Sino-German-Workshop
October 11-12, 2004, Shanghai (China)

Experimental investigations and numerical modelling of metal melt flows in induction furnaces

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Industrial process requirements for melting in induction furnaces

→ Optimisation of the heat and mass exchange in the melt

- Mixing and homogenisation of the entire melt
- Homogenisation of the temperature, avoiding of local overheating, but realizing of sufficient superheating of the entire melt
- Intensive stirring at the melt surface (melting of small-sized scrap, carburization process)
- Avoiding of erosion and clogging of the ceramic lining
- Avoiding of melt instabilities, splashing or pinching
- Intensive stirring for cleaning of the melt (zinc removing)

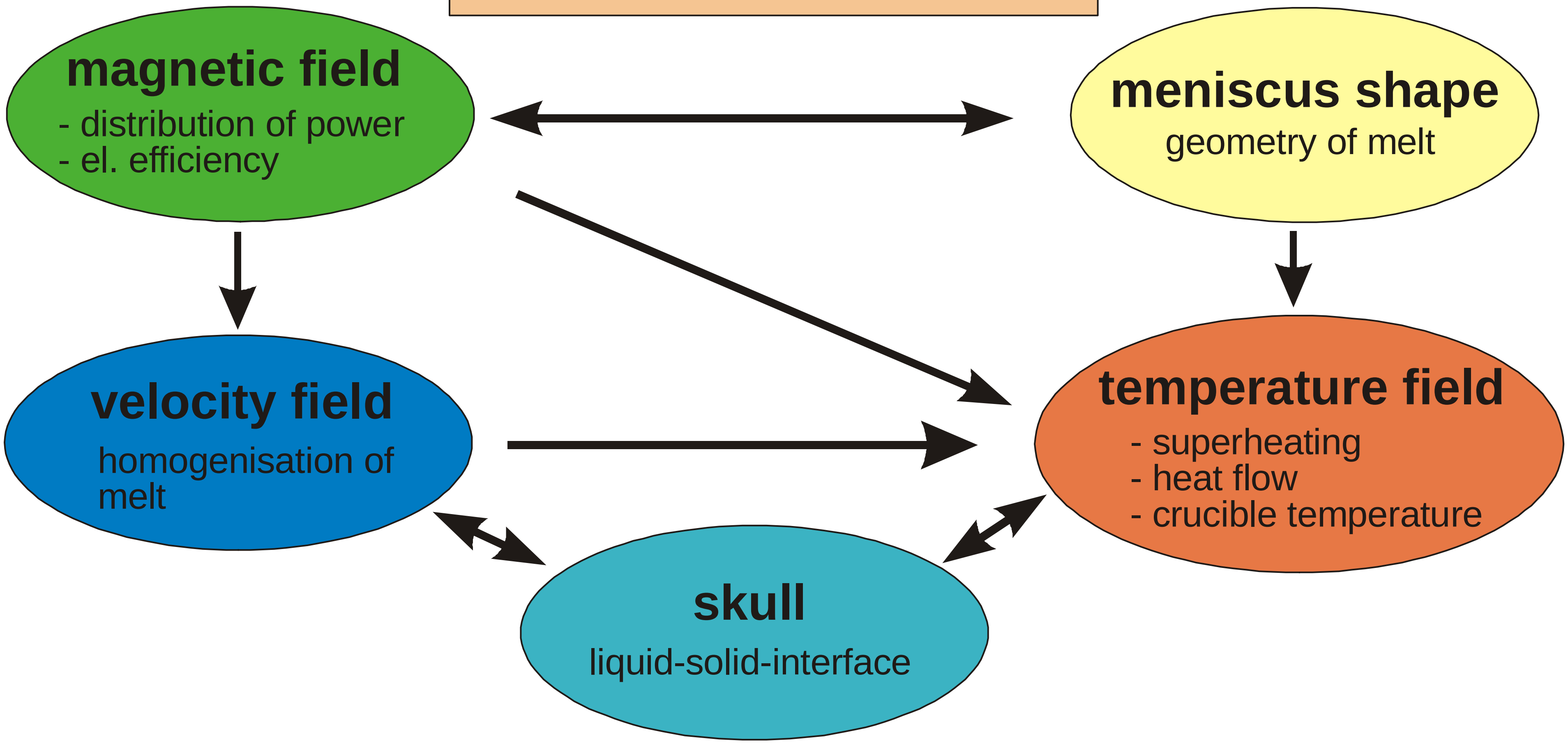
Main features of the induction furnace metal melting processes

- Heat and mass transfer and the temperature distribution in the melt are determined by <u>3D instationary turbulent melt flows</u>

- <u>Experimental investigations</u>, e.g. measurements of the turbulent melt flows <u>are very limited in industrial furnaces</u>, experimental investigations are possible in model furnaces with model melts

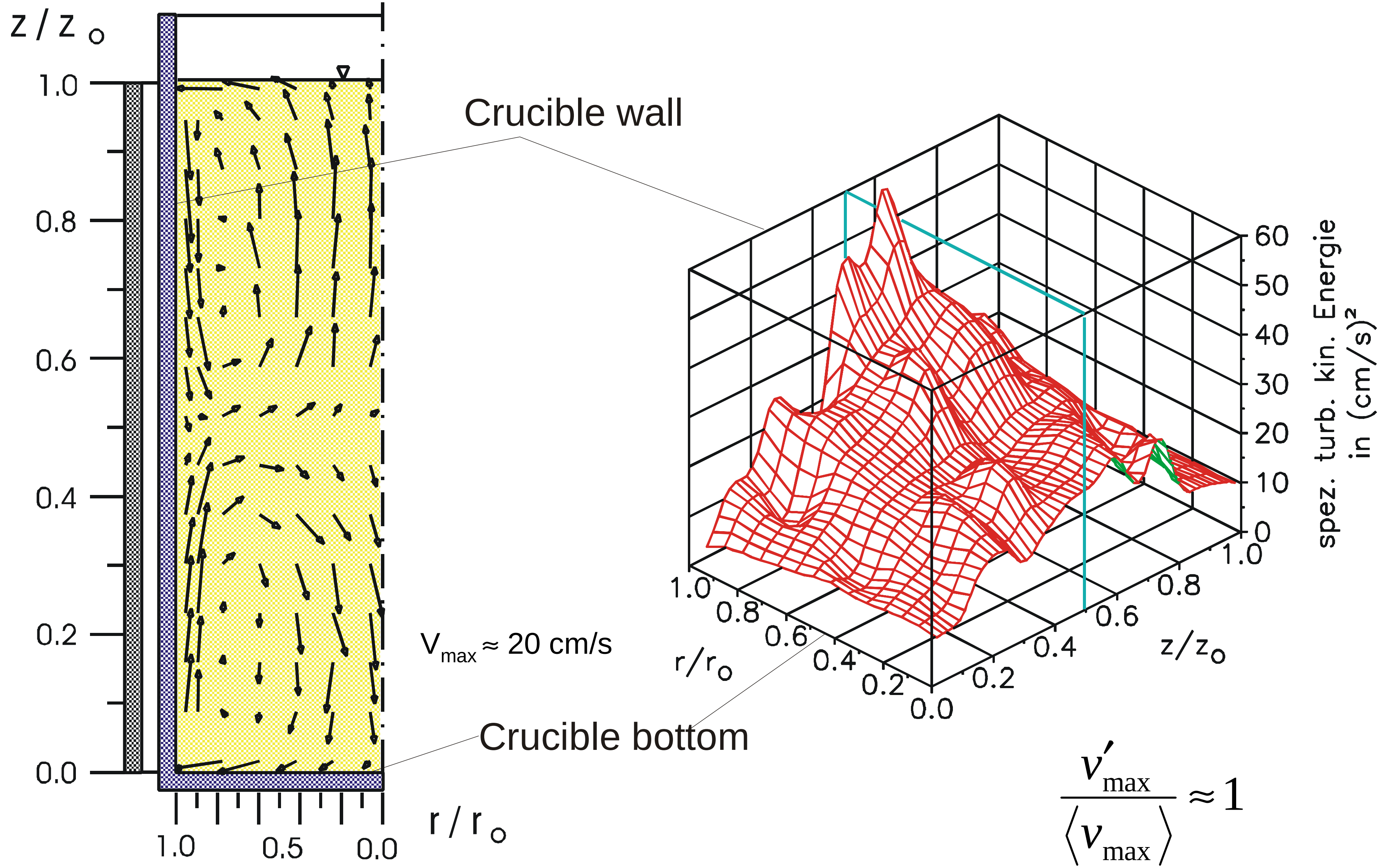
- Optimal design and optimisation of the operation behaviour of induction furnaces needs <u>3D instationary numerical simulation</u> of the turbulent melt flow and the heat and mass transfer using experimentally verified models

Physical Correlations



⇒ **optimization of design and operating parameters**

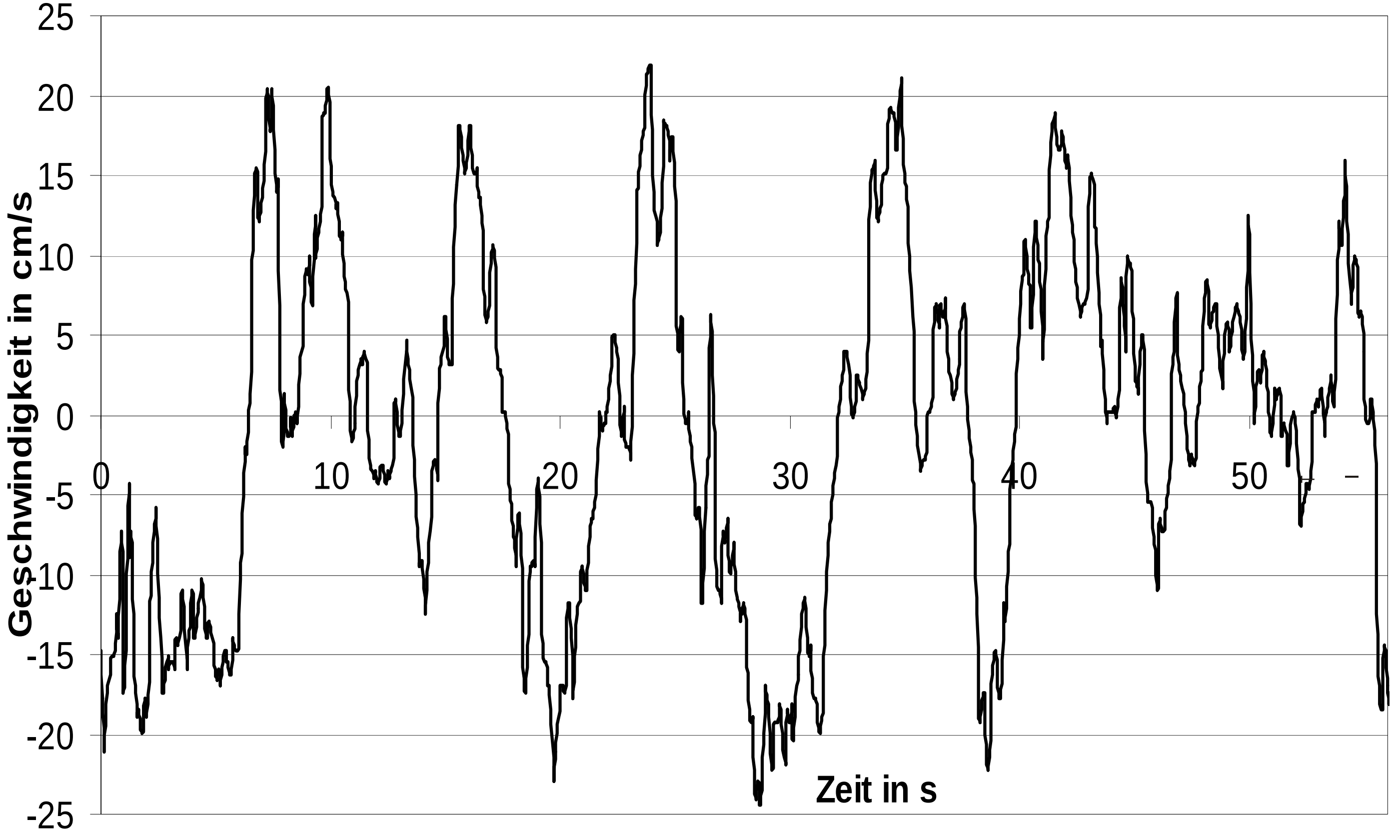
Melt flow measurements in induction crucible furnace

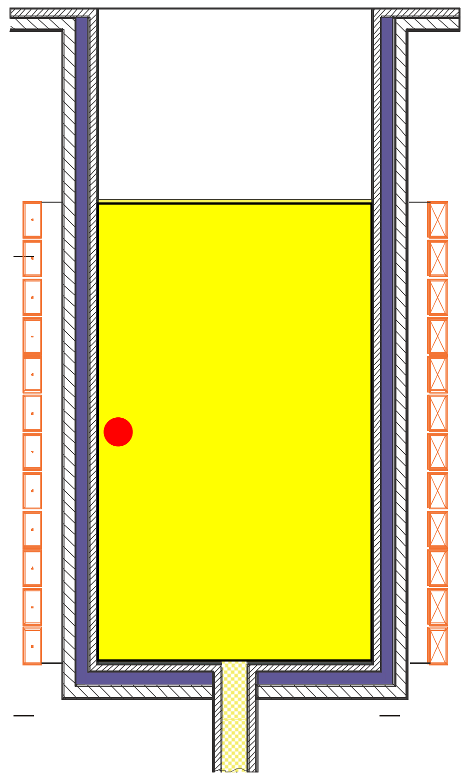


$$\frac{v'_{\max}}{\langle v_{\max} \rangle} \approx 1$$

Baake, E. et.al.: 1994

Measurement of local flow velocity (ICF): near the crucible wall between the main flow eddies

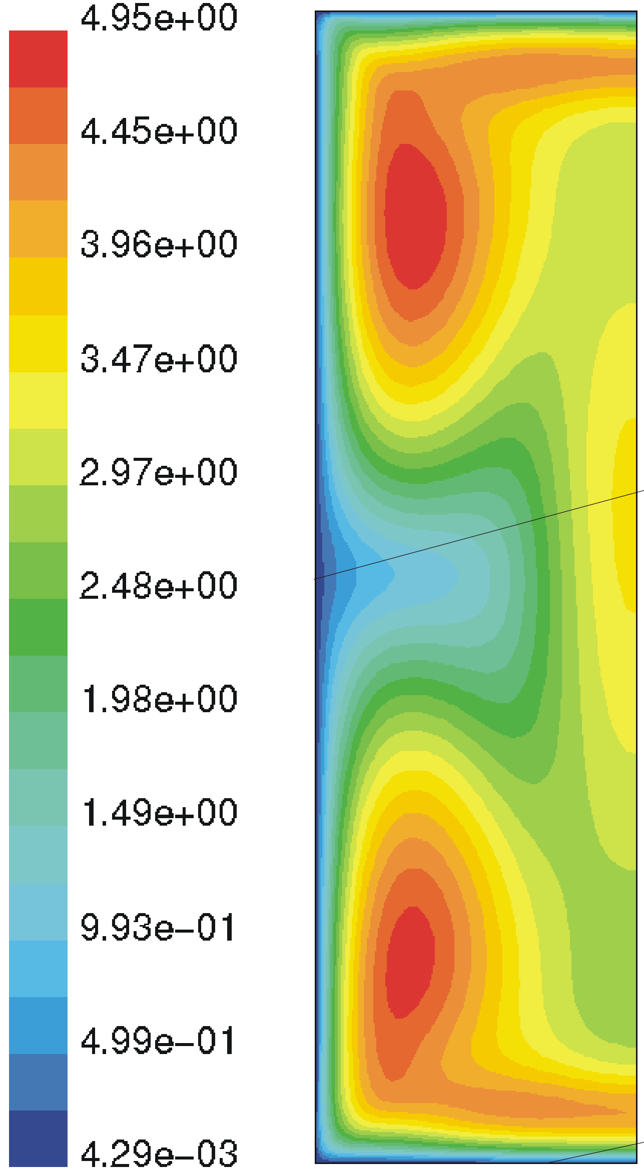


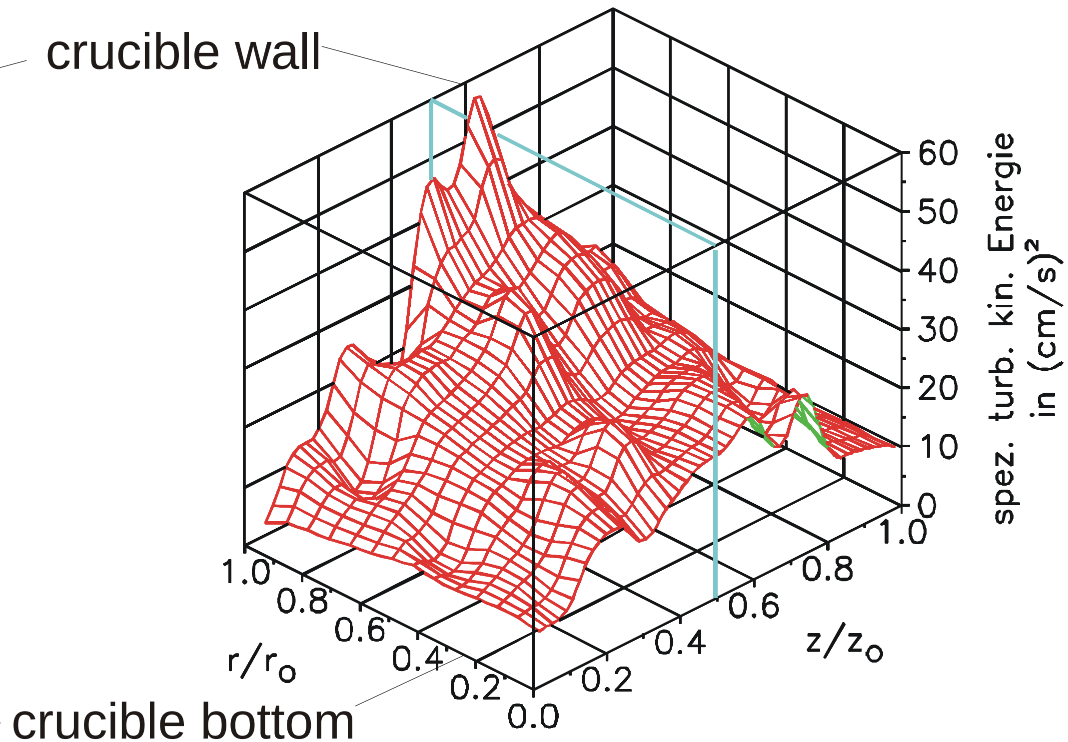


- Low-frequency oscillations
- Oscillation period: 8...12 sec

Application of 2D and 3D RANS (k-ε) turbulence models:

Calculation results of turbulent characteristics are different from measurement results





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RANS (k-ε model)

- Whole energy spectrum is modelled
- Relatively low mesh resolution requirements
- Steady-state simulations

DNS

- All scales are resolved directly
- Very high requirements for computational resources
- Simulations of industrial installations are impossible

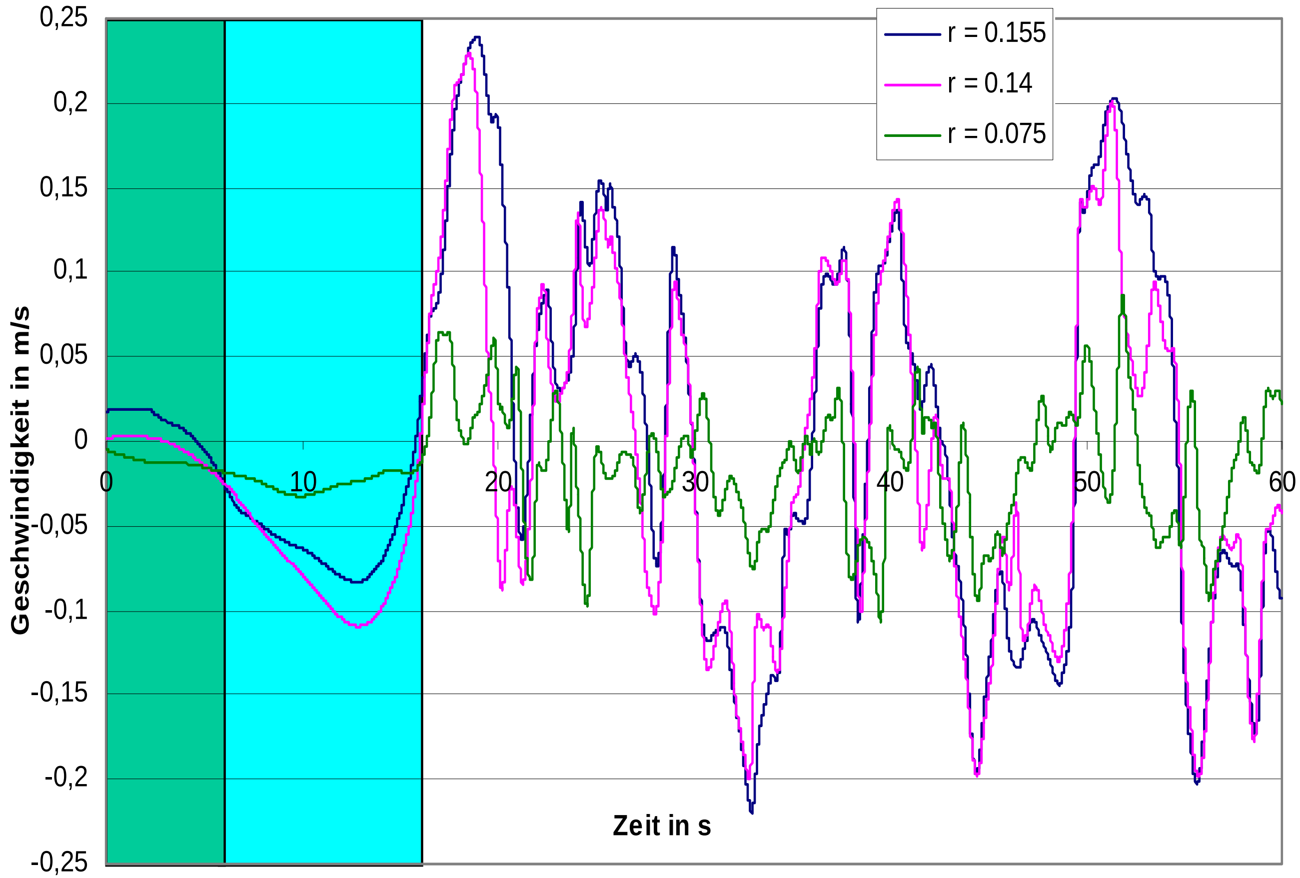
CFD problem

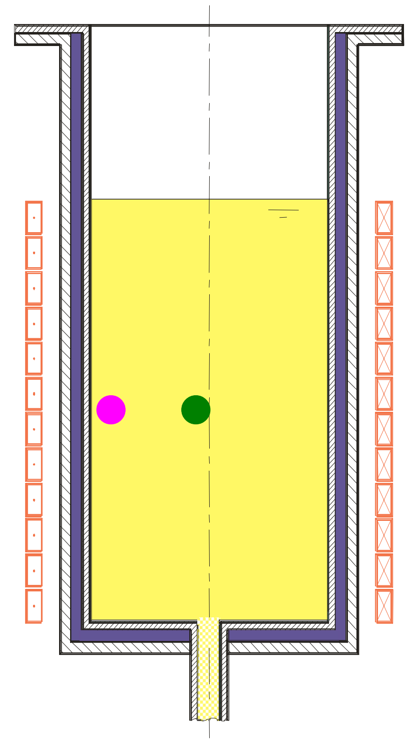
$Re \geq 10^4$

LES

- Large scales are resolved directly while only small scales are modelled
- Relatively high mesh resolution requirements
- Transient 3D simulations

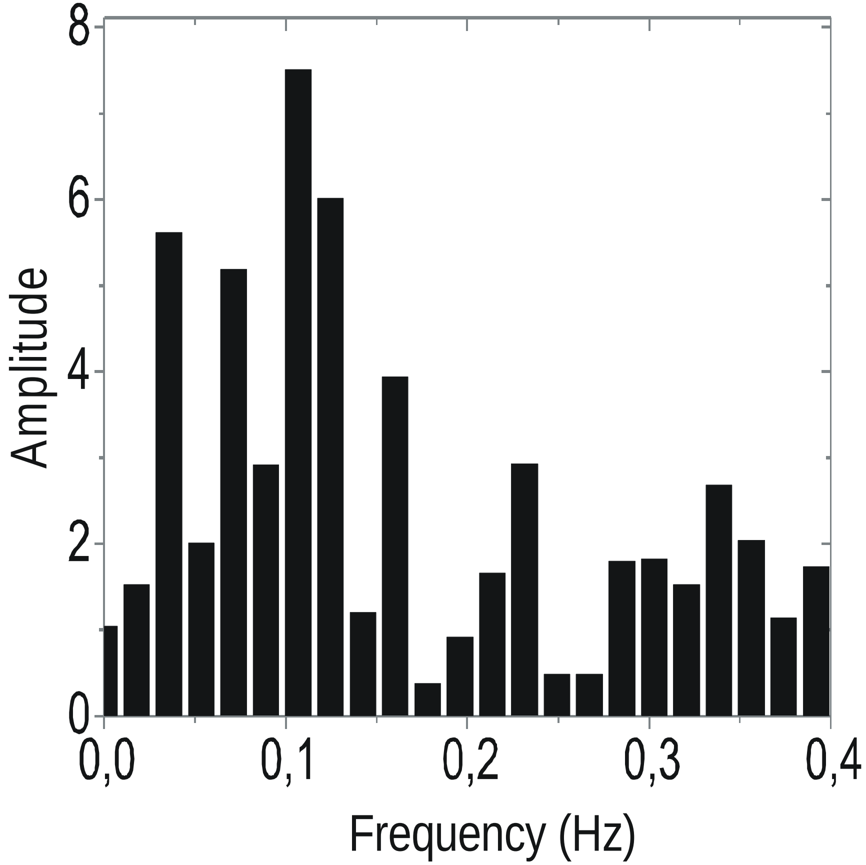
Calculated local flow velocity: (3D transient LES)



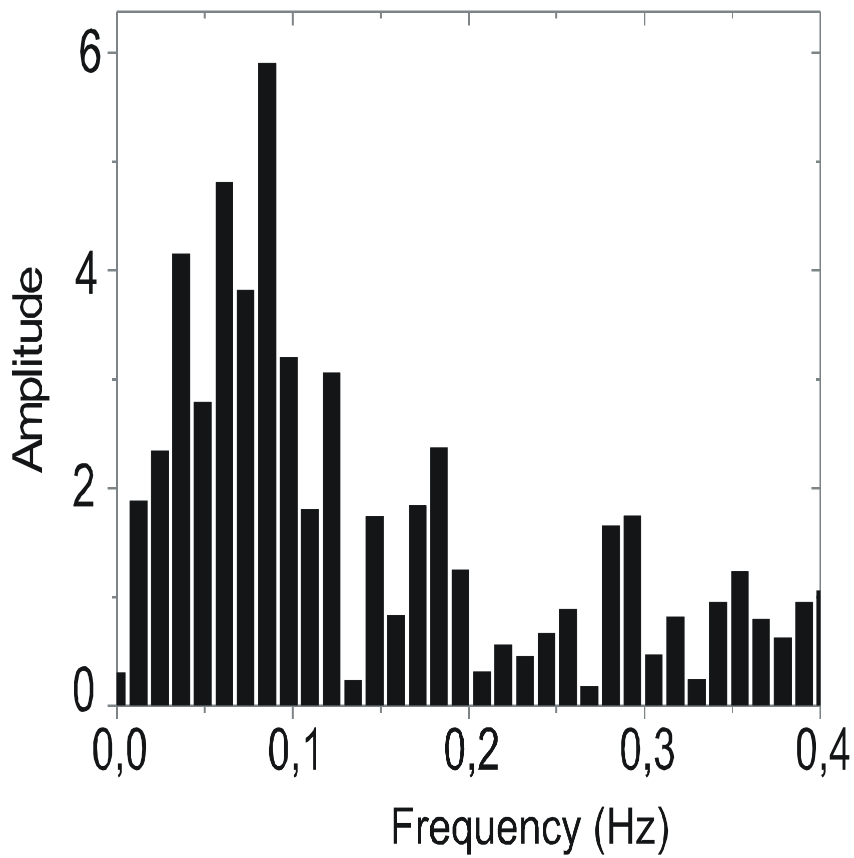


- ➥ **Low-frequency oscillations**
- ➥ **Oscillation period: appr. 10 sec**

Fourier analysis of the measured and calculated oscillations of the axial velocity components near the crucible wall between the main flow eddies

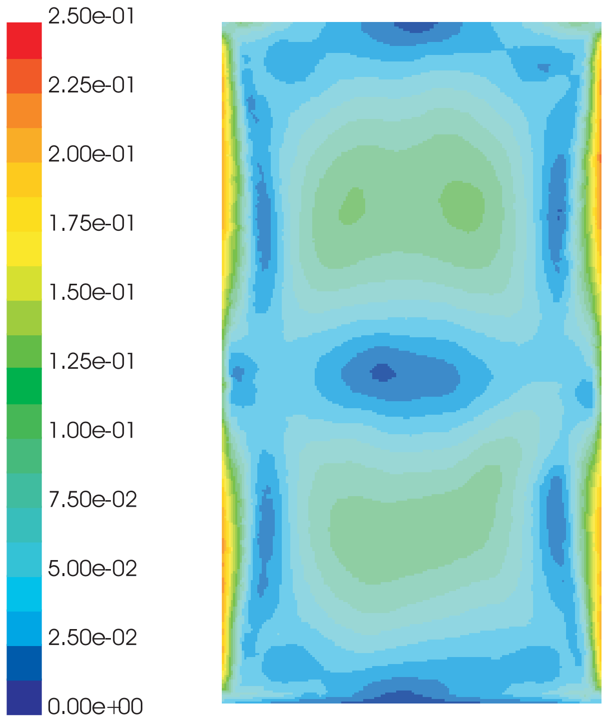


Measurement

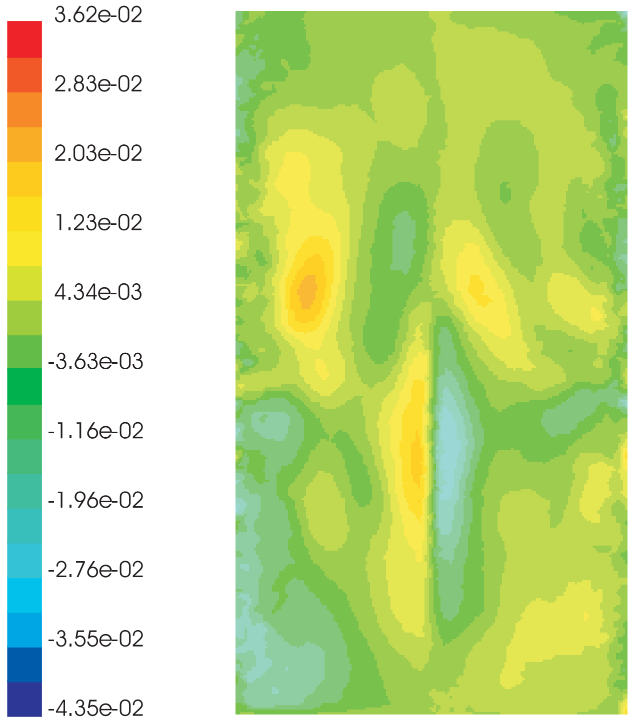


Calculation

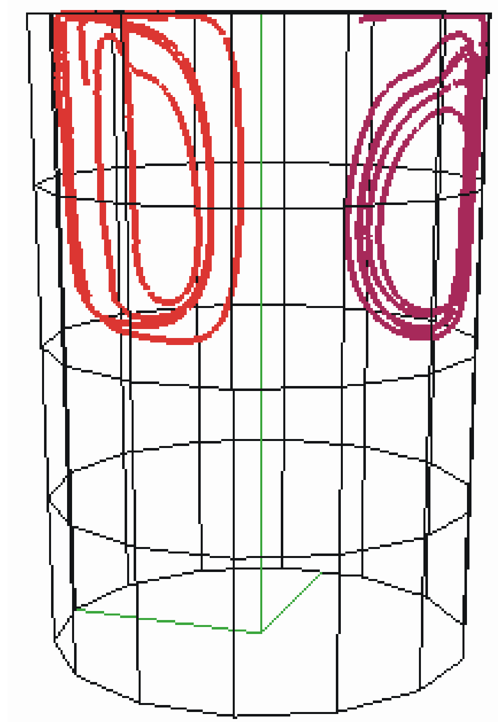
Long-time period averaged velocity field in the melt of the ICF (3D transient LES)



velocity magnitude

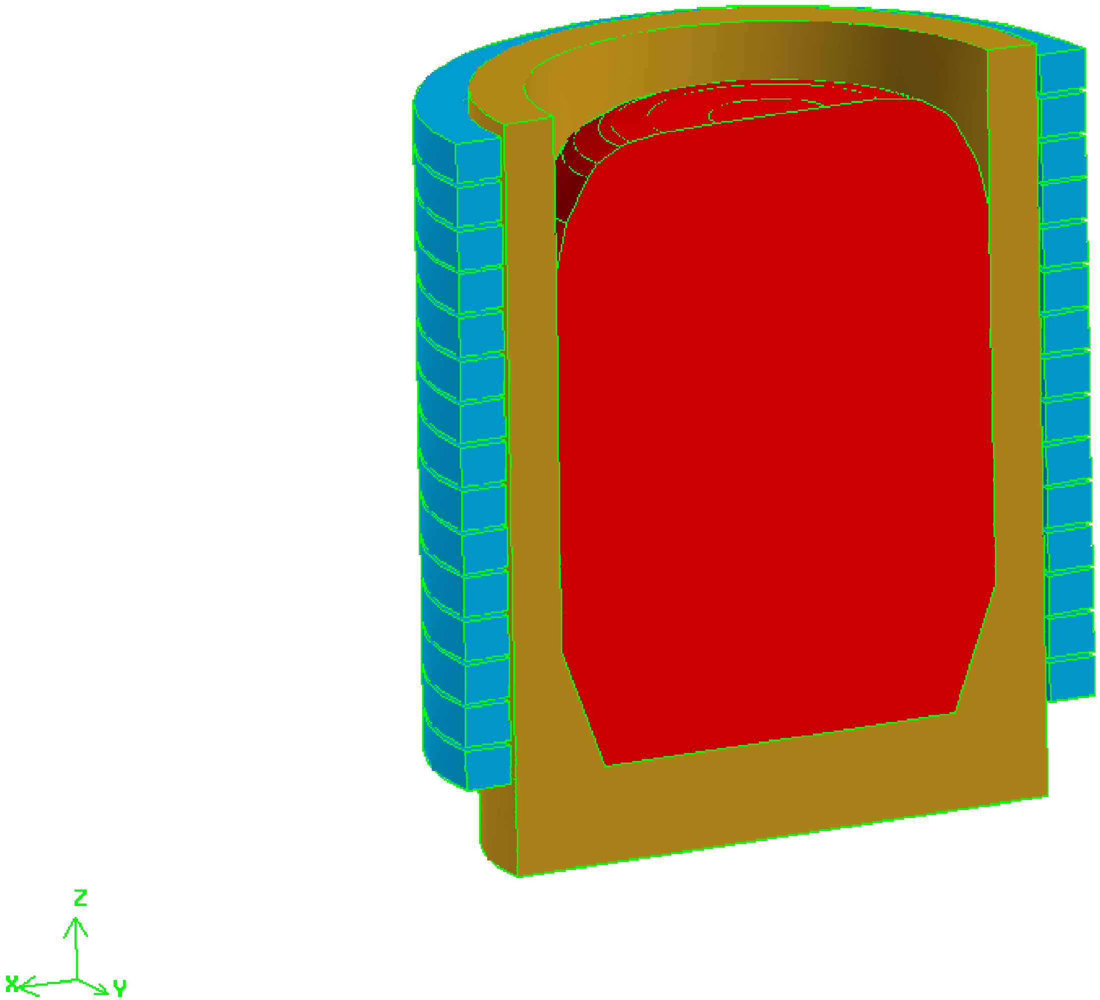


azimuthal velocity



particles trajectories

3D hydrodynamic model of an industrial induction crucible furnace



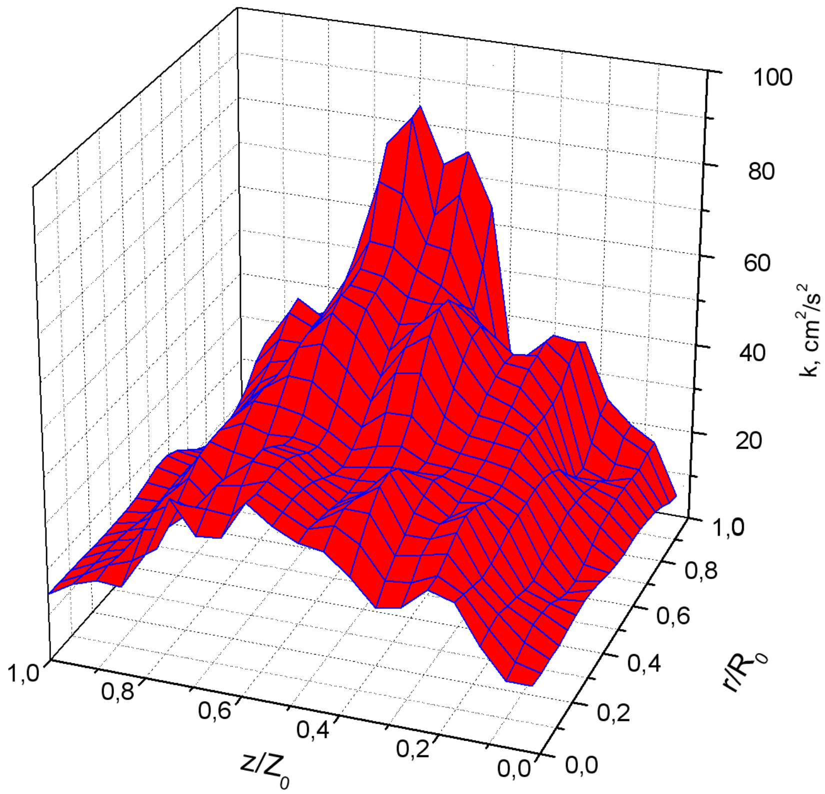
P = 4540 KW

H_{ind} = 1.33 m

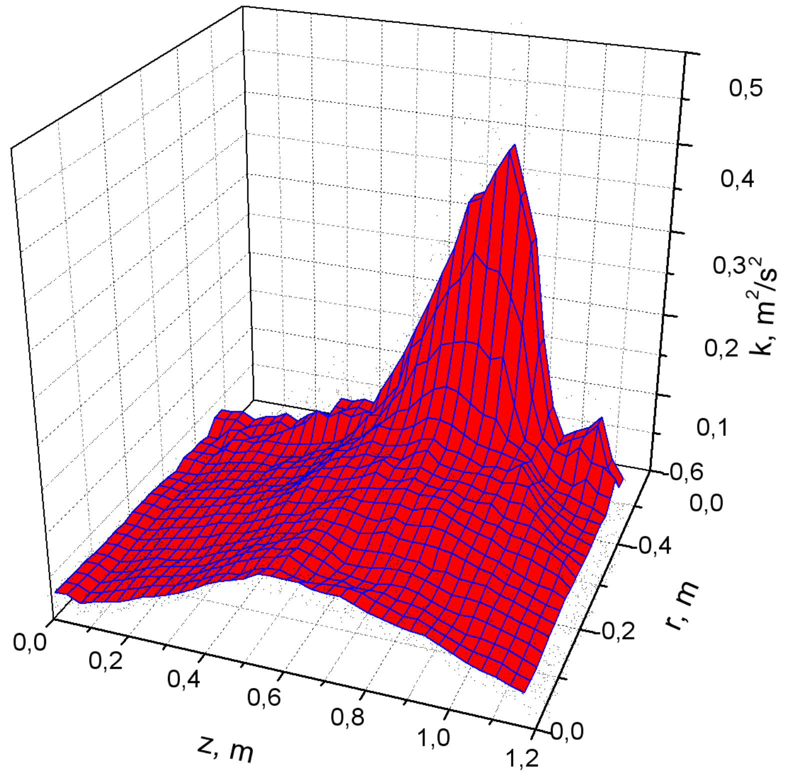
R_{cr} = 0.49 m

Filling level 90 %

Kinetic energy of the oscillations

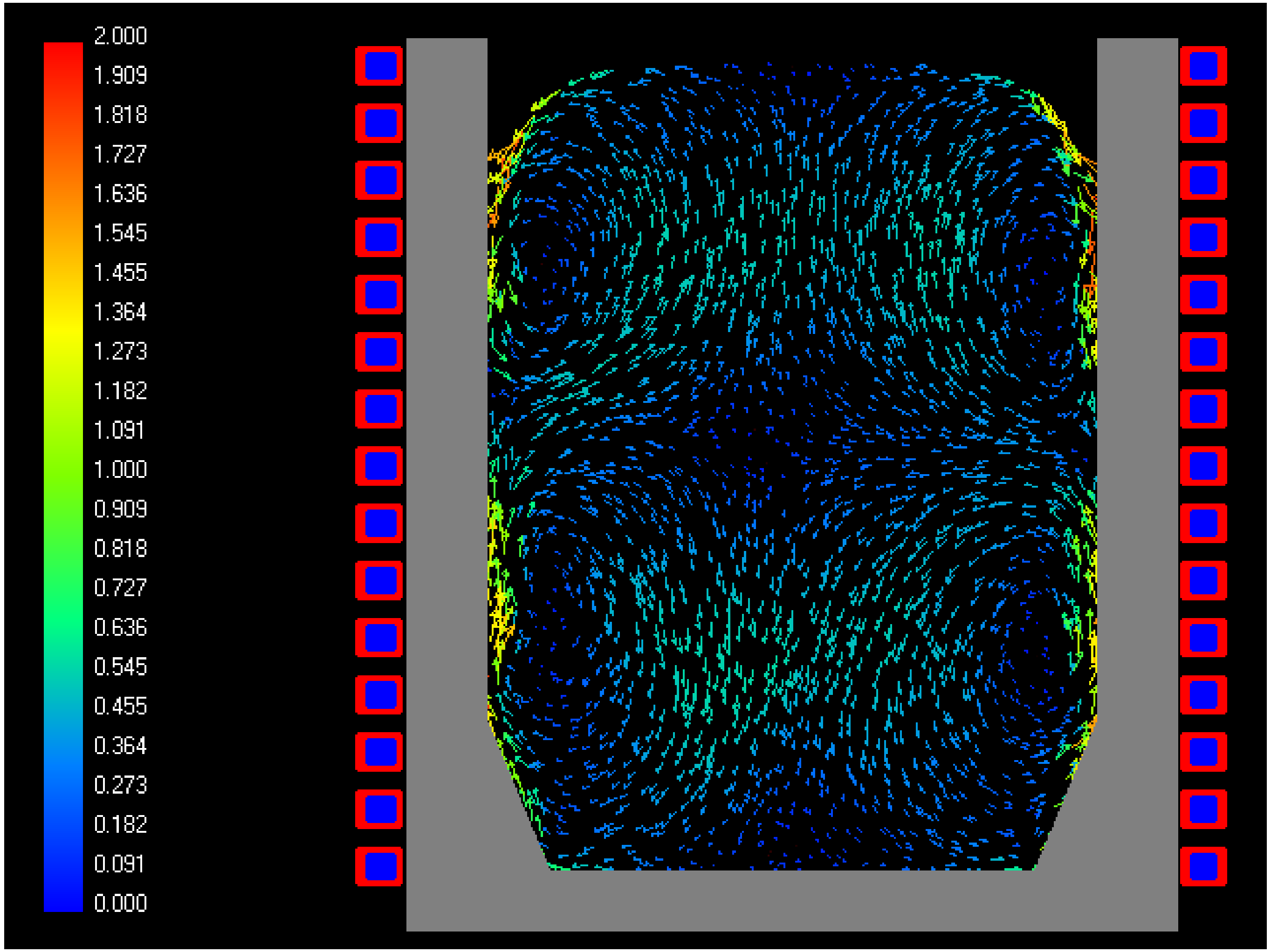


Experiment
(model furnace)

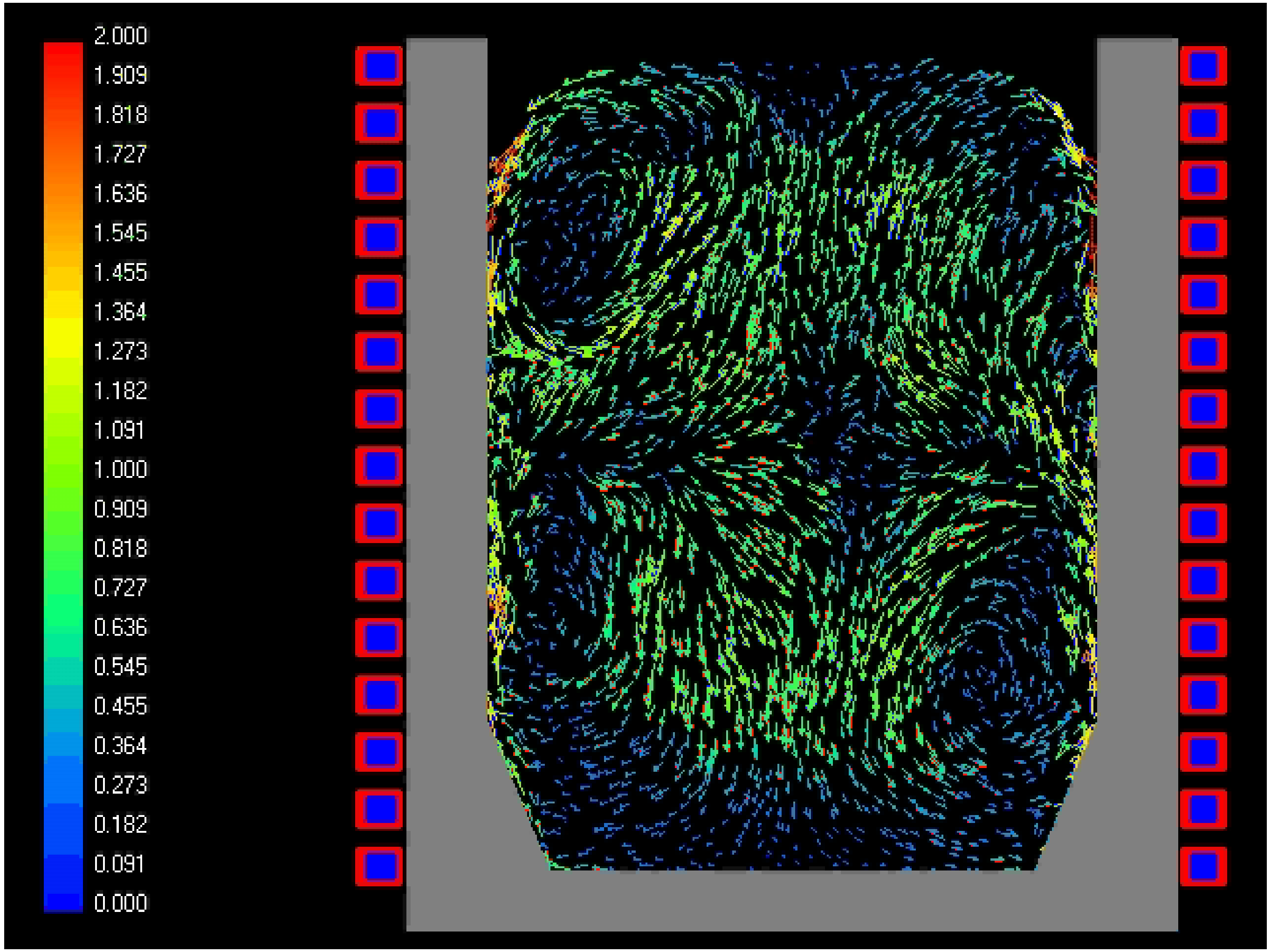


Calculations
(industrial furnace)

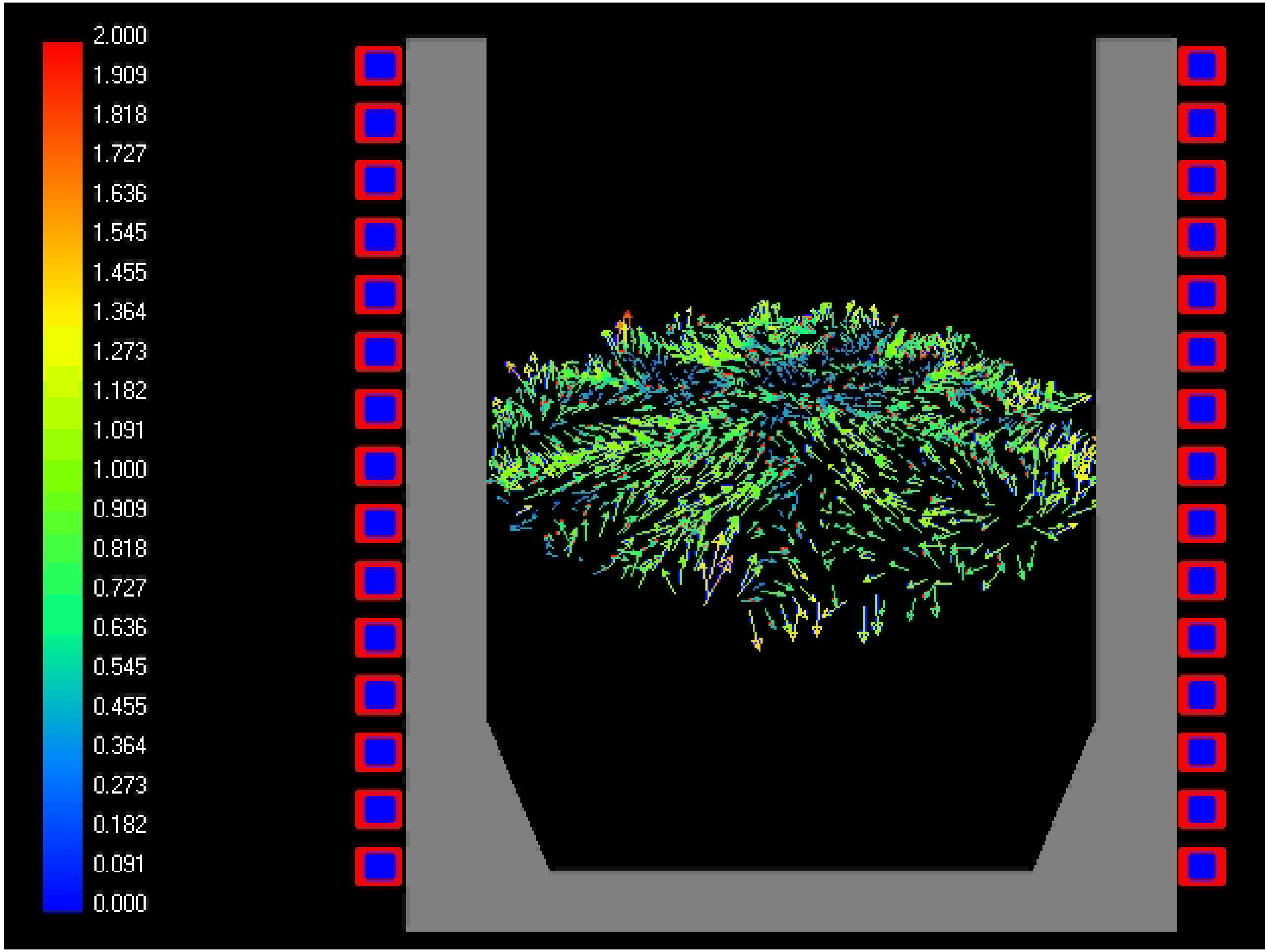
Time-averaged flow pattern [m/s]



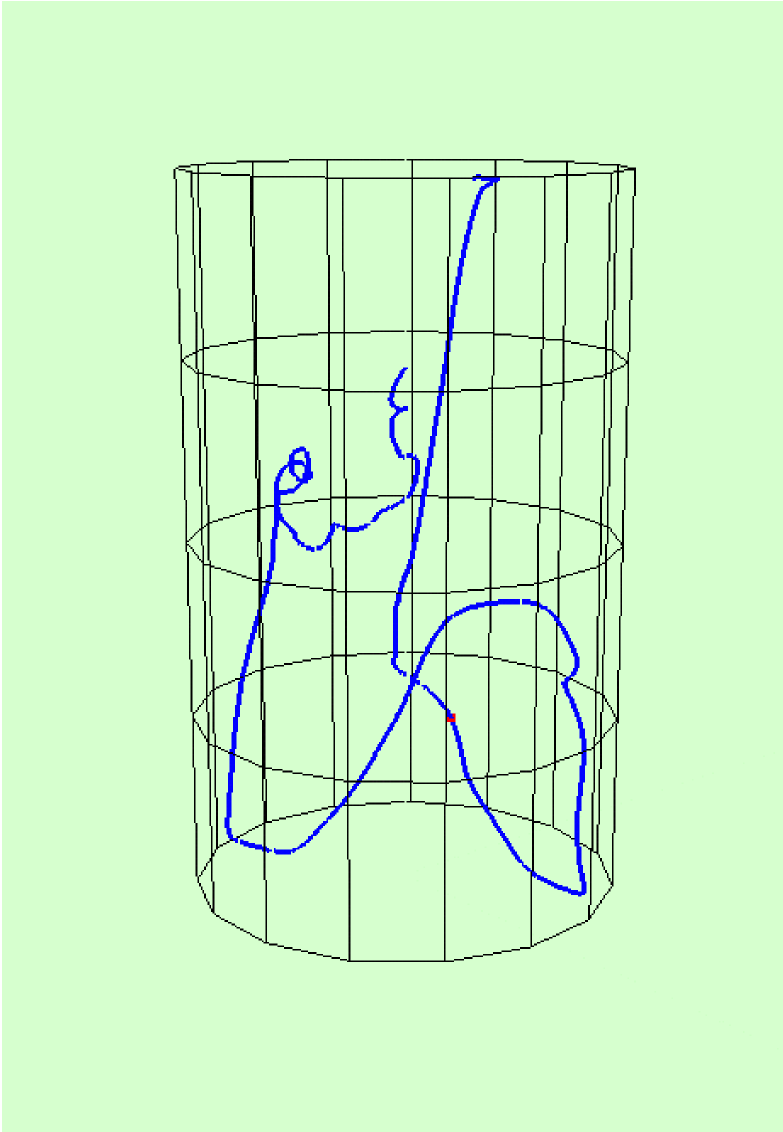
Transient flow development [m/s]



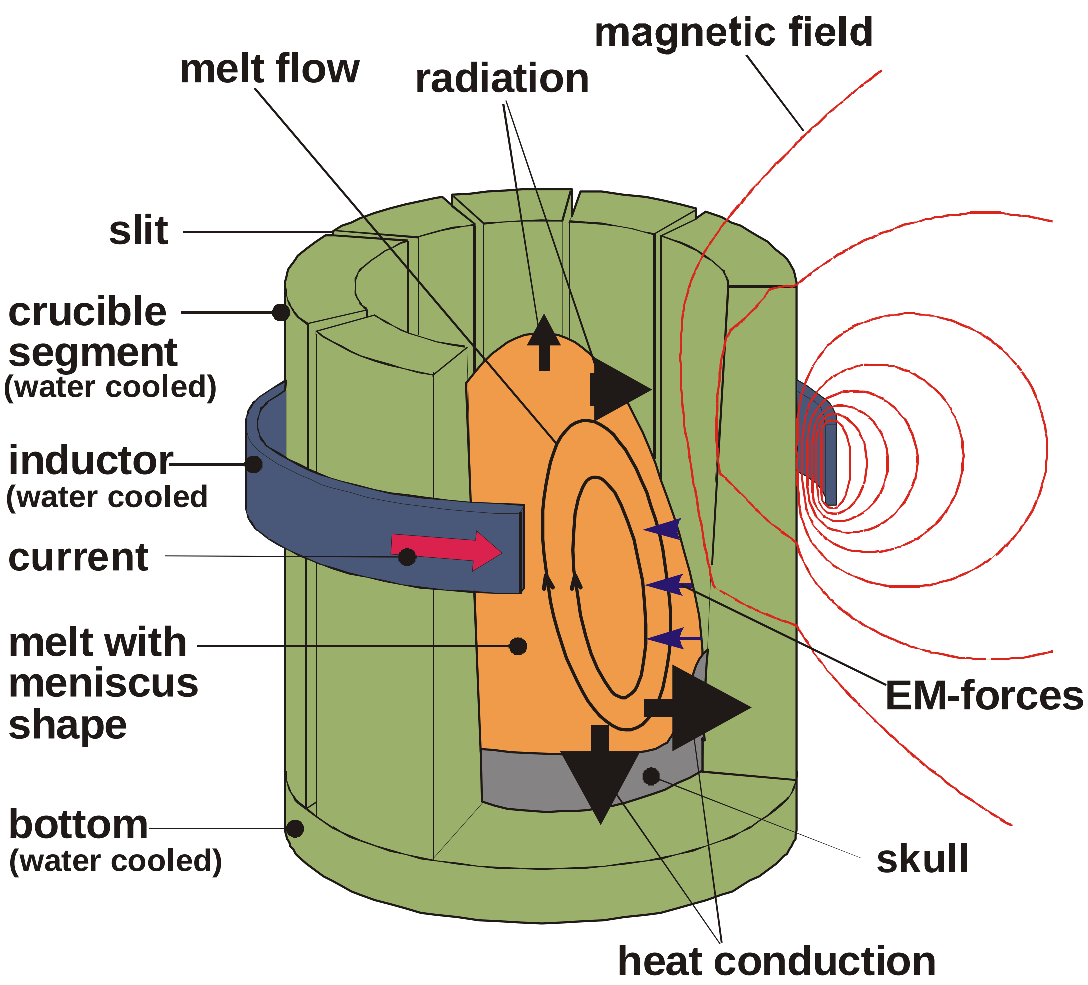
Transient flow development (cross-section) [m/s]



Calculation of the particle tracing in the melt of the ICF (3D transient LES)

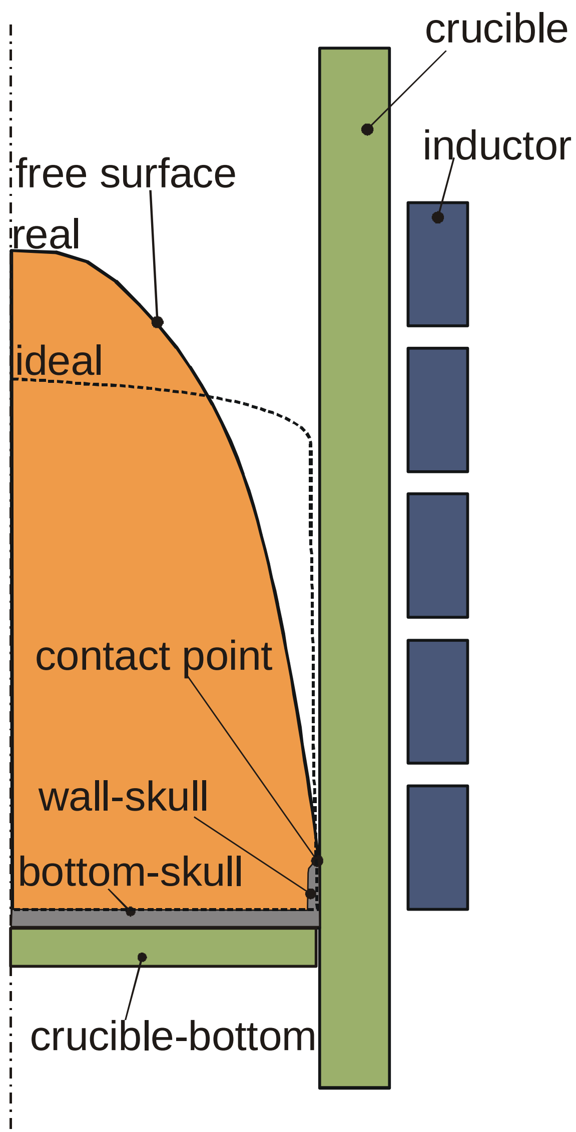


Features of the Induction Furnace with Cold Crucible



- slitted crucible to realize efficient electromagnetic transparency
- free melt surface, based on electromagnetic forces
- water cooled bottom and crucible segments leads to solid layer (skull)
- heat losses by radiation and conduction depending on the meniscus shape

Cold crucible induction furnace



Optimisation of electromagnetic and thermal parameters

- **Maximisation of the overheating temperature, which is the key parameter of the process**
- **Improvement of the total efficiency of process**
- **Reliable, reproducible and stable melting process**

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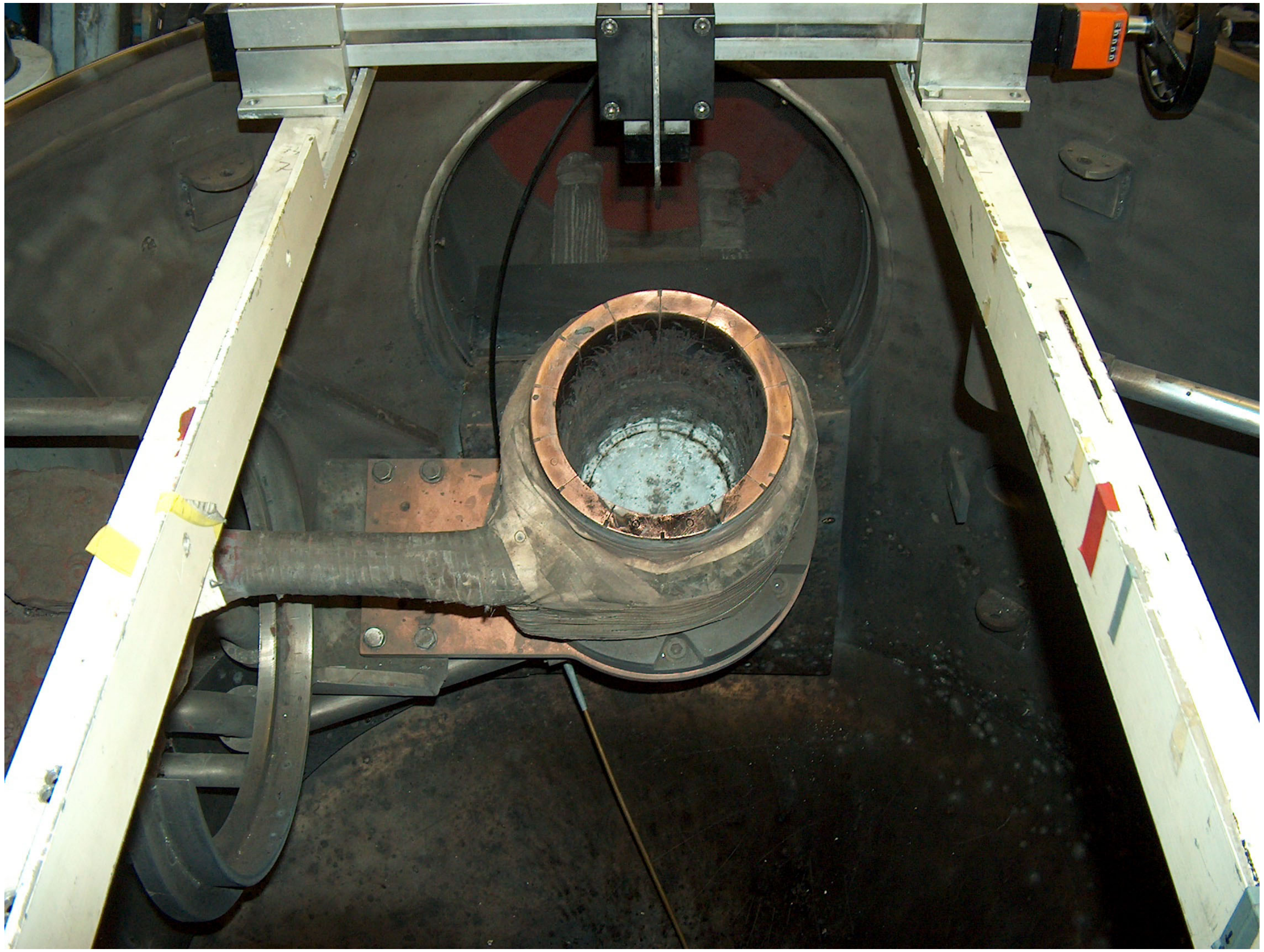
Experimental set-up for semi-levitation melting

R_c = 72.5 mm
H_i = 208 mm

5 coil turns

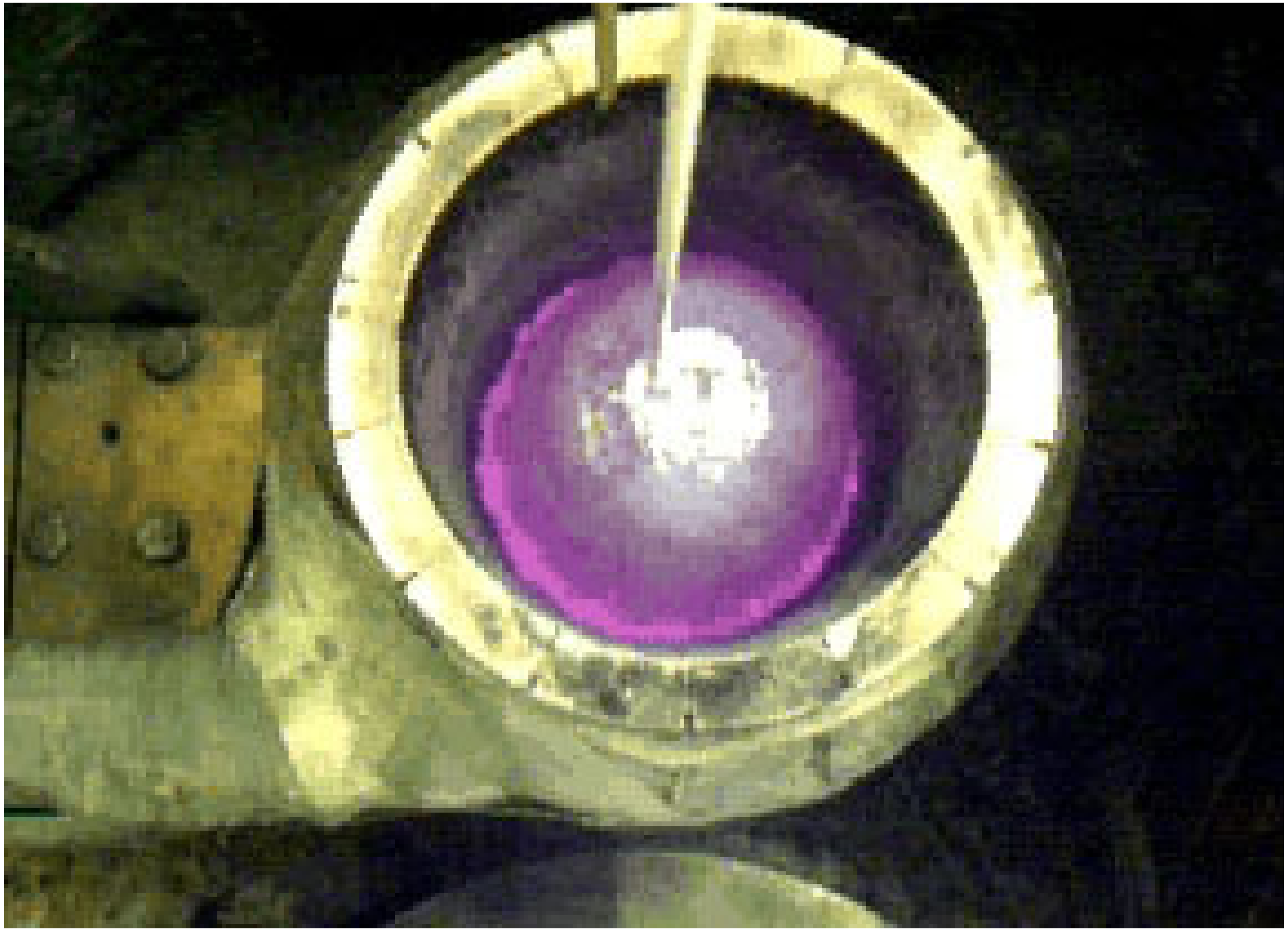
P = 200 kW
f = 9.2 kHz

T = 660-720°C

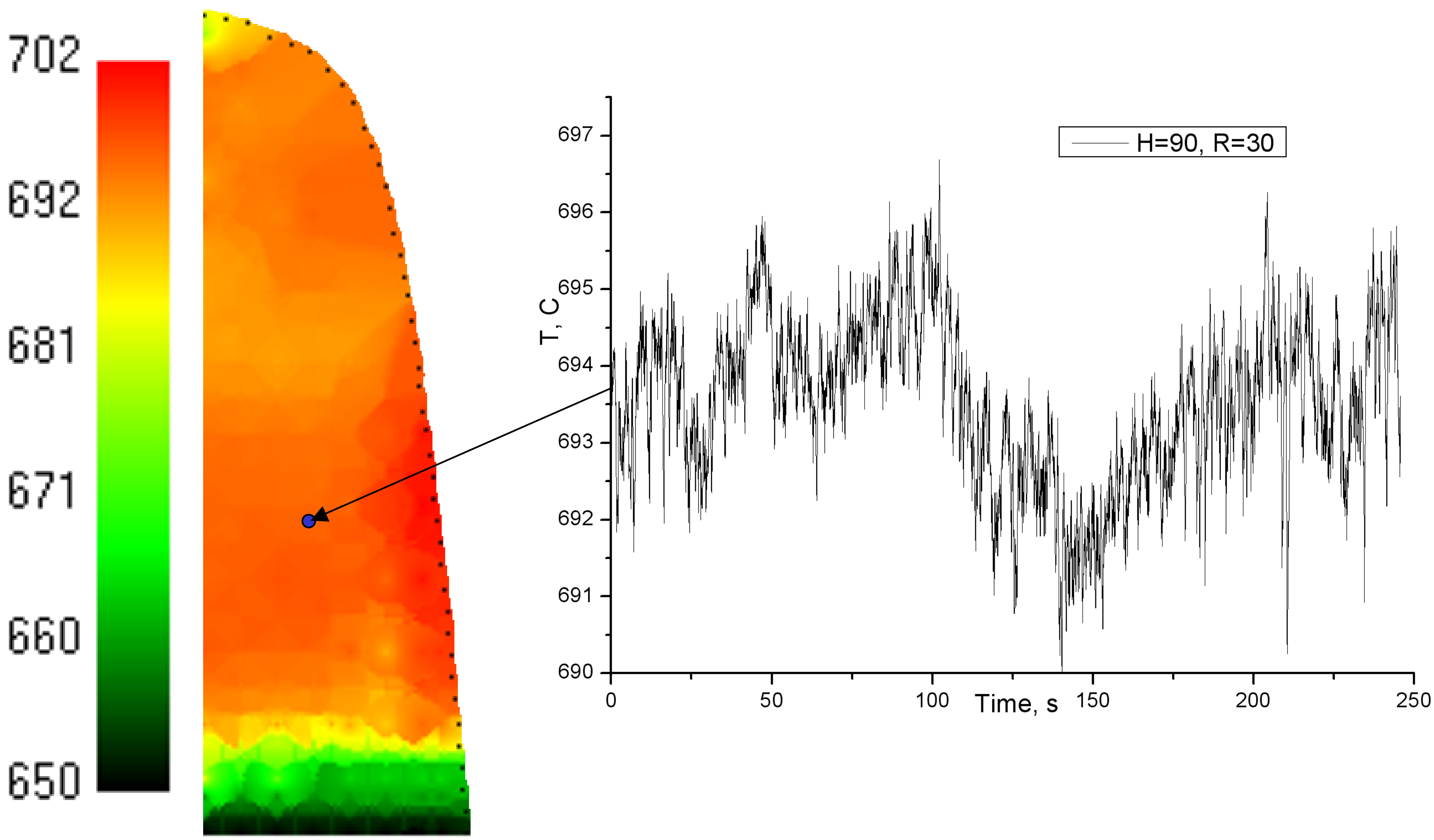


Melting process of Aluminium

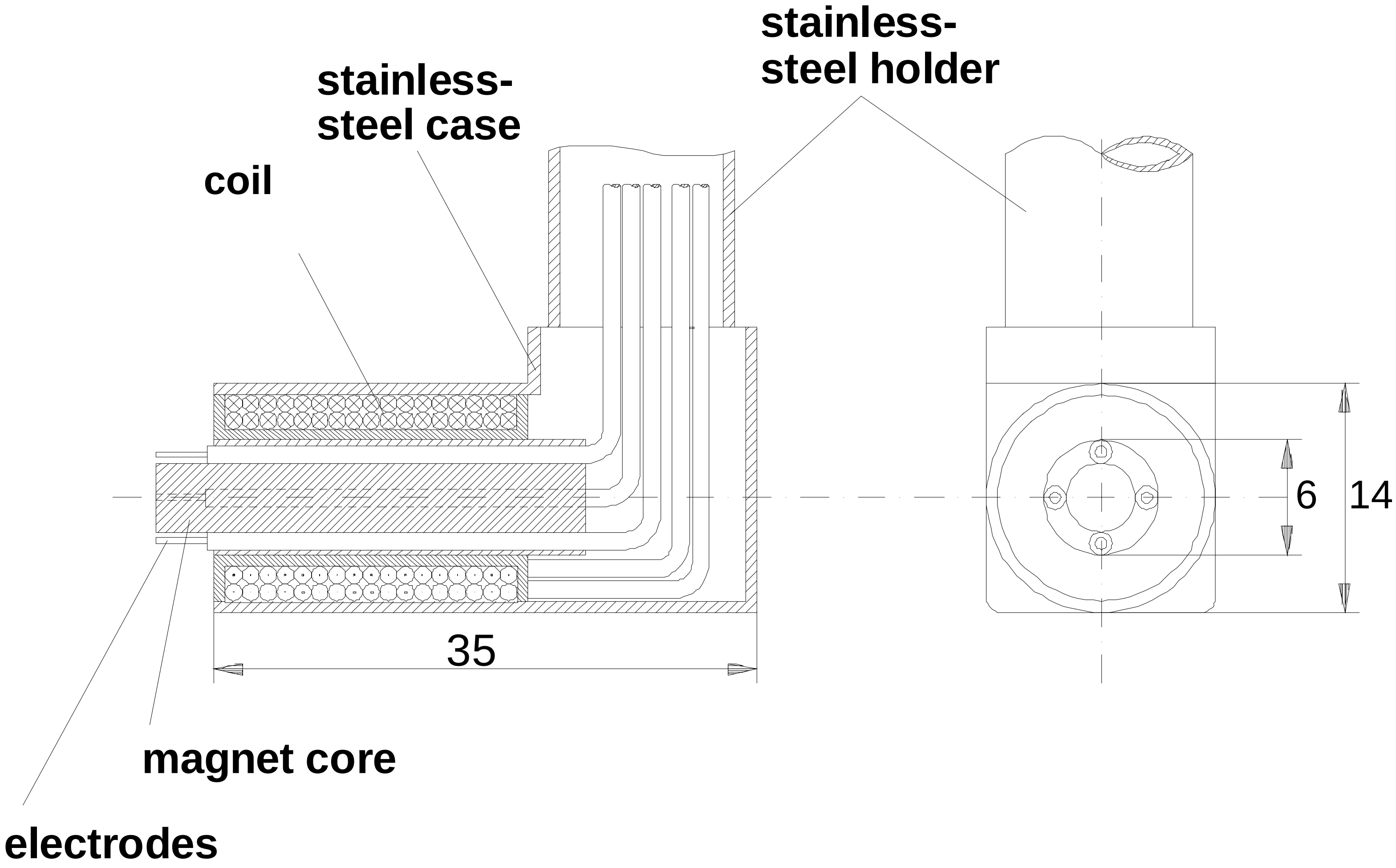
Temperature measurements in Aluminium



Measured temperature field in Aluminium



Melt flow measurements in Aluminium with the electromagnetic velocity probe



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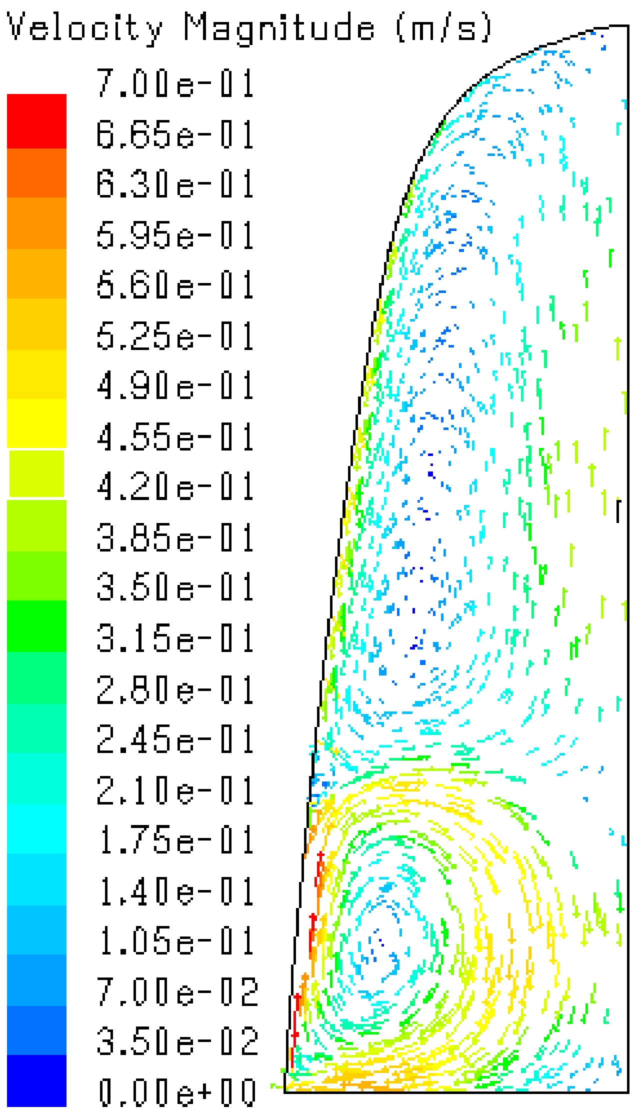
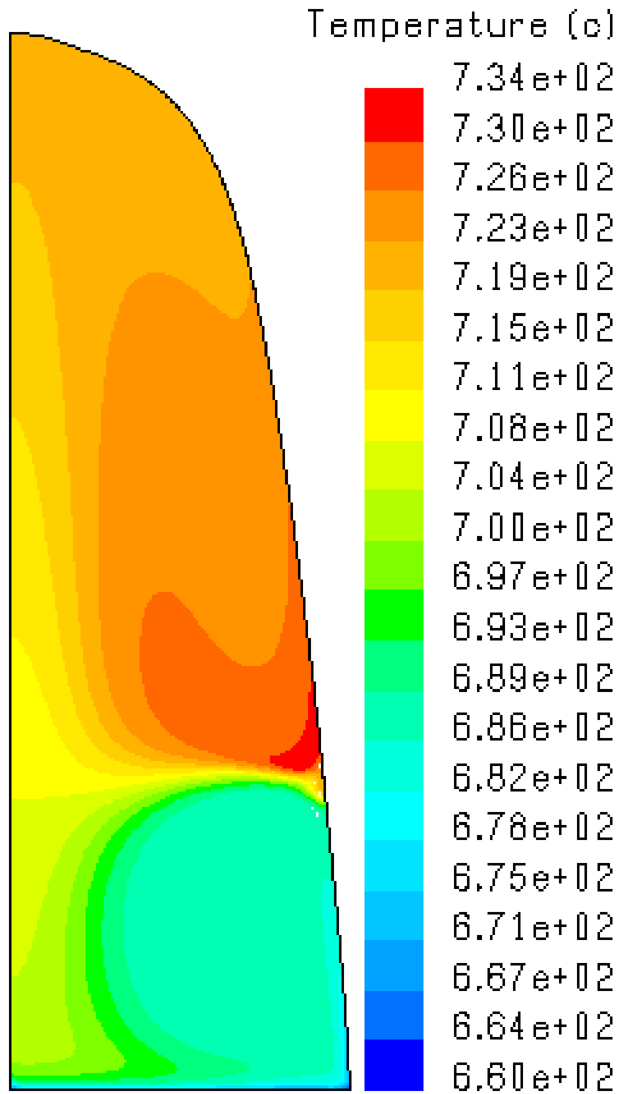
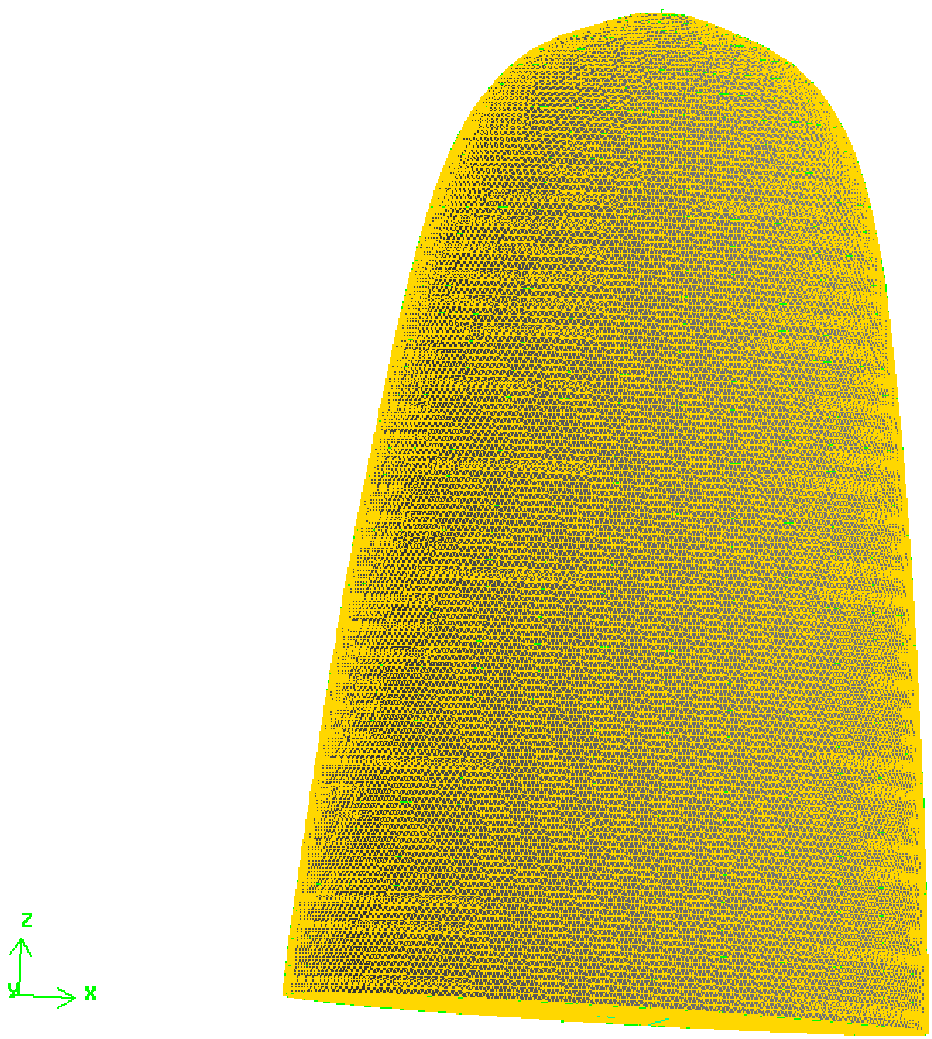
Flow pattern and temperature distribution simulated with 2D RNG k-ε turbulence model





3D LES-model for Aluminium melting



$\sim 3.8 \cdot 10^6$ elements

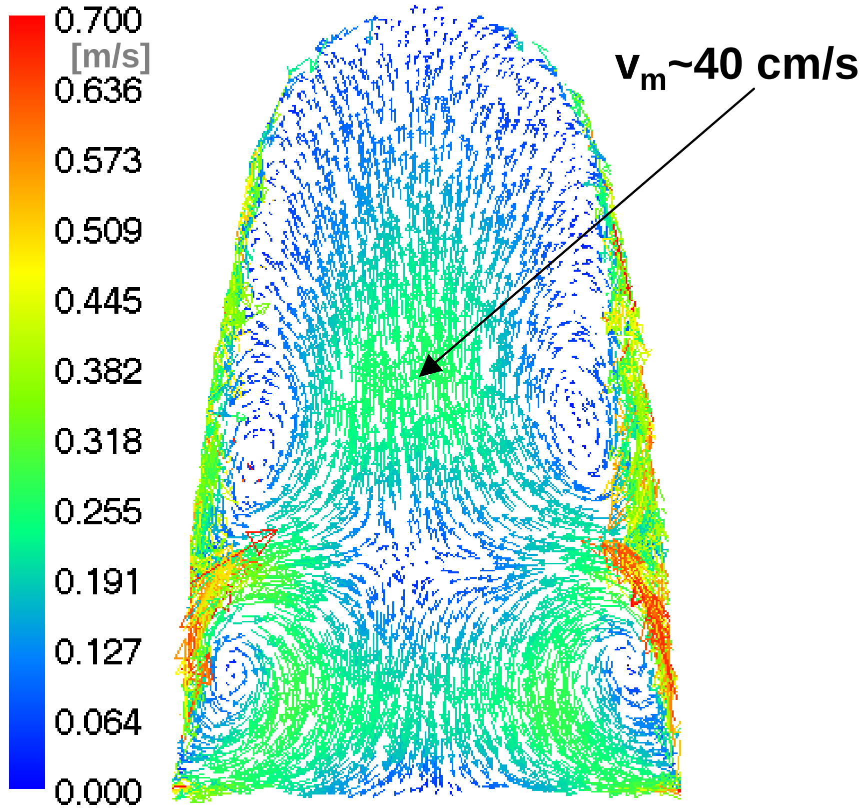
Time step 10 ms

Smagorinsky-Lilly subgrid viscosity model

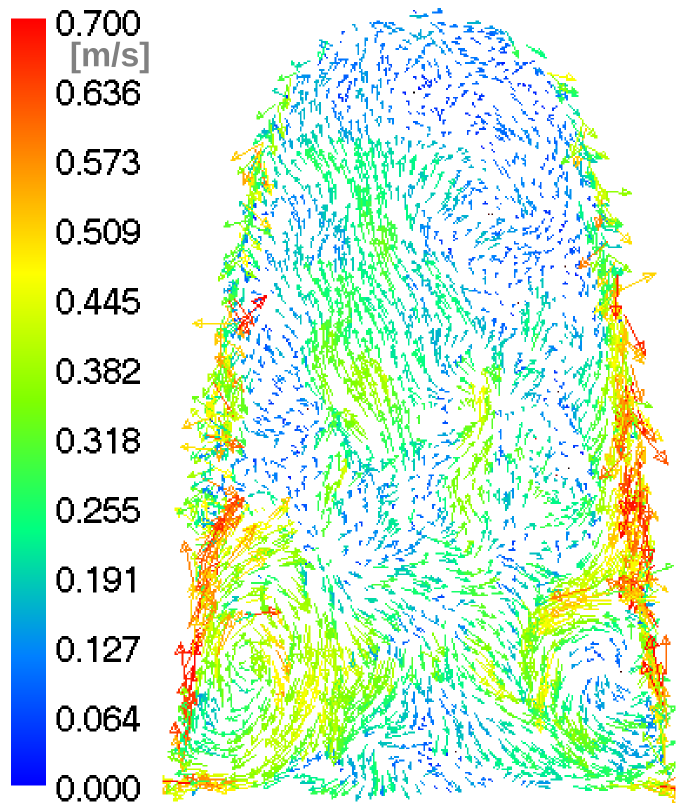
Parallel computations with FLUENT 6.1 software at the HLRN*-system

*HLRN – scientific supercomputer network of North Germany

Results of 3D transient LES modeling



Time-averaged flow pattern



An intermediate flow pattern

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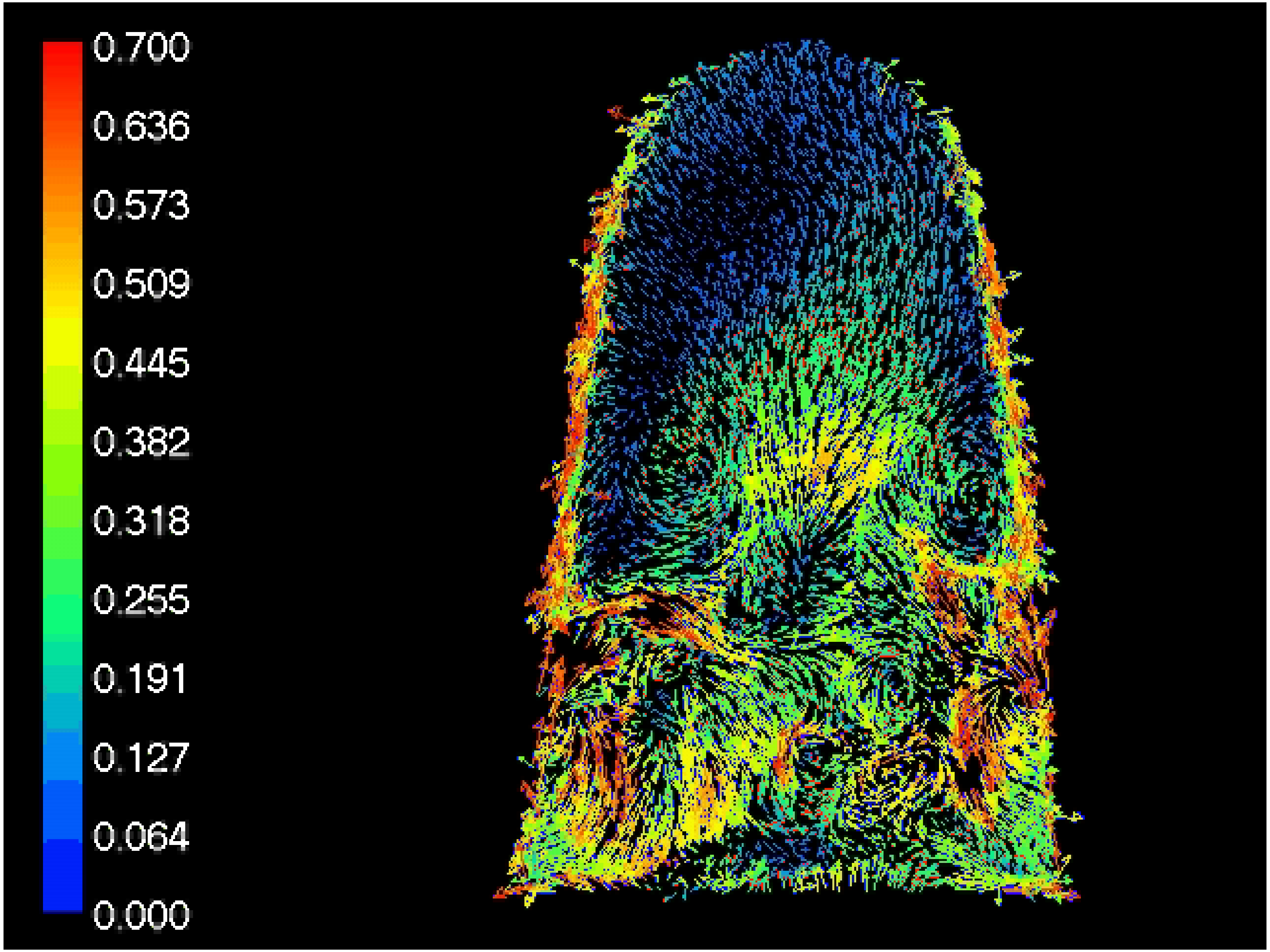
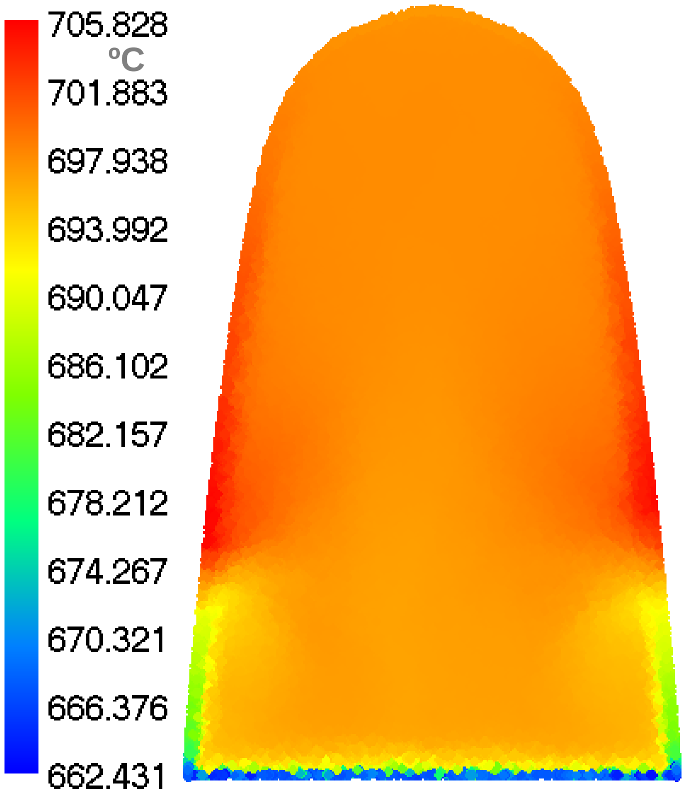
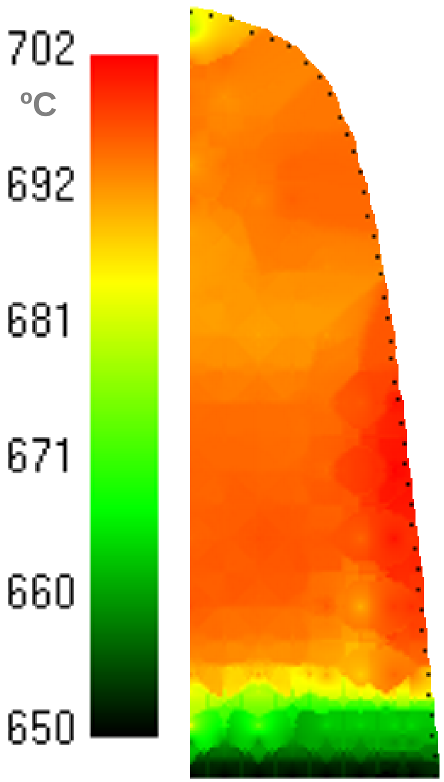
Results of 3D transient LES modeling



Results of 3D transient LES modelling

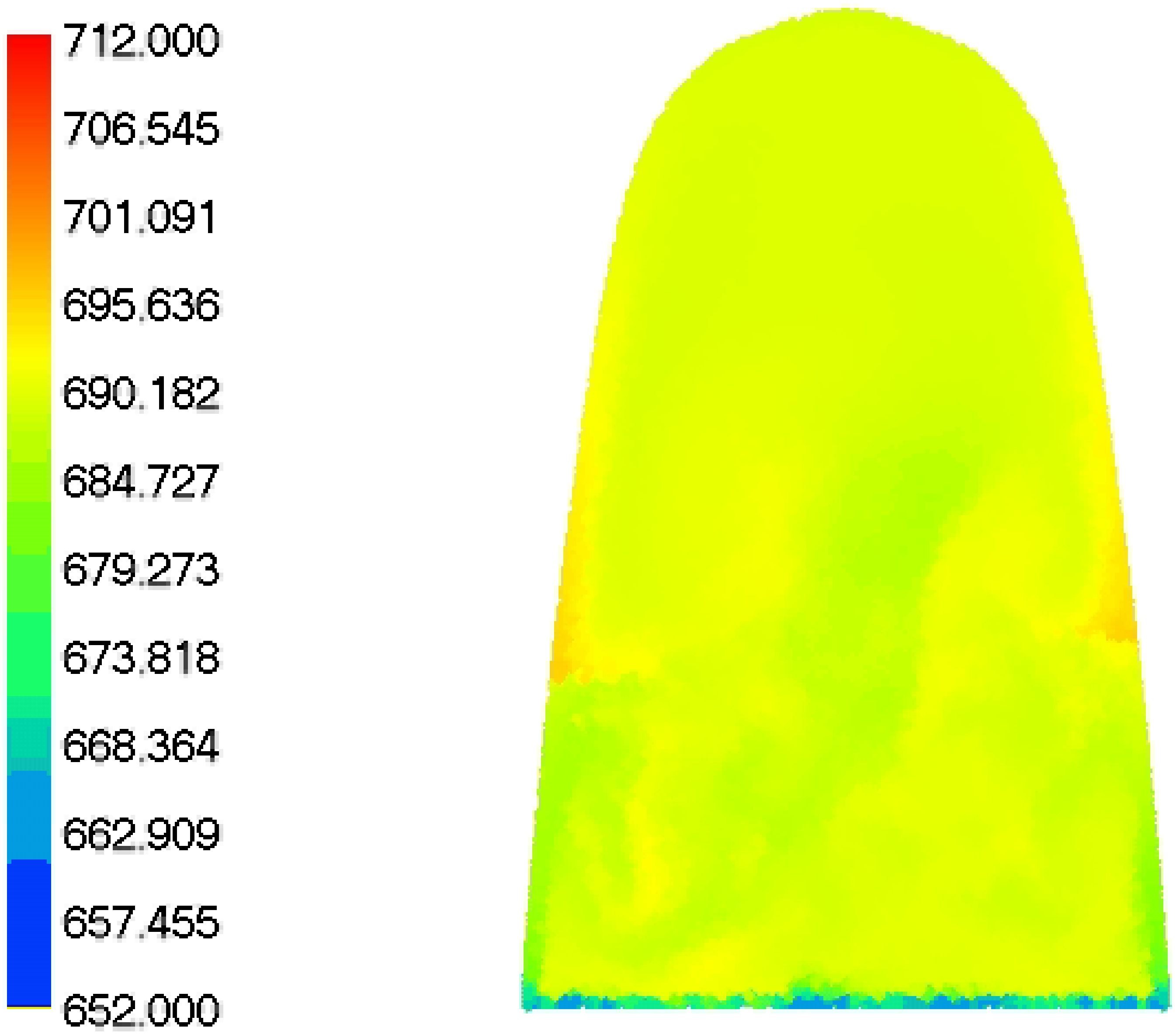


Time-averaged temperature distribution

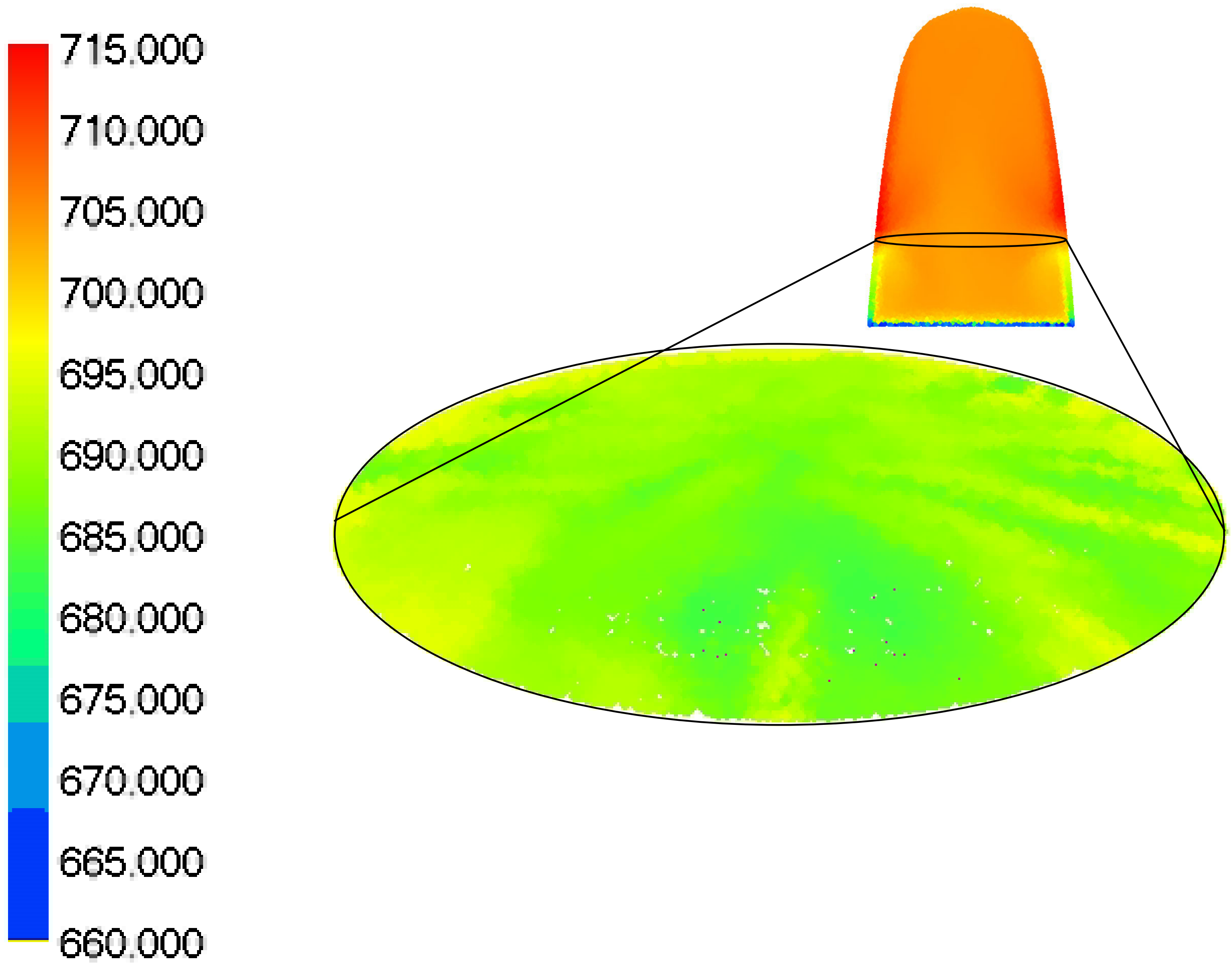


Measured temperature distribution

Results of 3D transient LES modelling



Results of 3D transient LES modelling



Conclusions

- **Heat and mass transfer processes in the melt of induction furnaces are significantly influenced by large scale low-frequency oscillations of the recirculating flow main eddies**

- **Comparison of the LES modelling results with experimental results show good agreement**

- **3D-transient LES is a reliable numerical tool to simulate the turbulent melt flow with in-stationary low-frequency flow oscillations in induction melting installations**