Thermochemical Modeling of the Blast Furnace Raceway Zone

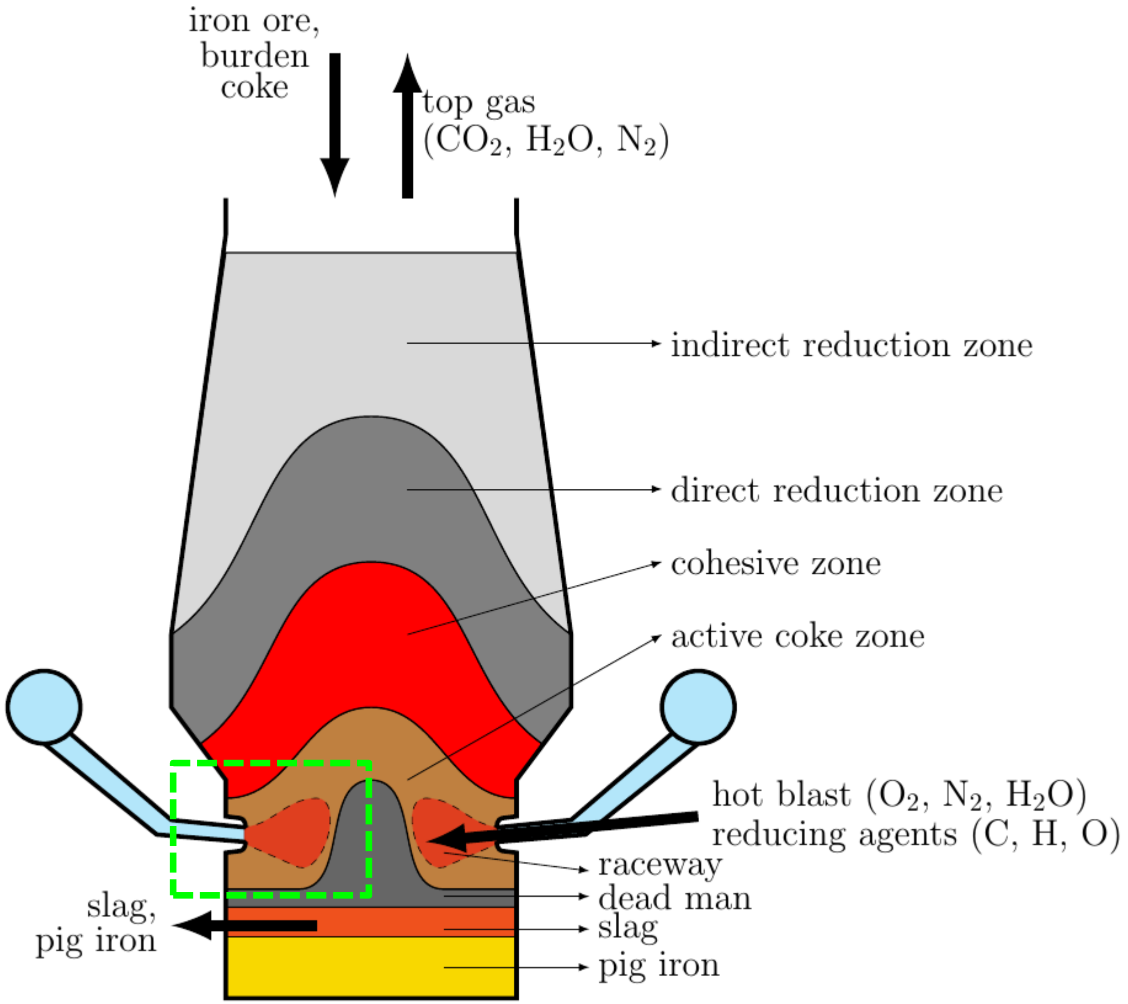
Markus Bösenhofer, Eva-Maria Wartha, Matthias Kiss, Michael Harasek

Introduction

What is the raceway zone?

- Cavity next to tuyeres

Why is the raceway zone important?



Schematic overview blast furnace process.

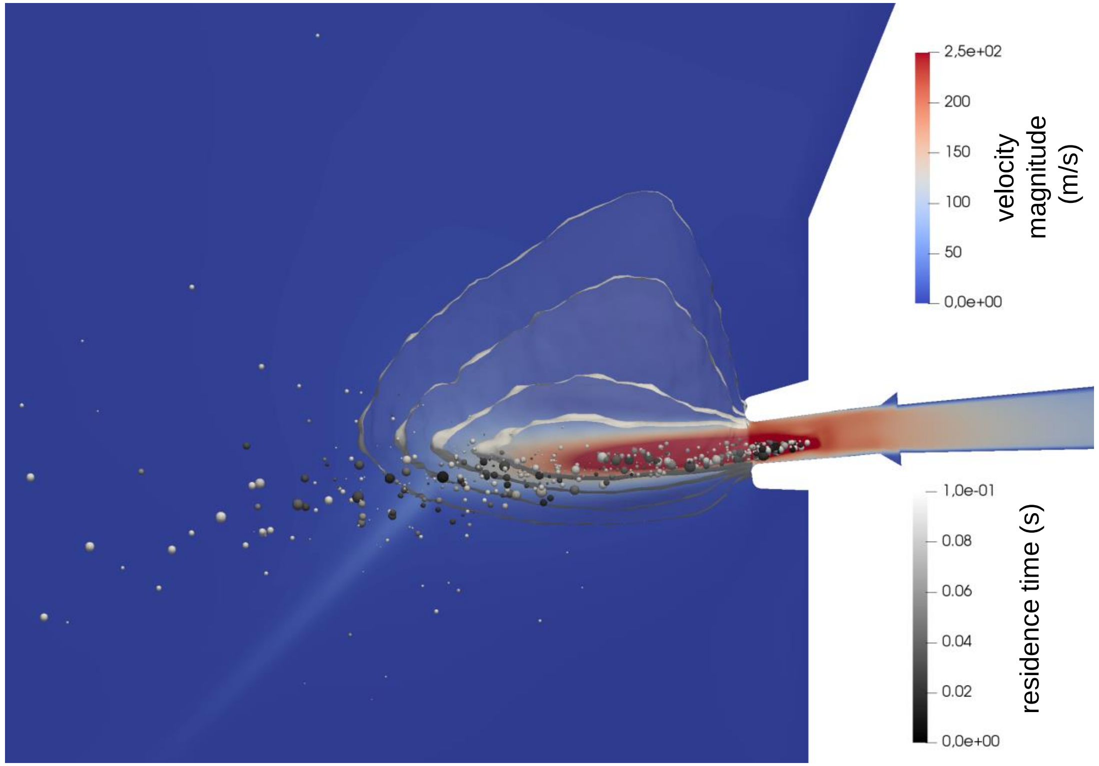
Introduction

What is the raceway zone?

- Cavity next to tuyeres

Why is the raceway zone important?

- Thermochemical processes influence efficiency
- Injection alternative reducing agents (ARAs)
- Reduction of metallurgical coke consumption

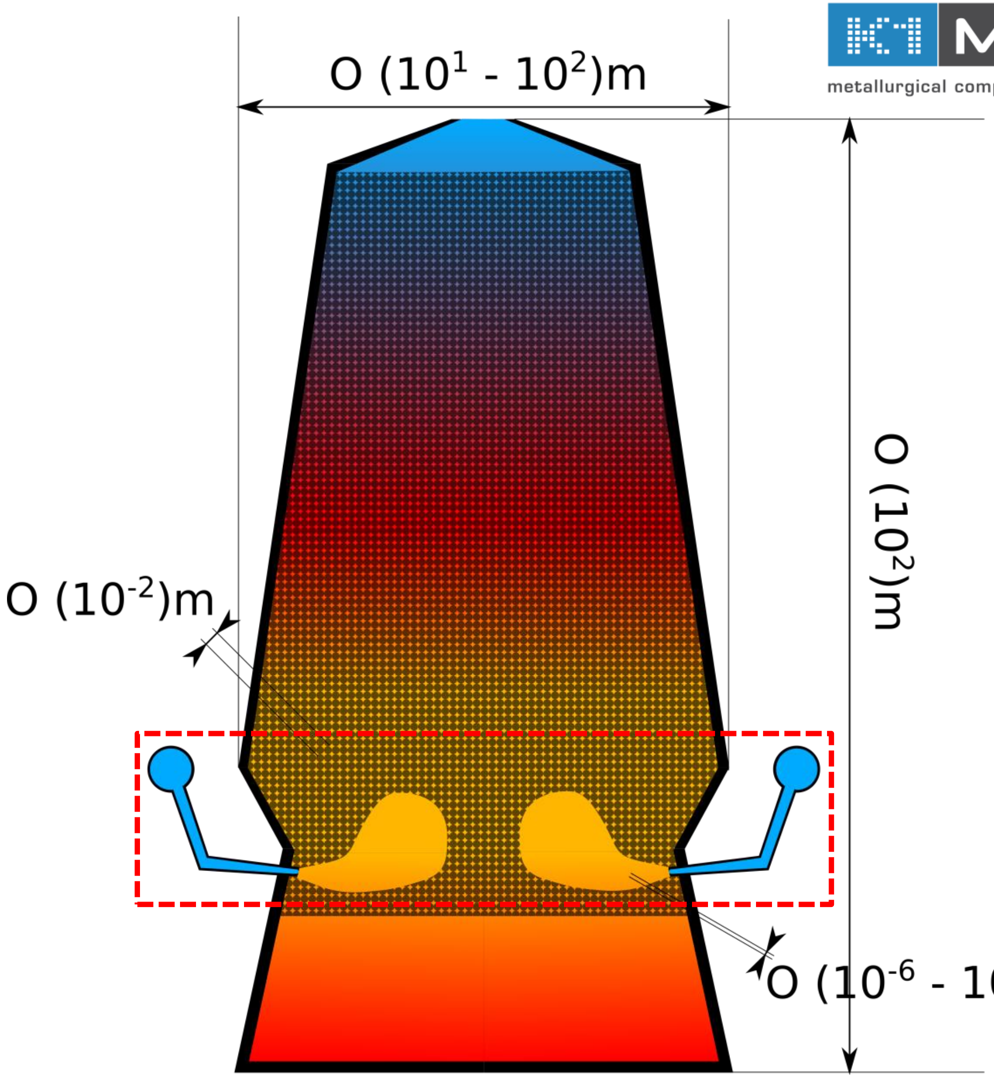


Hot blast velocity and PCI residence time in the raceway zone.

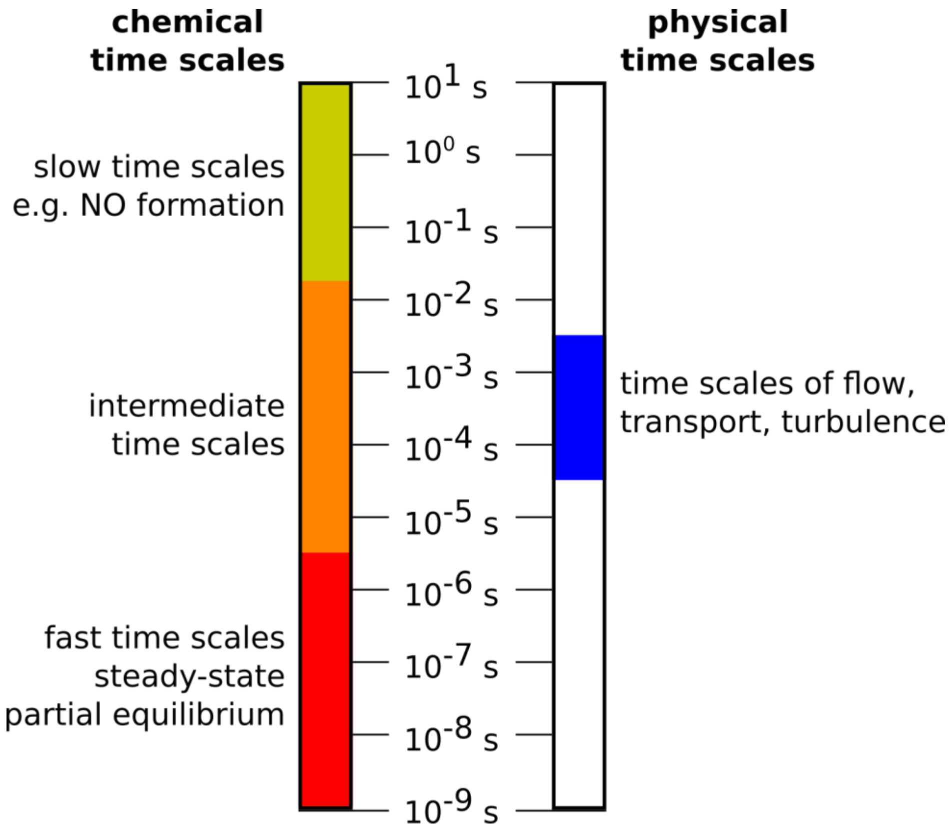
Involved Length Scales

Geometrical scales

- Blast furnace size
- Coke/Ore/Aggregates
- ARAs



Involved Time Scales



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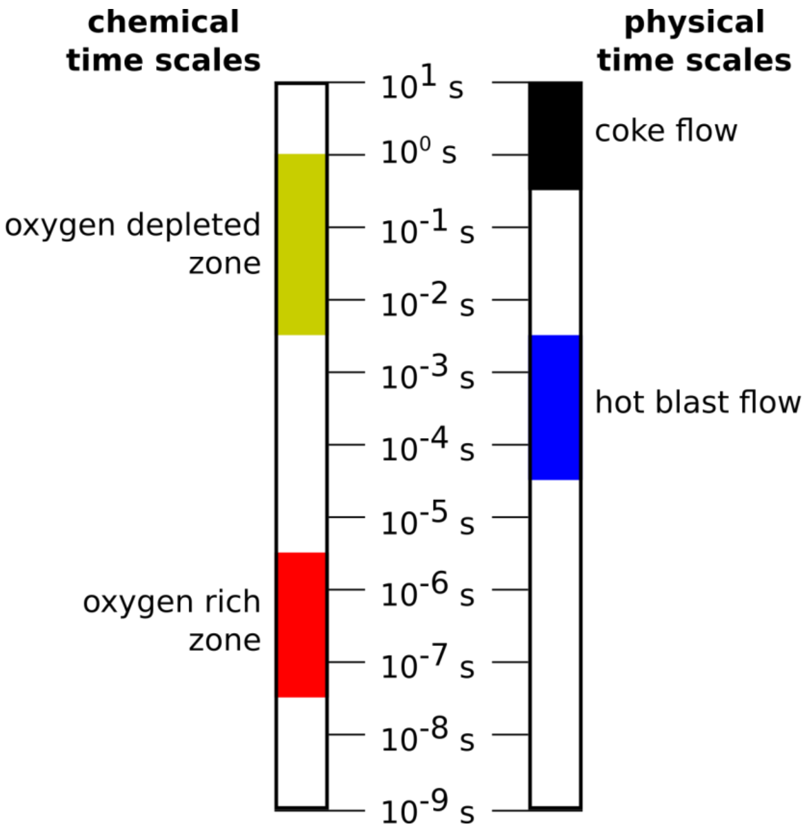
Involved Time Scales

Chemical scales

- ARA/coke conversion
- Gas-phase chemistry

Physical scales

- Gas/solid flow
- Turbulence
- Mass transport/transfer



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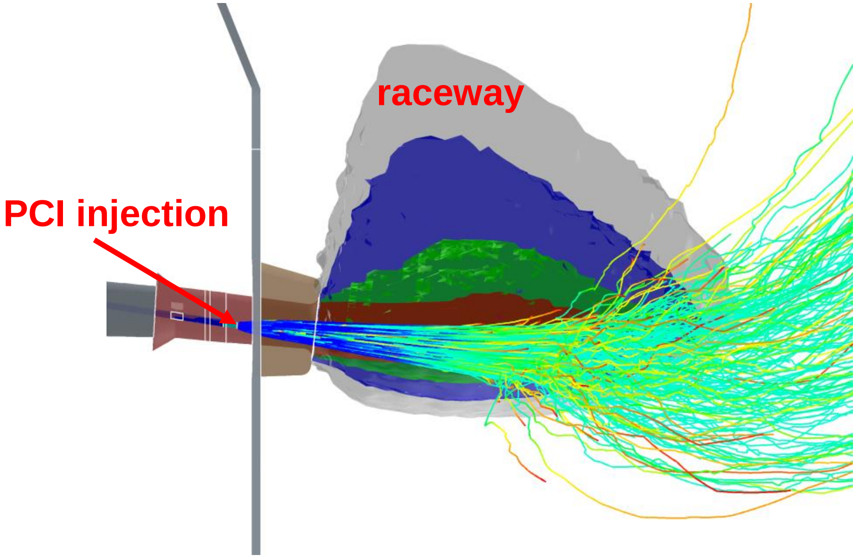
Raceway Conditions

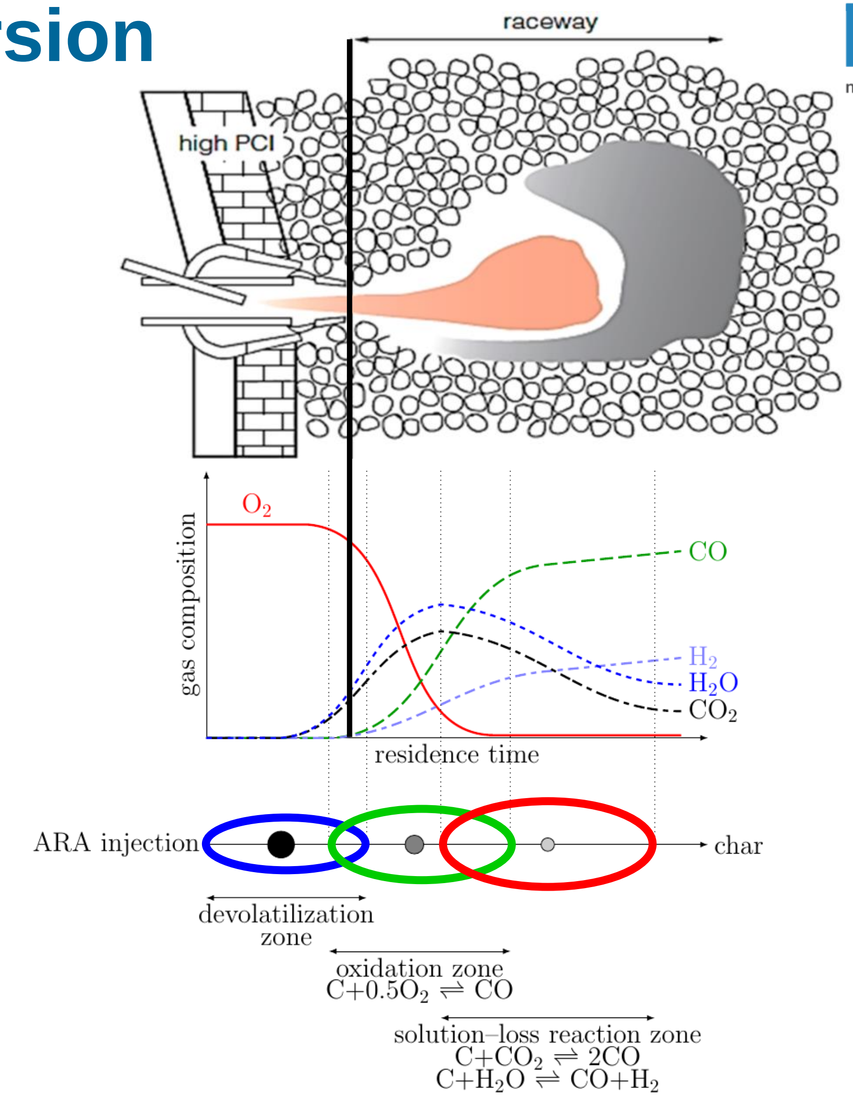


Fixed raceway shape based on literature, colors indicate porosity: 0.9 (red), 0.8 (green), 0.7 (blue), 0.6 (grey)[1]

Temperature	Heating rates	Pressure	Relative velocity	Flow type	Residence time
1200 – 2500 K	10^4 – 10^6 K/s	2 – 5 $bar_{(a)}$	< 1- 100 m/s	Turbulent	< 100 ms

[1]C. MAIER (2015): NUMERICAL MODELING OF THE BLAST FURNACE PROCESS – INJECTION OF AUXILIARY REDUCING AGENTS INTO THE RACEWAY, PHD THESIS, TU WIEN
[2]M. BÖSENHOFER ET AL. (2020): SUITABILITY OF PULVERISED COAL TESTING FACILITIES FOR BLAST FURNACE APPLICATIONS, IRONMAKING & STEELMAKING, VOL 47(5), PP. 574-585

Thermochemical ARA conversion



©T. KAMIJOU ET AL. (2000): PC COMBUSTION IN BLAST FURNACE. IN ADVANCED PULVERIZED COAL INJECTION TECHNOLOGY AND BLAST FURNACE OPERATION, VOLUME 1, PP. 63–82

What are ARAs?

- Pulverized carbon carriers
- Particle size: 10 µm – 10 mm

ARA conversion:

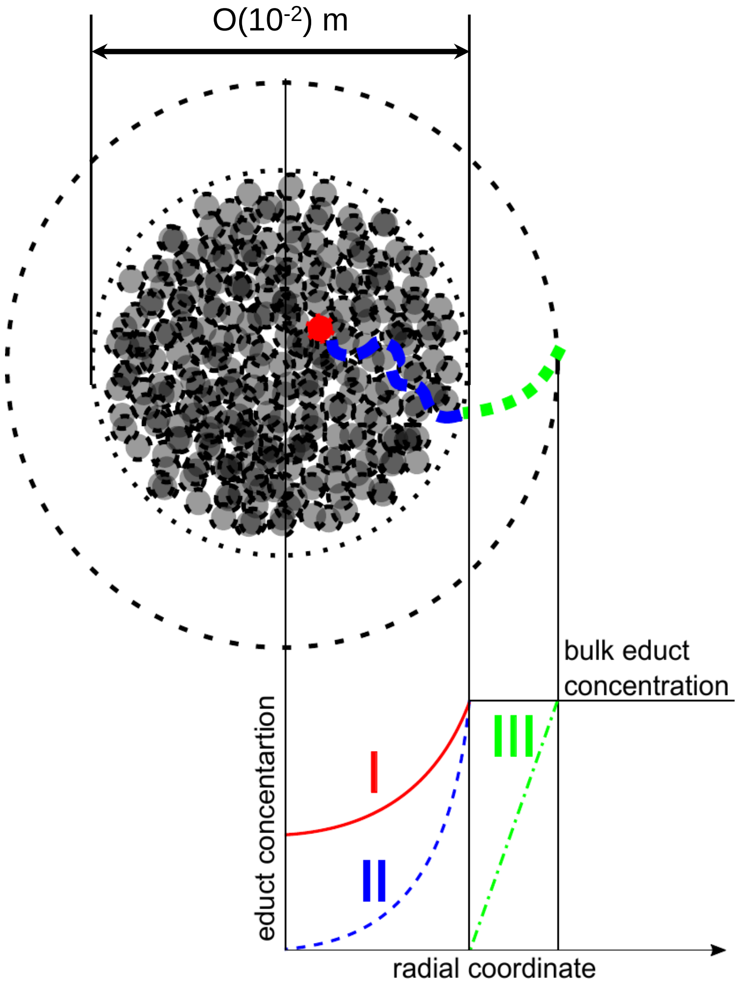
- Drying → thermal or equilibrium
- Devolatilization → single or two-step
- Oxidation → diffusion limited
- Gasification → diffusion limited

Thermochemical Conversion Coke/Ore

Coke conversion:

- (Unreacted) progressive core
- Effective rate expression:

$$k_{eff,j} = \frac{1}{\frac{1}{\mathrm{k}_{\mathrm{kin,j}} \cdot \eta_{\mathrm{j}}} + \frac{1}{h_{BL,\mathrm{j}} A_{coke} c_{\mathrm{j}}^{1-v}}}$$



© M. BÖSENHOFER ET AL. (2019): MULTIPHASE REACTIVE SYSTEMS – ANALYSIS OF INVOLVED TIME SCALES, PROCEEDINGS: 9TH EUROPEAN COMBUSTION MEETING (ECM), 6 PAGES

Thermochemical Conversion Coke/Ore

Coke conversion:

- (Unreacted) progressive core
- Effective rate expression:

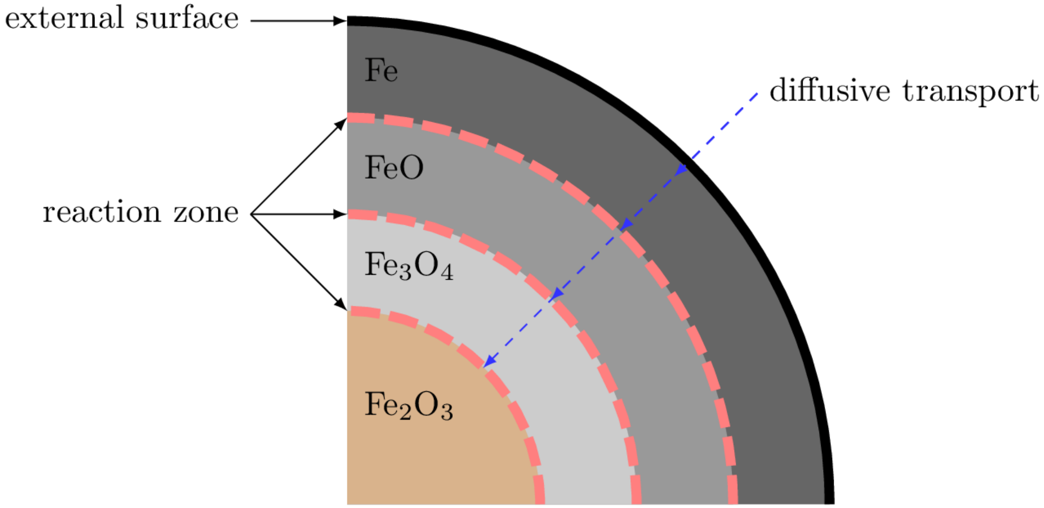
$$k_{eff,j} = \frac{1}{\frac{1}{\mathrm{k_{kin,j}} \cdot \eta_j} + \frac{1}{h_{BL,j} A_{coke} c_j^{1-v}}}$$

Iron ore conversion:

- Unreacted shrinking core
- Effective rate expression:

$$\frac{1}{k_{\mathrm{eff,i}}} = \frac{1}{\mathrm{A_s} h_{\mathrm{m,i}}} + \sum_{l>L} \left(\int_{r_{l+1}}^{r_l} \frac{dA}{D_{\mathrm{eff,i}} A(r)} + \sum \frac{1}{k_{\mathrm{i,l}}} \right) + \frac{1}{k_{\mathrm{i,L}}}$$

$$k_{\mathrm{eq,i}} = \left(k_{\mathrm{eff,i}} + \frac{k_{\mathrm{eff,i}}}{K_{\mathrm{eq}}} \right) \cdot \left(c_{\mathrm{i}} - \frac{c_{\mathrm{j}}}{K_{\mathrm{eq}}} \right)$$



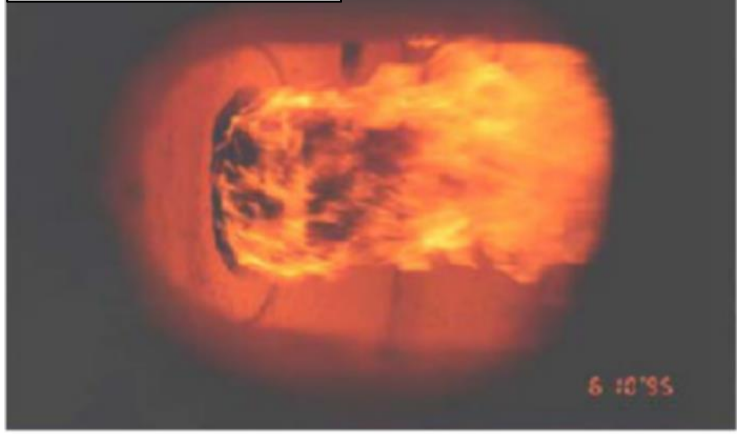
© M. BÖSENHOFER ET AL. (2023):AN EULERIAN-BASED REDUCTION MODEL FOR IRON ORE PARTICLE REDUCTION, AISTECH 2023, 8 PAGES

Gas-phase chemistry

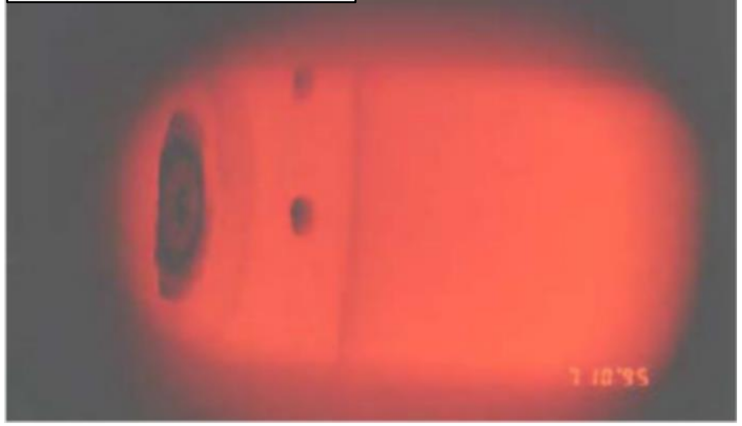
Challenges:

- Different combustion regimes
- Multiple gas species sources (coke, ore, ARAs)
- Widely scattered characteristic scales
- Turbulence

classical combustion



flameless combustion



© V. PANEBIANCO (2016): A NUMERICAL STUDY OF TURBULENCE-FLAME INTERACTION IN MILD COMBUSTION, PHD THESIS.

Gas-phase chemistry

Challenges:

- Different combustion regimes
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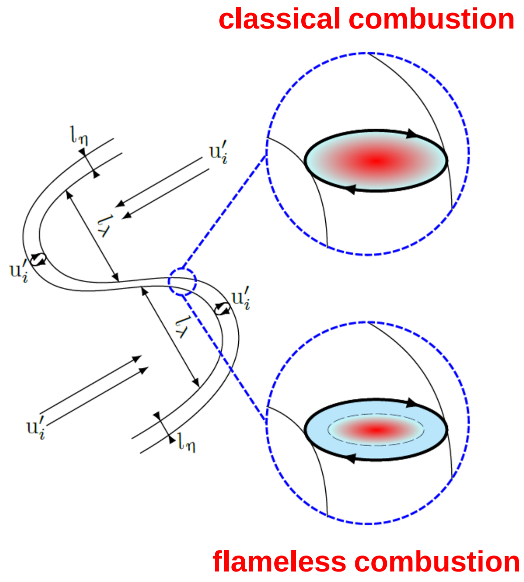
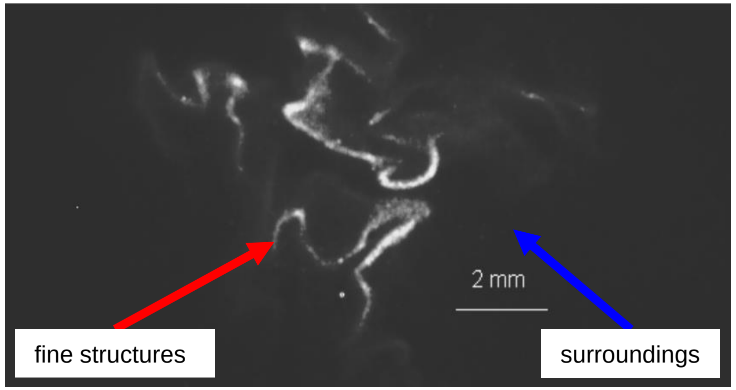
Eddy Dissipation Concept (EDC):

- Based on turbulence energy cascade
- Covers multiple regimes



Comparison fine structures classical and MILD combustion.[1,2]



Reacting structures of a premixed opposing jet flame.[3]

[1] M. BÖSENHOFER ET AL. (2018): THE EDDY DISSIPATION CONCEPT—ANALYSIS OF DIFFERENT FINE STRUCTURE TREATMENTS FOR CLASSICAL COMBUSTION, ENERGIES 11(7):1902
[2] H. TENNEKES (1968): SIMPLE MODEL FOR THE SMALL-SCALE STRUCTURE OF TURBULENCE. THE PHYSICS OF FLUIDS, 11(3), PP. 669–671
[3] P. MAGNUSSEN (2009): INVESTIGATION INTO STRUCTURE AND BEHAVIOR OF LAMINAR AND TURBULENT FLAMES BY PLANAR LASER-INDUCED FLUORESCENCE MEASUREMENTS, PHD THESIS, NTNU

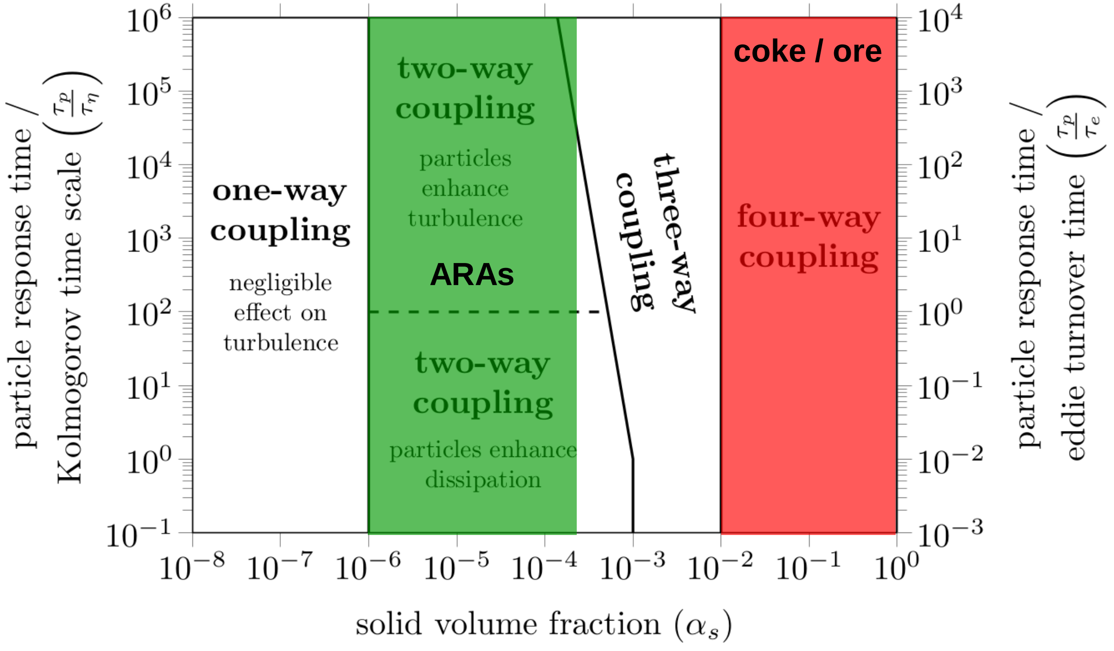
Multi-Phase Modeling

Involved phases:

- Gas
- Solid (coke, ore)
- Liquid (iron, slag)
- ARAs (pulverized solids)

Modeling strategy:

- Euler-Euler-Lagrange
- Continuous solid phases (KTGF)
- Point mass/1D Lagrangian ARA phases

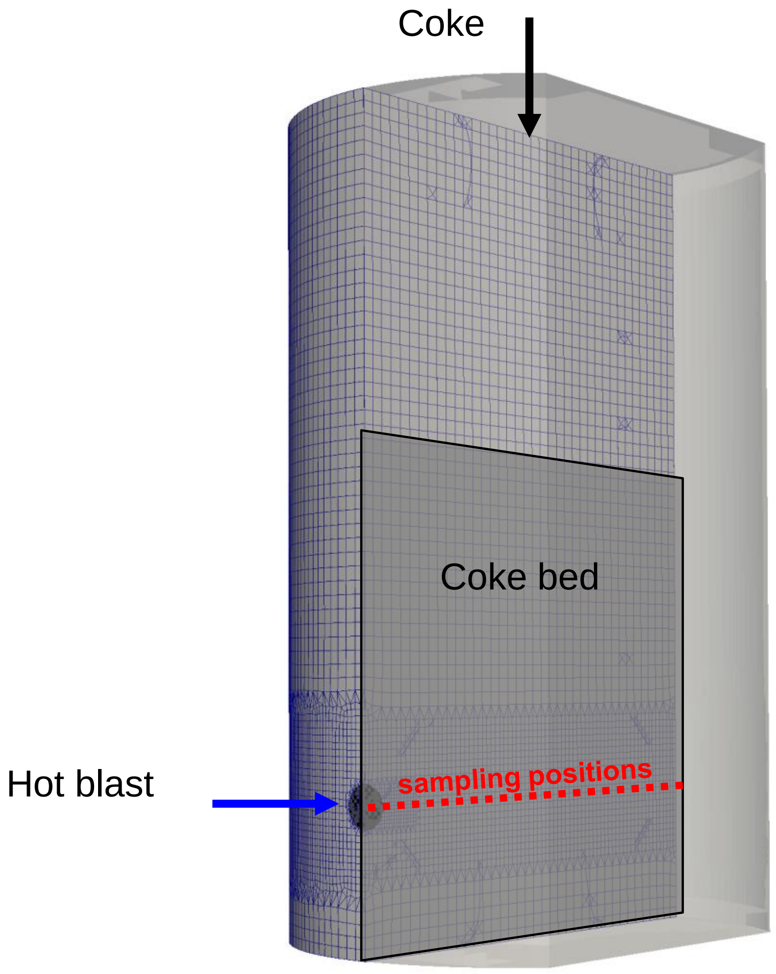


© S. ELGHOBASHI (1994): ON PREDICTING PARTICLE-LADEN TURBULENT FLOWS, APPLIED SCIENTIFIC RESEARCH, VOL. 52, 309-329.

Model Validation

Lab-Scale blast furnace:

- Experimental raceway formation
- Measurement of species concentration in the raceway



Schematic illustration and mesh of the experimental setup from[1]

[1] H. NOGAMI ET AL. (2004) RACEWAY DESIGN FOR THE INNOVATIVE BLAST FURNACE, ISIJ INTERNATIONAL 2004;44:2150–8

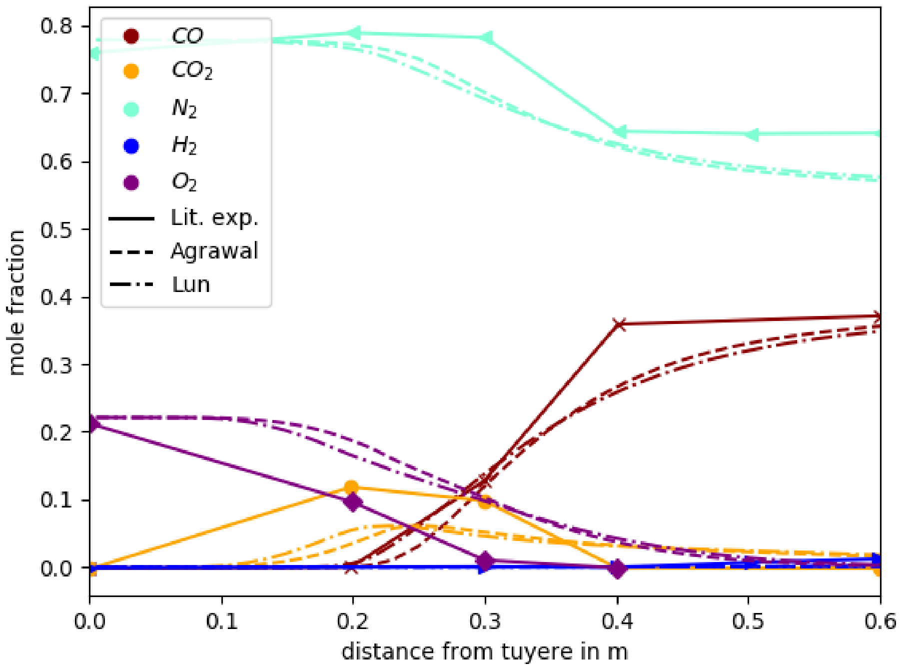
Model Validation

Lab-Scale blast furnace:

- Experimental raceway formation
- Measurement of species concentration in the raceway

Simulations results:

- No significant difference between KTGF closures
- Good agreement with experiments



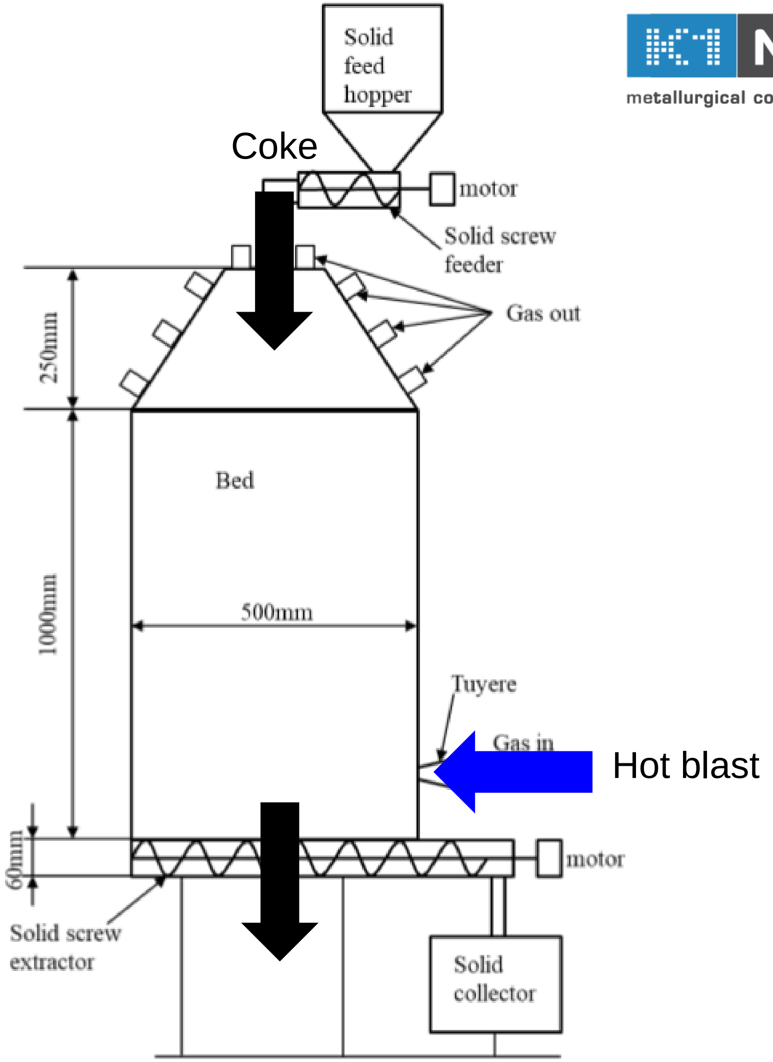
Comparison experimental and simulation result

Modeling Study – Raceway Size

Influence Coke :

- 2D experiments on raceway formation
- Continuous feeding from top
- Gas tight continuous discharging at bottom
- Varying coke conversion rates:

Case ID	Rate Variation
C0	$0 \cdot k_{eff,i}$
C1	$0.5 \cdot k_{eff,I}$
C2	$k_{eff,I}$
C3	$100 \cdot k_{eff,i}$



Schematic illustration of the case setup.[1]

[1] V. MOJAMDAR, G.S. GUPTA, A. PUTHUKKUDI, RACEWAY FORMATION IN A MOVING BED, ISIJ INT. 58 (2018) 1396–1401.

Modeling Study – Raceway Size

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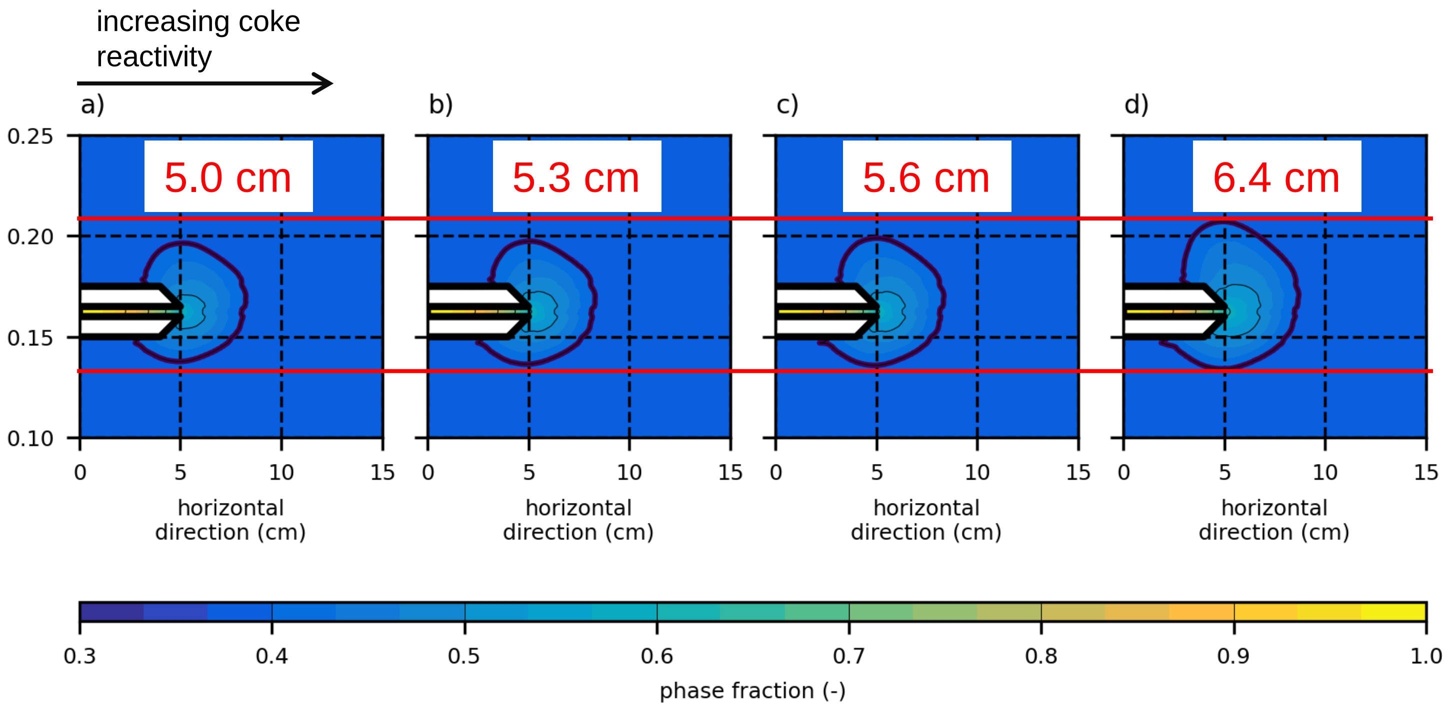
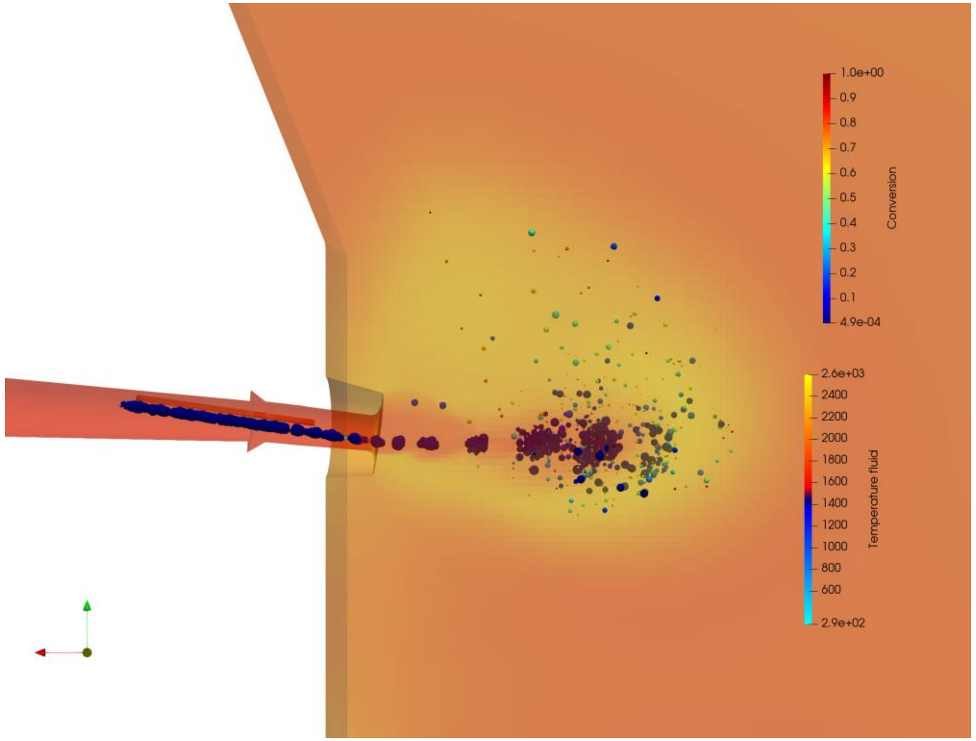


Hot blast phase fraction contours. a) C0; b) C1; c) C2; d) C3.

Summary & Outlook

- Thermochemical raceway modeling complex:
  - Length/time scales
  - Multiple phases
  - Chemistry
- Comprehensive modeling framework
  - General multiphase reactors
- Investigation of blast furnace operation
  - ARA injection investigations
  - Coke consumption



Snapshot representative PCI injection simulation.

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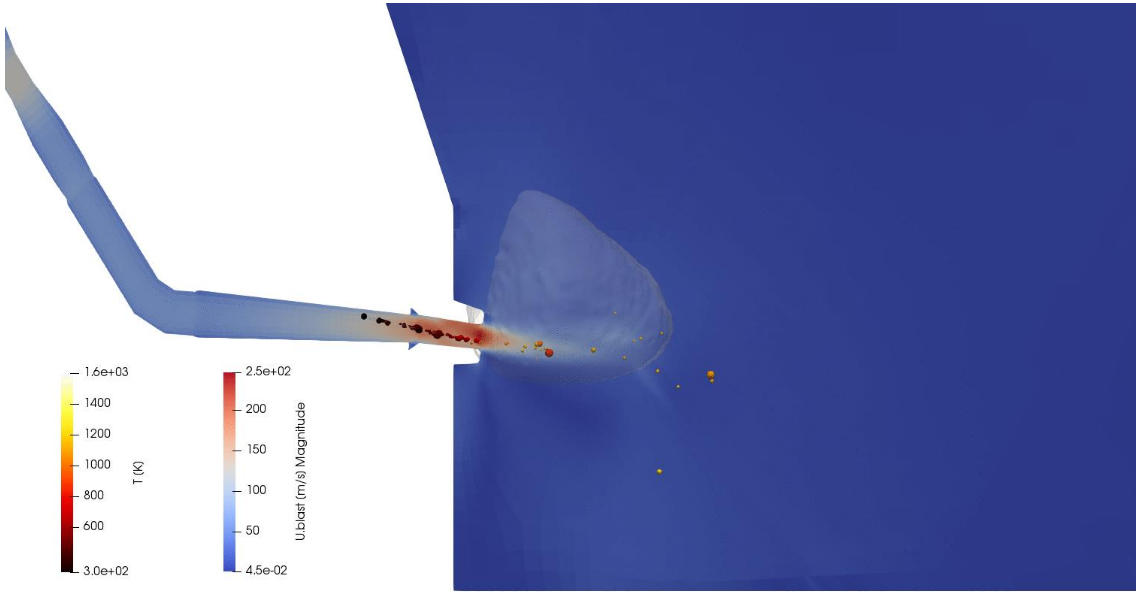

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