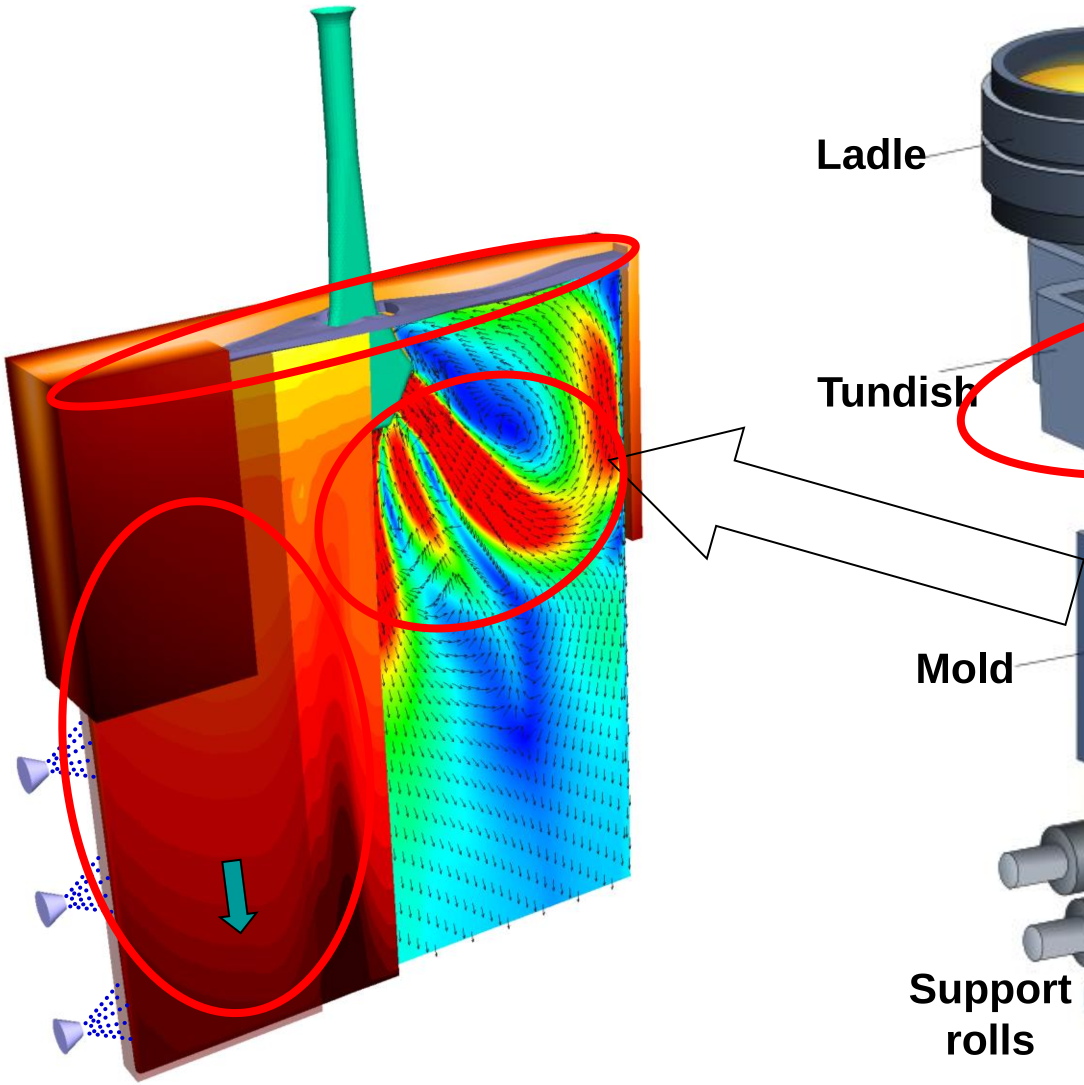
"Current results of the solidification modelling in continuous casting"

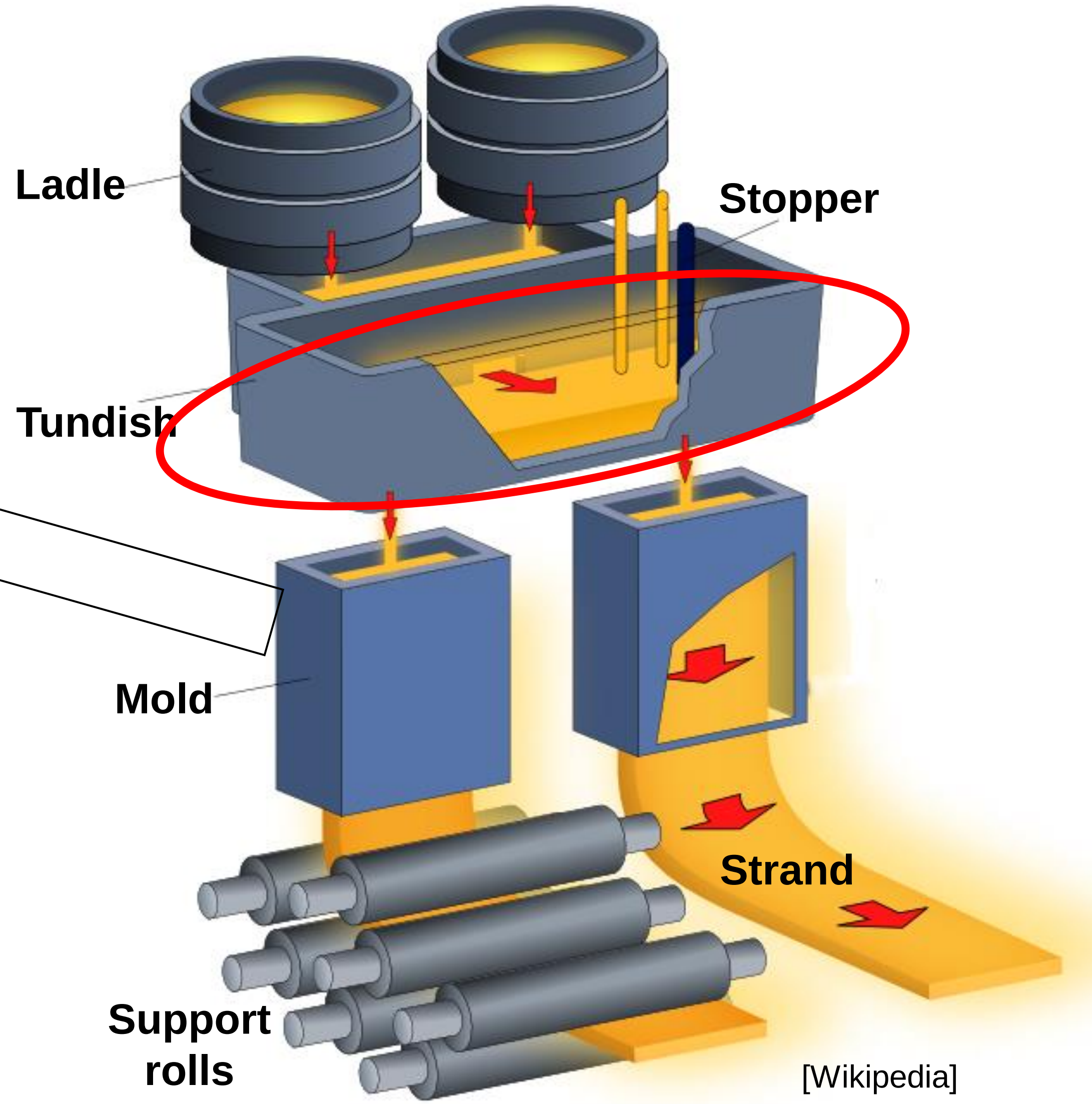
Dr. Alexander Vakhrushev

OUTLINE

- Introduction
- Modelling of casting process
- Inclusions modelling
- Liquid slag model verification
- Heat transfer through the refractory
- Conclusions & outlook

Processes to simulate: continuous casting



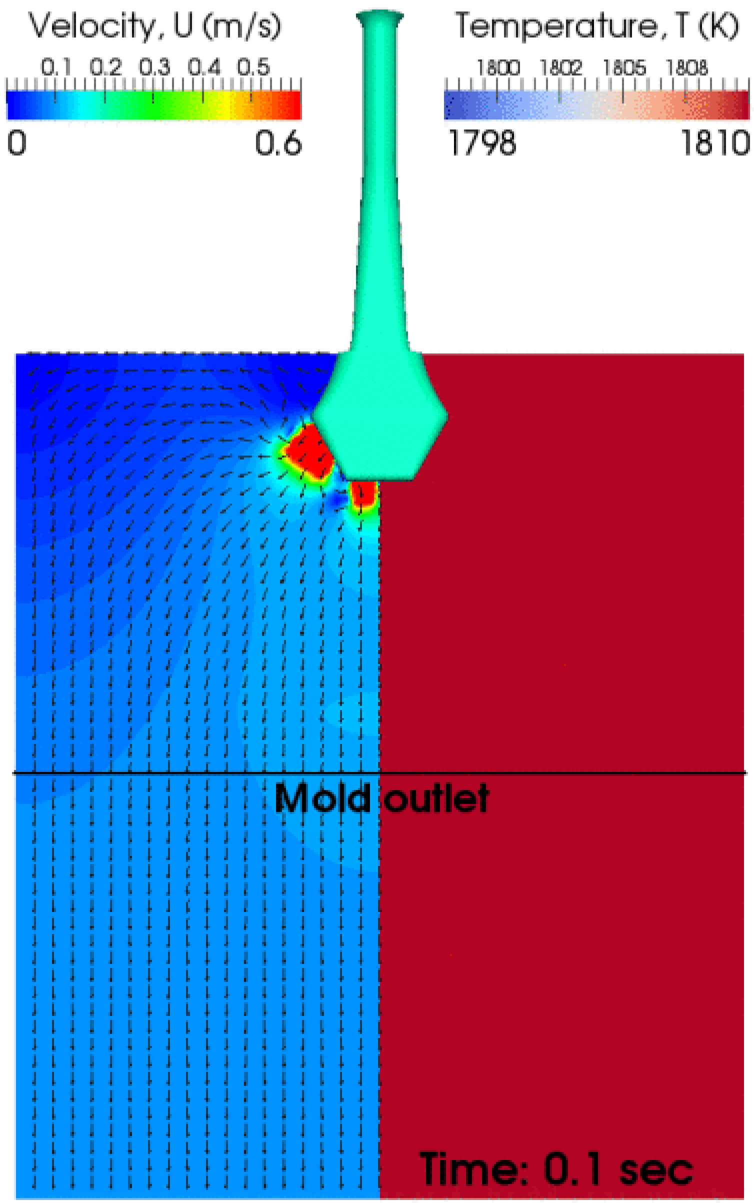


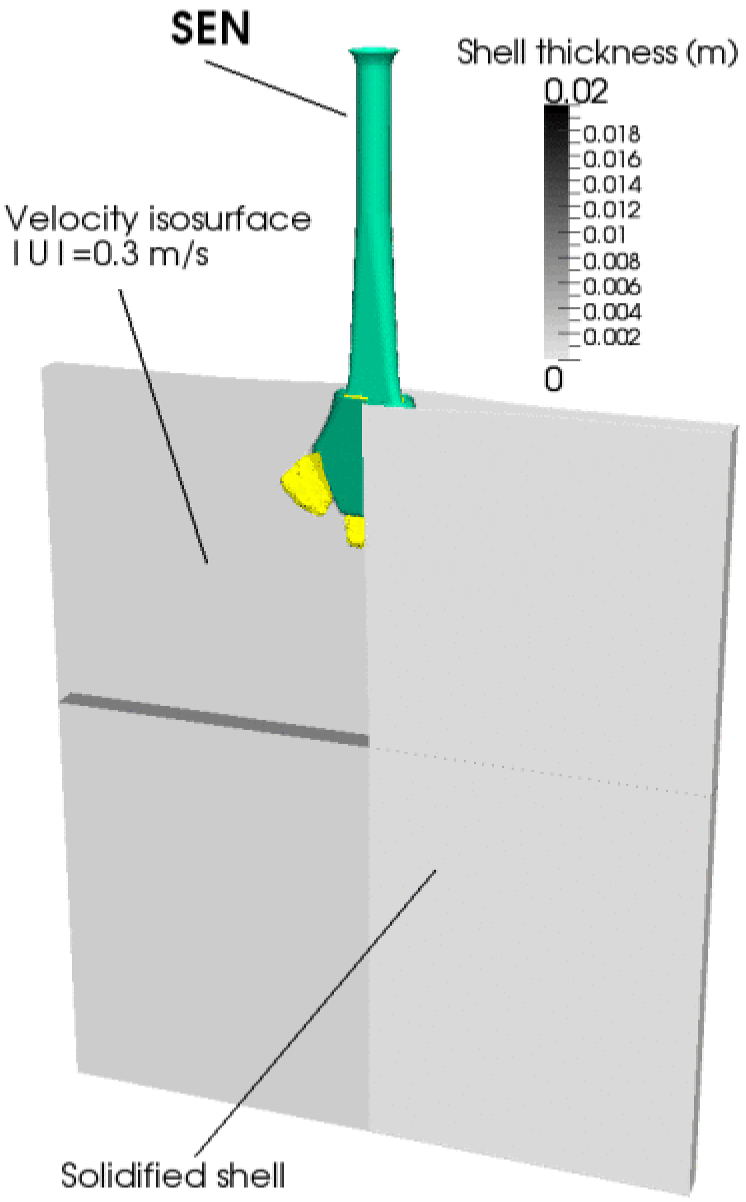
[Wikipedia]

OUTLINE

- Introduction
- **Modelling of casting process**
- Inclusions modelling
- Liquid slag model verification
- Heat transfer through the refractory
- Conclusions & outlook

Results of the thin slab casting simulation





METALLURGICAL AND MATERIALS TRANSACTIONS B

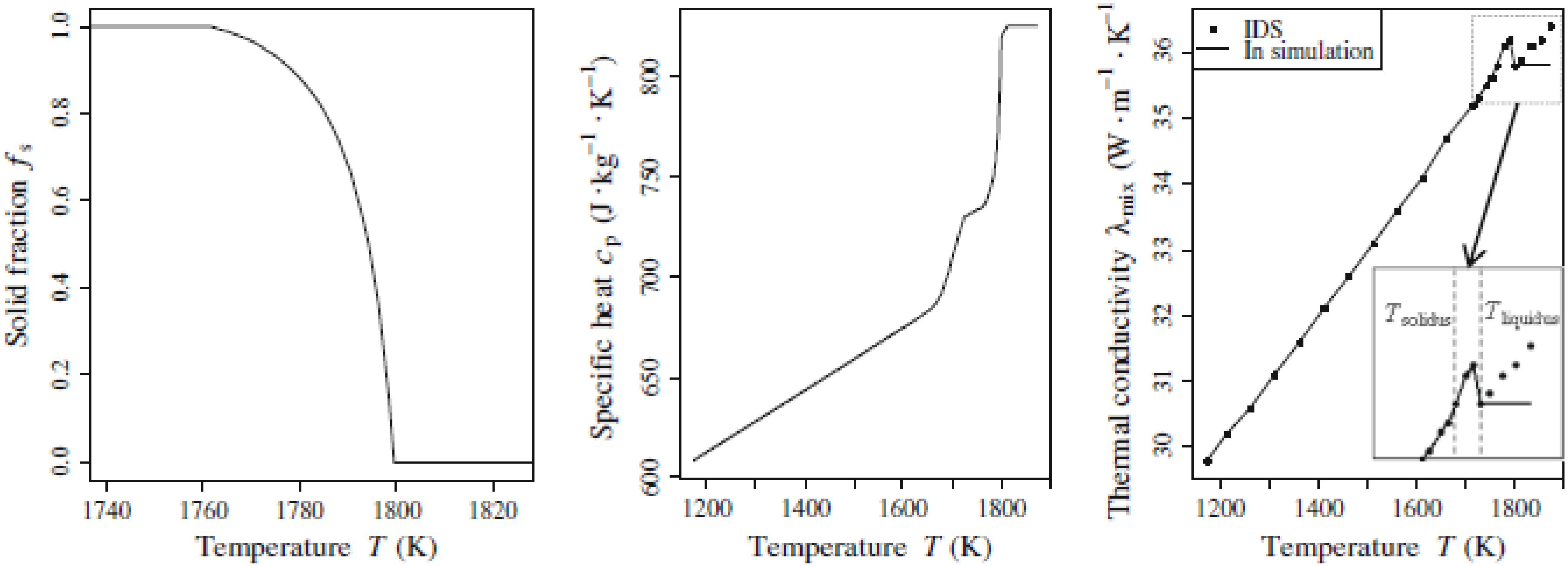
Numerical Investigation of Shell Formation in Thin Slab Casting of Funnel-Type Mold

A. VAKHRUSHEV, M. WU, A. LUDWIG, Y. TANG, G. HACKL, and G. NITZL

- **We got 10 pages of comments & questions**
  - **Constructive**
  - **Didn't require a content change**
  - **Some interesting results were added**

- **Enforced some important improvements:**
  - **Direct usage of T-dependent properties (IDS)**
  - **Reconsider heat fluxes (narrow face)**

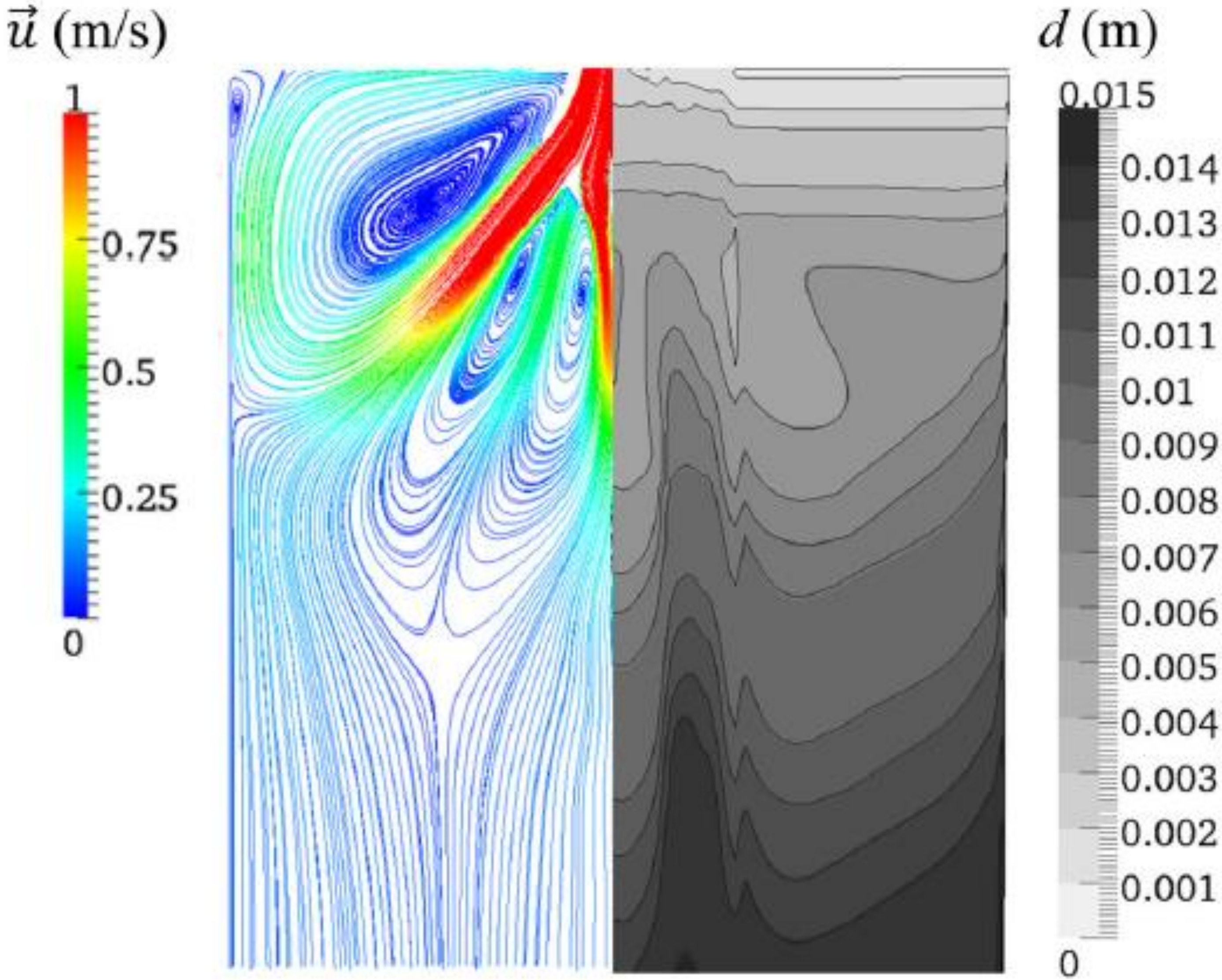
Direct usage of the IDS data



Solid fraction   Specific heat   Thermal conductivity

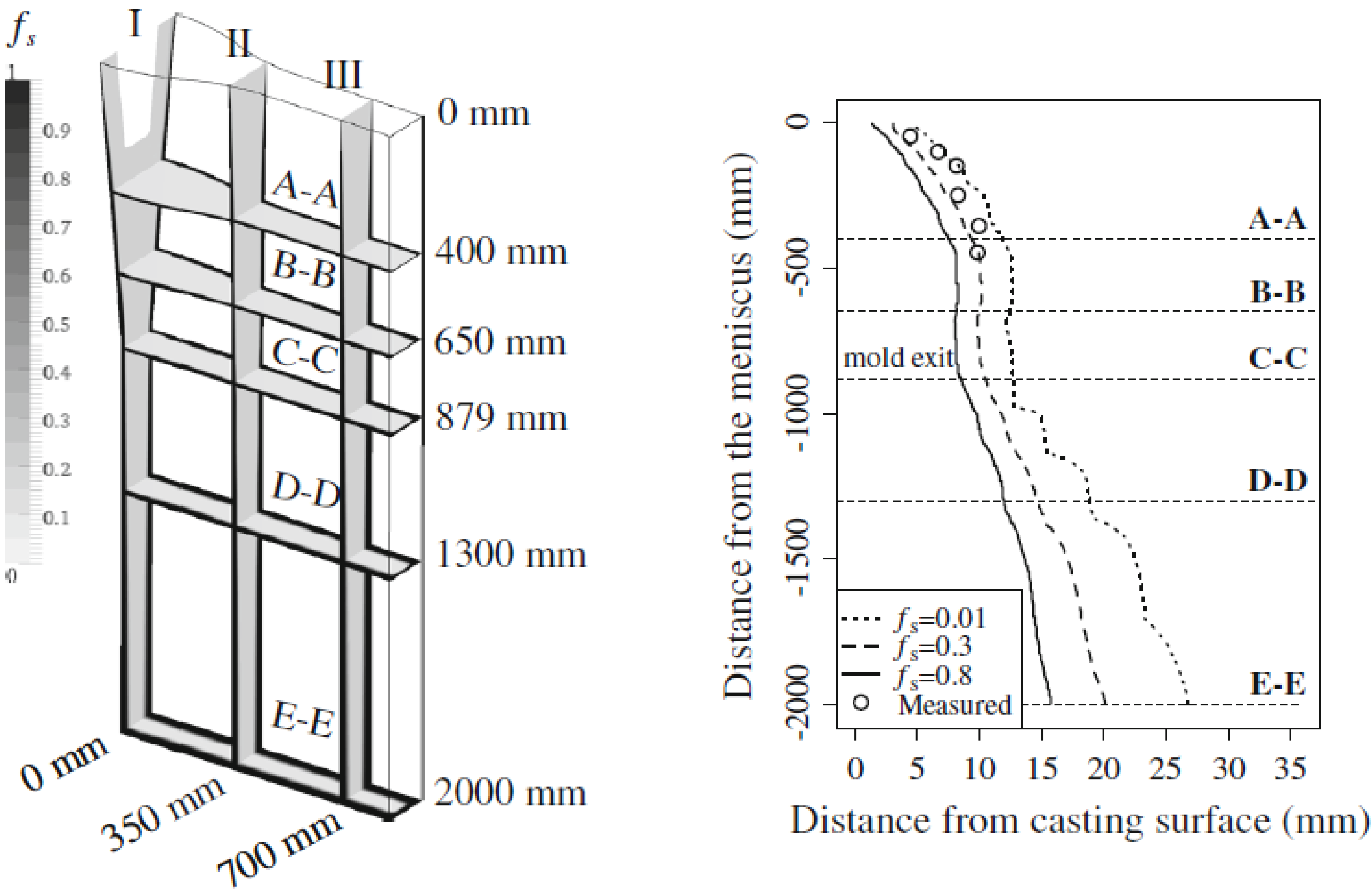
idsToOPENCAST.py IDS_data_file_name_prefix

Flow / solid shell interaction



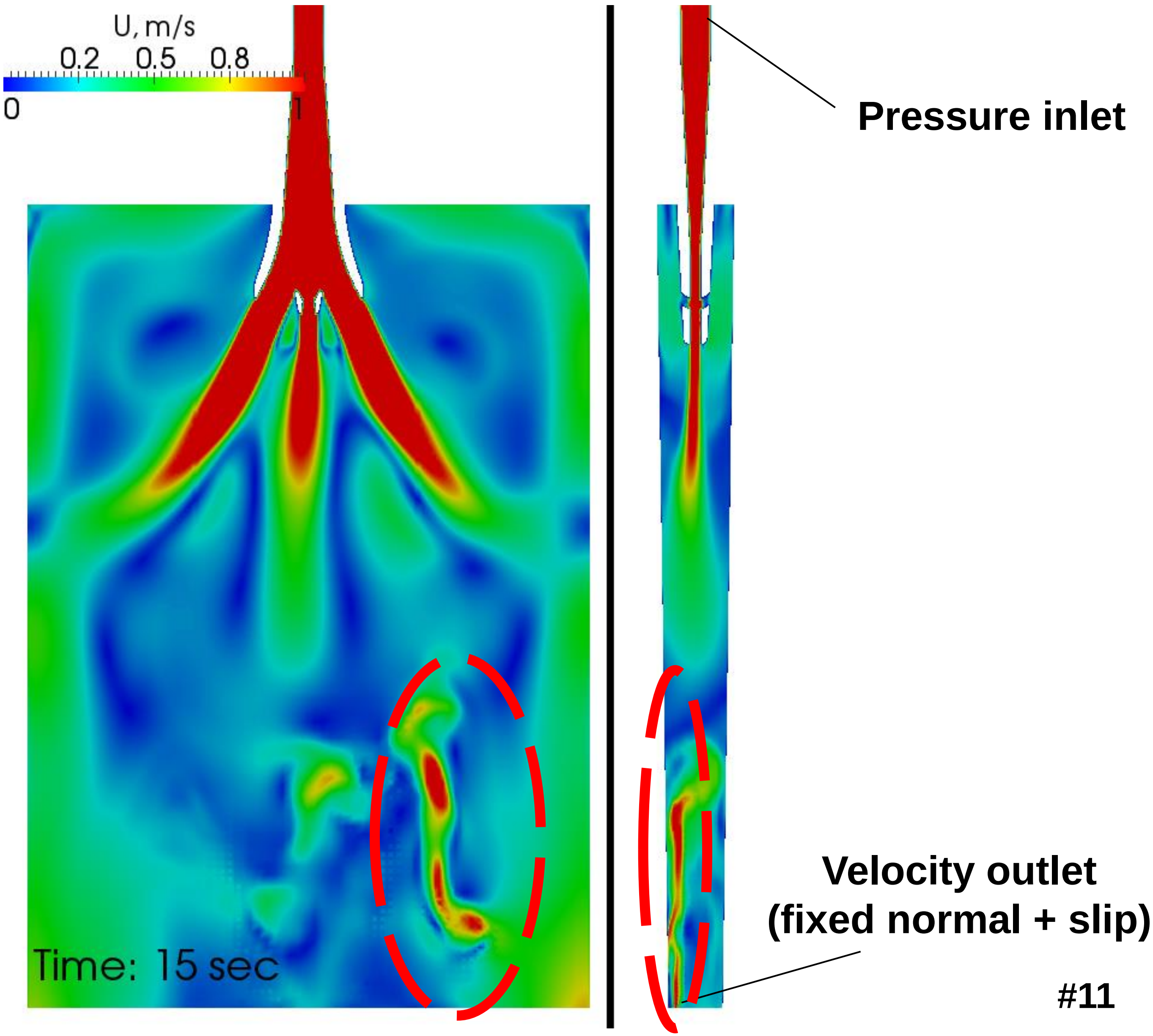
Stream lines Shell thickness

Shell thickness verification: 30% of solid



Cut I

Tipp: strong back flow for some designs



Boundary conditions to suppress backflow

- **Pressure inlet:**

  turbulentIntensityKyneticEnergyInlet, I=4%

  turbulentMixingLengthDissipationRateInlet, d=0.07*D

- **Velocity outlet:**

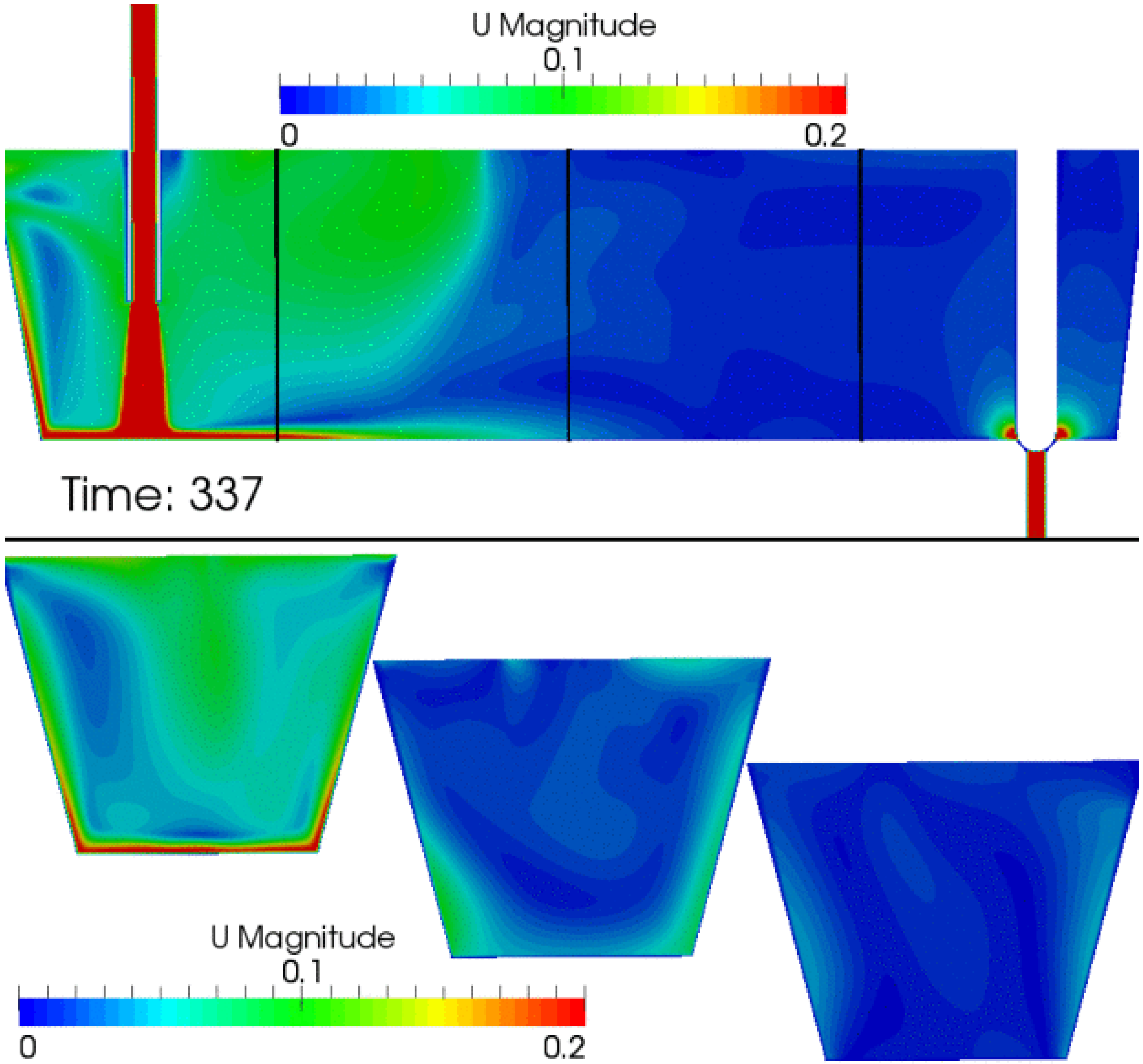
  fixedNormalSlip with casting velocity

  No back flow at all

OUTLINE

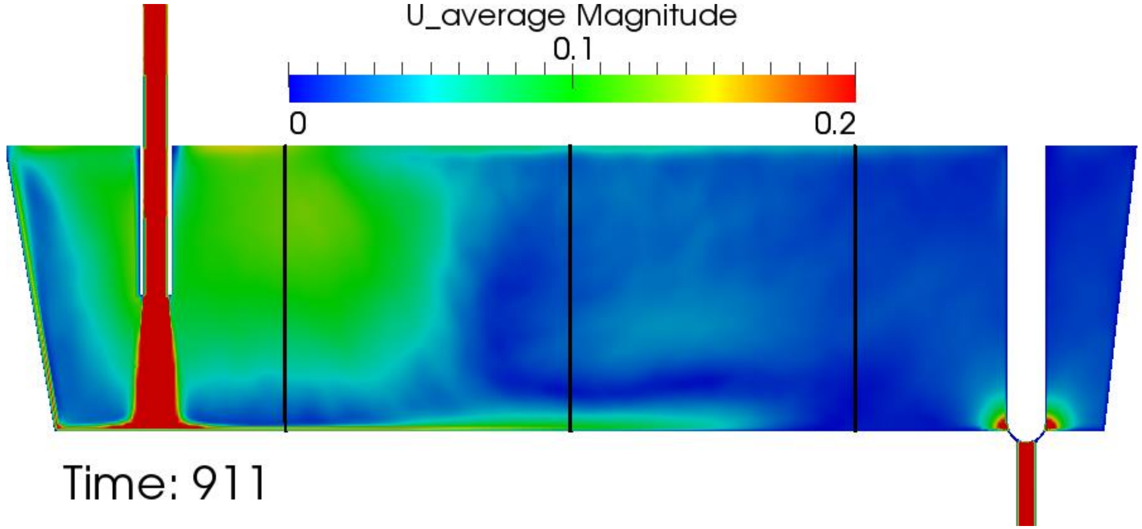
- Introduction
- Modelling of casting process
- **Inclusions modelling**
- Liquid slag model verification
- Heat transfer through the refractory
- Conclusions & outlook

DNS flow simulation in a tundish

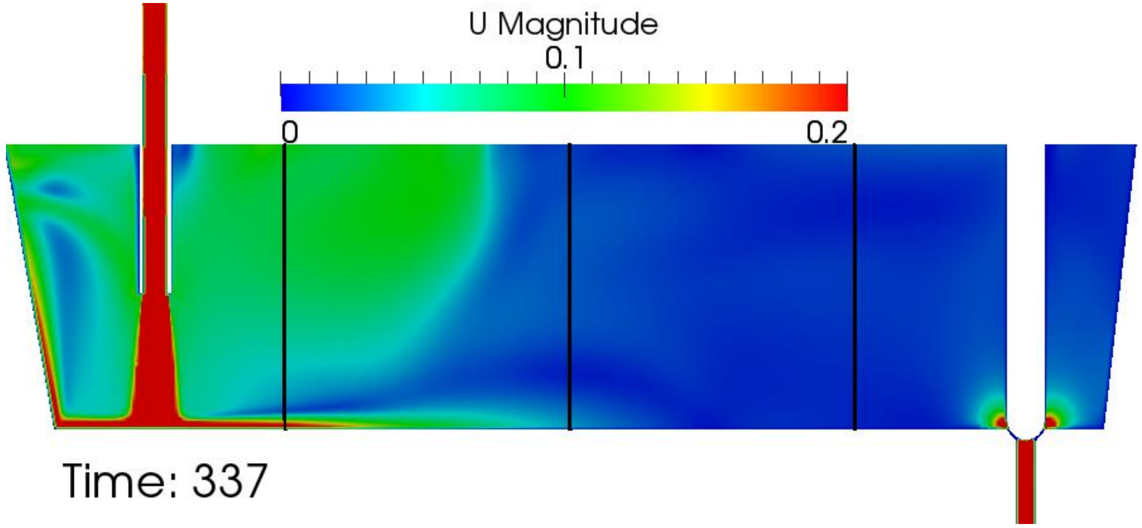


DNS vs. RANS flow simulation in a tundish

DNS



K-epsilon

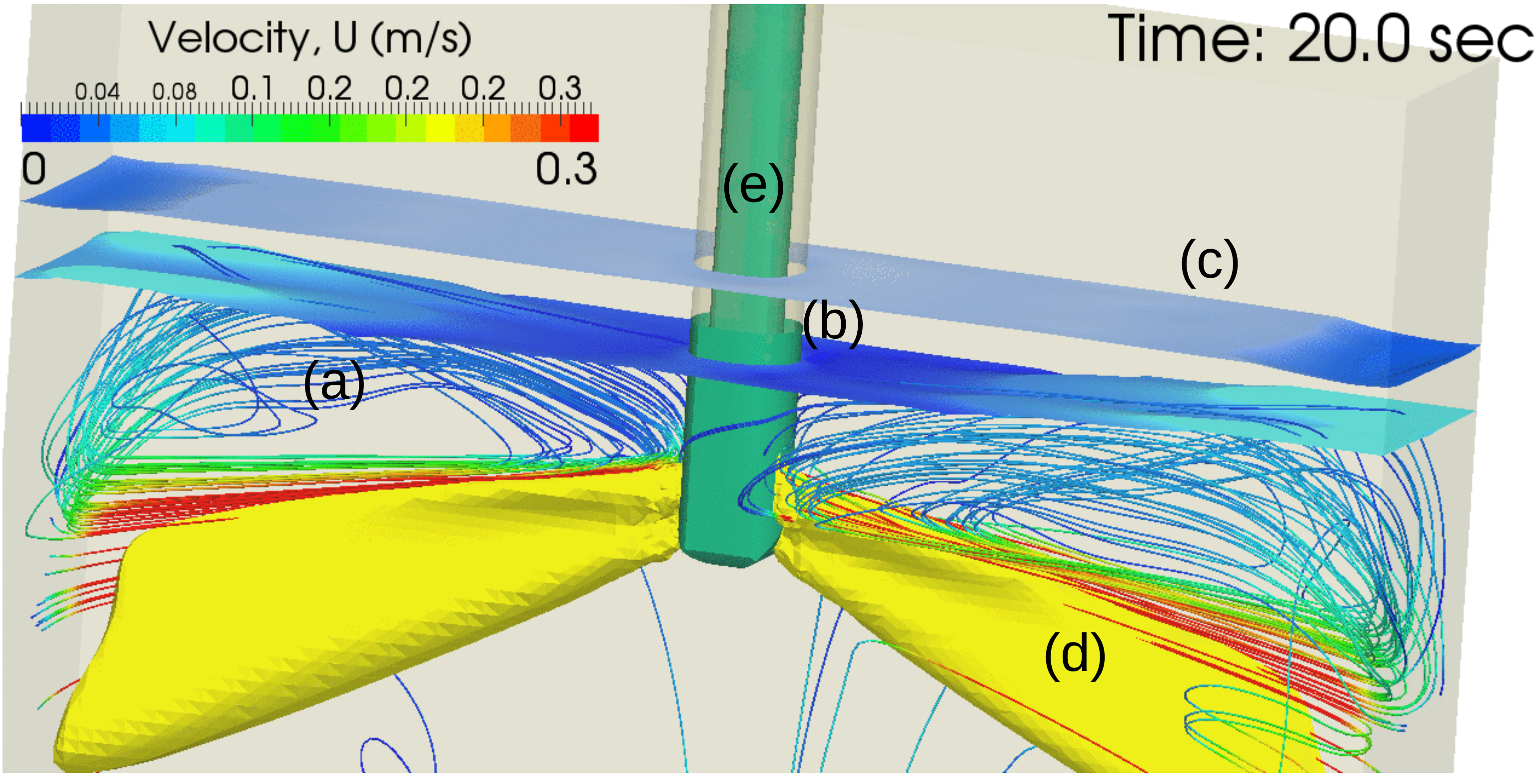


Particle flow in a tundish (DNS simulation)

OUTLINE

- Introduction
- Modelling of casting process
- Inclusions modelling
- **Liquid slag model verification**
- Heat transfer through the refractory
- Conclusions & outlook

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

Governing equations of the numerical model

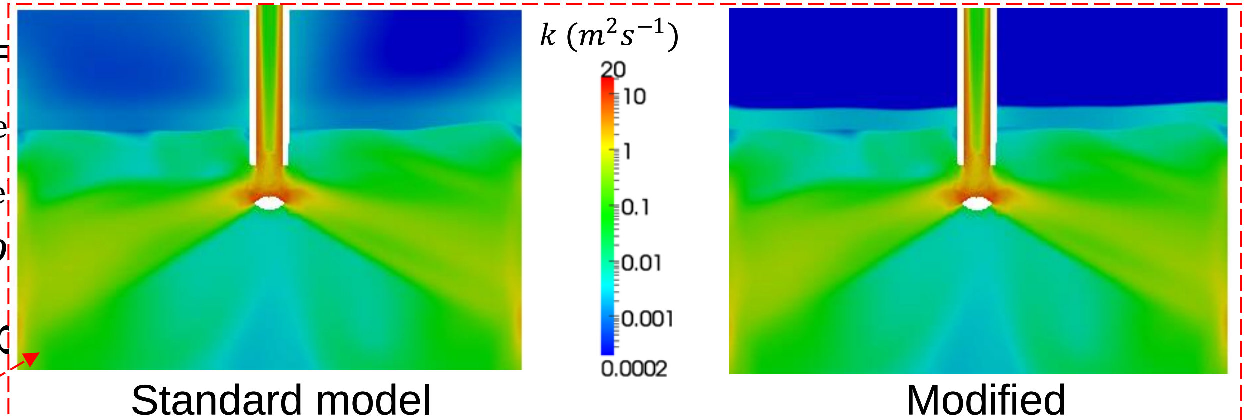
Mixture properties:

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

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

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

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



Incompressible turb

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

$$\frac{\partial \rho \vec{u}}{\partial t} + (1 - \alpha_{\mathrm{air}}) \nabla \cdot (\rho \vec{u} \otimes \vec{u}) = -\nabla p + \nabla \cdot (2\mu_{\mathrm{eff}} \mathbf{D}) + \rho \vec{g} + \vec{S}_{\mathrm{surf}} \tag{6}$$

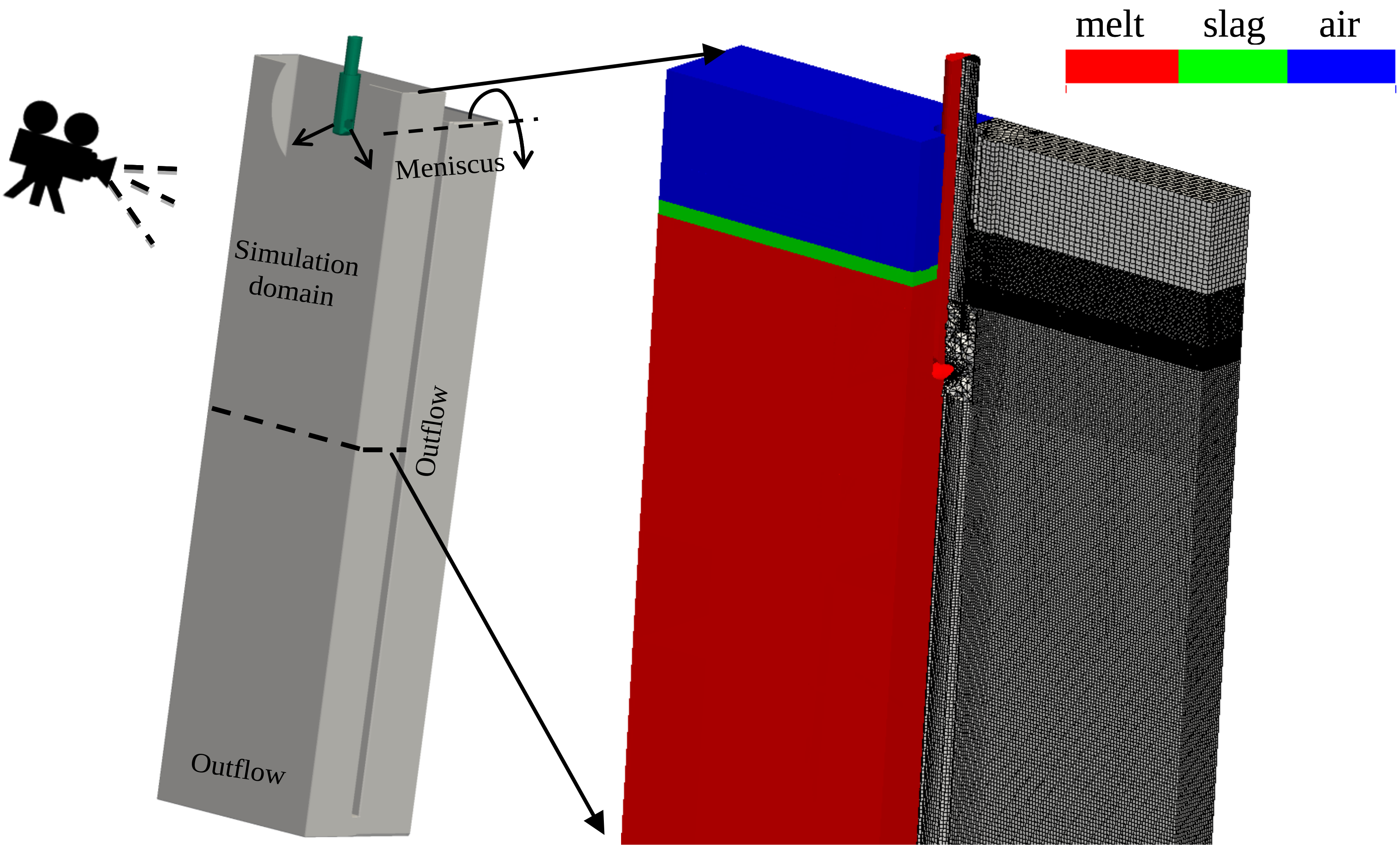
$$\vec{S}_{\mathrm{surf}} = \sum_{i,j} \sigma_{ij} \kappa_{ij} (\alpha_j \nabla \alpha_i - \alpha_i \nabla \alpha_j) \quad \text{where} \quad \kappa_{ij} = -\nabla \cdot \frac{(\alpha_j \nabla \alpha_i - \alpha_i \nabla \alpha_j)}{|\alpha_j \nabla \alpha_i - \alpha_i \nabla \alpha_j|} \tag{7}$$

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

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

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

Experimental setup and simulation domain

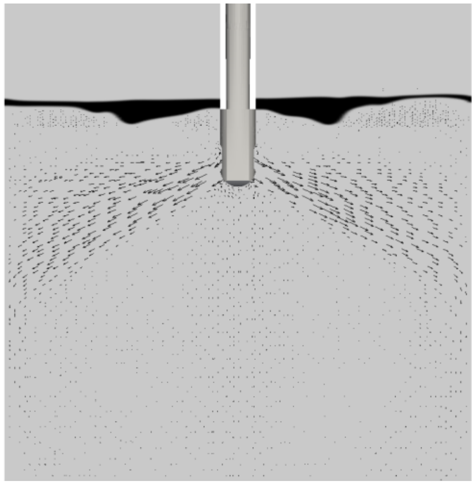


Water modelling results

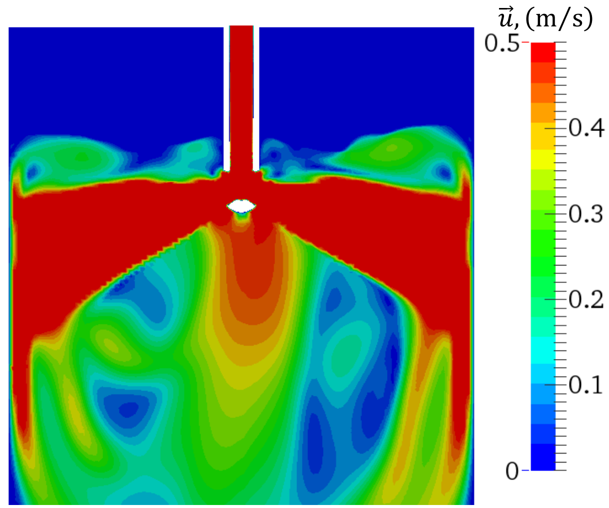
1.5 m/min

Simulation results / comparison with experiment

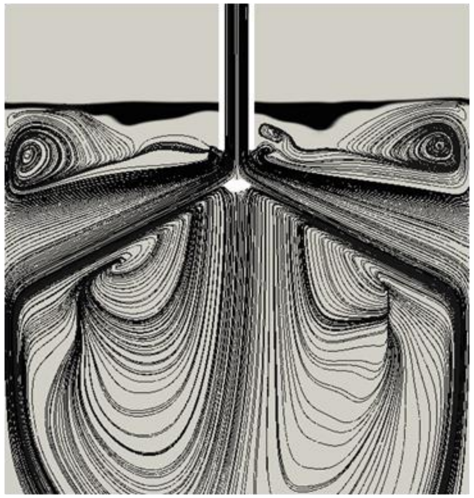
Flow simulation:



Slag position / velocity vectors

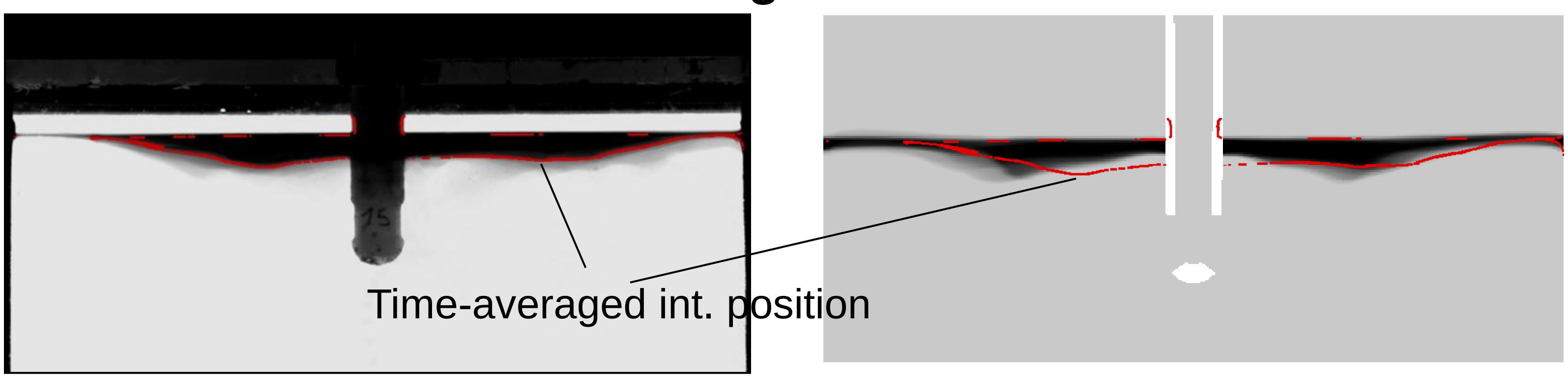


Velocity magnitude



Stream-lines

Comparison with the water modelling results:



Experiment

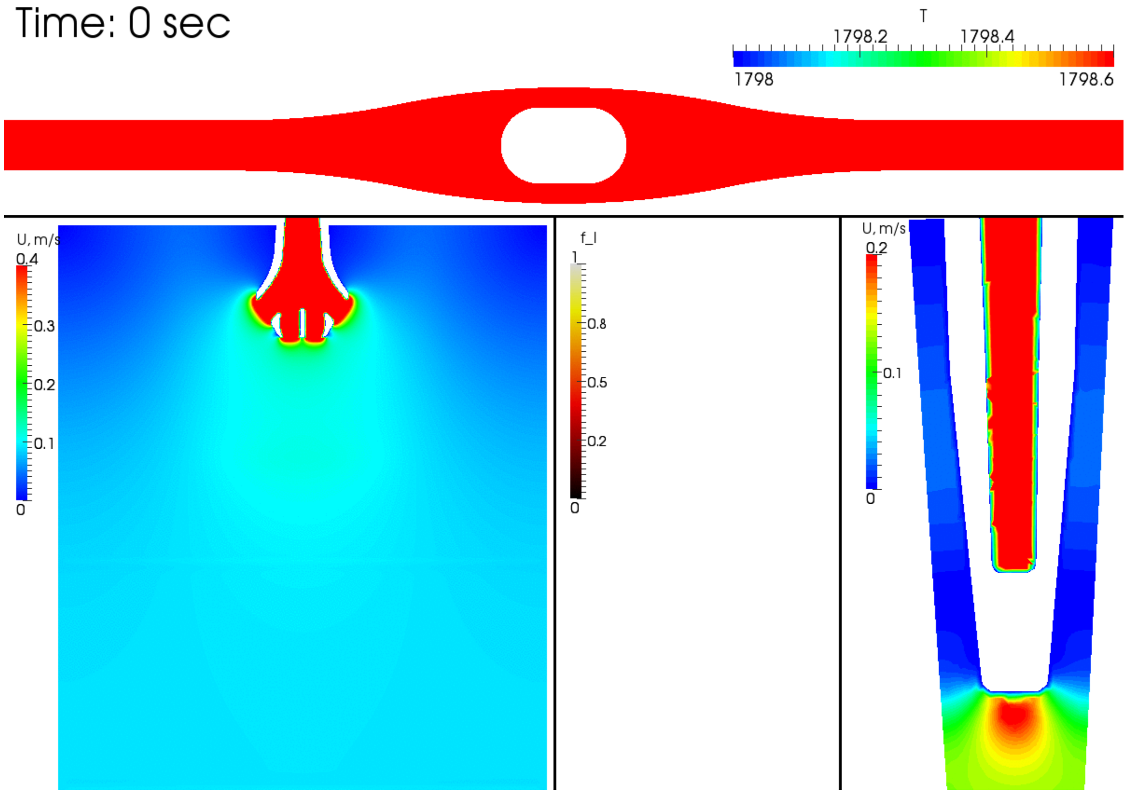
Simulation

OUTLINE

- Introduction
- Modelling of casting process
- Inclusions modelling
- Liquid slag model verification
- **Heat transfer through the refractory**
- Conclusions & outlook

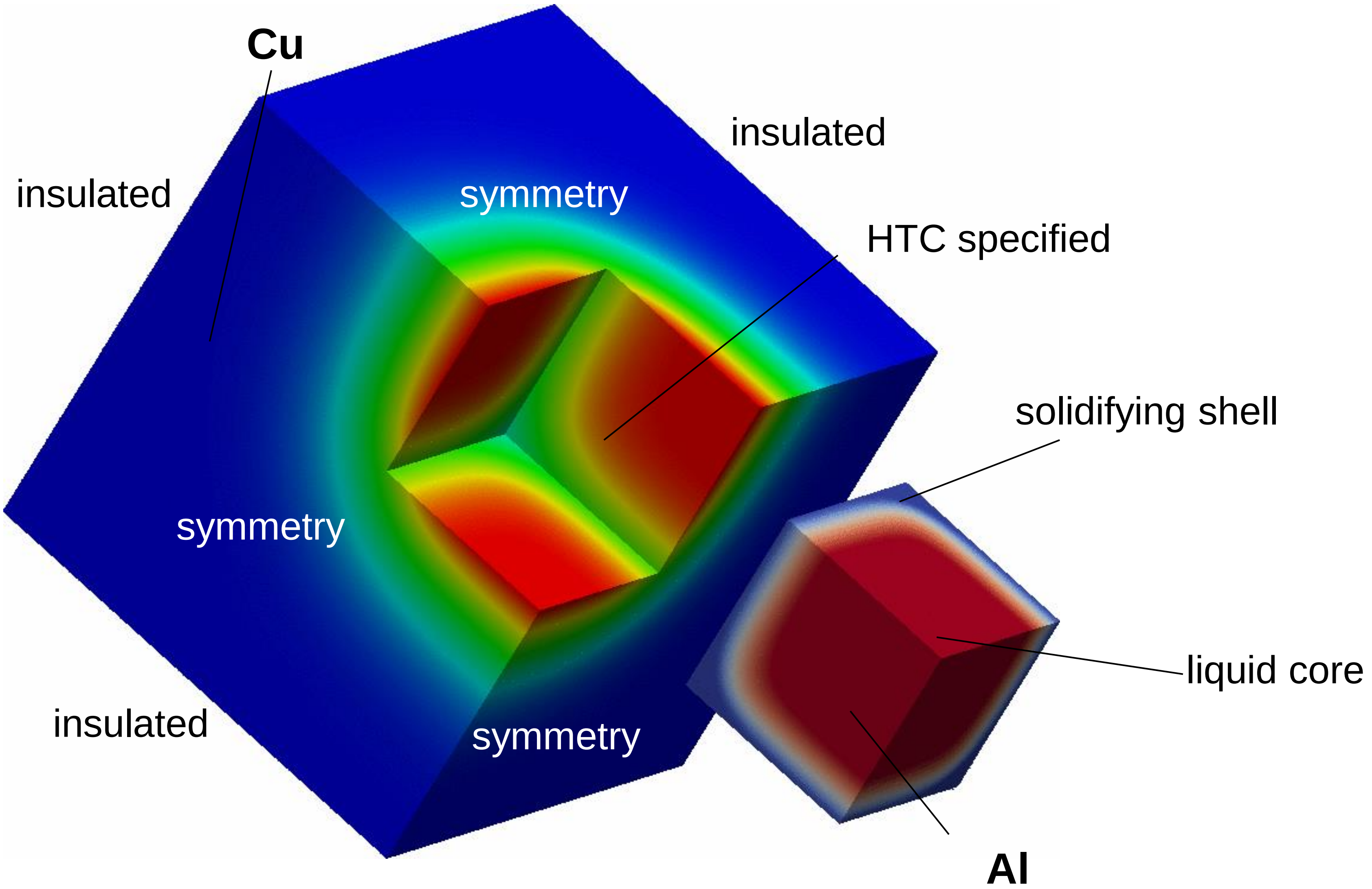
Heat transfer through refractory: motivation

- Estimate heat losses through the SEN
- Can it lead to the solidification at the flow stagnation zones?

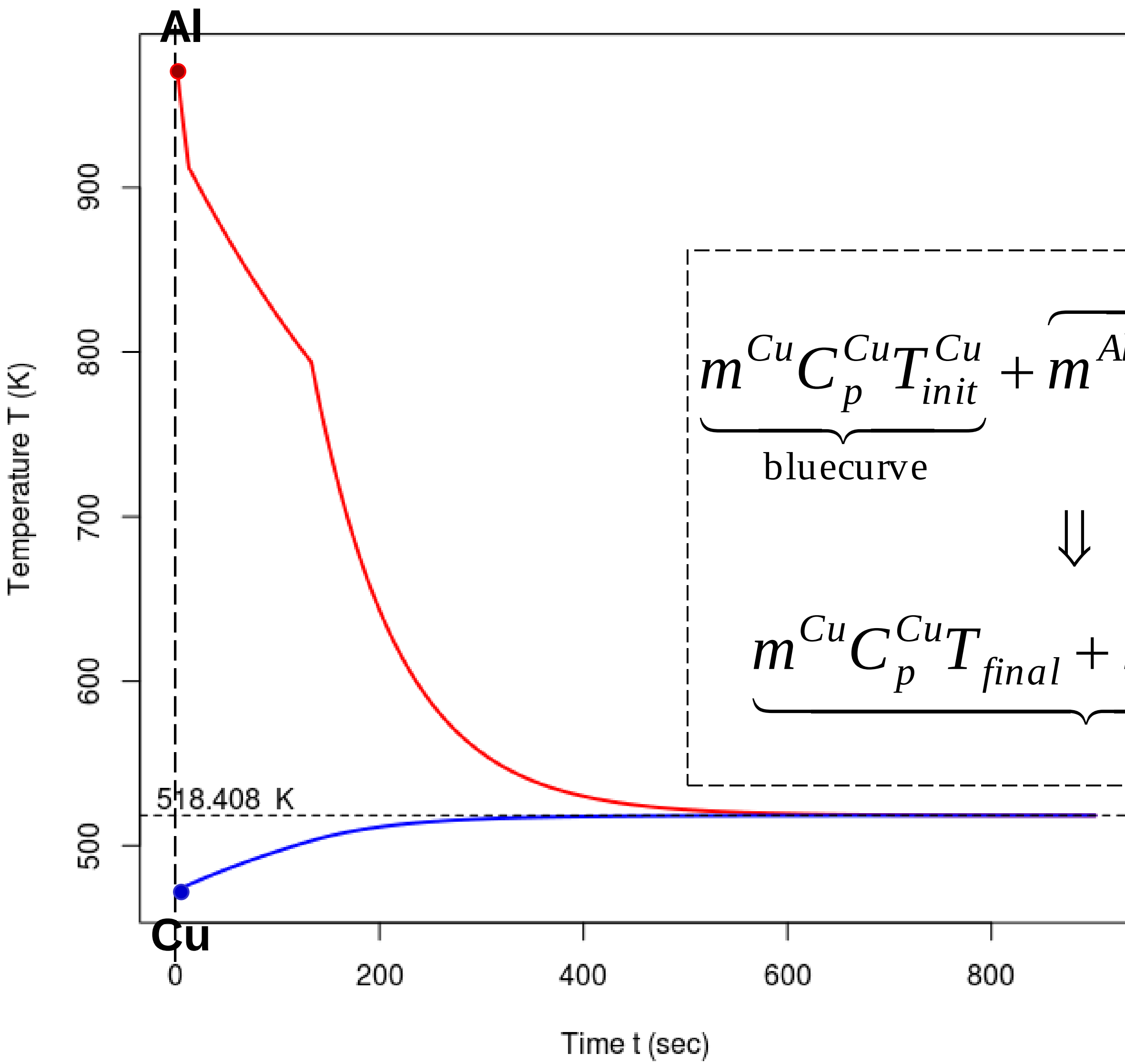


when ~ 1 K of superheat is predicted !!!

Model development: ÖGI solidification benchmark



Model development: ÖGI solidification benchmark

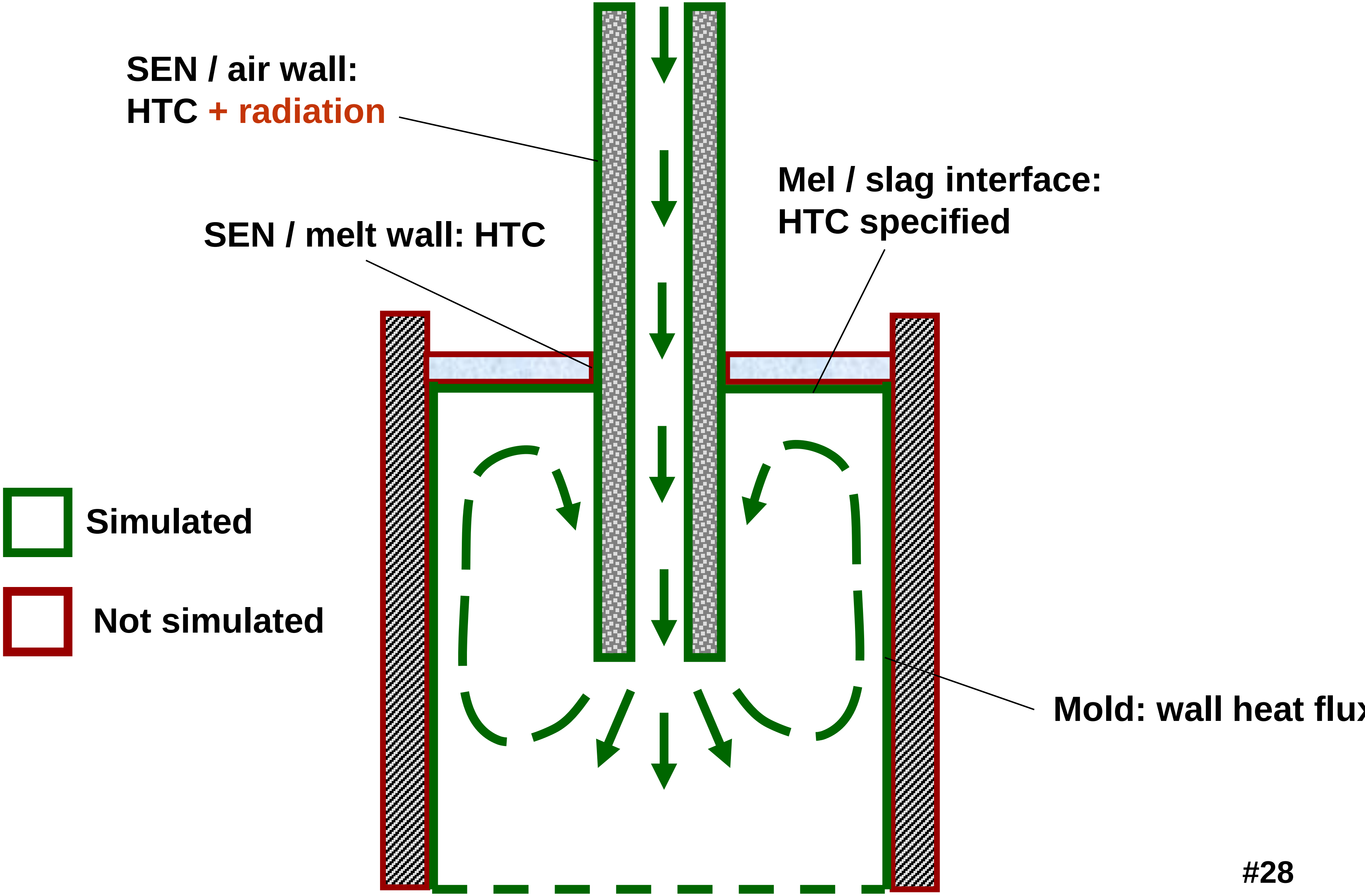


$$\underbrace{m^{Cu}C_p^{Cu}T_{init}^{Cu}}_{\text{bluecurve}} + \overbrace{m^{Al}\left(C_p^{Al}T_{init}^{Al} + L\right)}^{\text{red curve}}$$

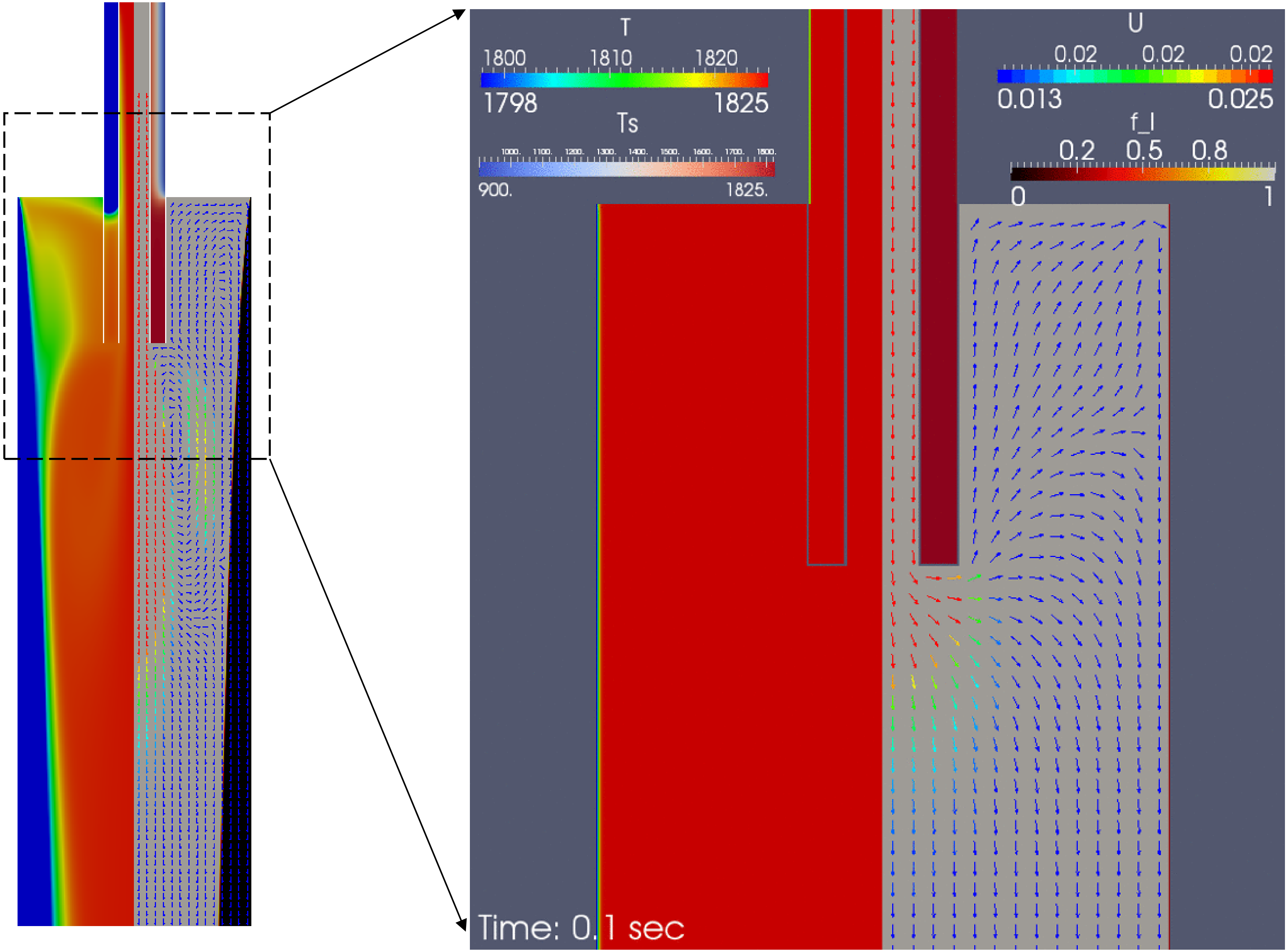
$$\Downarrow$$

$$\underbrace{m^{Cu}C_p^{Cu}T_{final} + m^{Al}C_p^{Al}T_{final}}$$

2D solidification with the heat transfer in SEN



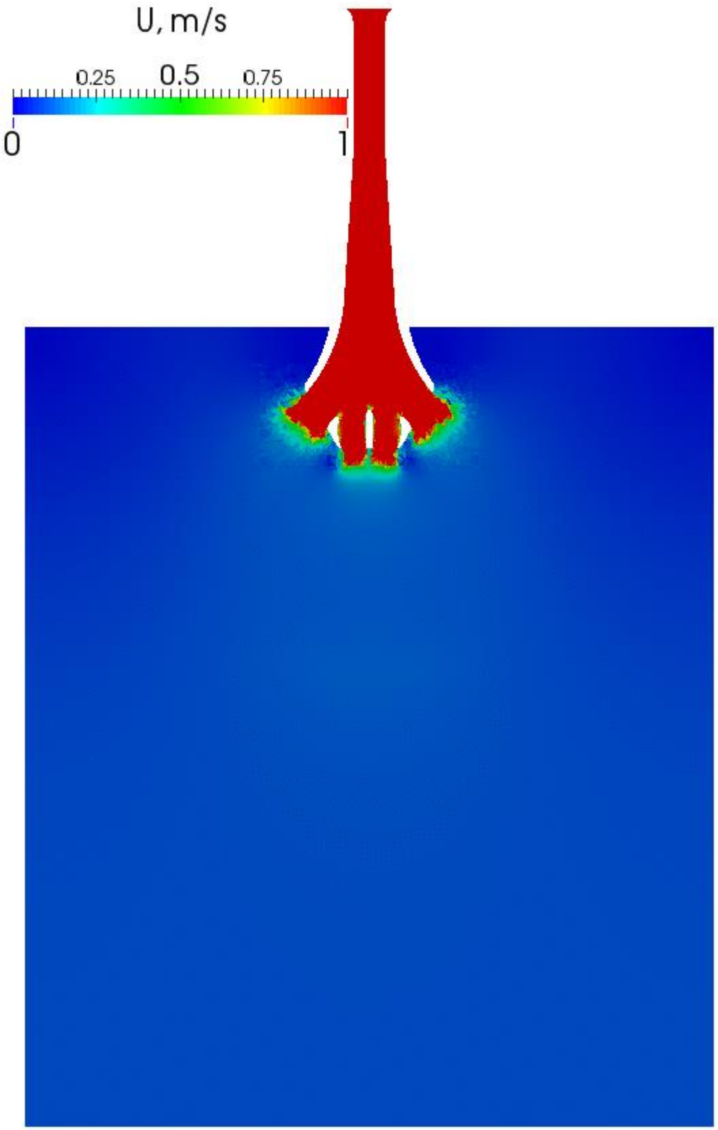
2D solidification with the heat transfer in SEN



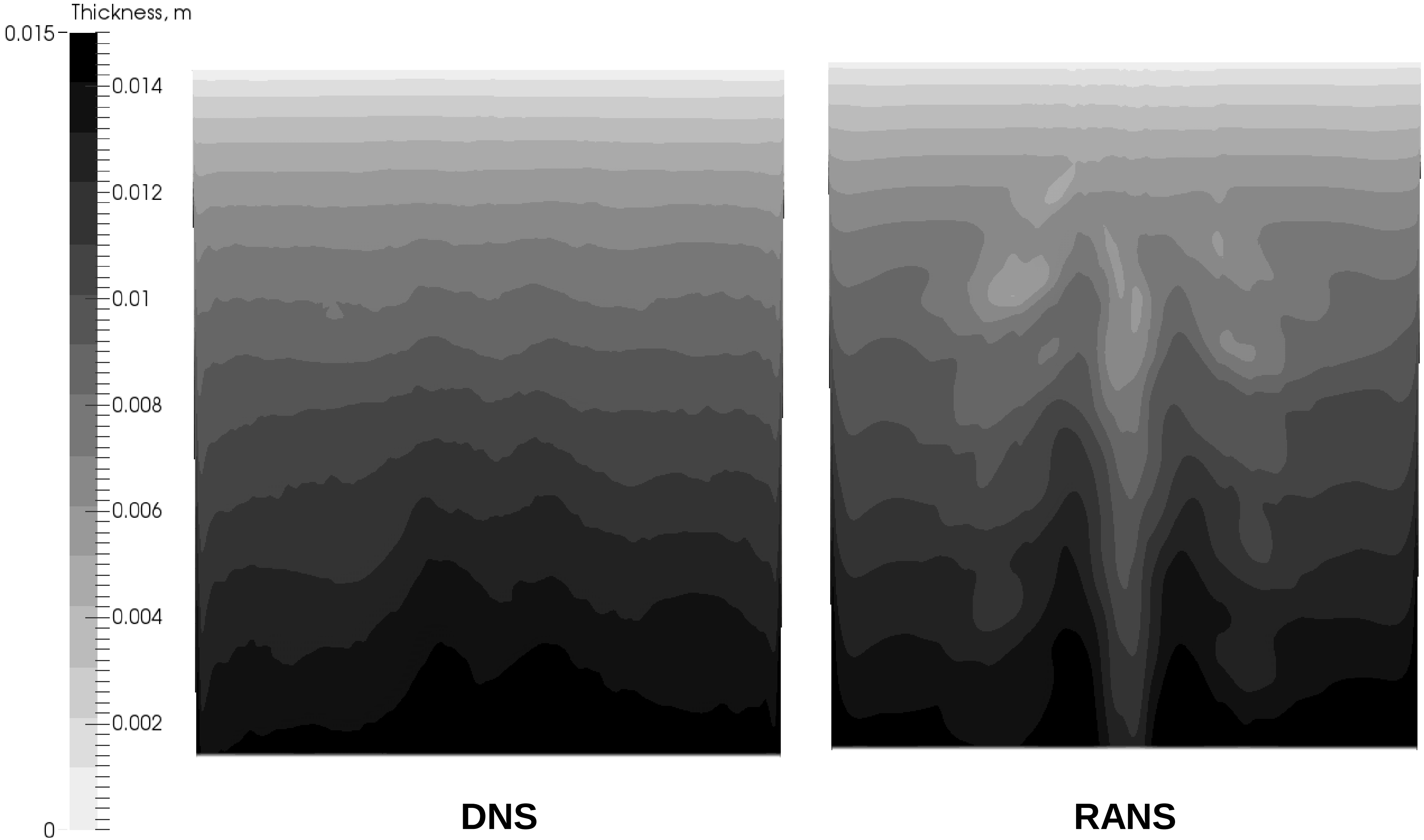
OUTLINE

- Introduction
- Modelling of casting process
- Inclusions modelling
- Liquid slag model verification
- Heat transfer through the refractory
- **Conclusions & outlook**

Shell formation (DNS)

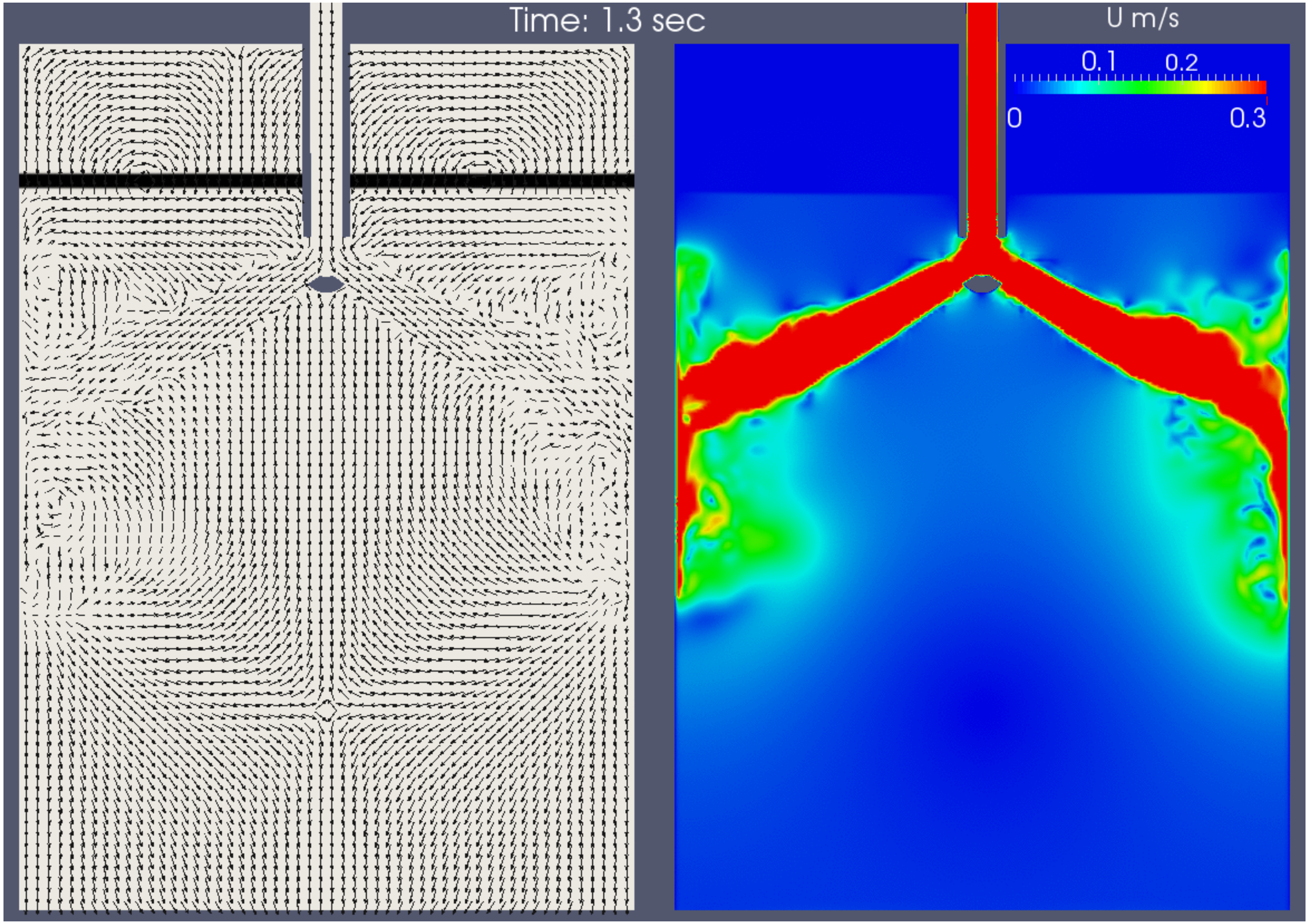


Shell thickness: comparison DNS vs. RANS

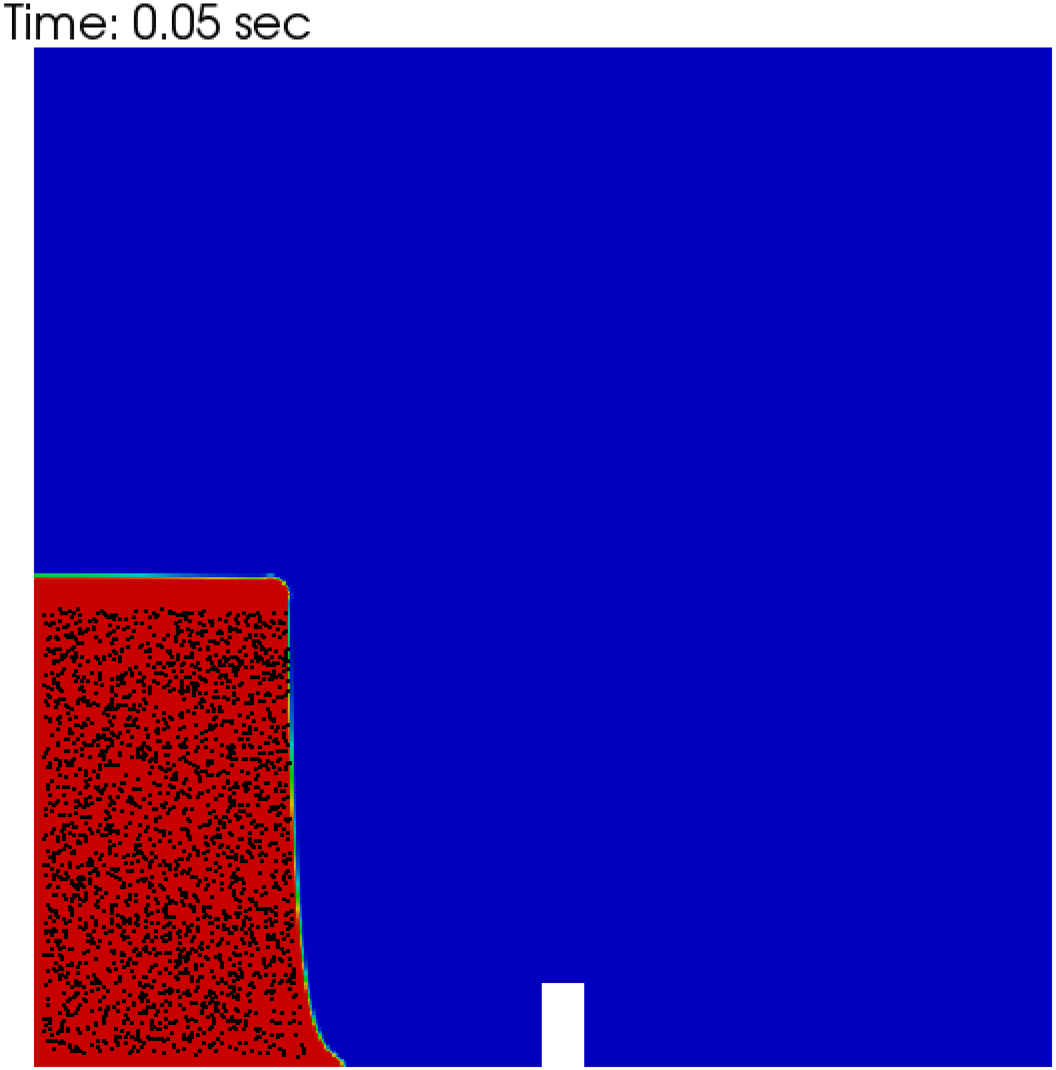


DNS **RANS**

Future work: DNS simulation of a free surface



Particle simulation with 2 phase VOF



THANK YOU FOR YOUR ATTENTION!