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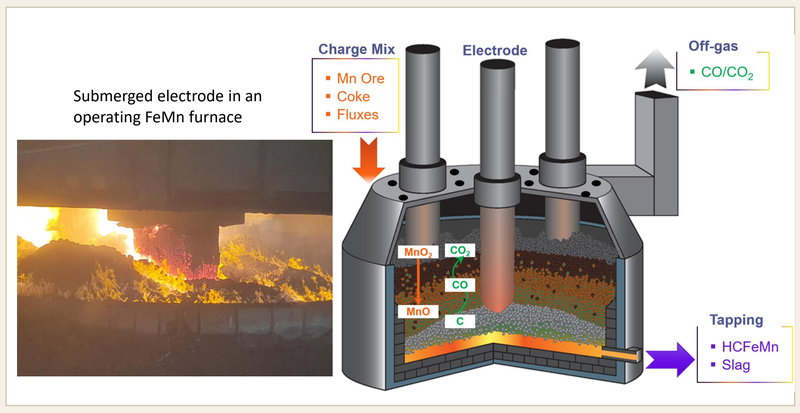
Modeling of the Søderberg Electrode

A coupled electro-thermal solver in OpenFOAM for FeMn furnace electrodes

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1 Industrial Context

Submerged-arc furnaces (SAFs) producing ferromanganese (FeMn) draw very high currents of **100-150 kA** through three Søderberg electrodes, dissipating 30-80 MW per furnace into the reduction reactions that convert Mn-rich ores into alloys for steelmaking.



FeMn submerged-arc furnace : the three electrode columns descending through the burden to the smelting zone.

2 The Søderberg Electrode

Self-baking electrodes are continuously consumed at the tip and re-formed at the top: **green paste** is poured cold into a sheet-steel casing fitted with internal steel fins, then progressively heated by Joule and induction effects as it descends, passing through softening, pyrolysis and finally graphitisation before being consumed at the arc.

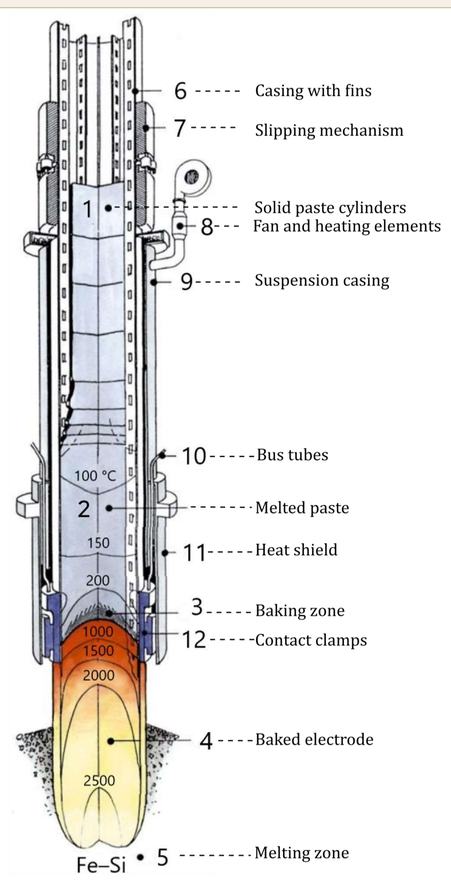


Illustration of a Søderberg electrode column, courtesy of Elkem Carbon : paste path from casing (top) through air-heating, baking and arc zones.

3 Why Model It?

- **Locate the baking isotherm (≈ 773 K)** → too low risks paste breakthrough; too high wastes thermal energy and accelerates casing consumption.
- **Predict response to operational changes** → current intensity, slipping rate, paste formulation, casing geometry, fins arrangement, before committing capital.
- **Access internal fields that resist instrumentation** → thermocouples survive only on the casing, the model is the sole window onto current density, temperature and σ(T) inside the active volume.
- **Provide an inexpensive surrogate for campaign optimisation** and root-cause analysis of electrode breakage incidents.

Typical operating envelope

Electrode current I	**136 kA**
Slipping rate	**24.4 mm / h**
Arc tip temperature	**2000 K**
Inlet paste temperature	**323 K**
Electrode radius	**0.95 m**
Modelled length	**5.70 m**

4 Coupled Electro-Thermal Model

Steady-state, axisymmetric (5° wedge). The electric potential φ and temperature T are coupled through σ(T) and the volumetric Joule source.

Current continuity

$$\nabla \cdot (\sigma(T) \nabla \varphi) = 0$$

Energy (advection–diffusion–source)

$$\nabla \cdot (\rho C_p U T) - \nabla \cdot (k \nabla T) = Q_j + Q_{ind} - \rho L \, \partial f_\ell / \partial T \cdot U \cdot \nabla T$$

Joule heat

$$Q_j = \sigma(T) \, |\nabla \varphi|^2$$

Mass-conserving slipping velocity

$$U(T) = u_{slip} \cdot \rho_{baked} / \rho(T) \qquad \text{(paste / mixed)}$$

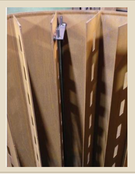
5 Multi-zone Material Model

Four cellZones: **paste**, **mixed compound** (paste + steel fins), **casing** (steel), **clamps** (Cu). σ(T), k(T), Cp(T) piecewise-linear, with latent heat (200 kJ/kg) absorbed across the [673, 873] K mushy band.

Mixed-compound rule (fin-area derived):

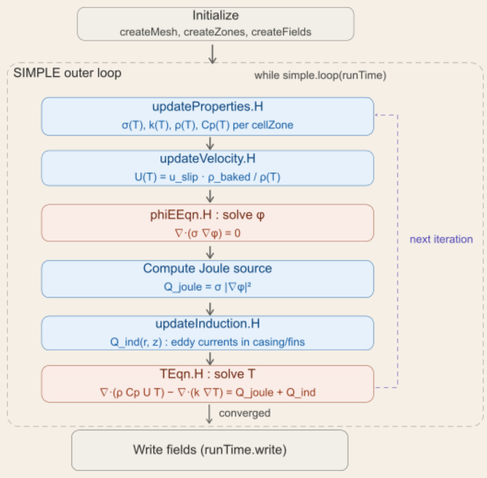
$$X_{mix} = (1 - \alpha \, p_{steel}) \, X_{paste} + \alpha \, p_{steel} \, X_{steel}$$

$$p_{steel} = \rho_{steel} A_{fins} / (\rho_{steel} A_{fins} + \rho_{paste} A_{paste})$$



6 OpenFOAM Implementation

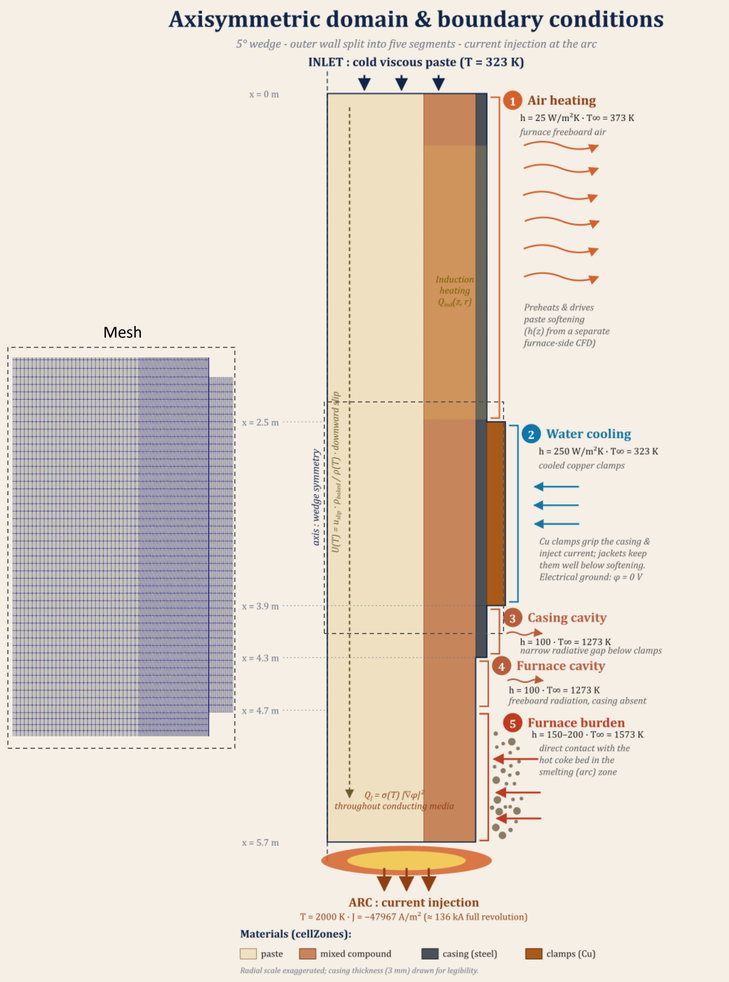
Custom solver **`soderbergFoam`** (Foundation v13). Outer SIMPLE loop couples φ and T. σ(T) and U(T) refreshed every iteration. Cell zones built by **`topoSet`**; current injection on the arc patch as **`codedMixed`** with refGrad = −J/σ_face for a constant-current condition (~136 kA full revolution). Outer-wall heat transfer as Robin BCs with per-segment (h, T∞) calibrated from the air-heating sub-model.



7 Supporting Sub-models

- **Paste softening / rheology** : viscous-paste descent model upstream of the baking zone; sets the inlet density and slip boundary conditions.
- **Air-heating coefficient** : separate furnace-side CFD provides the convective h(z) extracted along the casing outer surface, used as the Robin BC here.
- **Induction heating** : proximity of current bars to the casing modeled as a volumetric eddy-current source with axial + radial exponential decay.

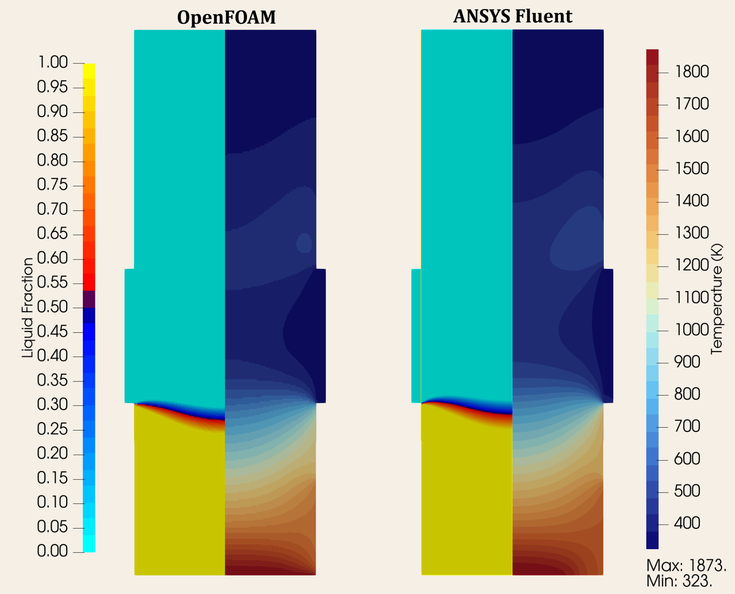
8 Mesh & Boundary Setup



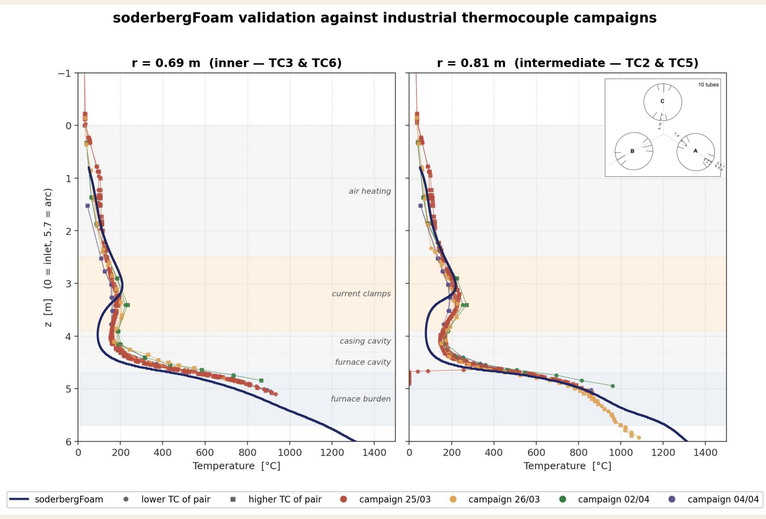
Mesh & BC : four cellZones (paste, mixed compound, casing, clamps), ~21 000 hex cells. Inlet (top), arc outlet (bottom), 5 outer-wall Robin BCs.

9 Validation

Cross-validation against a **reference Fluent case** and against **industrial thermocouple campaigns** (TC at r = 0.93 m, multiple campaigns).

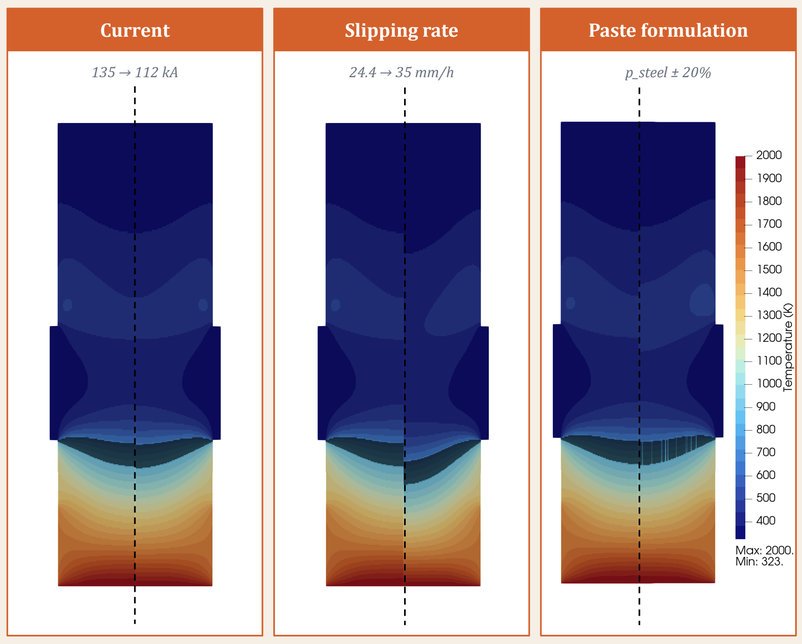


Validation of soderbergFoam against ANSYS Fluent for Søderberg electrode baking. Each panel shows liquid fraction (left half) and temperature (right half); the paste-to-carbon transition front is captured at the same axial position by both solvers.



soderbergFoam vs. industrial thermocouple data at r = 0.69 m (TC3/TC6, left) and r = 0.81 m (TC2/TC5, right) over four campaigns (25/03 and 04/04).

10 What-if Scenarios



11 Take-aways

- **An OpenFOAM solver for the coupled electro-thermal problem in a self-baking electrode**, with temperature-dependent conductivity, latent heat of baking, and induction heating treated explicitly.
- **Agrees with the Fluent reference case and with plant thermocouple readings**; the implementation is open and maintained in-house at Eramet.
- **Lets operational and design changes be tested numerically before committing to a plant trial.**

12 Next Steps

- **Couple to a furnace-side CFD model** so the air-heating boundary condition becomes self-consistent rather than imposed from an offline extraction.
- **Move from steady state to transient operation,** slipping changes, current ramps, off-spec paste batches, using the converged steady field as initial condition.
- **Extend to 3-D to resolve inter-electrode coupling and non-axisymmetric paste distribution.**
- **Release the solver publicly to support OpenFOAM work in electrometallurgy.**

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Acknowledgments
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Selected references
[1] O. Yani Søderberg Electrode Modeling: Simulation of Electrode Paste Softening and Baking (Eramet, 2025).
[2] OpenFOAM Foundation v13 source.
[3] B. Larsen. Electrode Models For Søderberg Electrodes.