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Modelling of an ensemble averaged electric arc in a laboratory-scale electric arc furnace

Comsol European Conference:
Munich, 25-27 October 2023

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The project has received funding from the European Union's Horizon 2020 research and innovation program under Grant Agreement N°869268.

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Outline

I. Background – Motivations – Objectives

II. Modelling and Numerical Model

III. Main Results

IV. Conclusions – Perspectives

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Before starting, who we are… www.simtecsolution.fr

SIMTEC : Fundamentals

- French Numerical modelling consultancy
- Leader in France of the COMSOL Certified Consultants, key partner worldwide
- 7 members Eng.D. + Ph.D.
- Main partners:
  - big international companies
  - laboratories
- Involved in the Research projects like EU FP (SHARK, SisAl)/ PhD supervision

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Background

→ EU project SisAl Pilot

→ Optimization of the silicon production in Europe

→ Recycling materials and using a carbon-emission friendly technology

→ Silicon production experiments are conducted on laboratory and pilot scales

→ Different types of furnaces

→ The process optimisation relies on both the experiments and the numerical modelling

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Motivation

→ Optimize furnace operation: predict possible thermal damages or heat losses

→ Increase the raw material melting efficiency

Objectives

→ Simulate the furnace preheating and the initial slag melting in a laboratory-scale electric arc furnace (EAF)

  → Perform an ensemble averaging of the electric arc effects (radiation, heat source, Lorentz force)

  → Model the mass, momentum, and heat transport with phase change

→ Validate the model against available experimental data

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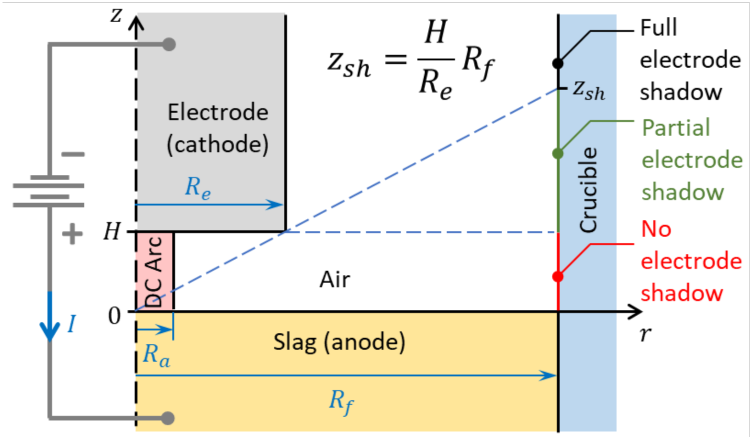
Modelling approach

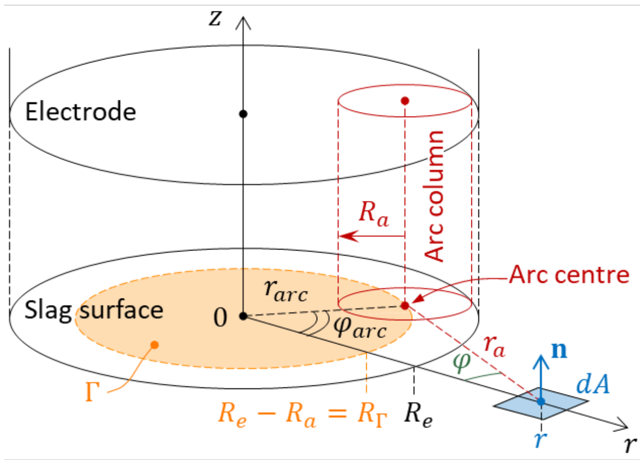
→ Make use of the 0D Channel-Arc model [1]

→ Arc temperature and voltage drop



→ Compute instantaneous arc effects (radiation, heat source, Lorentz force) relative to the instantaneous arc position

→ Compute ensemble-averaged arc effects for a uniform probability of the arc position



→ Use COMSOL Multiphysics® to simulate heat, mass and momentum transport in EAF

[1] G. A. Saevarsdottir, H. L. Larsen and J. A. Bakken, "Modelling of industrial ac-arcs. High Temperature Material Processes," *An International Quarterly of High-Technology Plasma Processes*, no. 3(1), 1999

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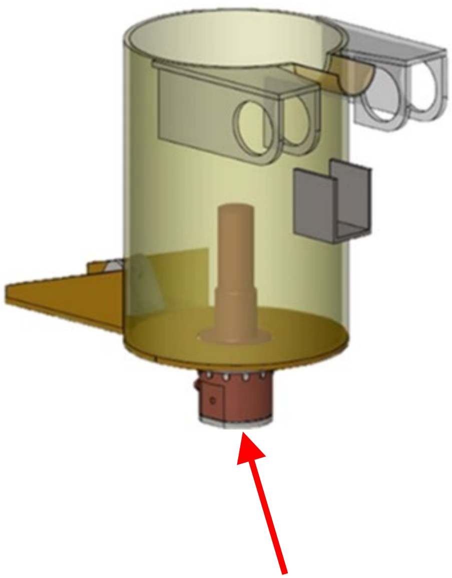
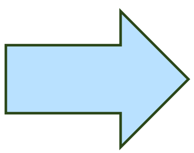
Geometry and materials

Shell geometry of the Electric Arc Furnace

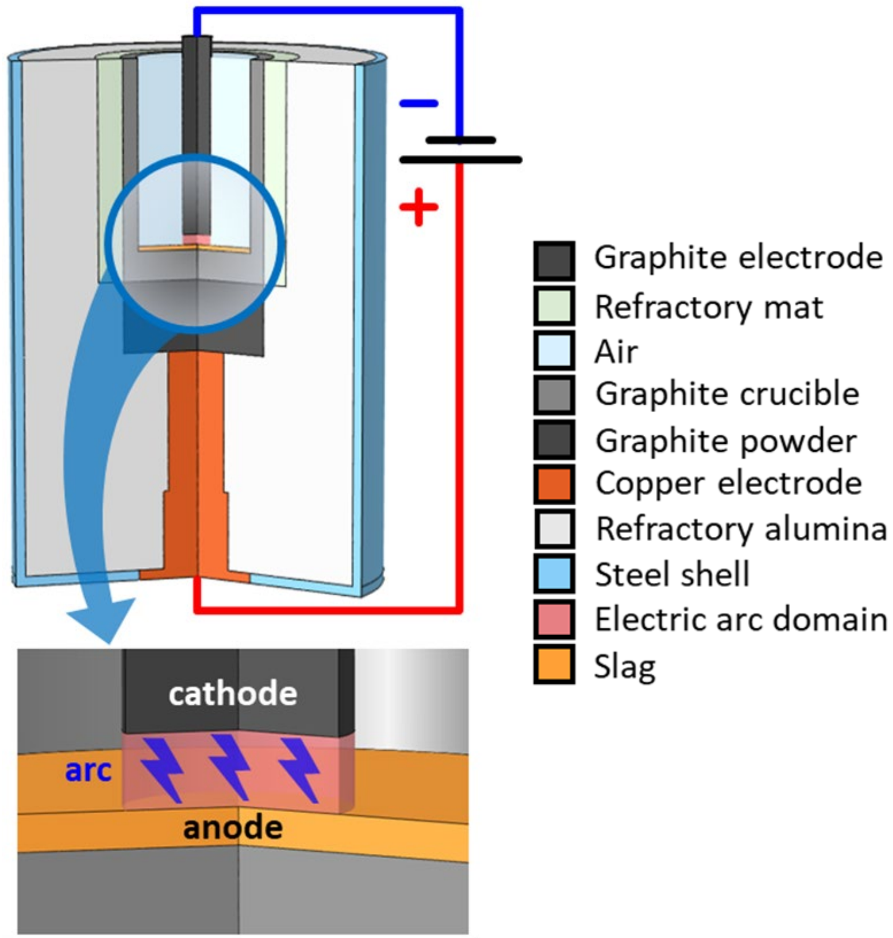


Water cooled copper electrode



Axial symmetry assumption

Model geometry



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Geometry and materials

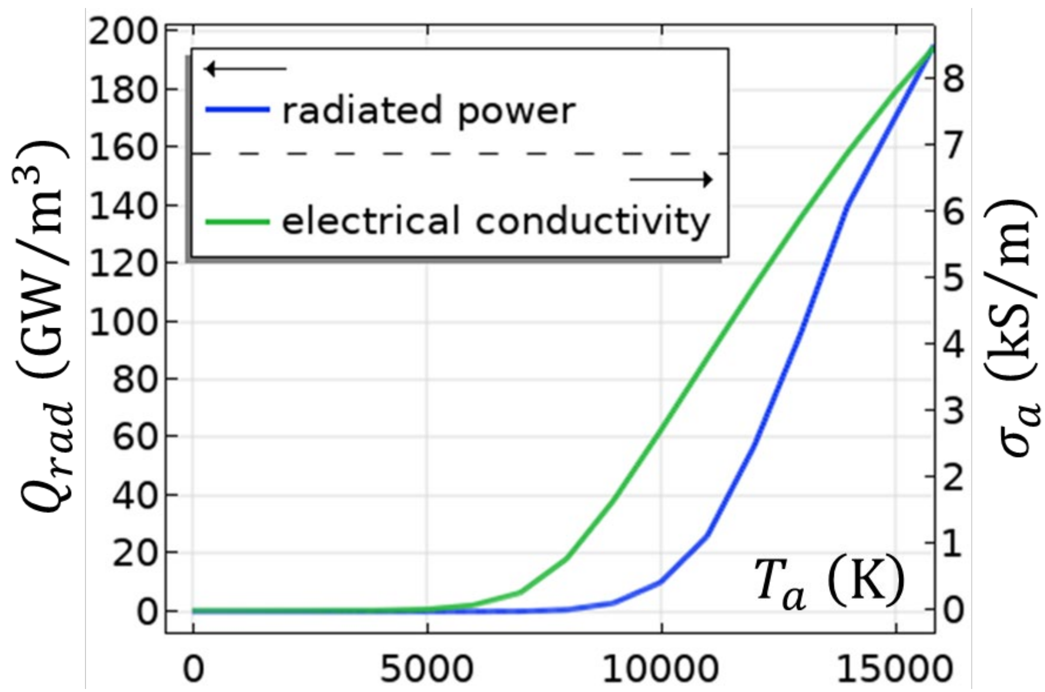
Slag properties

→ Slag properties as functions of its composition and temperature are modelled with different models from literature, including the Ken Mills model [2]

Other materials

→ Properties from literature or from the material supplier

Air plasma properties [3]



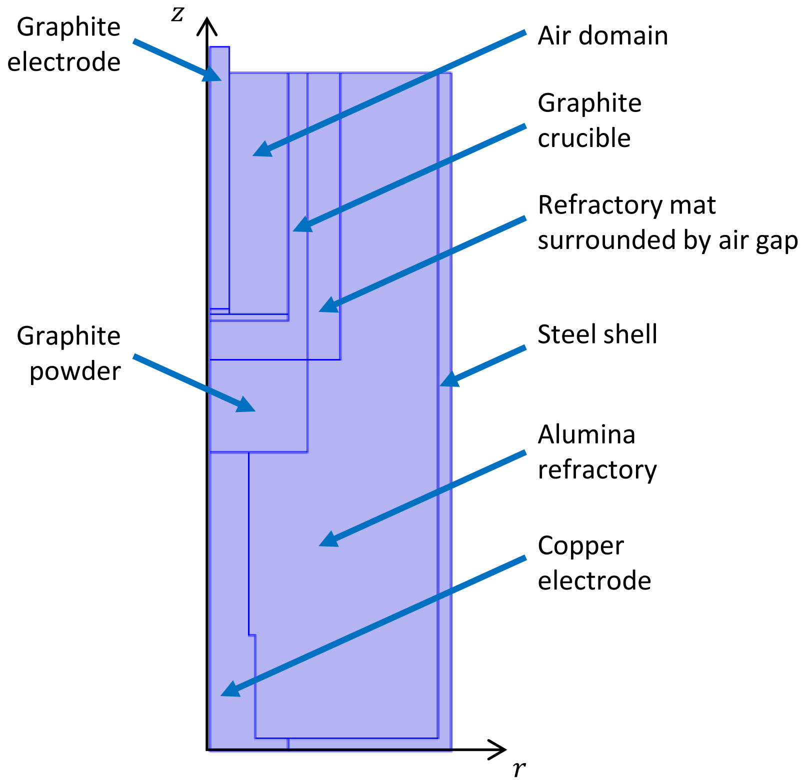
[2] K. C. Mills, L. Yuan and R. T. Jones, "Estimating the physical properties of slags.," *J. S. Afr. Inst. Min. Metall.*, vol. 111, no. 10, pp. 649-658, 2011.
[3] Q. G. Reynolds, *Mathematical and computational modelling of the dynamic behaviour of direct current plasma arcs, PhD Thesis*, University of Cape Town, 2009.

Physics

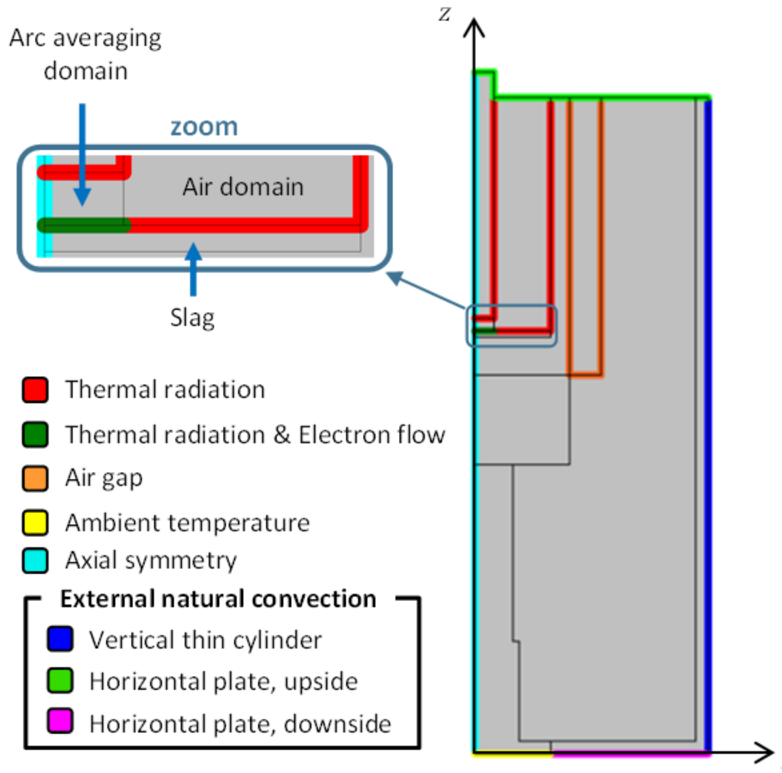
→ Heat Transfer in Solids and Fluids with phase change

→ Surface-to-Surface Radiation

Domain



Boundary conditions



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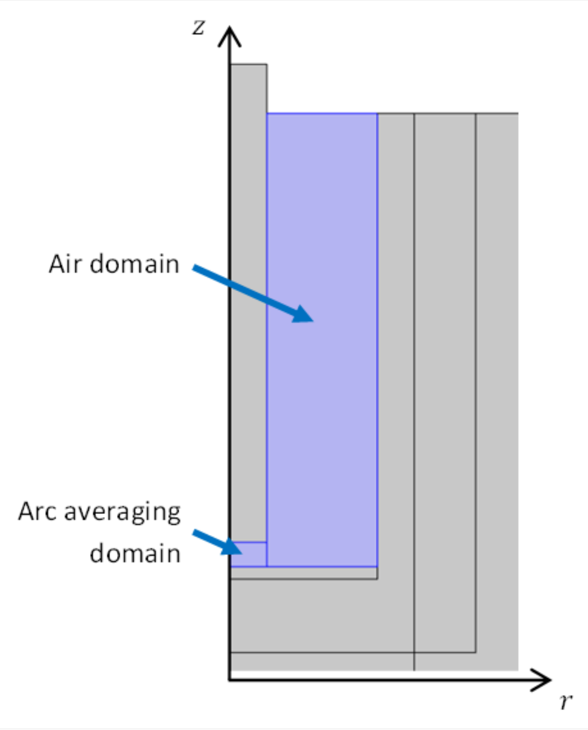
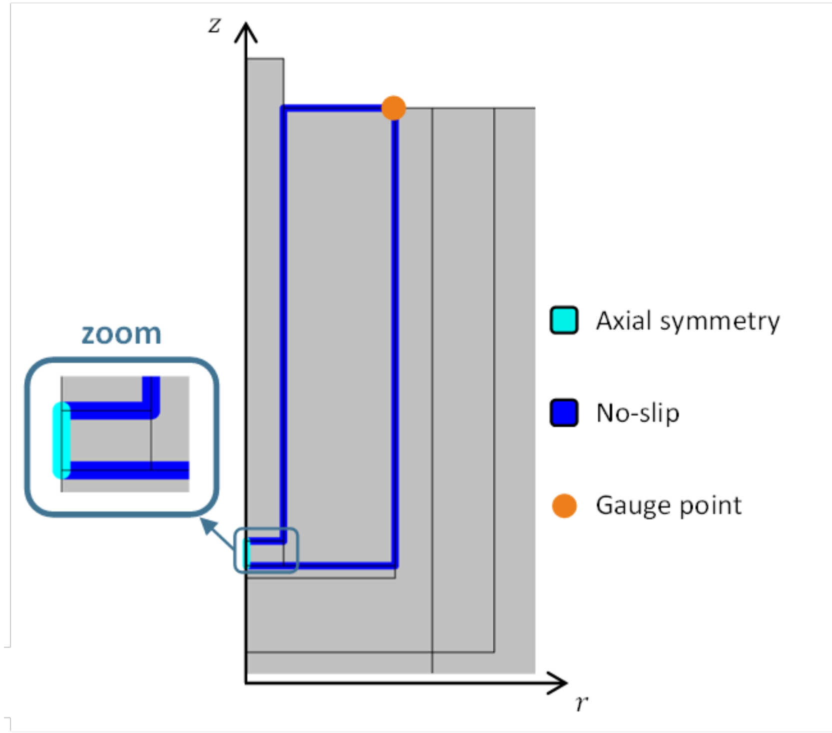
Physics

→ Turbulent Flow k-ε model in gas

Domain



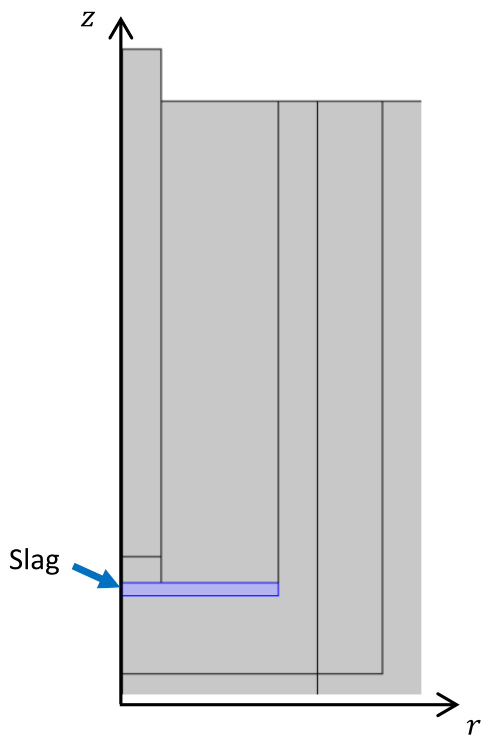
Boundary conditions



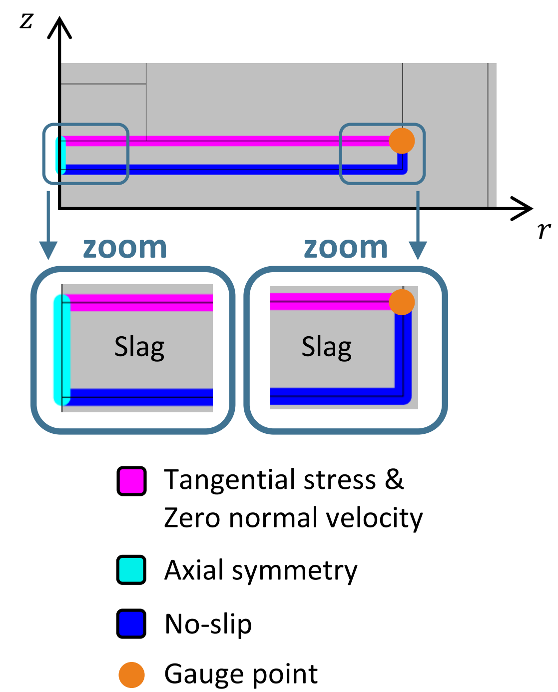
Physics

→ Turbulent Flow k-ε model in the liquid phase of the slag layer

Domain



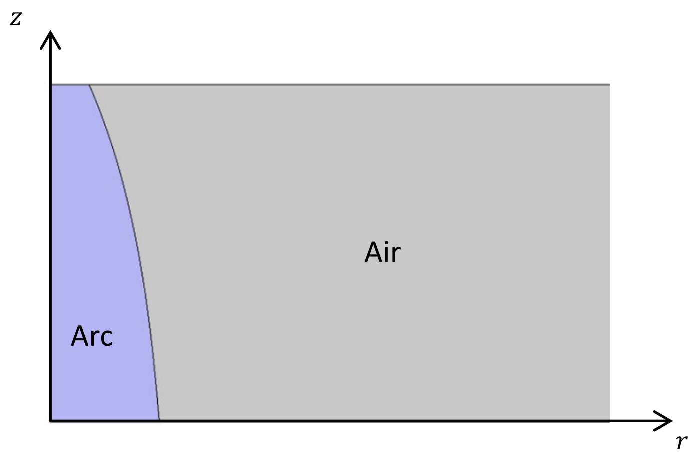
Boundary conditions



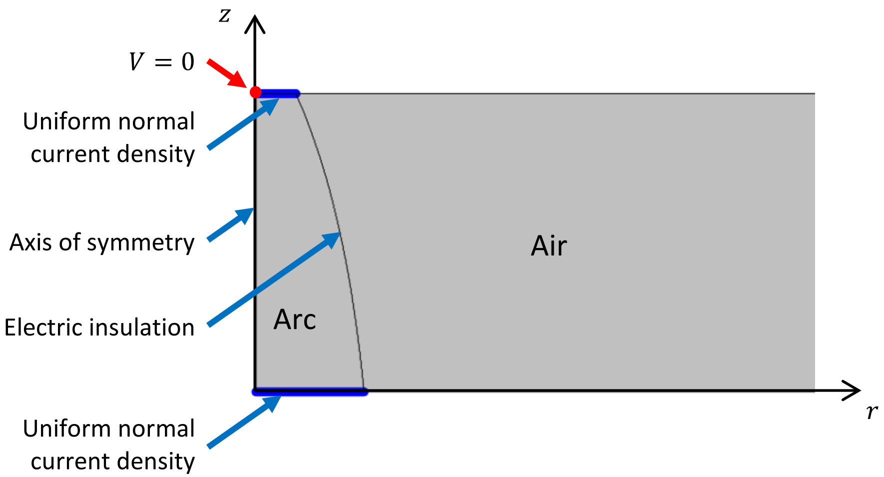
Physics

→ Electric Current in an instantaneous electric arc

Domain



Boundary conditions



→ The arc shape is modelled according to the Bowman model [4]

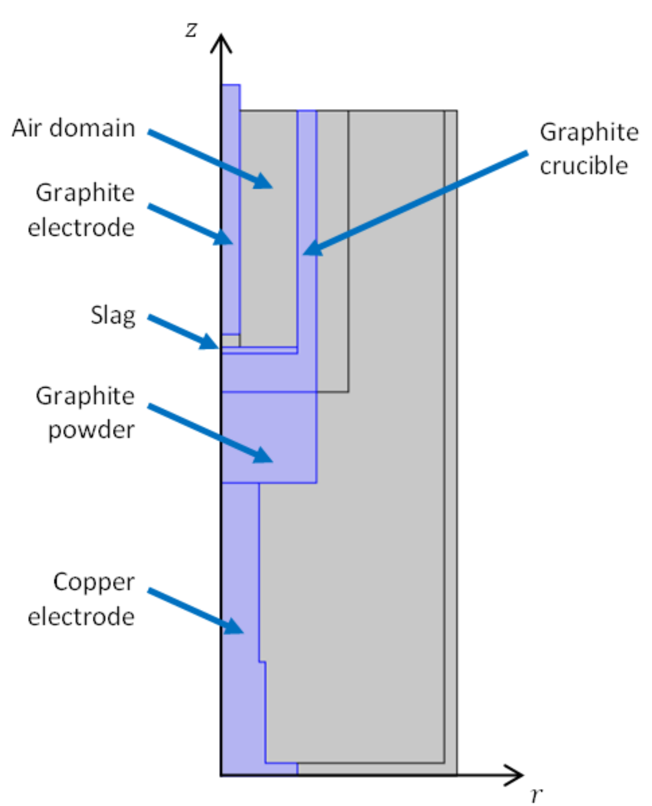
→ This shape is used to compute the instantaneous Lorentz force

[4] B. Bowman, "Properties of arcs in DC furnaces," in *Electric furnace conference proceedings*, 1994.

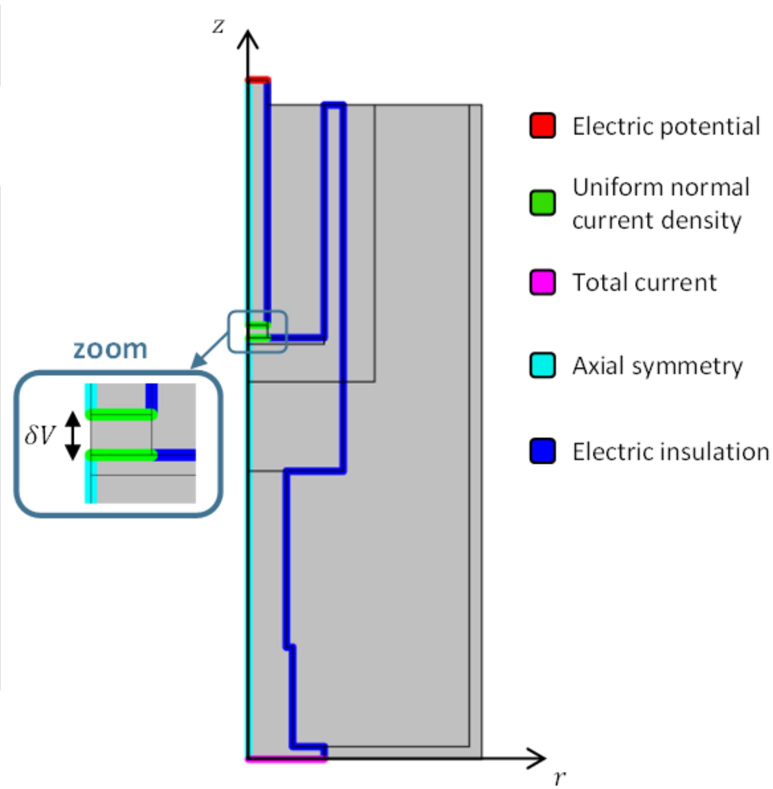
Physics

→ Electric Currents to simulate the Joule effect in electrically conducting materials

Domain



Boundary conditions



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Physics

→ Deformed Geometry to simulate variable electric arc shape

→ Global and Domain ODEs to compute quantities associated with the ensemble averaging of the electric arc

Meshing

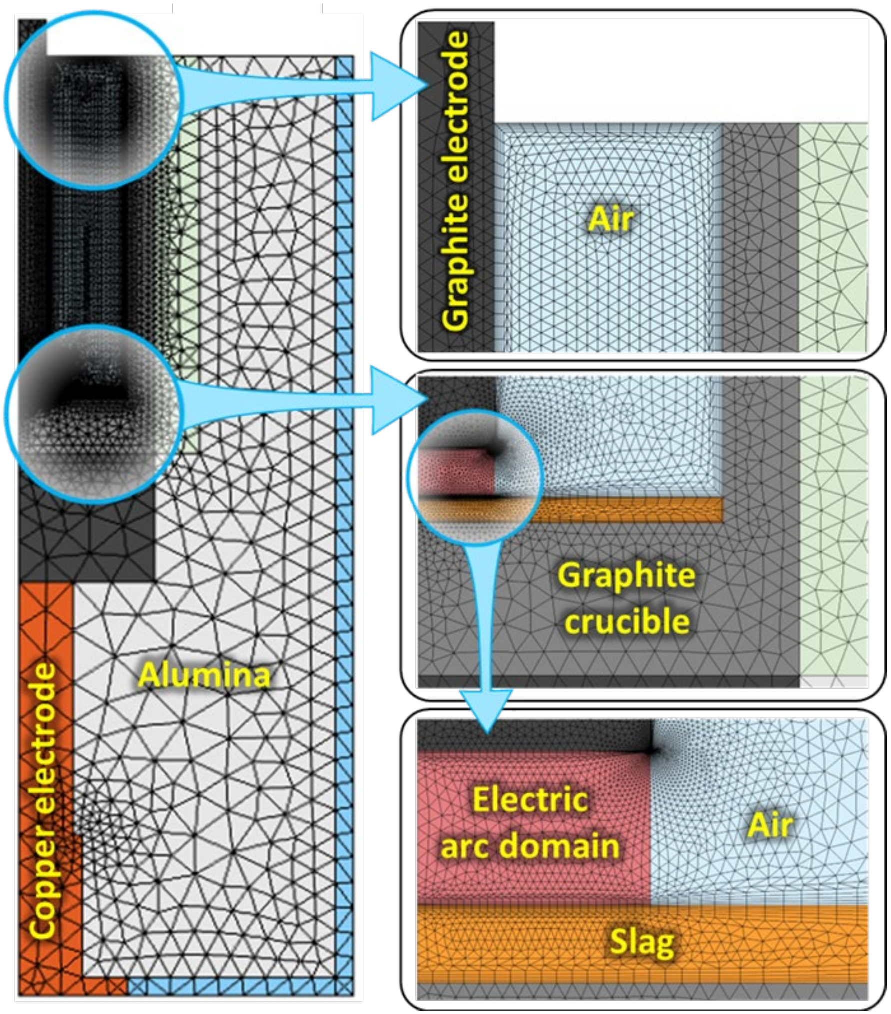
→ Triangular mesh

→ Boundary layer in fluids

→ 13200 linear mesh elements

→ 114000 DOF

Principal computational domain



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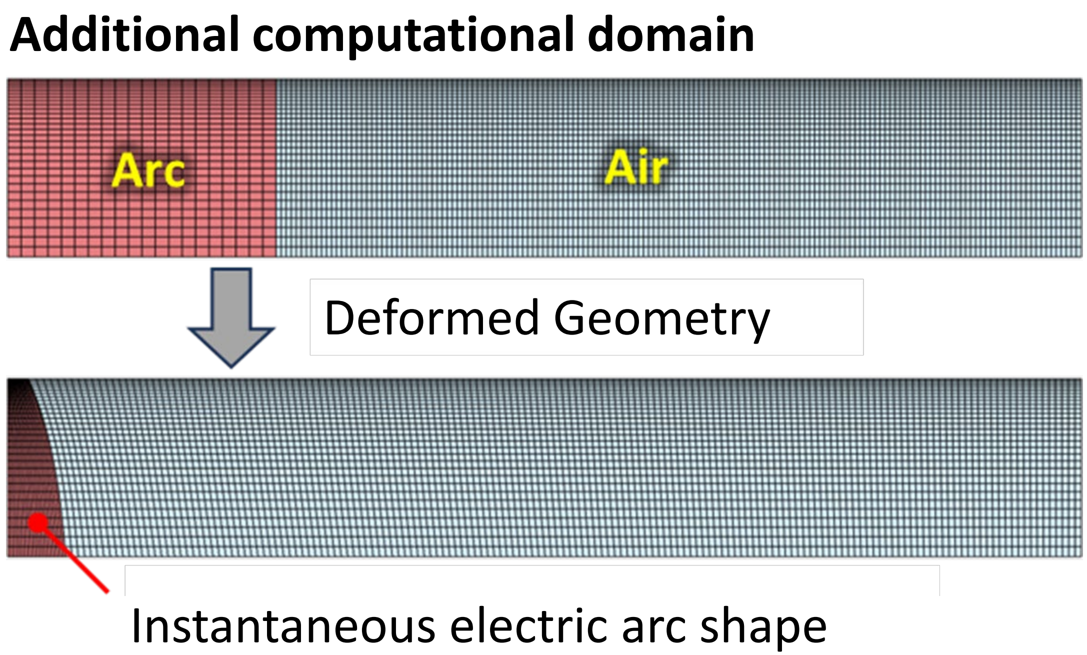
Meshing



→ 3600 mesh elements

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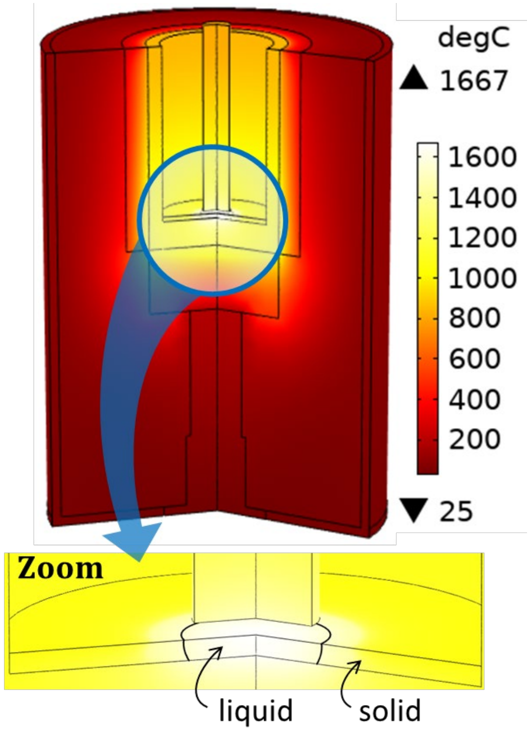
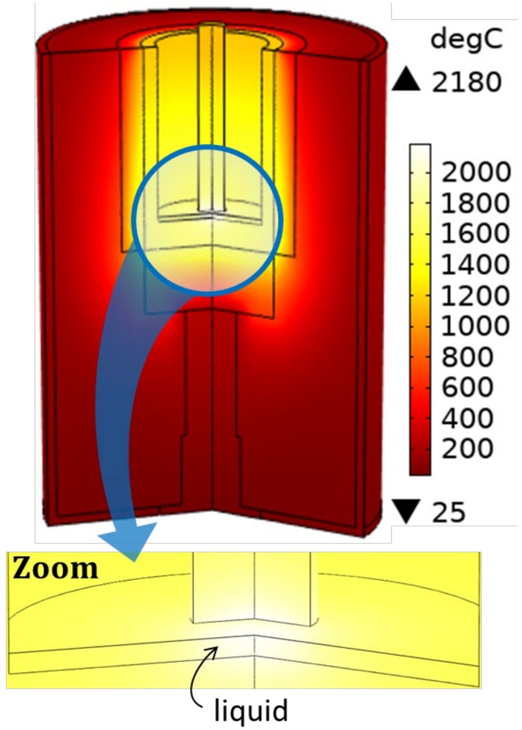
III. Main Results

Computed temperature fields

$P = 3.5\ \mathrm{kW}$ $\quad$ $\mathrm{Time} = 10^4\ \mathrm{s}$



$P = 7\ \mathrm{kW}$ $\quad$ $\mathrm{Time} = 10^4\ \mathrm{s}$



→ After almost 3 hours of furnace operation, the process is not yet stationary

→ Numerically, the slag layer is completely melted in 10^4 seconds if $P \geq 6.3\ \mathrm{kW}$

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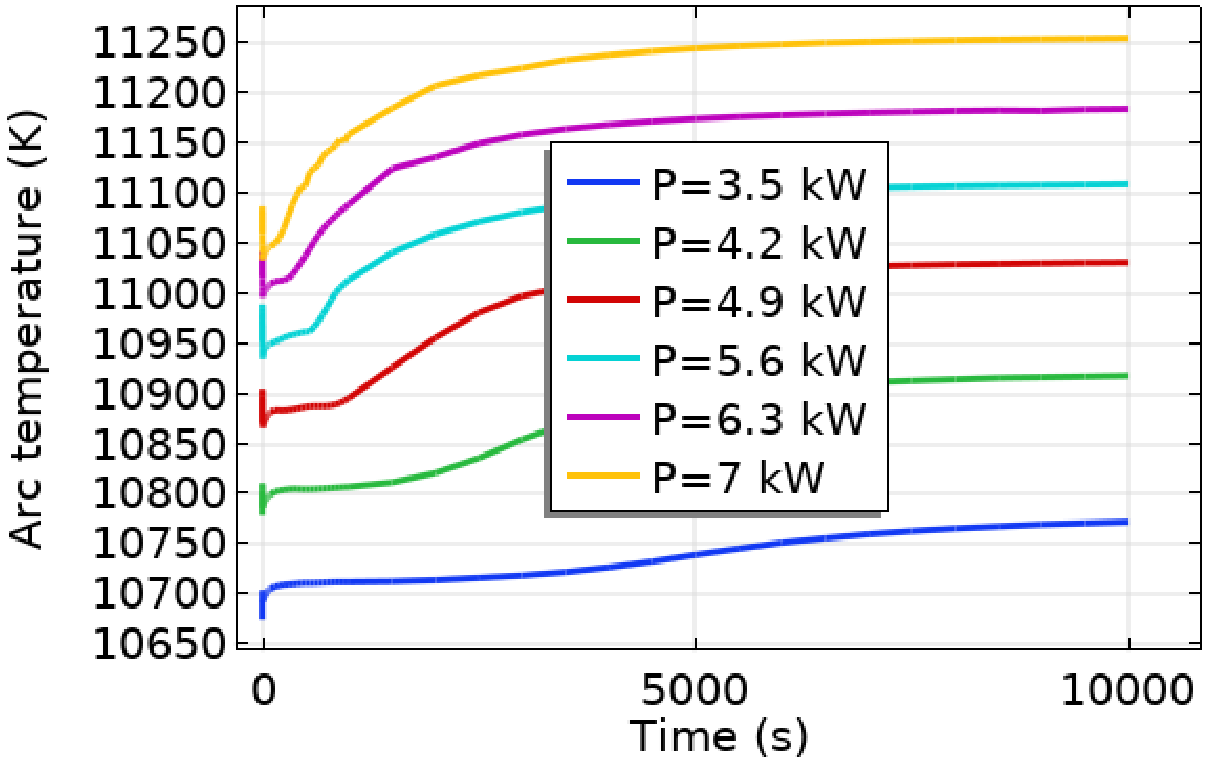
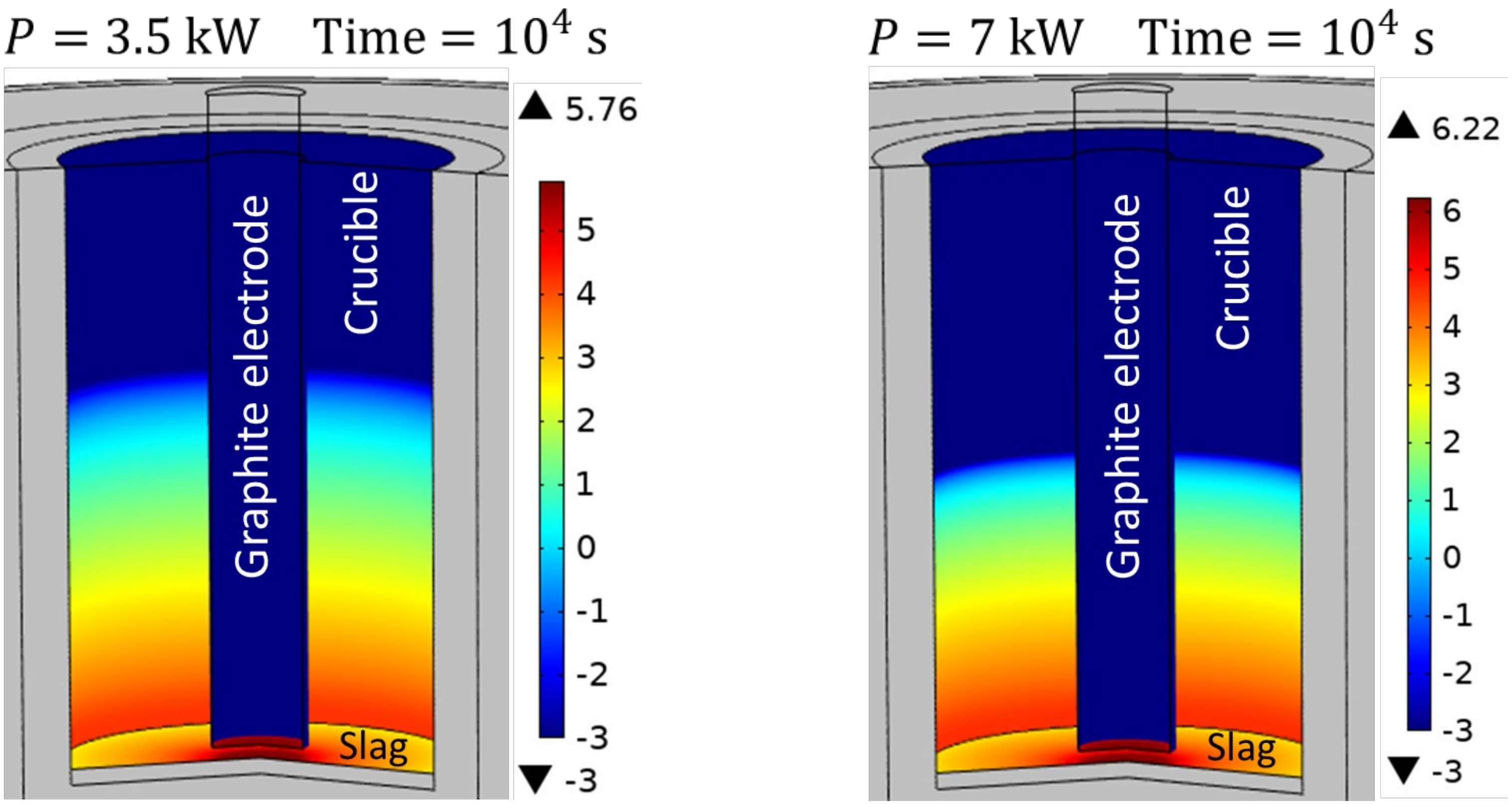
Electric arc temperature



→ The plasma conductivity varies from 3.6 to 4.1 kS/m

→ The instantaneous plasma velocity in the arc column varies from 137 to 185 m/s

Log_{10} of the averaged irradiance due to arc radiation



→ The highest irradiance is at the center of the slag surfaces: 575 to 1660 kW/m^2 depending on P

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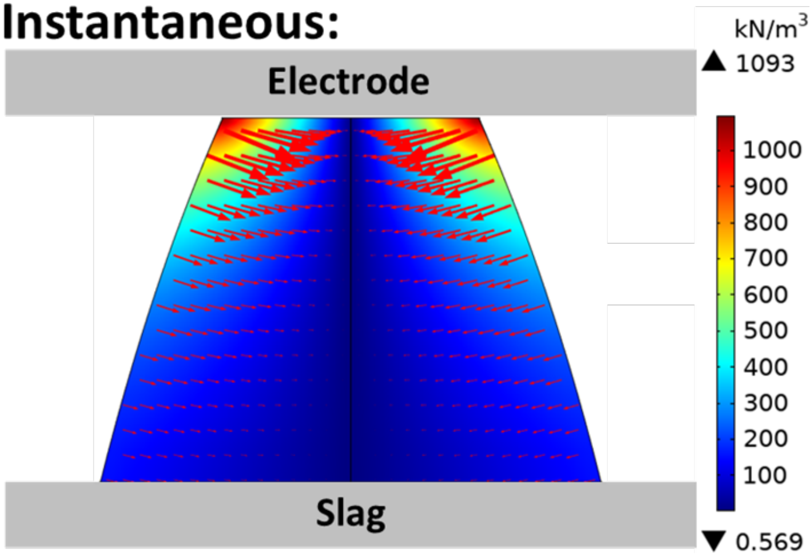
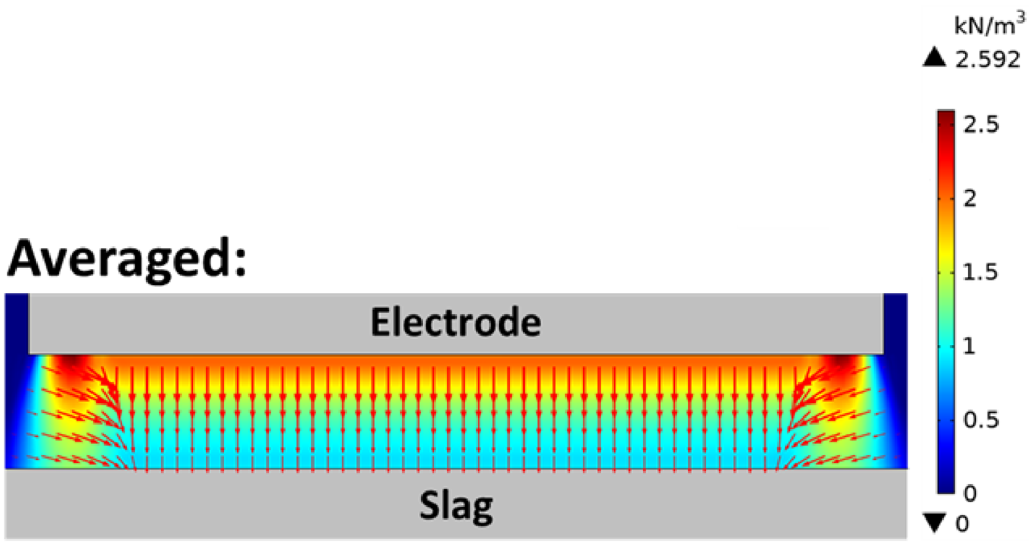
Lorentz force

$$P = 7\ \mathrm{kW} \qquad \mathrm{Time} = 10^4\ \mathrm{s}$$

Instantaneous:



Averaged:



→ The maximum of the averaged Lorentz force is located under the edge of the electrode

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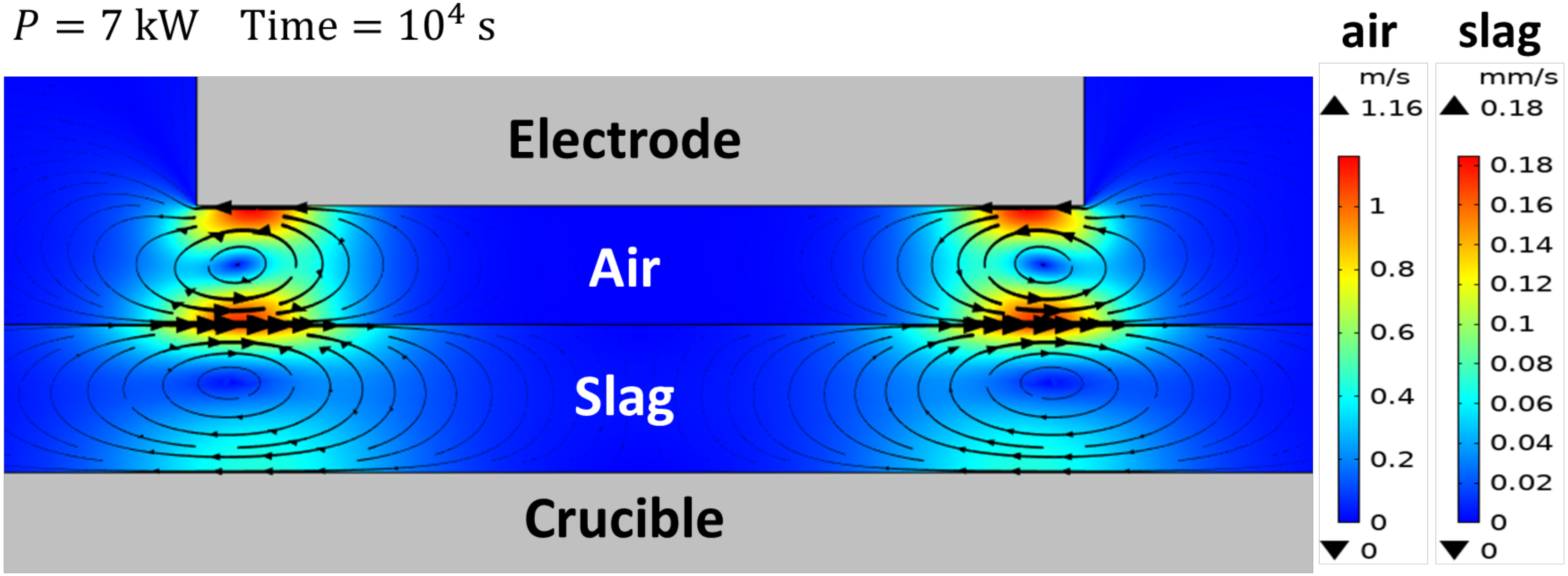
Reynolds averaged velocity field

$P = 7\ \mathrm{kW} \quad \mathrm{Time} = 10^4\ \mathrm{s}$



→ The maximum air velocity reaches about 1 m/s under the edge of the electrode

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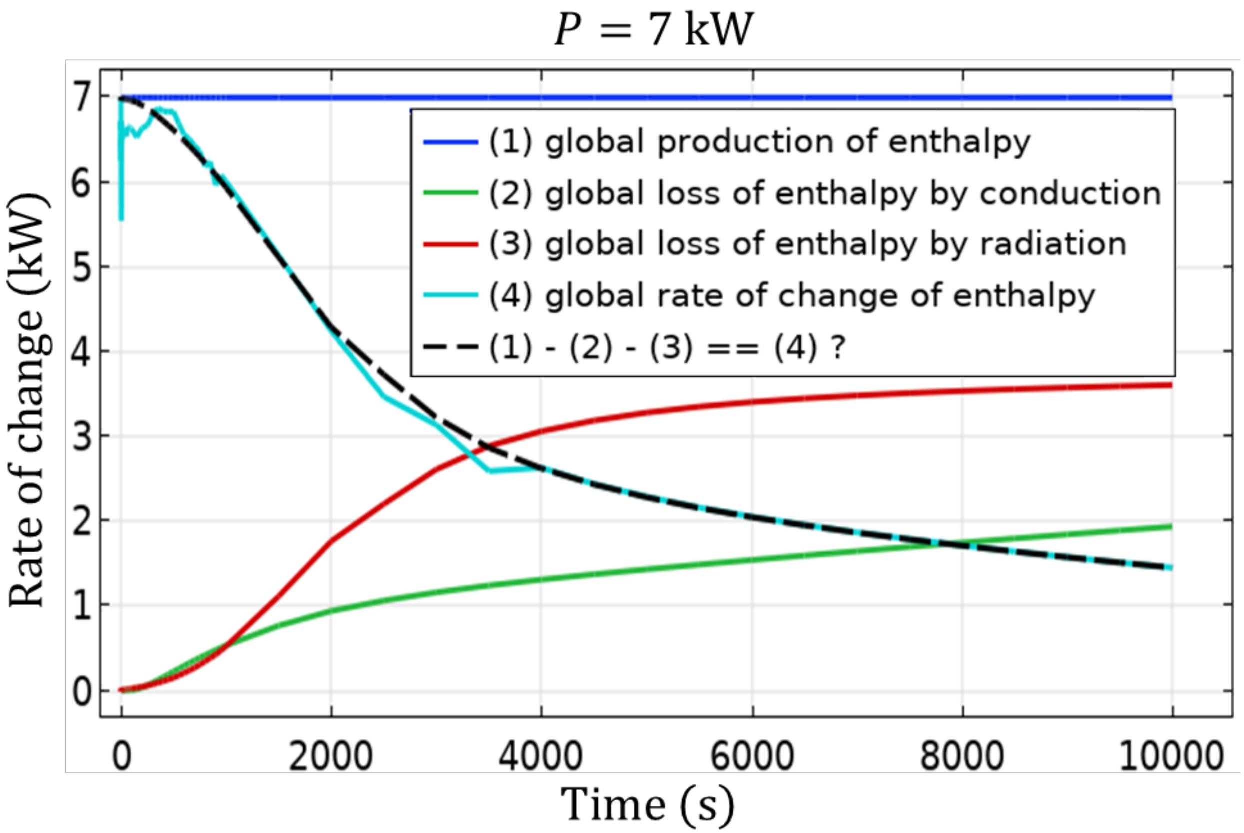
Global balance of enthalpy



→ The global enthalpy conservation is well satisfied

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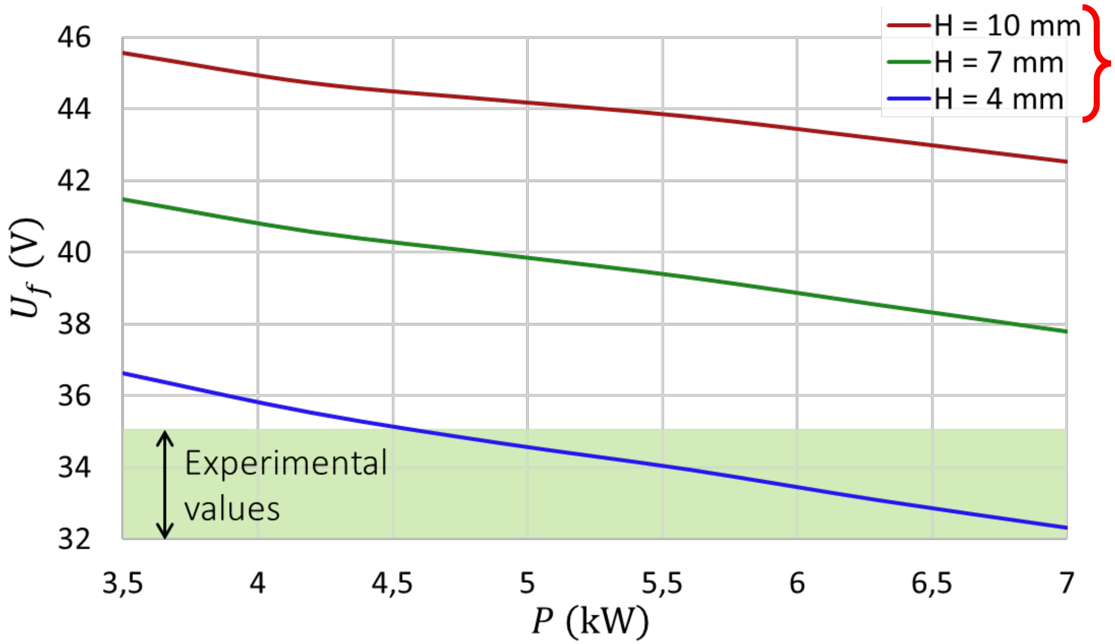
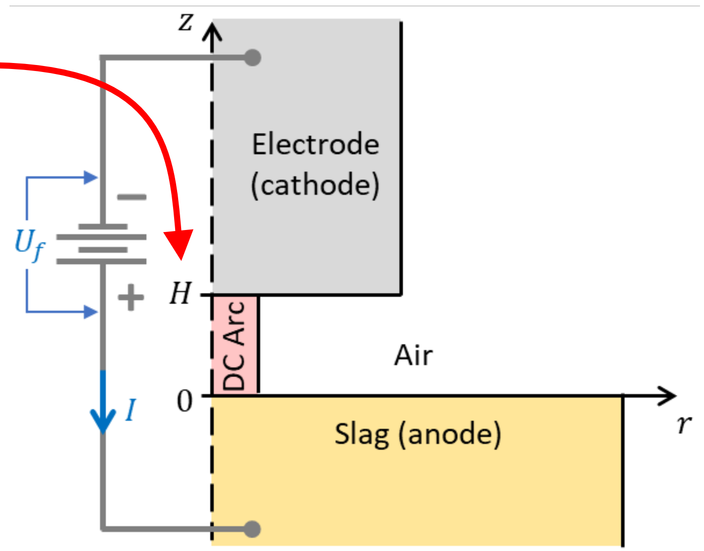
Voltage drop across the furnace terminals





H = arc length

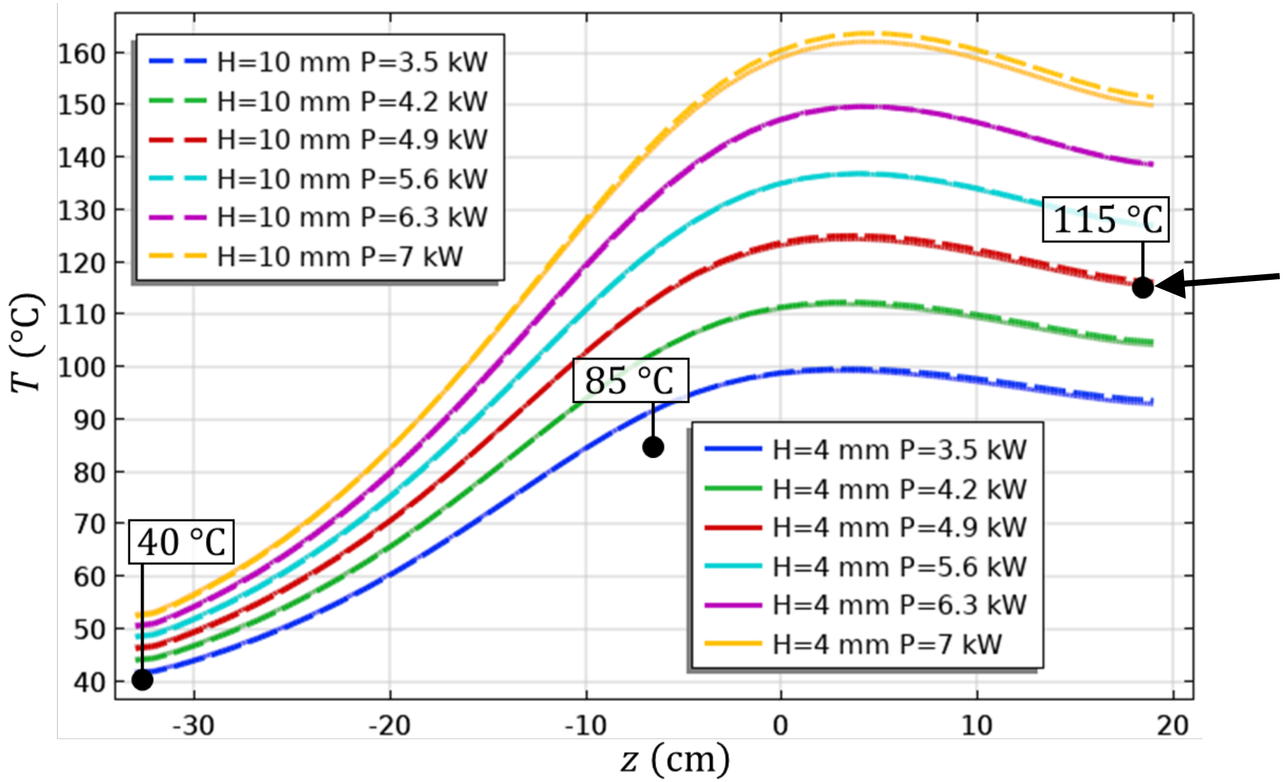
U_f = voltage drop across furnace terminals

→ As P increases, U_f reduces due to decreasing resistance of the slag layer

→ As arc length H decreases, U_f reduces due to decreasing resistance of the arc

→ The model predicts U_f values similar to the experimental ones when $H \leq 4$ mm

Computed and measured shell temperature



Lines = computed

Markers = measured

→ Shell temperature is not sensitive to the arc length H

→ According to the model, the long-term experimental input power must be around 3.5 kW

→ At the top of the furnace, the numerical temperature is underestimated, which is explained by overestimated heat losses as the off-gas system is not modelled

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Conclusions

→ Successful simulation of the preheating of the laboratory-scale Electric Arc Furnace (EAF) and the initial slag melting in it

→ The ensemble averaging of the Channel-Arc model is demonstrated to be an efficient approach for simulating a distributed heat source in an EAF

→ Plausible material temperatures in the neighbourhood of the electric arc

→ The simulated average temperature on the surface of the liquid slag pool (1594 to 1716 °C) falls within the range of experimental measurements

→ The work is validated against experimental data by fitting temperature and voltage measurements

→ The model has shown that for a complete melting of the initial slag layer, the initial input power should be above 6.3 kW, which is also confirmed in practice

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Perspectives

→ The developed model can be further used to optimize the furnace operation:

→ To predict possible thermal damages or heat losses

→ To increase the raw material melting efficiency

→ The presented ensemble averaging approach can be applied to other electric arc problems with a similar geometry

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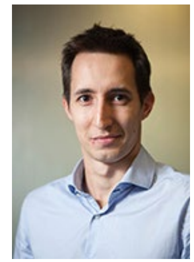
To finish...

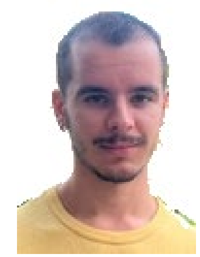
Thank you!

Q&A?

Our question: What about a coffee to discuss your topic? ☺



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