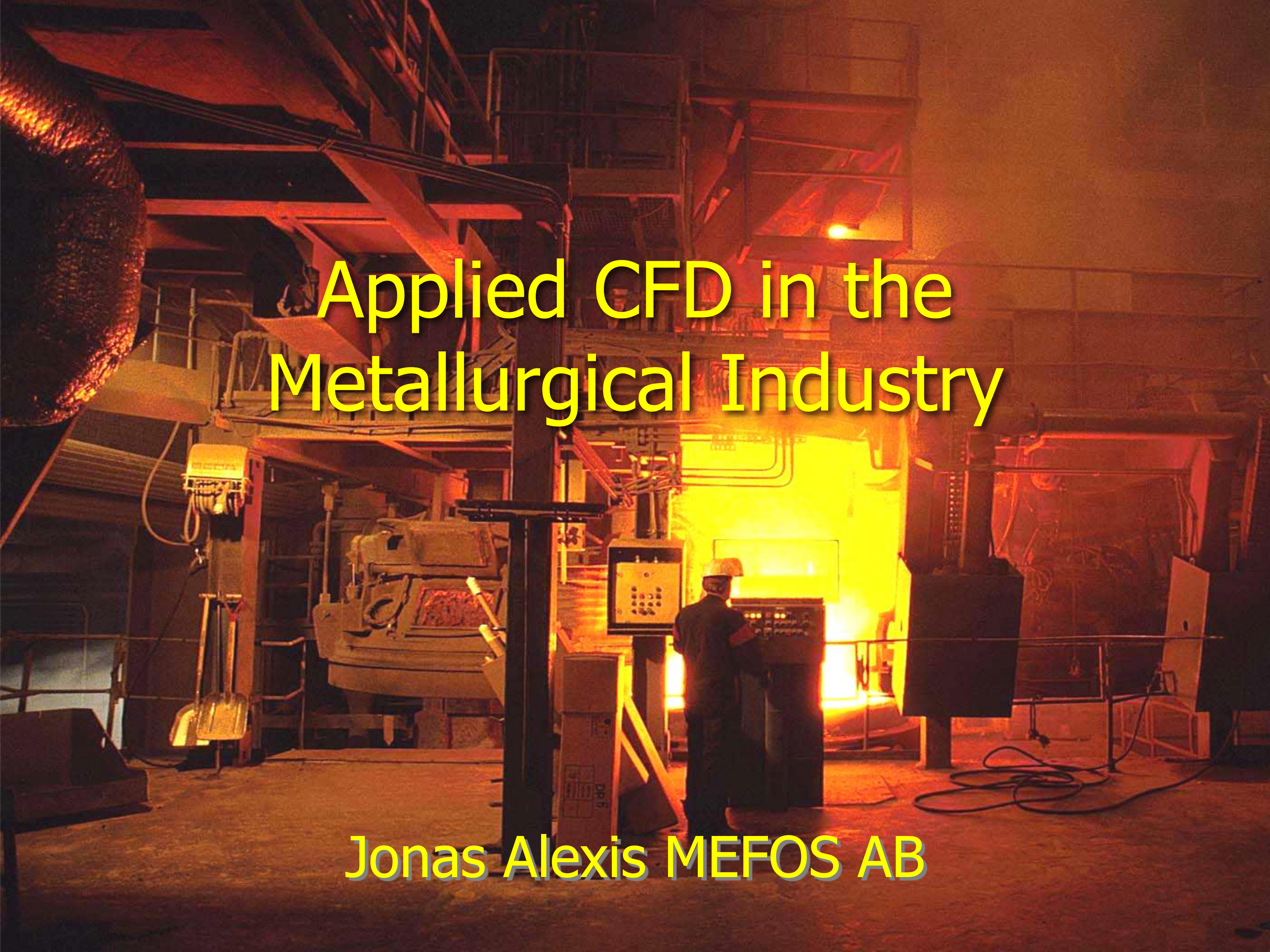


Applied CFD in the Metallurgical Industry

Jonas Alexis MEFOS AB

Outline

- Why are MEFOS modelling Metallurgical processes
- What is applied CFD at MEFOS
- Example: Sulphur Refining of Steel
  - — Transport description
  - — Reaction model
  - — Reaction Zone
    - * Scalar equation model
    - * Empirical model
- Validation
  - — Transport Equation
  - — Sulphur refining
- Conclusions

Why are MEFOS modelling metallurgical processes?

The goal for the metallurgical industry is to achieve the **material properties** needed for production of a given product. This requires **control** of the amount of:

- Alloying elements (C, Si, Mn, Cr, Al ..)
- Other elements (S, N, H, P, Cu, Zn ..)
- Unwanted non-metallic particles (Inclusions). Also composition and size distribution

•Continuous **measurement** and **sampling** for **process control** is difficult in most process steps. The models are therefore needed for:

- Optimisation of the different process steps
- Development of process control systems
- Enhanced understanding
- Education

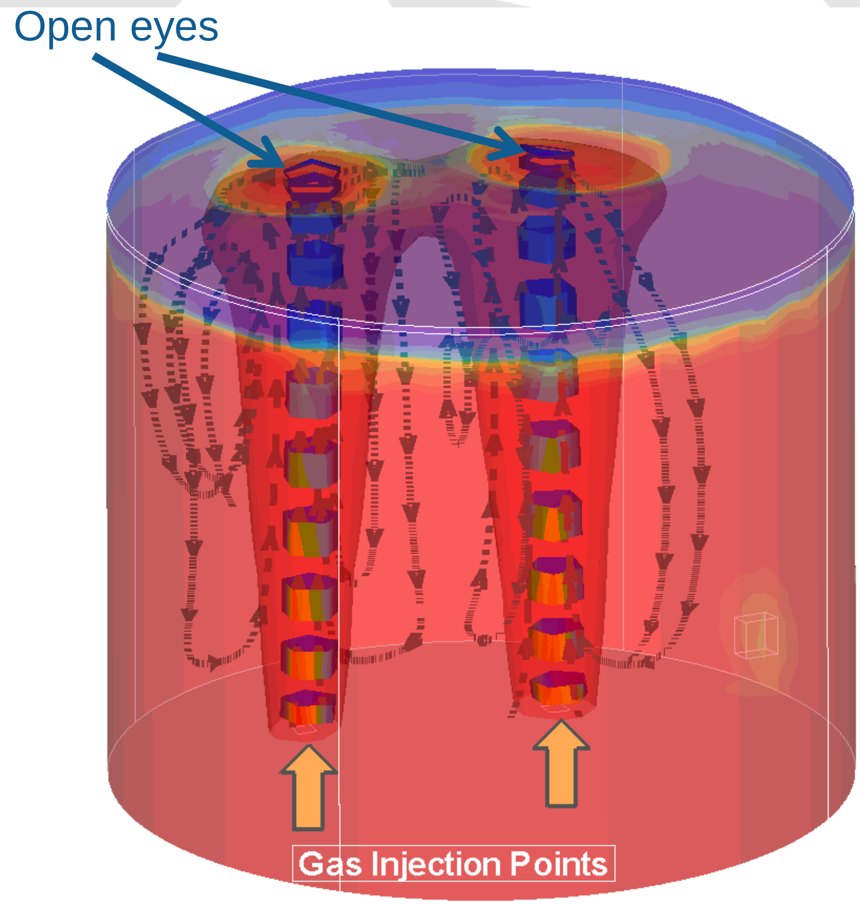
What is applied CFD at MEFOS

When fundamental models are missing or impossible to realize because of the lack of data, which is often the case, other methods need to be utilised.

One example: Fundamental data needed to describe the slag/metal-interface in a stirred ladle during sulphur refining is missing. Instead, empirical models of that interface, based on sampling at the steel plant can be used. The use is necessary if sulphur-refining in a production ladle is to be simulated.

Sulphur Refining

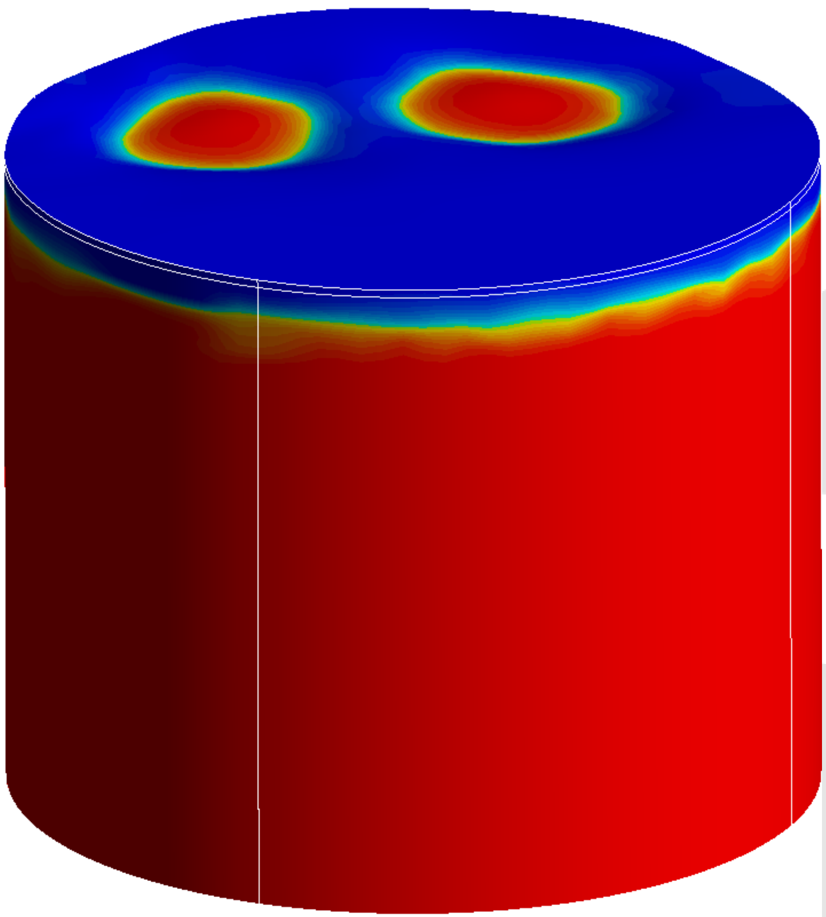
Transport description (Gas Stirring)



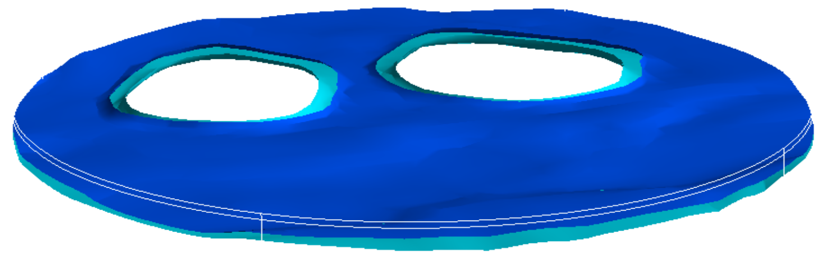
Ladle Radius = 1.25 m
Steel Weight = 65 t
Slag Weight = 1200 kg
Gas Flow Rate = 100 Nl/min

Sulphur Refining

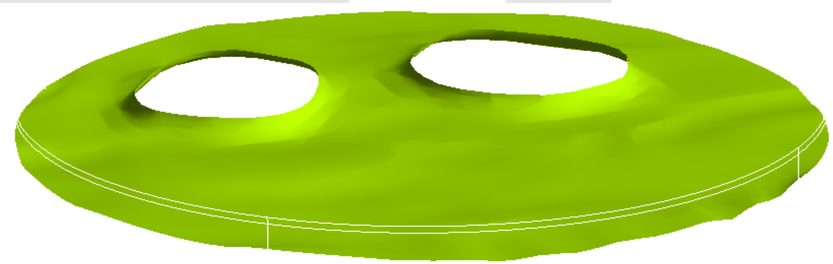
Transport description (Gas Stirring)



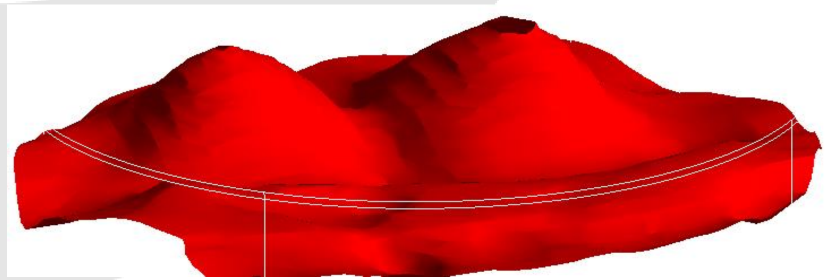
Gas Stirred Ladle



Slag Layer



Interface (Reaction zone)



Steel Surface

Sulphur Refining

Reaction Model

$$2\,[Al] + 3\,[O] = Al_2O_3$$

$$[Fe] + [O] = FeO$$

$$[Mn] + [O] = MnO$$

$$2\,[Si] + [O] = SiO_2$$

$$[S] + (O^{2-}) = [O] + (S^{2-})$$

5 equations 6 unknowns (Al, Fe, Mn, Si, S and O)!!!

Sulphur Refining
Reaction Model

Equation 1. ΔAl is related to ΔAl_2O_3

Equation 2. ΔFe is related to ΔFeO

Equation 3. ΔMn is related to ΔMnO

Equation 4. ΔSi is related to ΔSiO_2

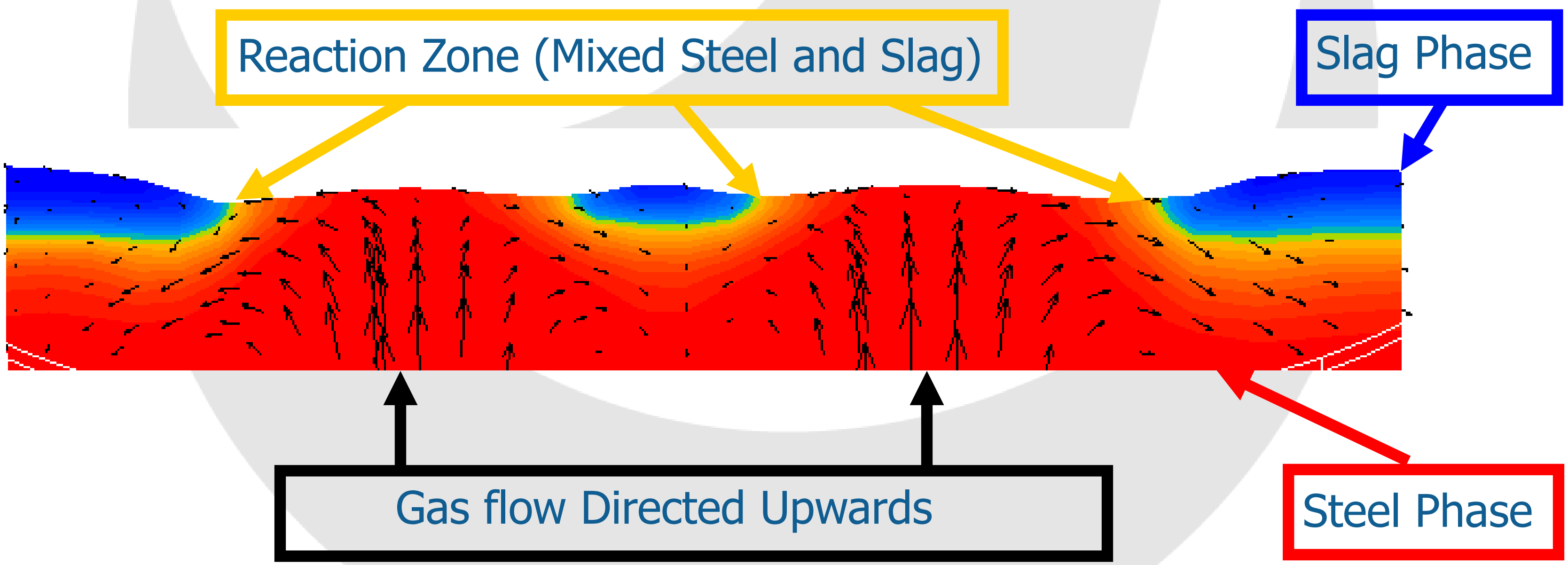
Equation 5. $\Delta[S]$ is related to $\Delta(S)$

Δ O is related to:

$$\Delta[wt\%O] = \Delta[wt\%O]_{Al_2O_3} + \Delta[wt\%O]_{FeO} + \Delta[wt\%O]_{MnO} + \Delta[wt\%O]_{SiO_2} + \Delta[wt\%O]_{S}$$

Reaction Zone
Scalar Equation model

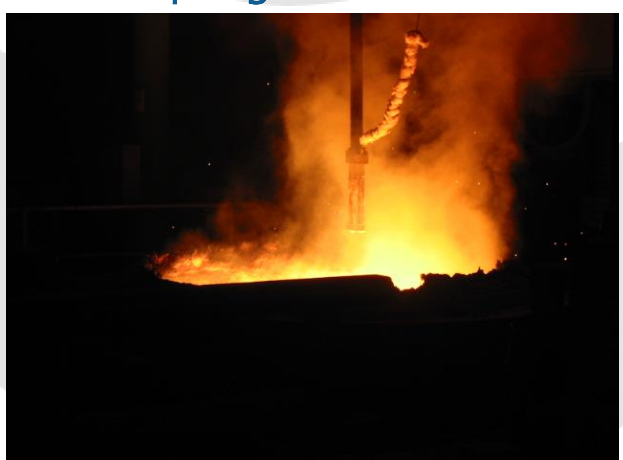
Top part of a Plane in the in the ladle, through the open eyes



Reaction Zone

Sampling (Empirical model)

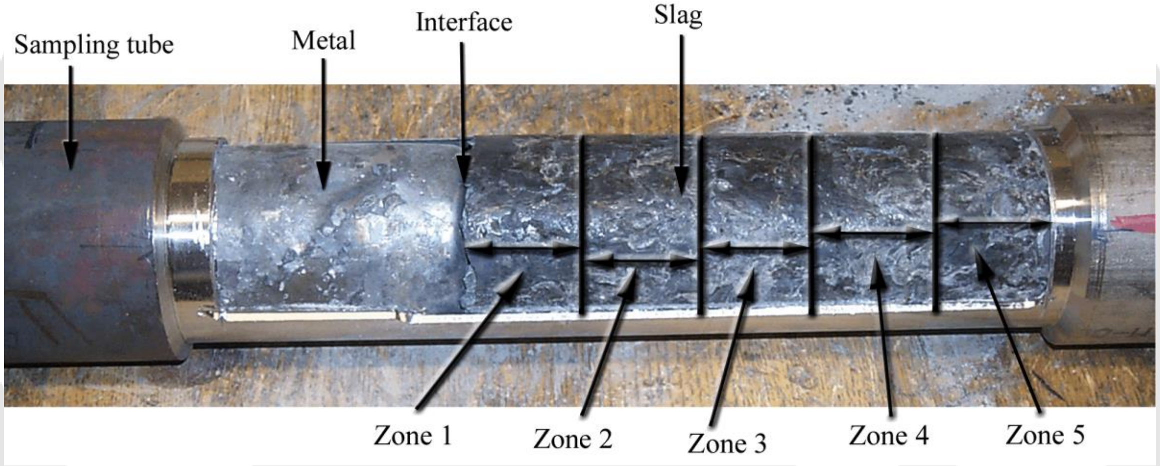
Sampling in the ladle



Sampler

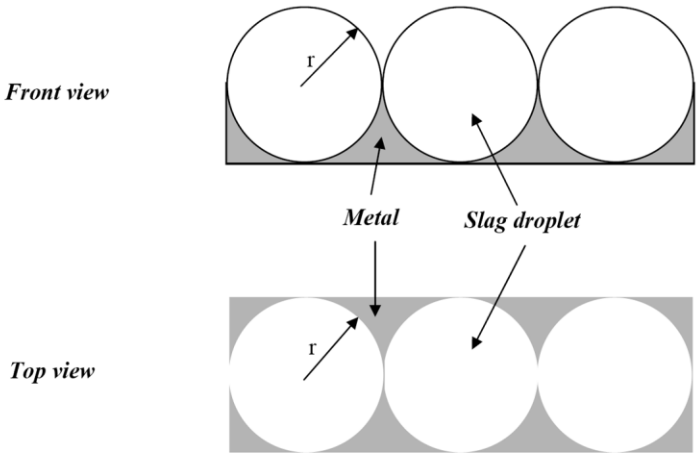
After sampling

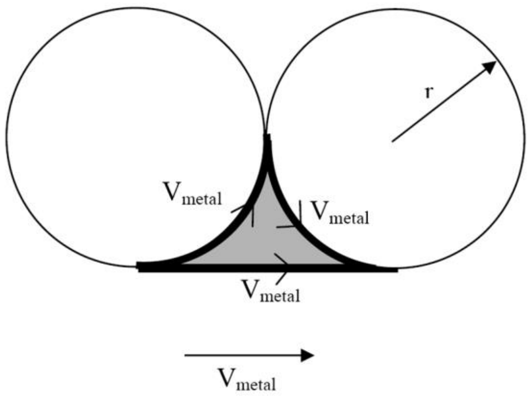
Reaction Zone
Sampling (Empirical model)



After sampling and quenching, each sample was mechanically opened. The metal bulk, slag bulk and slag-metal interface can be easily identified. Thereafter, the slag part was physically divided into a number of zones on the basis of the distance from the slag-metal interface. The width of each zone was not constant for all the samples. Small pieces of collected slag were analyzed using light optical microscope (LOM) and scanning electron microscope (SEM). The chemical compositions of the slag samples were analyzed and the sulphur contents were determined.

Reaction Zone
Empirical Model





The figures shows schematically the contact of metal with the lowest layer of slag droplets and the flow of metal associated with slag droplets. The following assumptions are made:

1. After stabilization of the flow, the whole slag layer is in droplet form.
2. All slag droplets are spherical and having the same size and shape.
3. The linear velocity of the metal along the periphery of the slag droplet is equal to the velocity of the bulk flow of the metal at the slag-metal interface.
4. The contribution of the metal film covering each slag droplet to the rate of mass exchange is negligible.

Reaction Zone
Empirical Model

The metal volume associated with each slag droplet can be expressed by:

$$v = \frac{1}{2}\left[(2r)^3 - \frac{4}{3}\pi r^3\right] \qquad (1)$$

The mass of the metal associated with all slag droplets is given by:

$$M_{total\_cell} = \frac{1}{2}\left[(2r)^3 - \frac{4}{3}\pi r^3\right]\left(\frac{a^2}{4r^2}\right)\rho_m \qquad (2)$$

The average time to travel a distance of 2 r can be evaluated by

$$t_{av} = \frac{1}{2}\left(\frac{\pi r}{V_{metal}} + \frac{2r}{V_{metal}}\right) \qquad (3)$$

The time required to flush out all the metal can be written as

$$t_{flush} = t_{av} = \frac{1}{2}\left(\frac{\pi r}{V_{metal}} + \frac{2r}{V_{metal}}\right) \qquad (4)$$

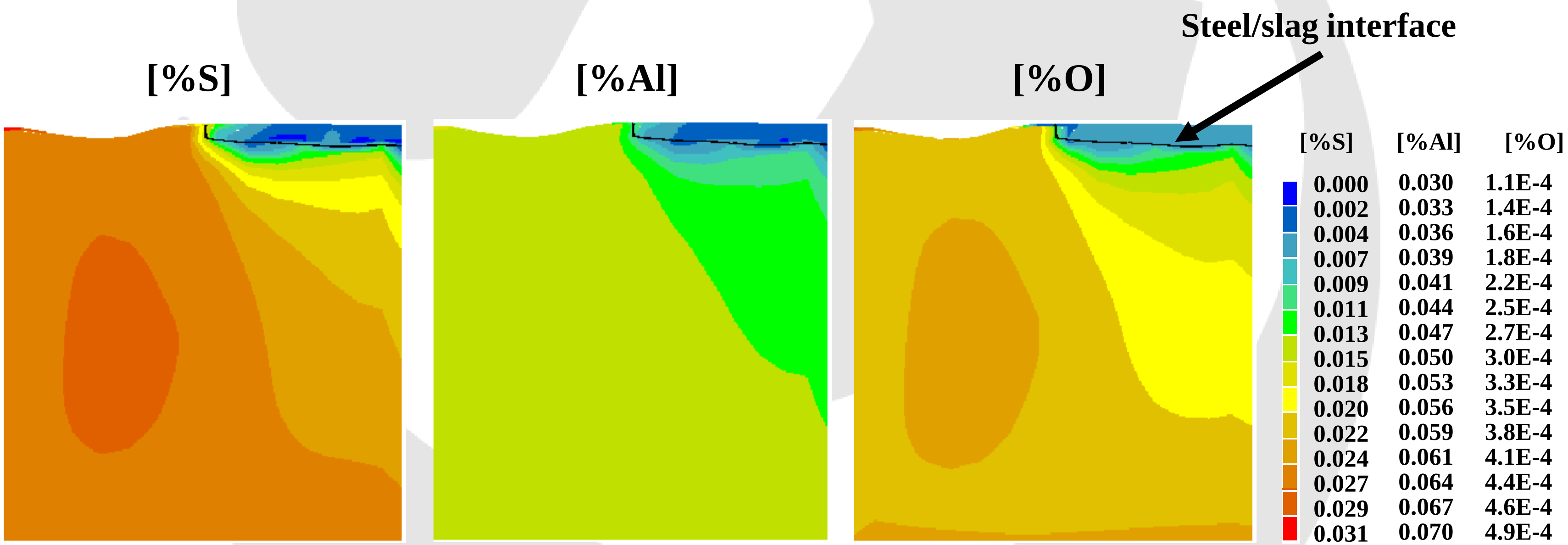
The flush-out rate of the metal in a unit cell can be expressed by:

$$K_{metal} = \frac{M_{total\_cell}}{t_{flush}} \qquad (5)$$

Eqs. (2) to (5) lead to

$$K_{metal} = 0.185\rho_m V_{metal} a^2 \qquad (6)$$

Sulphur Refining and Reoxidation Model

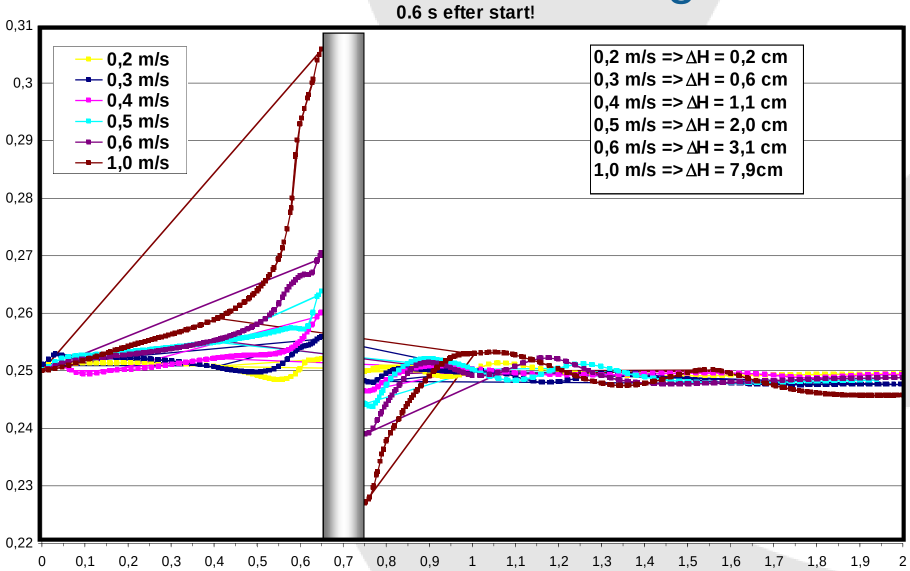


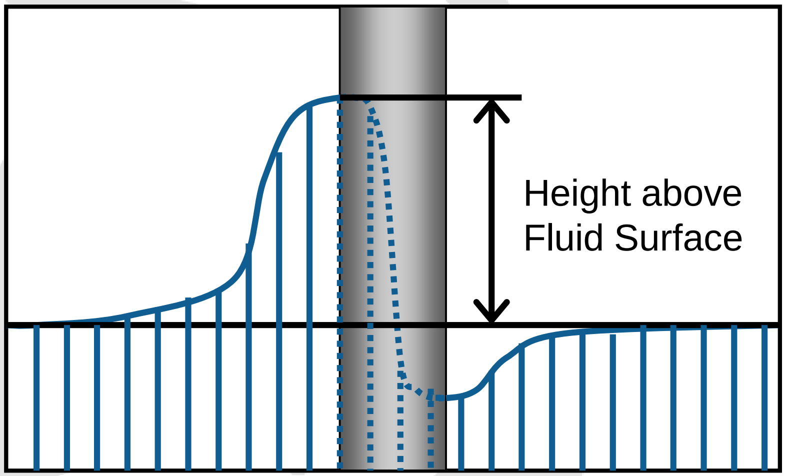
Validation
Transport description

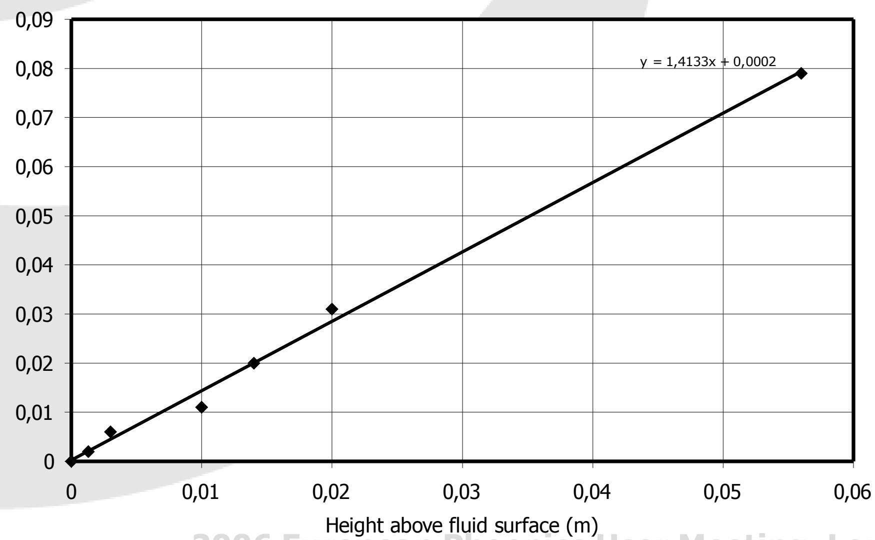
Velocity measurements with graphite rods

Validation
Wave Height Model

Simulated waveheight







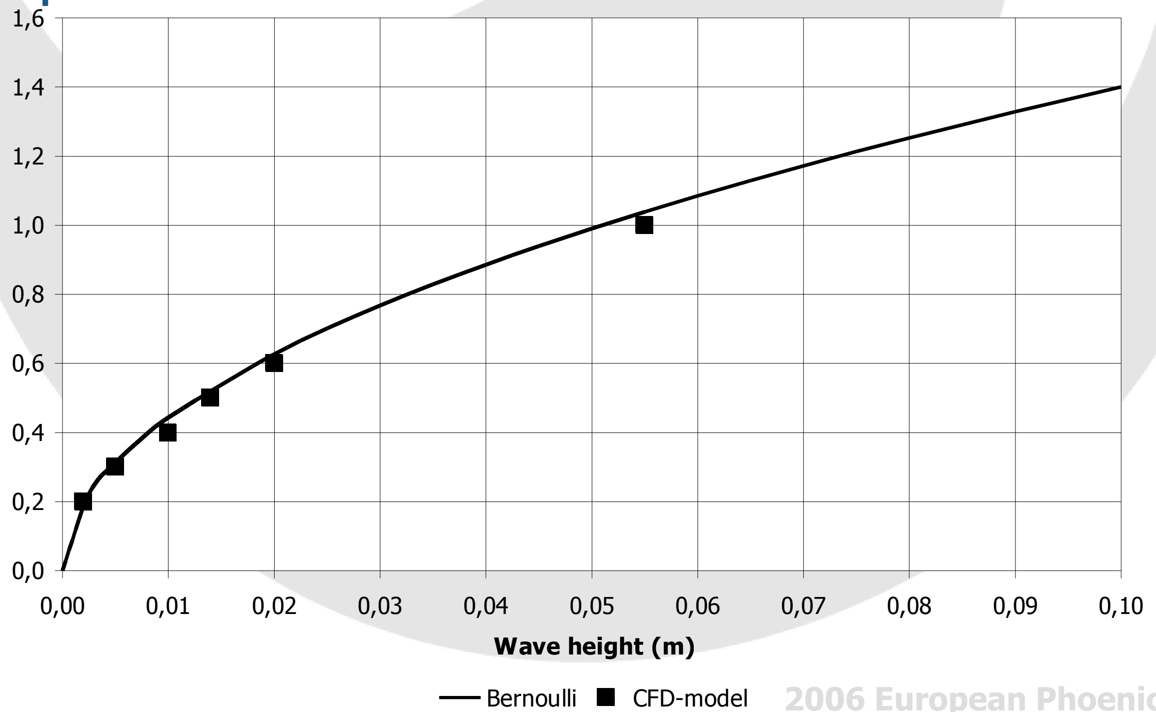
Validation

Validation of Wave Height Model

Bernoulli's equation for incompressible flow

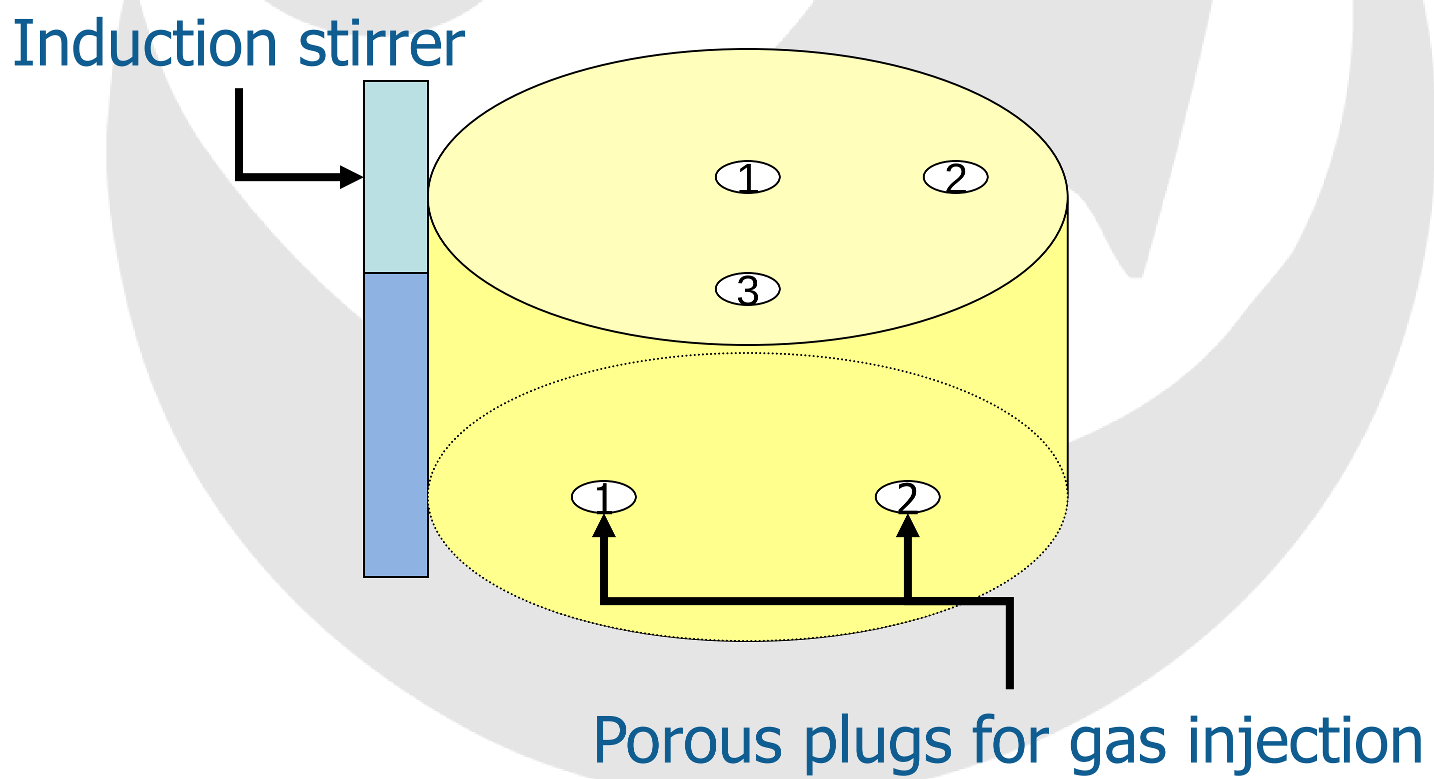
$$\frac{v^2}{2} + gh + \frac{p}{\rho} = Cons\tan t \Rightarrow v_0^2 = 2gh_1 \Rightarrow v_0 = \sqrt{2gh_1}$$

Comparison between Bernoulli and simulation



Validation
Transport Description

Measuring positions in the ladle

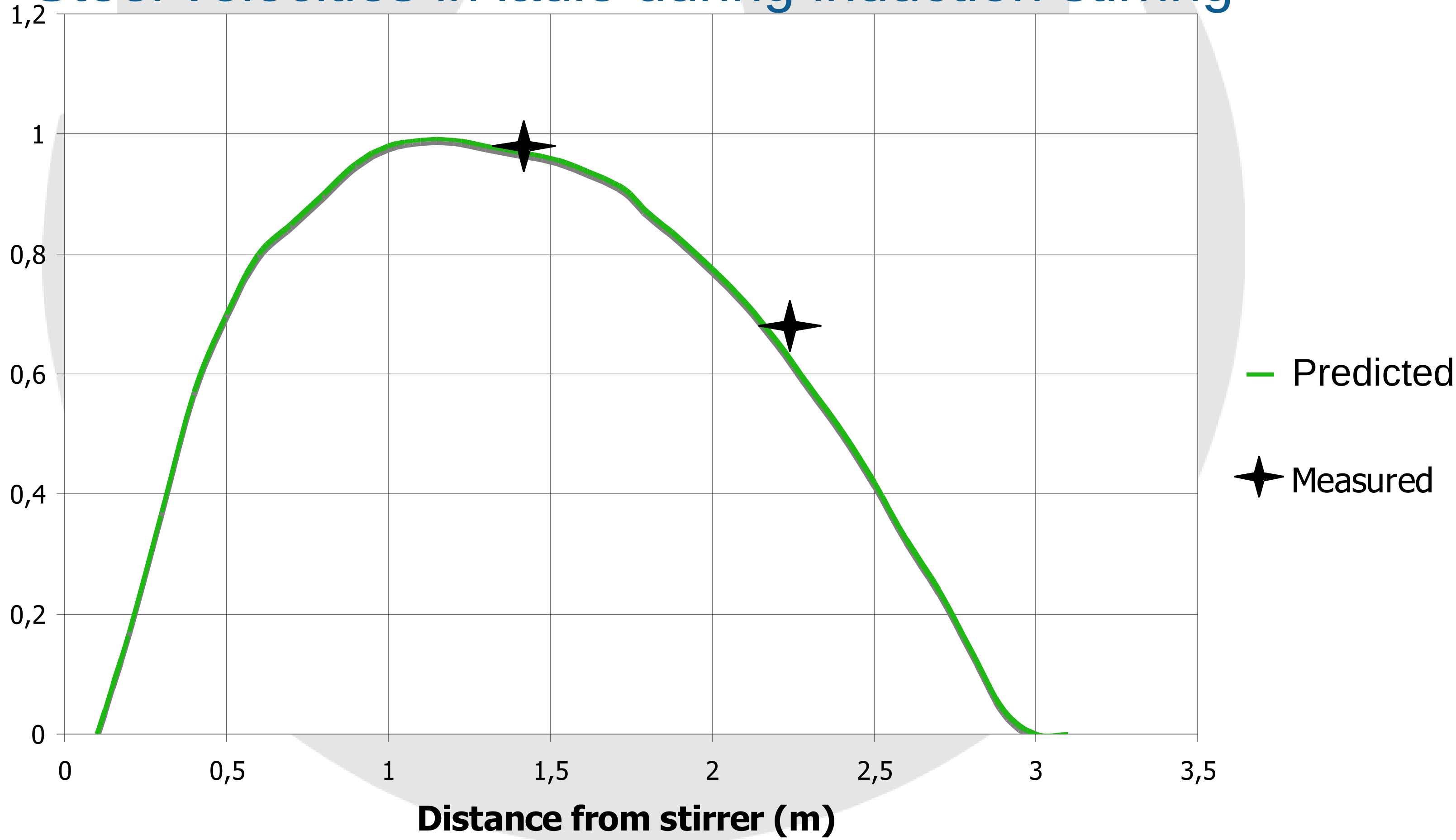


Validation
Transport Description

Velocity measurements with graphite rods

Validation
Transport Description

Steel velocities in ladle during induction stirring

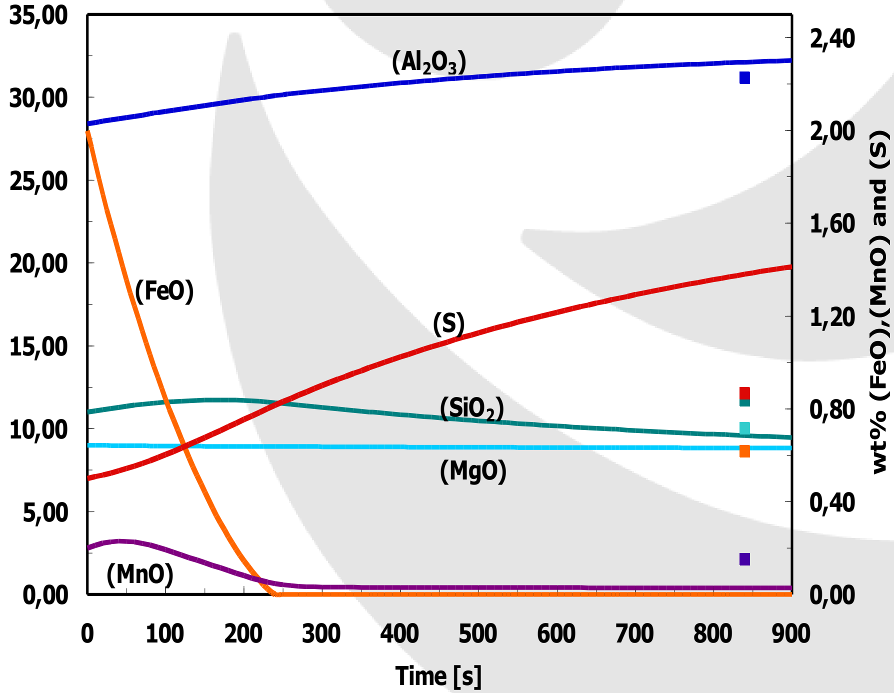


Validation
Sulphur Refining and Reoxidation

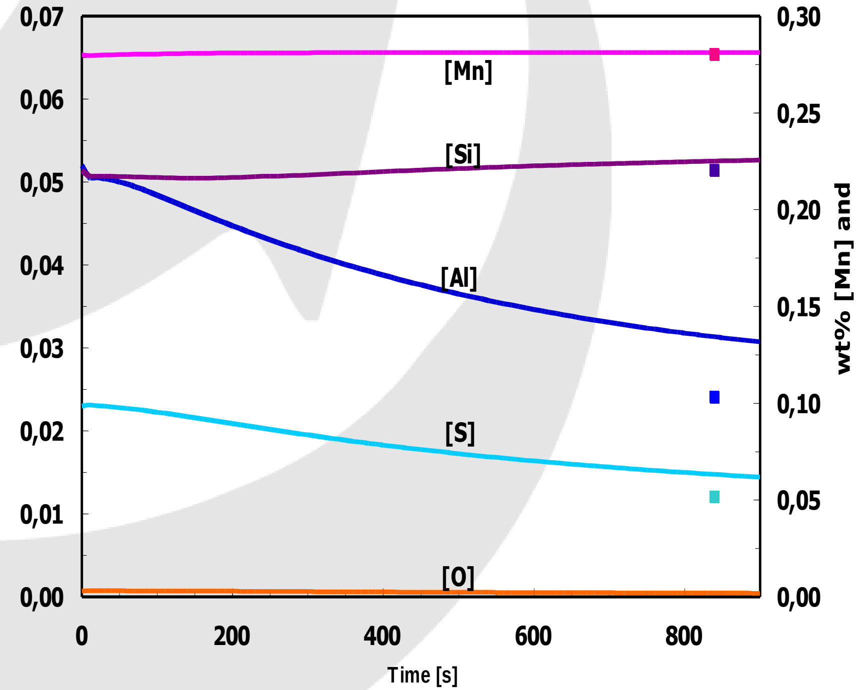
For a validation of the ”Sulphur refining and reoxidation predictions from the model a comparison between predicted results and data from the industry was performed. Slag and Steel was sampled before and after the sulphur refining process. The process took 850 seconds and was performed in vacuum making it impossible to sample during the process. The two sets of Slag and Steel samples were analysed and used as input data and resulting Steel analysis respectively.

Validation
Sulphur Refining and Reoxidation

Slag analysis



Steel analysis



■ Meaured — Predicted

Conclusions

- For a Qualitative description (Parametric studies) a simpler reaction zone model can be used.
- For a Quantitative description of Sulphur refining, the development of empirical models describing the reaction zone in a steel ladle must be utilised due to the lack of data prohibiting development of a fundamental model.