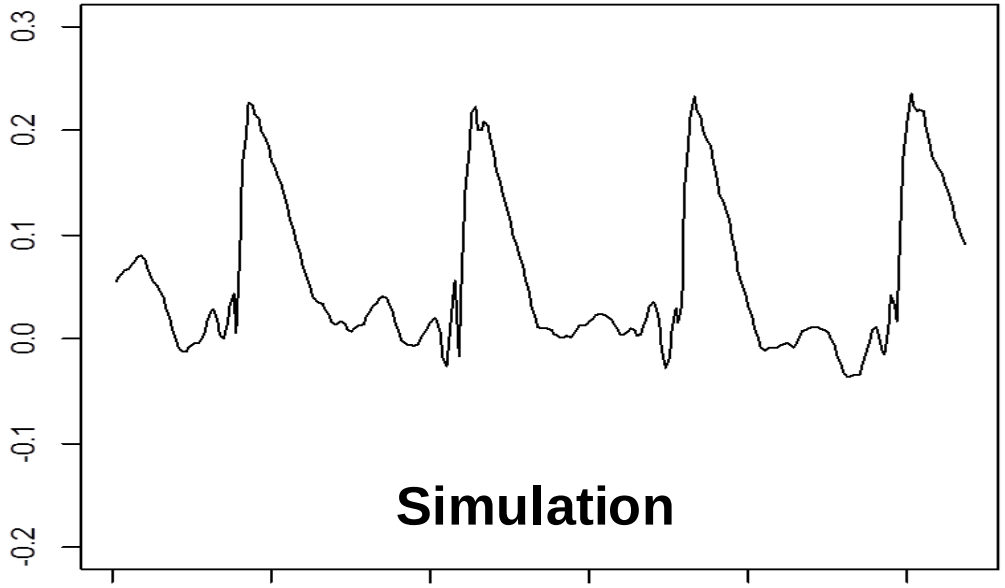
Coarse grid

Fine boundary layer

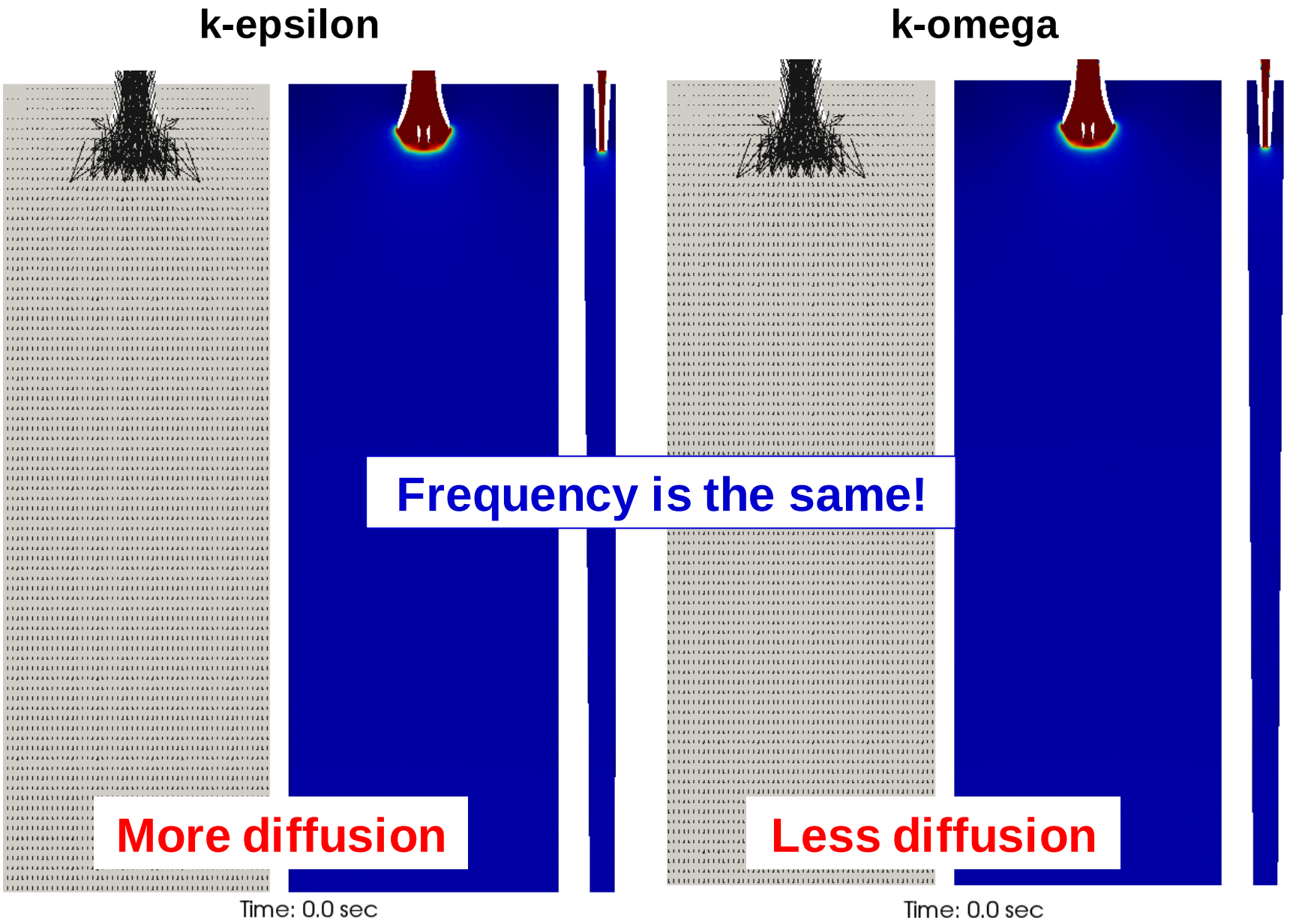
Sub-menicsus velocity probes



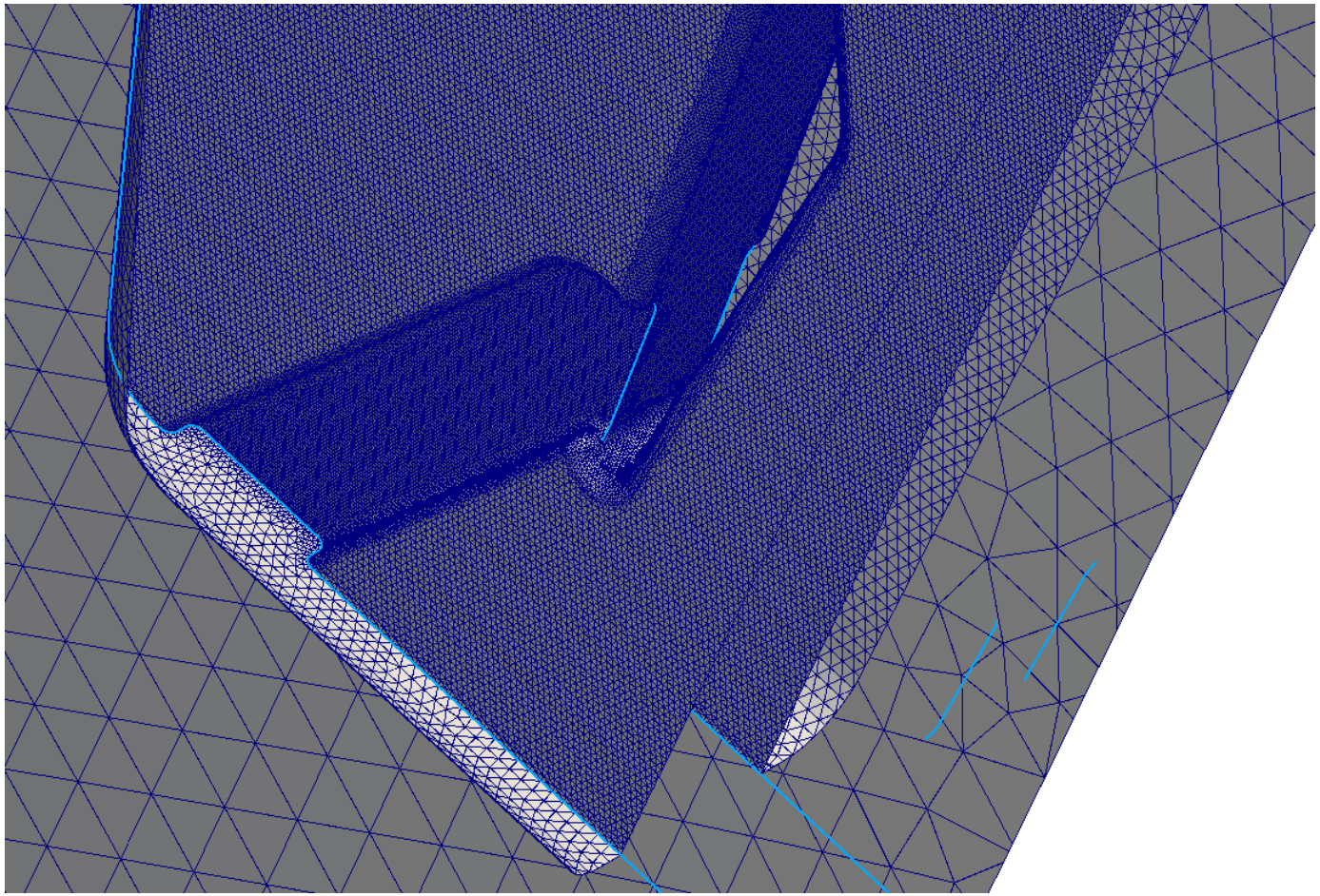




#28 Different turbulence models on the fine mesh



Advanced meshing technique



C A D → S A L O M E → snappyHexMesh

C A D → snappyHexMesh → refineMesh

THANK YOU FOR YOUR ATTENTION!

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