Selected papers from 10th International Conference on Computational Fluid Dynamics in the Oil & Gas, Metallurgical and Process Industries

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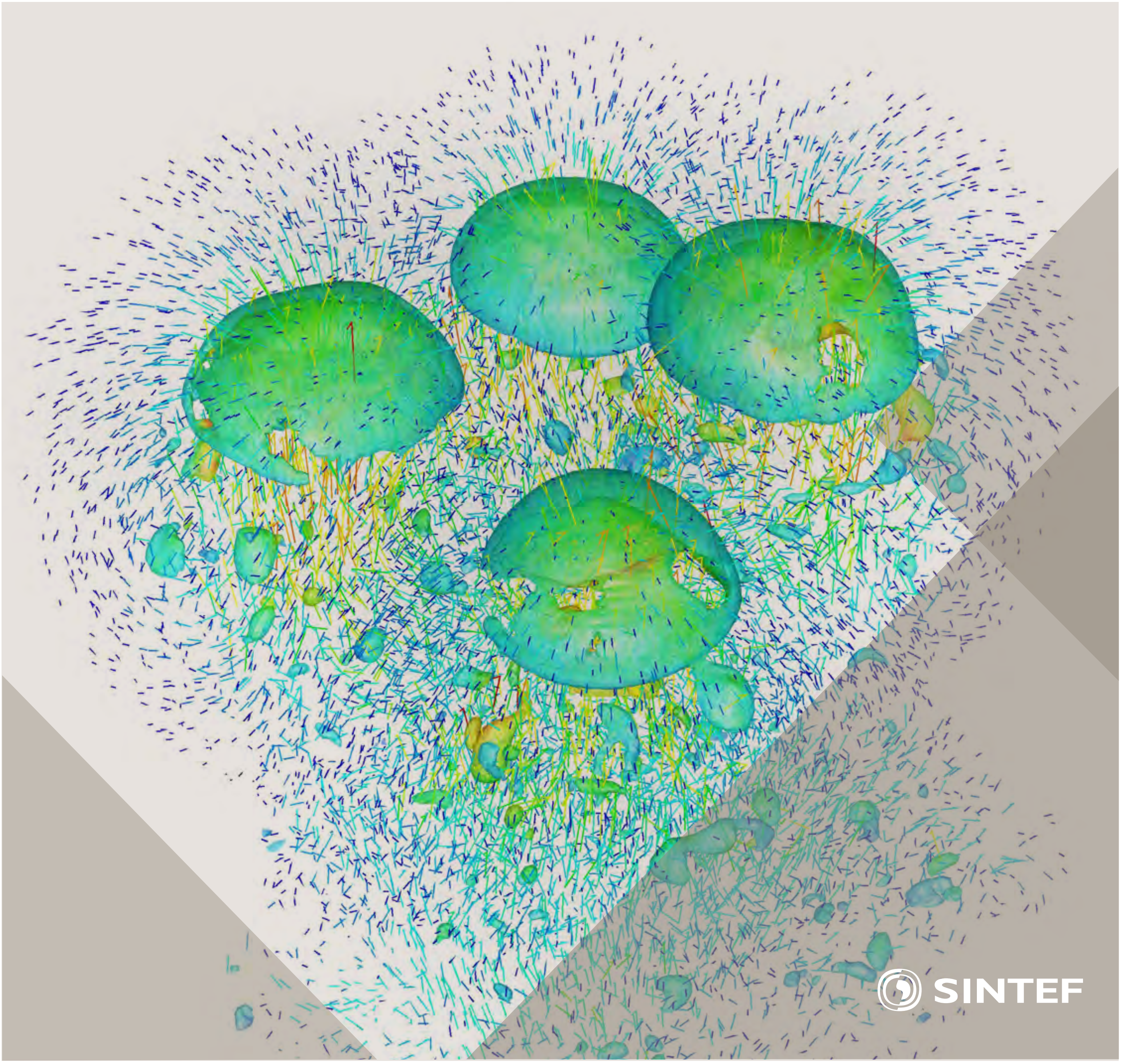
Progress in Applied CFD



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Editors:
Jan Erik Olsen and Stein Tore Johansen

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PREFACE

This book contains selected papers from the 10th International Conference on Computational Fluid Dynamics in the Oil & Gas, Metallurgical and Process Industries. The conference was hosted by SINTEF in Trondheim in June 2014 and is also known as CFD2014 for short. The conference series was initiated by CSIRO and Phil Schwarz in 1997. So far the conference has been alternating between CSIRO in Melbourne and SINTEF in Trondheim. The conferences focus on the application of CFD in the oil and gas industries, metal production, mineral processing, power generation, chemicals and other process industries. The papers in the conference proceedings and this book demonstrate the current progress in applied CFD.

The conference papers undergo a review process involving two experts. Only papers accepted by the reviewers are presented in the conference proceedings. More than 100 papers were presented at the conference. Of these papers, 27 were chosen for this book and reviewed once more before being approved. These are well received papers fitting the scope of the book which has a slightly more focused scope than the conference. As many other good papers were presented at the conference, the interested reader is also encouraged to study the proceedings of the conference.

The organizing committee would like to thank everyone who has helped with paper review, those who promoted the conference and all authors who have submitted scientific contributions. We are also grateful for the support from the conference sponsors: FACE (the multiphase flow assurance centre), Total, ANSYS, CD-Adapco, Ascomp, Statoil and Elkem.

Stein Tore Johansen & Jan Erik Olsen

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CONTENTS

MULTI-SCALE MODELING OF HYDROCARBON INJECTION INTO THE BLAST FURNACE RACEWAY

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ABSTRACT

Injection of alternative reducing agents via lances in the tuyères of blast furnaces is widely applied to reduce the consumption of metallurgical coke. Besides liquid hydrocarbons and pulverized coal the injection of recycled waste plastics is possible, offering the opportunity to chemically reuse waste material and also utilize the energy contained in such remnants.
In this work CFD models were developed and implemented that capture the multiphase nature of reducing agent injections, accounting for homogenoeus and heterogeneous reactions of materials in charge. The model is applied to the raceway zone of the blast furnace. Various geometry setups are investigated and discussed aiming at increasing the knowledge on impact of these parameters on the conditions in the blast furnace.

Keywords: CFD, multiphase heat and mass transfer, multiscale, blast furnace, direct injection.

INTRODUCTION

The majority of liquid raw iron is produced via the blast furnace route, traditionally utilizing metallurgical coke as the main reducing agent. Aiming at a reduction of primary resources, using alternative reducing agents such as liquid hydrocarbons, natural gas and waste plastics contributes to the reduction of coke rates. In the blast furnace these agents also deliver the heat necessary for melting processes as well as endothermic reduction reactions.
To optimize the utilization of the input materials, thorough examination of the impact of fuel injection is necessary. However, due to the extreme conditions in the blast furnace, the application of experimental techniques is very limited. A promising alternative is to conduct numerical experiments applying the methods of computational fluid dynamics. In this work, models are developed to study the process that takes place on multiple scales and aspects, e.g. in terms of (Pirker, 2014):

- length scales: wide range from microscopic length scales where heterogeneous chemical reactions take place on defects in the atomic structure towards global flow phenomena in the blast furnace shaft
- time scales: variation from very fast processes and high velocities in the zone of hot blast injection to comparatively low velocities of coke bed movement
- multiple phases: appearance of solid, liquid and gas phases and intense interactions

The blast furnace studied is operated by voestalpine Stahl GmbH in Linz, Austria. This furnace is arranged with equipment allowing for the utilization of a wide range of alternative reducing agents including natural gas, processed waste plastics, heavy fuel oil and tar etc. Currently, a facility for the injection of pulverized coals is installed. A schematic illustration of this blast furnace is given in figure 1.
To successfully model the utilization of feed materials in the blast furnace it is necessary to apply considerable simplifications considering e.g. the representation of the various phases and chemical reactions in order to limit the computational effort to affordable levels. An important aspect is also the definition of sound boundary conditions to properly describe the conditions at the edges of the simulation domain and reliably compute thermophysical properties of involved material streams.

MODEL DESCRIPTION

CFD-simulations were carried out using the framework of the multi-purpose solver ANSYS FLUENT® v6.3.23 (FLUENT, 2007). The modeling capabilities of the solver were extended to include the description of multiple phases such

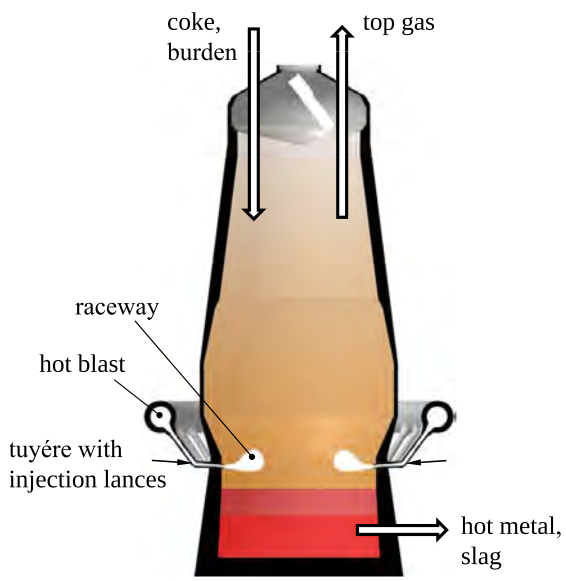

Figure 1: Blast furnace scheme.

as solid coke, gases, injected liquid hydrocarbons and plastic particles, accounting for heterogeneous heat and mass transfer phenomena. This was done by compiling user-defined subroutines into the code to implement the functionality necessary to describe processes in the raceway of blast furnaces. Non-equilibrium between the slowly descending bed of metallurgical coke and counter-currently ascending gases is considered by solving separate sets of conservation equations applying a multi-grid method (Maier *et al.*, 2012b, 2013b).

Simulation of coke bed movement

The flow of solids charged to the blast furnace has considerable influence on the operating characteristics as the loading of iron ore and coke on top of the bed and the bulk flow in shaft, raceway and hearth zone determine the operational stability to a great extent (Dong *et al.*, 2007; Zaïmi *et al.*, 2000). While the burden move further downwards coke is partially gasified and iron ores are reduced. The ore is molten in the cohesive zone. Below this region coke remains as the only solid material, allowing for liquid raw iron and slag to move downwards, countercurrently to hot blast moving towards the top of the furnace. The flow of solids in a blast furnace is mainly driven by melting of iron ore and conversion of coke in the raceway zone.

For the simulation of the flow of solid matter several approaches of problem formulations are available, including e.g. discrete elements methods (DEM), Euler-granular models or viscous flow models (Dong *et al.*, 2007).

Simulation setups applying discrete elements methods rely on the computation of the movement of individual particles by integrating Newton's law of motion for every single discrete particle. This offers the possibility to evaluate particle trajectories and interaction forces from first principles. However, in industrial apparatuses the number of particles is very large, therefore a tremendous computational effort is to be expected (Hilton and Cleary, 2012).

The so-called Euler-granular method is commonly implemented for flow simulation of gas and granular solids (Wen and Bi, 2011). Solid and fluid media are treated as continuous, fully interpenetrating with separate conservation equations. This approach makes use of the kinetic theory of gases to describe inter-phase exchange coefficients between gas or liquid and granular materials and requires a time-resolved solution procedure.

Application of viscous flow models for moving beds of particles is based on the representation of the bed as a continuous, single-phase fluid with modified viscosity (Nogami and Yagi, 2004; Zhang *et al.*, 1998). Therein, friction between particles is described by introducing a fictive solids viscosity that can be used in the Navier-Stokes equations. This approach offers the big advantage that the flow field of solid matter can be calculated using a finite volume solver. Furthermore, computations can be performed applying steady-state solvers, avoiding computationally very demanding time-discretization of the conservation equations.

The currently implemented model treats the bed of coke applying continuum fluid mechanics, including the ability to describe the driving forces for coke movement (i.e. coke utilization by oxidation and gasification reactions, momentum transfer from hot blast). Various authors state the possibility to model the movement of a bed of solids as a viscous fluid with properties of *Bingham media* (Nogami and Yagi, 2004; Schatz, 2000; Chen *et al.*, 1993).

In this model viscous properties are described by two parameters: yield viscosity μ_0 and yield stress τ_0. These parameters were determined experimentally for various solid matters. Parameters for coal particles were used in the present study ($\mu_0 = 1230\,\mathrm{Pas}$, $\tau_0 = 1.14\,\mathrm{Pa}$) (Nogami and Yagi, 2004).

As coke particles are usually larger than the length scale of roughness of the furnace refractory lining, the typically applied no-slip boundary condition for solid velocities is not valid (Zhang *et al.*, 1998). Therefore, in the simulation of coke flow a slip boundary is applied at rigid walls.

Hot blast injection, raceway cavity

In the lower region of the blast furnace oxygen-enriched air, preheated to high temperatures is injected at velocities of up to $200\,\mathrm{m/s}$ via tuyères. Due to the high momentum of the gas jet and consumption of coke via heterogeneous reactions, a cavity is formed adjacent to each tuyère. In the core of this structure the void fraction of the coke bed approaches unity, leaving space for alternative reducing agents injected via lances in the tuyère. The size and shape of the cavity determines the travelling distances of injected materials from the injection lance tip to the impaction position on the coke bed and therefore the time available for gasification and combustion reactions.

In the current model framework, to limit computational efforts to reasonable levels, the formation of the raceway zone is not computed explicitly during the solution process but given as a boundary condition. The cavity is implemented by defining a porosity profile in the coke bed, its shape is taken from from literature sources (Zhou, 2008). The size of the raceway cavity is calculated depending on the actual blast furnace operating conditions considering rates and properties of injected hot blast as well as geometry issues (i.e. tuyère diameter, height of the coke bed in the furnace shaft etc.) applying a one-dimensional model (Gupta and Rudolph, 2006). This model accounts for the impact of blast momentum, hearth diameter, coke particle properties as well as height and void fraction of the coke bed in the blast furnace on raceway formation. Particle friction was identified as an important factor. For the blast furnace the decreasing part of the hysteresis curve of the raceway formation process was reported to be the determining step. The parameters used to compute the raceway size are summarized in table 1.

Table 1: Properties of blast furnace coke particles, applied for the computation of raceway size using the model of Gupta and Rudolph (2006).

property	value	
coke particle density	1100	$\mathrm{kg/m^3}$
particle size	25	mm
particle shape factor	0.7	–
angle of particle-particle friction	43.3	°
coke bed porosity	0.5	–
upward facing fraction of raceway	0.8	–
coke bed height (max. fill level)	26	m
hearth diameter	12	m

The impact of hot blast velocity on the raceway size at typical operating conditions as calculated applying this model is shown in figure 2. In the case of a constant blast rate, blast momentum increases with decreasing tuyère diameter, therefore the penetration depth of hot blast is enhanced and cavity volume is estimated to increase by a factor of approx. 2.8 as the tuyère diameter is decreased from 160 to 130 mm.

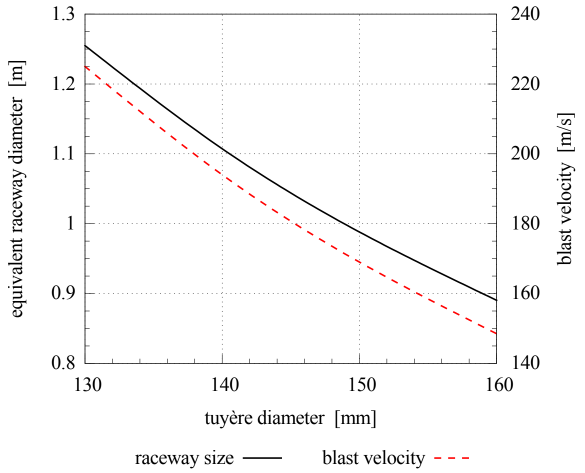

Figure 2: Variation of raceway size with respect to tuyère diameter. Hot blast rate per tuyère: 9900 $^{\mathrm{Nm}^3}/_{\mathrm{h}}$ at 1220 °C, operating pressure 4.2 bar$_g$, oxygen enrichment to 27.4 $\%_{v/v}$ O_2.

Measurements of the coke bed voidage at stopped blast furnaces and hot model experiments showed that the porosity varied between approx. 0.3 near the boundary of the raceway cavity and 0.5 further away (Gupta and Rudolph, 2006). Therefore, the porosity in far-field of the raceway was implemented as $\varepsilon = 0.5$. The resulting porosity distribution in the computational domain, highlighting the raceway cavity, is shown in figure 3.

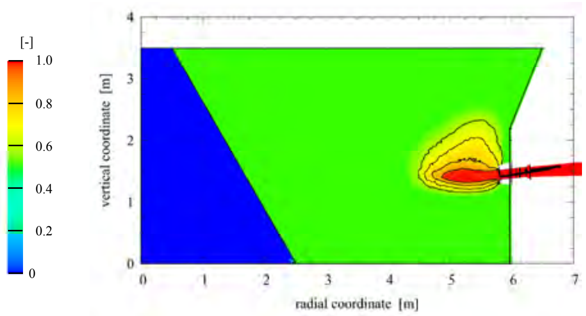

Figure 3: Porosity field in the blast furnace.

Injection of alternative reducing agents

The injection of liquid hydrocarbons and plastic particles is modeled applying tracking schemes in a Lagrangian frame of reference. Heating rates are computed accounting for contributions from laminar and turbulent convective transfer as well as radiation. The release of mass from the liquid fuel to the gas phase is computed applying a multicomponent evaporation model based on temperature dependent saturation pressures of mixture components.

At conditions in a blast furnace raceway, injected waste plastic particles exhibit non-isothermal behavior (Maier *et al.*, 2013a). This results from very high heat transfer rates due to high relative velocities and intense radiation interaction. As the thermal conductivity of injected plastic particles is rather low, thermolysis takes place near the particle surface while the core temperature remains constant.

In the simulation setup user-defined routines were hooked to the solver to properly model the release of alternative reducing agents to the gas phase.

Homogeneous reactions

Rates of homogeneous gas-phase reactions are calculated considering reactant mixing on finest scales of turbulent eddies in a set of global reactions. The considered reactions are (for detailed discussion of reaction rates please refer to (Jordan *et al.*, 2008a,b)):

$$\mathrm{CH_4 + 2\,O_2 \longrightarrow CO_2 + 2\,H_2O} \qquad \text{(R 1)}$$

$$\mathrm{2\,CO + O_2 \longleftrightarrow 2\,CO_2} \qquad \text{(R 2)}$$

$$\mathrm{2\,H_2 + O_2 \longrightarrow 2\,H_2O} \qquad \text{(R 3)}$$

$$\mathrm{CO + H_2O \longleftrightarrow CO_2 + H_2} \qquad \text{(R 4)}$$

$$\mathrm{CH_4 \longleftrightarrow C_s + 2\,H_2} \qquad \text{(R 5)}$$

Cracking of hydrocarbon vapor to form smaller gaseous constituents as well as combustion is modeled in the gaseous regime:

$$\mathrm{C_{19}H_{30} + 17\,O_2 \longrightarrow 19\,CO + 15\,H_2O} \qquad \text{(R 6)}$$

$$\mathrm{C_{19}H_{30} + 6\,O_2 \longrightarrow H_2 + 7\,CH_4 + 12\,CO} \qquad \text{(R 7)}$$

$$\mathrm{C_{19}H_{30} \longrightarrow C_s + 3\,H_2 + 6\,CH_4} \qquad \text{(R 8)}$$

Heterogeneous reactions

Heterogeneous reactions of coke with gas mixture components are evaluated considering major reaction routes such as oxidation, steam and CO_2 gasification and methanation (reactions R 9-R 12; kinetic expressions for reaction rates are given in table 2):

$$\mathrm{CH_xO_y(s) + (\frac{x}{4} - \frac{y}{2})\,O_2 \xrightarrow{k_{O_2}} CO_2 + \frac{x}{2}\,H_2O} \qquad \text{(R 9)}$$

$$\mathrm{CH_xO_y(s) + CO_2 \xrightarrow{k_{CO_2}} 2\,CO + y H_2 + (\frac{x}{2} - y)\,H_2O} \qquad \text{(R 10)}$$

$$\mathrm{CH_xO_y(s) + (1-y)\,H_2O \xrightarrow{k_{H_2O}} CO + (1 + \frac{x}{2} - y)\,H_2} \qquad \text{(R 11)}$$

$$\mathrm{CH_xO_y(s) + (2 + y - \frac{x}{2})\,H_2 \xrightarrow{k_{H_2}} CH_4 + y\,H_2O} \qquad \text{(R 12)}$$

Table 2: Kinetic rate expressions for heterogeneous reactions.

	rate expression	reference
R 9	$k_{O_2} = 3.8 \cdot 10^7 \cdot e^{-\frac{150500}{R \cdot T_{coke}}}$	(Rumpel, 2000)
R 10	$k_{CO_2} = 2.7 \cdot 10^5 \cdot e^{-\frac{185200}{R \cdot T_{coke}}}$	(Rumpel, 2000)
R 11	$k_{H_2O} = 3.42 \cdot T_{coke} \cdot e^{-\frac{129700}{R \cdot T_{coke}}}$	(Tepper, 2005)
R 12	$k_{H_2} = 0.00342 \cdot T_{coke} \cdot e^{-\frac{129700}{R \cdot T_{coke}}}$	(Tepper, 2005)

Rates of reactions are computed resolving educt species transport on a particulate scale, accounting for boundary layer diffusion, diffusion in the porous coke structure and intrinsic reaction kinetics (see fig. 4).

The thickness of the particle boundary layer strongly depends on local gas flow conditions, particle properties and coke bed voidage and is calculated with respect to local turbulence and gas phase properties. The diffusive transport processes are considered as a series of resistances to the actual chemical reaction (for a detailed description of the reaction model please refer to (Maier *et al.*, 2012b)). This approach allows for the computation of effective reaction kinetics for wide temperature ranges.

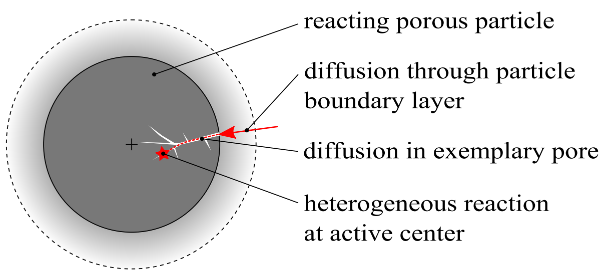

Figure 4: Schematic illustration of educt species diffusion from gas bulk flow towards the actual reaction site.

Rates of CO_2-gasification of metallurgical coke as a function of temperature at various gas-solid relative velocities are shown in figure 5. In this chart, pressure and species concentrations are similar to conditions at the boundary of a blast furnace raceway. At moderate temperatures, the overall rate of CO_2 gasification is limited by reaction kinetics. As temperatures increase, rate of reaction kinetics rise in the order of e^T, while the dependence of diffusive transport on temperature is represented by a power-law. Consequently, at high temperatures reactant concentrations in the porous coke particles decline, resulting in a limitation of the overall reaction rate.

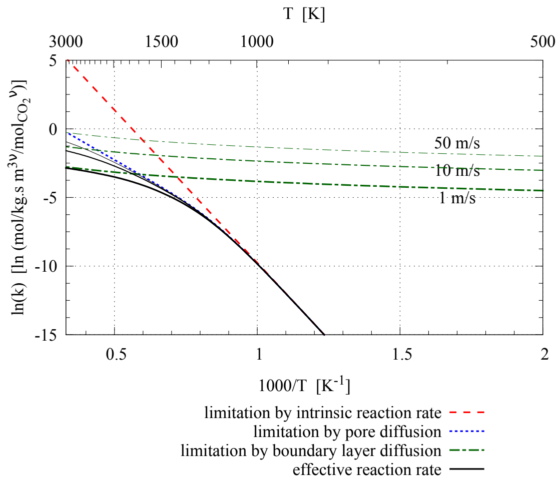

Figure 5: Heterogeneous CO_2 gasification of metallurgical coke. Conditions: gas velocities $1\,{}^{m}/_{s}$, $10\,{}^{m}/_{s}$ and $50\,{}^{m}/_{s}$, $p = 5.1\,\text{bar}$, coke particle size 21 mm, coke bed voidage = 0.8, gas mixture: $10\,\%_{v/v}$ H_2O, $16.8\,\%_{v/v}$ CO_2, $5.7\,\%_{v/v}$ O_2, balance N_2.

The heat of reactions are computed from standard state enthalpy differences at local temperatures using polynomial expressions available for thermophysical properties (Lemmon *et al.*, 2014). The standard enthalpy of formation of solid coke was estimated from the tabulated values of gas species involved in the combustion reaction using the lower heat of combustion of coke given from experimental examination.
The model was implemented stepwise towards full model complexity, each module was validated by comparison of simulation results with experimental data, starting from simple processes involving heterogeneous heat transfer towards cases with homogeneous reactions and finally arriving at setups with heterogenous coke utilization (Maier *et al.*, 2012a,b, 2013a,b).

Geometry setup

The considered simulation domain consists of a segment of the blast furnace including one tuyère element (see fig. 6). Periodic boundary conditions are applied to the vertical cutting planes to properly link corresponding data structures on either side.

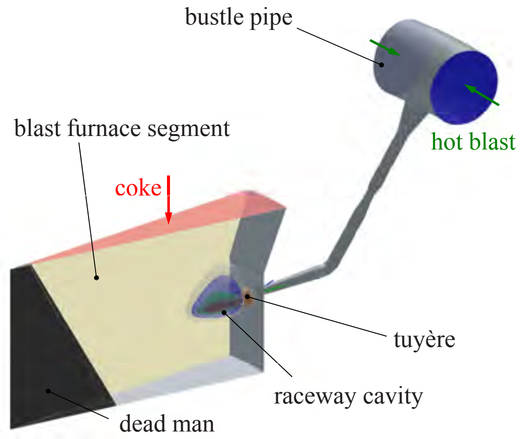

Figure 6: Overview of the simulation domain.

The geometry includes a detailed description of the tuyère and lances for injection of alternative reducing agents (fig. 7).

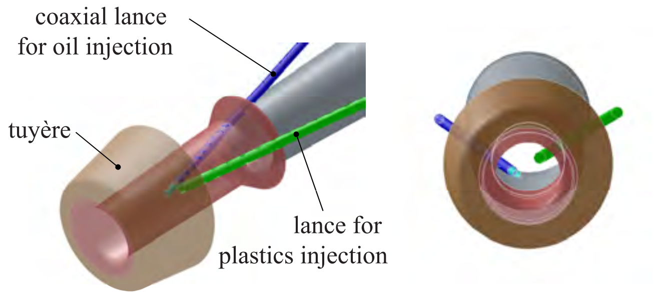

Figure 7: Geometry of simulation domain, detail: Tuyère and lances for injection. Left: isometric, right: front view.

RESULTS

In the next sections simulation results for the full blast furnace geometry are discussed. Basic operating conditions of the furnace are summarized in table 3. In the parametric study conditions are varied, these are explained in the according subsections. The strategy is set up such that the effect of one specific parameter is studied at a time by variation, while keeping the remaining variables at base conditions.

Table 3: Blast furnace baseline operating conditions.

hot metal production rate	$360\,{}^{t_{hm}}/_{h}$
number of tuyères	32
tuyère diameter	140 mm
hot blast rate	$316000\,{}^{Nm^3}/_{h}$
hot blast temperature	1220 °C
hot blast O_2 concentration	$27.4\,\%_{v/v}$
operating pressure	$4.2\,\text{bar}_g$
liquid hydrocarbons rate	$55.1\,{}^{kg}/_{t_{hm}}$
plastics rate	$68.3\,{}^{kg}/_{t_{hm}}$

Baseline simulation results

In the base case, hot blast is injected at velocities of 194 m/s. First the gas follows the direction of the tuyère centerline. As the boundary of the raceway is reached, the void fraction of the coke bed decreases, therefore increasing pressure drop is exerted to the gas flow. As a consequence, the flow direction changes towards the gradient of the porosity profile, gases leave the raceway cavity in a radial direction (see fig. 8).

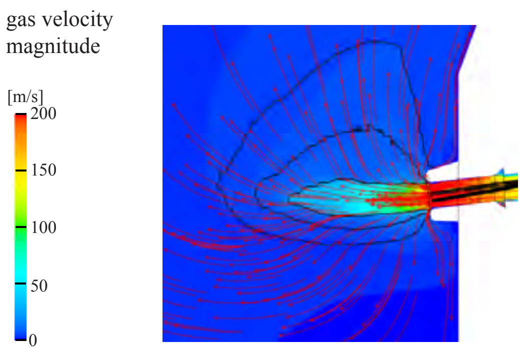

Figure 8: Gas flow field near the tuyère opening: Path-lines of gas flow and contours of velocity magnitude.

Due to inter-phase momentum transfer, coke particles are accelerated towards the center of the blast furnace. This is especially the case for material that enters the raceway cavity from top, falling into the gas jet. During the short time of flight these particles are not fully consumed by heterogeneous reactions, resulting in a circulating movement of coke particles in the zone near the tuyère opening (fig. 9). This behavior was also reported from experimental observation of operating blast furnaces using optical techniques (Kase *et al.*, 1982).

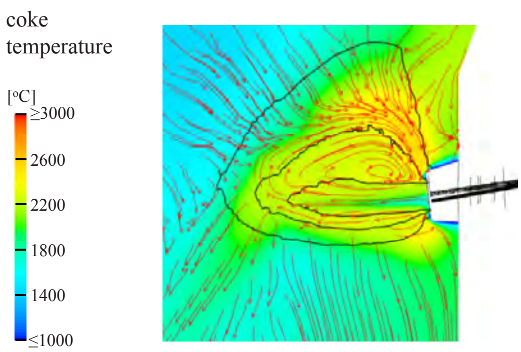

Figure 9: Coke flow and temperature field near the tuyère opening: Path-lines of coke flow and contours of coke temperature.

Liquid hydrocarbons that are utilized in the blast furnace under consideration consist of a mixture of heavy fuel oil and crude tar from coke production. Due to fierce conditions at fluid atomization, a fine droplet spray is achieved with a mean droplet diameter in the range of 100 μm. A fine spray is desired as it contributes to fast release of droplet mass to the gas phase and therefore efficient fuel utilization. The oil spray is readily evaporated just within the raceway cavity after residence times in the range of 10 ms (see droplet tracks in figure 10).

Waste plastics for injection are fed at much larger size classes (average particle diameter: 7 mm, see also fig. 11). Naturally this leads to longer residence times in the range of several seconds. This means that during time of flight particles pass the raceway zone and reach the boundary of the raceway cavity. In the simulations plastic particles are modeled to mechanically interact with the coke bed (note particle tracks in fig. 12). This behavior was also found in operating blast furnaces by investigation using high-speed imaging of the tuyère zone. The probability of reflection and/or impaction was evaluated based on the local level of coke bed porosity.

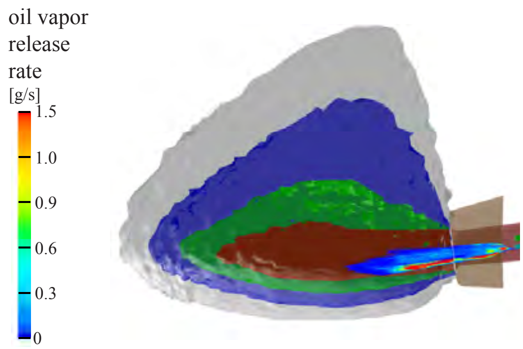

Figure 10: Trajectories of injected liquid hydrocarbons, colored by evaporation rate.

Figure 11: Processed waste plastics for injection into the furnace.

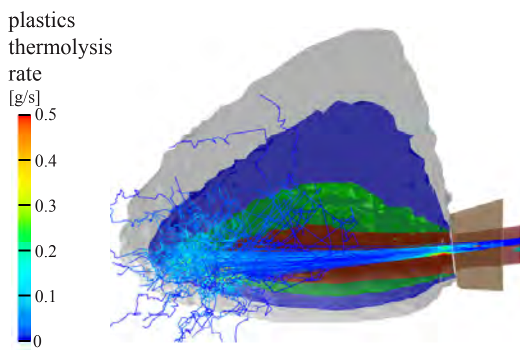

Figure 12: Trajectories of injected waste plastics, colored by thermolysis rate.

Right in front of the tuyère good mixing due to high turbulence intensity contributes to the rate of heterogeneous coke reactions as well as homogeneous reactions consuming pyrolysis products from gasification of injected alternative reducing agents. Oxygen contained in the hot blast is consumed fast, accordingly combustion products as well as heat of reactions are released in this zone. Consequently, in this zone coke temperatures reach maximal values to be expected in the blast furnace. Figure 13 shows the profile of gas species concentrations and temperature on a radial coordinate on tuyère level, also highlighting tuyère opening and

shape of the raceway cavity.
At the conditions present in a blast furnace, equilibria of Boudouard as well as water-gas reaction (reactions R 10 and R 11) are shifted to the right side, accordingly CO_2 and H_2O react with coke, releasing CO and H_2. These gases are utilized in the furnace for indirect reduction of iron oxides to raw iron. The heat required for these endothermic reactions is delivered by the reaction of injected materials and coke with oxygen introduced with the hot blast.

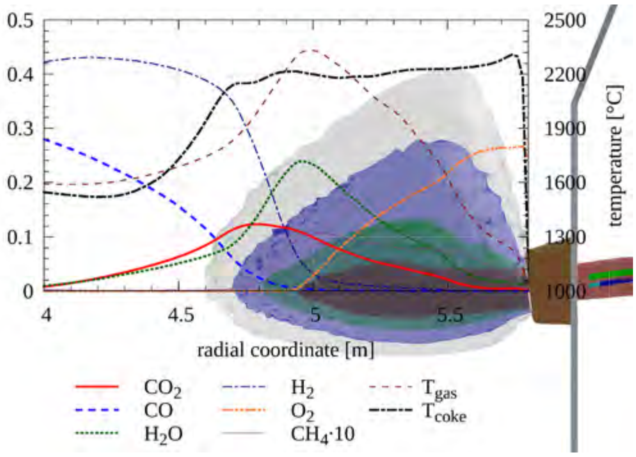

Figure 13: Radial species concentration and temperature profiles in the blast furnace on tuyère level.

The hurtling movement of coke particles in the raceway cavity also contributes to fuel utilization as heat is transferred convectively from zones with elevated temperatures (e.g. raceway boundary) towards the raceway core.

Tuyère diameter variation

To obtain stable furnace operation and successful feed utilization, deep penetration of hot blast into the coke bed is desired. As mentioned above, the diameter of the tuyères directly correlates to the hot blast momentum and consequently to the size of the raceway cavity. The effect of the inner diameter of the tuyères on heterogeneous coke reactions and utilization of injected alternative reducing agents was studied by conducting simulation runs with varying tuyère geometry while the hot blast rate was kept constant at the value given in table 3.

Table 4: Tuyère diameter variation.

case ID	tuyère diameter	raceway volume
case 1	140 mm	$0.71\,m^3$
case 2	150 mm	$0.51\,m^3$
case 3	160 mm	$0.37\,m^3$

As summarized in table 4, in the range of parameter variation the volume of the raceway cavity increases by a factor of approx. 1.9. Accordingly, the residence time of hot blast and therefore the time available for combustion of injected fuels increases together with mixing intensity, resulting in a shift of gas-phase species concentration profiles. In terms of coke bed void fraction, oxygen is consumed in regions further away from the raceway core, the CO_2-peak is shifted accordingly (see fig. 14).
The situation for the conversion of steam to H_2 via heterogeneous reactions is quite similar, as shown in figure 15. However, in the case with smallest raceway zone, case3, the

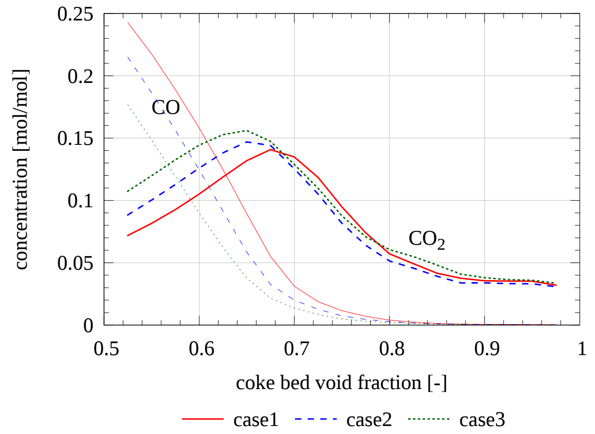

Figure 14: Tuyère diameter variation: CO and CO_2 concentration vs. coke bed void fraction.

boundary of the raceway is located closest to the tuyère opening. In this setup a part of the injected fuel oil spray is evaporated near the raceway boundary, causing a shift of the location of steam release with respect to the coke bed void fraction.
The volume of the raceway cavity is larger if a smaller tuyère is installed, as expected a deeper penetration of hot blast into coke bed is achieved, see e.g. coke utilization by heterogeneous water-gas shift reaction in figure 16.

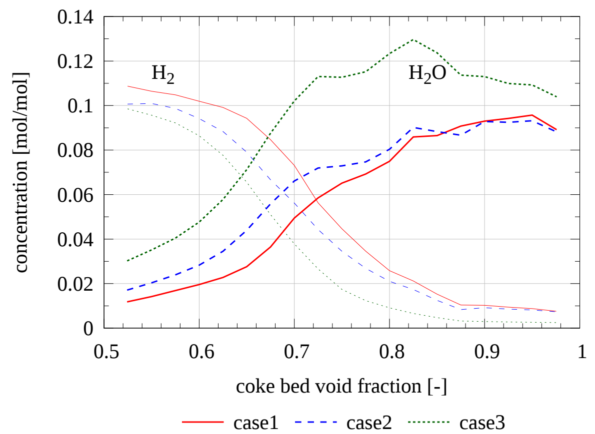

Figure 15: Tuyère diameter variation: H_2/H_2O concentration vs. cokebed void fraction.

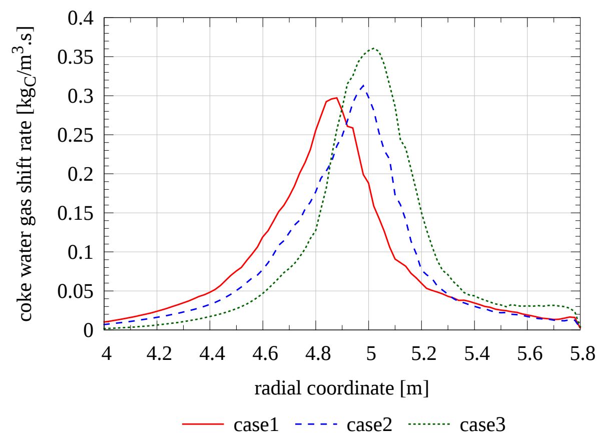

Figure 16: Tuyère diameter variation: Radial profile of coke consumption by steam gasification on tuyère level.

Lance tip position

The position of release of alternative reducing agents is determined by the position of lance tips. In the baseline setup, the lances for injection do not overlap each other (see fig. 7). Two additional geometry setups with deeper inserted lances as outlined in figure 17 were studied.

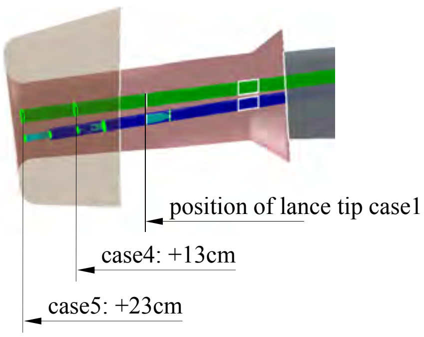

Figure 17: Sideview of tuyère and lances, highlighting range of lance tip position variation.

As expected as the lance tips are shifted towards the opening of the tuyère, the release of fuel oil vapor to the gas phase is transferred into the raceway cavity (fig. 18). In case 1 lance tips feature the largest distance to the tuyère opening. In this setup approx. 70 % of the fuel oil is evaporated within the tuyère, the remains is released in the core of the raceway cavity. In case 4 oil vapor release is already moved towards the coke bed but still gasification is completed in the region with void fractions of 90 – 100 %, while for case 5 already some oil gasification takes place in the boundary of the raceway zone.

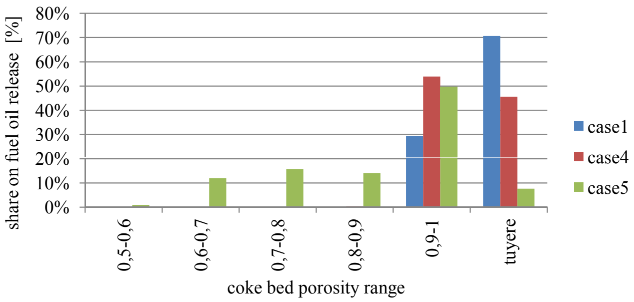

Figure 18: Location of fuel oil release, lance length variation.

Energy necessary to evaporate the fuel droplets is provided by radiation (far-field energy transfer) as well as locally from the gas phase by convective and conductive heat transfer. Therefore, at the point of fuel oil release a cooling impact is exerted on the gas flow until the combustion of volatiles overbalances this effect and temperature levels increase. In the blast furnace tuyères are installed with water-cooling systems to prevent materials from damage due to overheating. The cooling effect from oil pyrolysis influences the heat transferred via the inner surface of the tuyère and therefore the cooling duty, as summarized in table 5.

The location of the release of the oil spray also has an impact on the mean droplet residence times as the gas-temperatures in the surroundings of the spray vary. In case 5 the evaporating spray reaches very hot regions located near the boundary of the raceway cavity, therefore computed mean residence times are reduced significantly (table 5).

Due to the large particle sizes of injected waste plastics, lance length has only a minor impact on the position of plastics pyrolysis as compared to fuel oil release (fig. 19). However,

Table 5: Variation of lance tip position: Heat transfer via inner wall of tuyère, oil droplet and plastics residence times.

case ID	heat transfer rate	time to oil evaporation	time to plastics gasification
case 1	203 kW	4.36 ms	1.54 s
case 4	206 kW	3.20 ms	1.50 s
case 5	210 kW	2.10 ms	1.42 s

due to variation in gas-particle temperature differences plastics residence times vary in the range of 8 %.

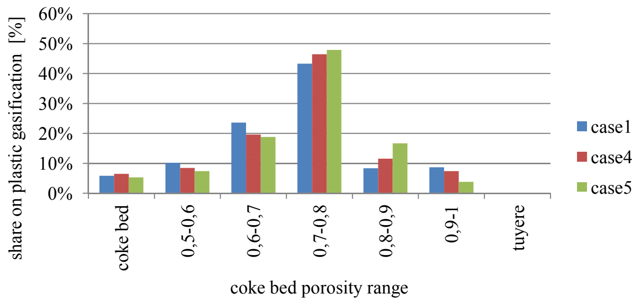

Figure 19: Location of plastics thermolysis, lance length variation.

CONCLUSIONS

A steady-state CFD model for alternative reducing agents injection into the raceway of ironmaking blast furnaces focussing on the utilization of feed materials by homogeneous and heterogeneous reactions was developed. In a parametric study the tuyère geometry was varied in terms of inner diameter and length of lances for injection. A smaller tuyère diameter contributes to increased penetration depth of hot blast into the coke bed, however at the cost of increased pressure drop of hot blast introduction. The position of the lance tip for injection of liquid hydrocarbons strongly influences estimated droplet residence times as well as the zone where oil evaporation takes place, also affecting the cooling duty of the tuyères.

The model will be applied to further operating conditions including e.g. oxygen enrichment levels, hot blast temperature and hot metal production rates. Future work will also include the extension of the model setup by a module for simulation of pulverized coal injection.

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