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Investigation of Alternative Reducing Agent Injection into the Raceway of Blast Furnaces using CFD

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CFD-models have been developed, implemented and validated to study the injection of plastics and heavy oil into the blast furnace raceway. Separate sets of conservation equations are solved for solid and gas phases, accounting also for heterogeneous transport phenomena. The model predictions deliver detailed insight to local conditions in the blast furnace and will be used for the optimisation of operating conditions, also aiming at further improvement of plant efficiency and economics.

1. Introduction

The classical blast furnace process utilizes coke as the main reducing agent to produce molten iron from iron ore. A promising approach to decrease coke demands and therefore the consumption of primary resources is the introduction of alternative carbon carriers, injected via lances through the tuyères into the raceway of the blast furnace (Fu et al., 2011). A wide variety of alternative reducing agents such as oil, crude tar, natural gas and waste plastics is utilized by voestalpine Stahl GmbH in Linz (Austria).

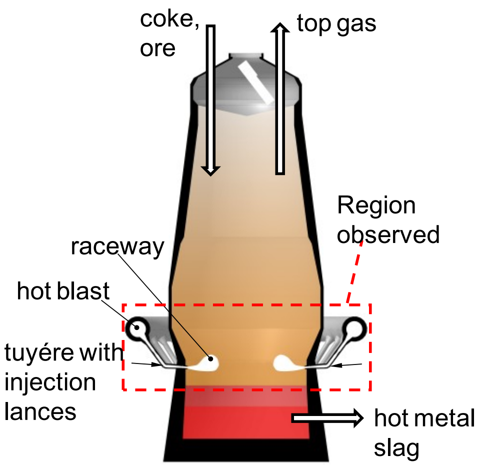

Figure 1: Scheme of the blast furnace, highlighting the zone under investigation (Maier et al., 2013).

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Prior to implementation of these measures on an industrial scale, thorough examination of the impact on the furnace operation is necessary. However, due to the extreme conditions the application of common experimental techniques to examine processes in the furnace is very limited. An alternative is to conduct numerical experiments using the methods of Computational Fluid Dynamics (CFD). In this work models have been developed to simulate the injection of plastics and heavy fuel oil into the blast furnace raceway (Figure 1).

2. CFD Model Setup

The main idea of the implemented CFD model is based on the solution of conservation equations for the coke phase slowly moving downwards in the shaft of a blast furnace as well as for the gas phase that counter-currently moves upwards, to be withdrawn at the top of the furnace. Inter-phase exchange is modelled by implementing mathematical expressions describing the physical processes. Injection of auxiliary reducing agents and the release of the injected material are modelled applying a Lagrangian frame of reference. Boundary conditions necessary to complete the definition of the set of conservation equations such as droplet size distribution from oil injection and thermophysical properties of plastic particles are determined experimentally (Jordan et al., 2010).
A detailed description of the heterogeneous reaction model including expressions for diffusion processes (Maier et al., 2012a), heterogeneous heat transfer (Maier et al., 2012b) and various submodels can be found elsewhere (Maier et al., 2013).

3. Model Validation

The model setup was validated in multiple steps, starting from simple processes involving heterogeneous heat transfer at various temperature levels, gradually increasing the complexity towards homogeneous gas-phase reactions and finally arriving at cases involving heterogeneous gas-solid reactions. The idea of thorough model verification was realized such that experimental setups from literature were adopted and implemented into a CFD model, simulation results were compared to experimental data to evaluate the reliability of the modelling tool.
Herein the main focus of attention is put on the analysis of the gasification model dealing with an important heterogeneous reaction in the blast furnace: CO_2-gasification of coke, also termed “solution loss reaction”. As this reaction proceeds, carbon monoxide is released that is utilized for indirect iron oxide reduction.

3.1 Experimental Configuration

An experimental method for the estimation of the reactivity of metallurgical coke in a CO_2-atmosphere that is widely applied in the iron producing industry since its introduction in the 1970s is the so-called NSC-test (named after the inventor, the Nippon Steel Corporation). In this testing procedure, 200 g coke in the size range of 19 – 21 mm is gasified with carbon dioxide at a temperature of 1,100 °C.
The test is operated as a batch-process, its standard duration is 2 h. After gasification, the percentage of the weight loss is evaluated (termed Coke Reactivity Index, CRI). The remaining coke is subjected to mechanical stresses in a tumbling drum to determine the Coke Strength after Reaction, CSR (Diez et al., 2002). Consequently, in this testing procedure coke to be used in the blast furnace process is characterized in terms of reactivity as well as its resistance to mechanical loads, two very important parameters responsible for stable and efficient operation of the blast furnace.
A general schematic illustration of the experimental setup of the NSC-test is shown on the left side in Figure 2. The coke is placed on a tray inside the oven that is heated to the desired gasification temperature. Gas moves through the coke bed from bottom to the top, heterogeneous reactions take place on the surface as well as in the pore structures of the coke particles, consuming the gasification agents and releasing the gasification products that are withdrawn on the top of the oven. The right sketch in Figure 2 shows the implementation of this experimental apparatus in the CFD-model, highlighting the aforementioned grid zones for the coke and the gas phase, respectively. Conservation equations are solved for both zones, inter-phase exchange (e.g. heterogeneous heat transfer and heterogeneous reactions) is calculated by implementing source terms in the governing equation sets evaluating local driving forces, such as temperature differences in the case of heat transfer.

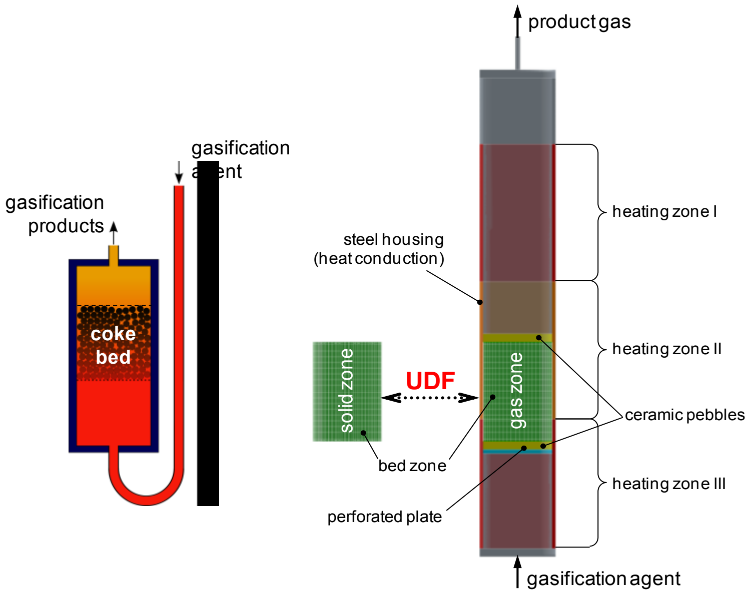

Figure 2: Schematic illustration of the NSC-test (left) and its implementation in the CFD-model (right).

In the standardized testing routine, coke is gasified at the above mentioned conditions and the overall coke consumption rate is estimated. The experiments conducted in the current work (by voestalpine Stahl GmbH) include the continuous measurement of the product gas composition using mass spectrometry. Consequently, concentration profiles can be used for comparison with the simulation results, being very valuable for validation purposes. Furthermore, apart from the standard routine the operating conditions were varied in terms of gasification temperature, composition of the gasification agent as well as size of the metallurgical coke (see a summary in Table 1; standard conditions: exp. 1).

Table 1: List of experiments and range of parameter variation. Reactant gas flow applied to all experiments: 5 L/min(STP).

exp. no.	T [°C]	dp [mm]	$CO_{2,\,inlet}$ [$\%_{(v/v)}$]	$N_{2,\,inlet}$ [$\%_{(v/v)}$]
1	1100	19 – 22.4	100	0
2	1100		25	75
3	1000		100	0
4	1000		50	50
5	1100	8 – 10	100	0

3.2 Simulation Results

Calculated rates of coke depletion due to CO_2 gasification for the range of experimental conditions are shown in Figure 3. In general, highest reaction rates appear near the bottom of the coke bed, as the partial pressures of carbon dioxide are highest in this region.

Significant differences (approx. factor 5) between gasification rates for the conditions studied were found. Highest reactivity appears for the case with smaller coke particles (exp. 5), being precipitated by higher specific surface of the particles as well as diffusion issues inside the particles: Smaller particle sizes allow for shorter diffusion distances of reaction educts in internal pore structures to the actual reaction sites. Consequently, a larger fraction of the inner particle surface is involved in heterogeneous reactions, increasing the overall rates of reaction (Liu and Niksa, 2004).

The rates of boundary layer and pore diffusion, intrinsic reaction rates and the resulting effective reaction rates for the experiments no. 2 and 5 are shown in Figure 4. At low temperatures, the limiting factor for the overall reaction rate is given by intrinsic reaction rates of CO_2 with solid coke. With increasing temperature, this rate increases exponentially, while the rate of boundary layer diffusion increases only in the order of $T^{1.75}$ (Maier et al., 2012a). Therefore, at high temperatures the concentration of educts inside coke particles declines and the diffusive transport of educt species through the boundary layer towards the particle surface becomes the main resistance. At intermediate temperatures, the diffusion of educts inside porous particle structures plays an important role, while at low and very high temperatures the effective reaction rate asymptotically approaches the intrinsic and the rate of boundary layer diffusion.

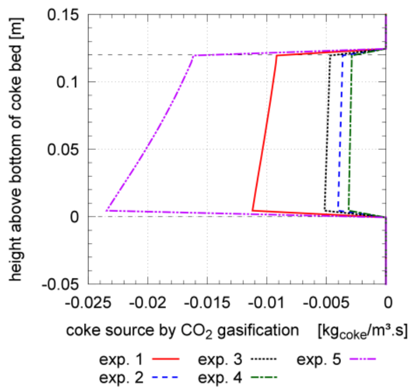

Figure 3: *Vertical profile of coke consumption rates due to the solution loss reaction, conditions as listed in Table 1.*

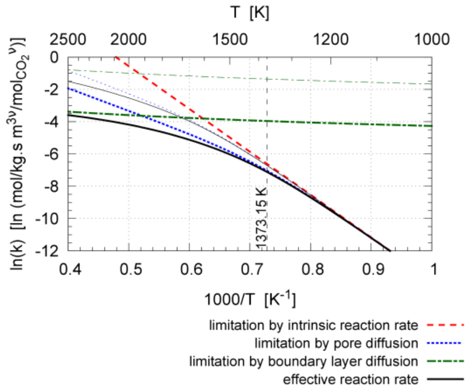

Figure 4: Reaction rates at mean concentration in the coke bed, bold lines: exp. 2, light lines: exp. 5.

As carbon dioxide is consumed, CO is released into the voids of the coke bed (see Figure 5).

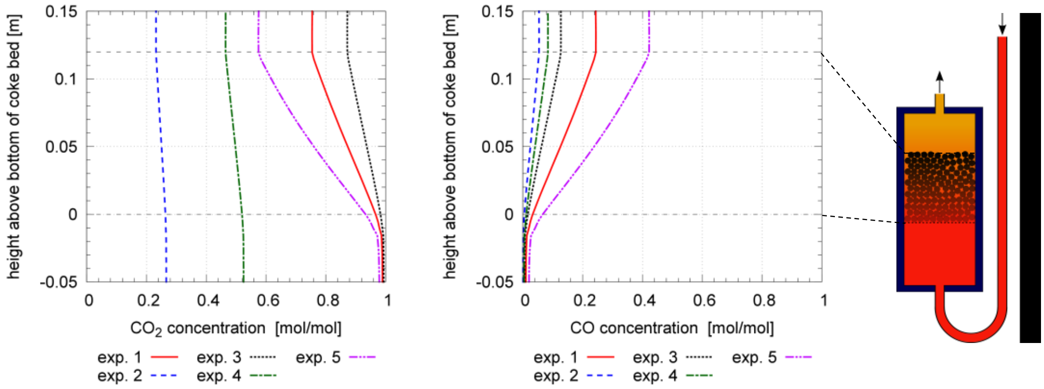

Figure 5: Profiles of CO_2 and CO mole fractions along the coke bed.

The comparison of product gas composition for the various experimental runs to the simulation results is shown in Figure 6. Very good agreement was found for the range of parameter variation, indicating that the model is able to capture and reproduce the main physical processes involved in CO_2 gasification of metallurgical coke.

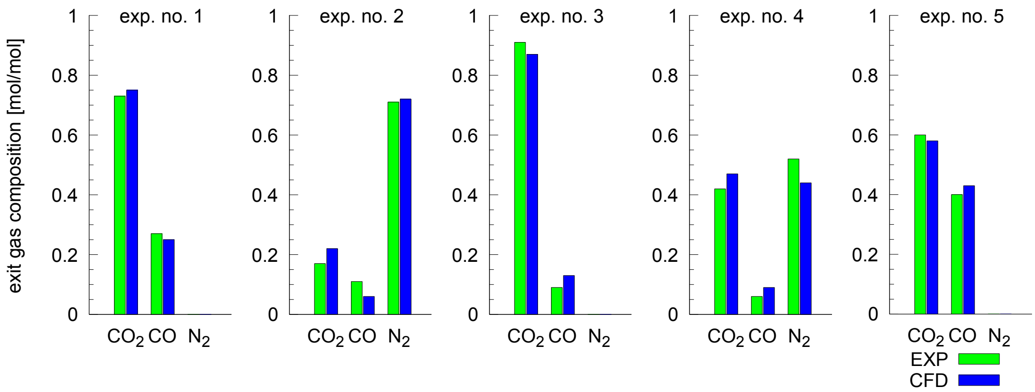

Figure 6: Product gas composition, comparison of exp. data and CFD results (major gas constituents).

4. Blast Furnace Simulation

The validated CFD model is applied to the actual blast furnace process (BF A, voestalpine Stahl GmbH Linz), focussing on the region in the vicinity of the tuyères (see also Figure 1). Simulation results for operating conditions featuring maximum plastic injection rates (96 kg/t hot metal) at heavy fuel oil rates adjusted accordingly (39 kg/t hot metal) are presented in the following.

Near the tuyère opening, a cavity is formed in the coke bed by the injection of hot blast, called *raceway*. The size and shape of this zone states an important boundary condition, as it determines e.g. the travelling distance of injected auxiliary reducing agents prior to interaction with solid coke. In the CFD-model the raceway is defined by implementing a spatially variable porosity distribution that is adopted from literature sources (Zhou, 2008).

Oxygen injected with hot blast is readily consumed in the vicinity of the tuyère by heterogeneous reaction with the coke and combustion of injected reducing agents, resulting in the release of CO_2 as well as heat of reactions (see Figure 7). After leaving the raceway cavity, carbon dioxide is consumed by the solution loss reaction, producing CO that is utilized for iron oxide reduction. Involved reduction reactions are endothermic, the heat necessary is delivered by the oxidation reactions.

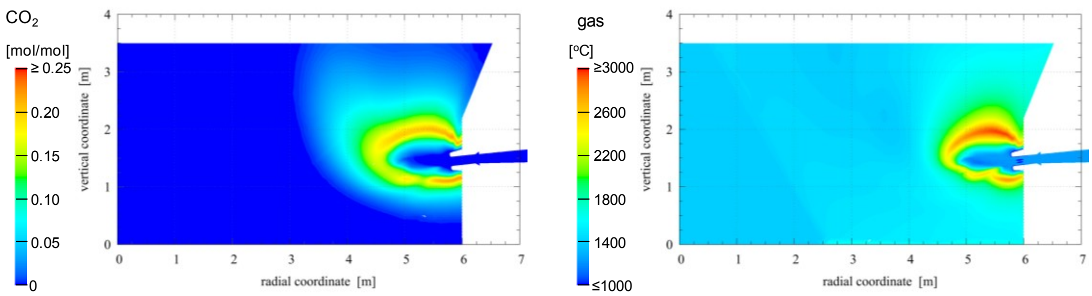

Figure 7: Left: Contours of CO_2 mole fraction. Right: Gas-phase temperature field.

Due to the high specific surface of the small droplets from fuel oil spray, oil vaporization for droplets with initially 200 µm diameter is completed after comparatively short residence times in the range of 13 ms (see Figure 8). Contrary to this, plastic particles (mean diameter of 7 mm) reach the boundary of the raceway cavity before pyrolysis is completed (flight time approx. 0.1 s).

In the simulation, particles are modelled to impact on the coke bed, releasing the remaining particle volatiles in place. The pyrolysis products are subjected to homogeneous reactions in the gas phase involving further breakdown to smaller hydrocarbons (e.g. CH_4) and oxidation reactions.

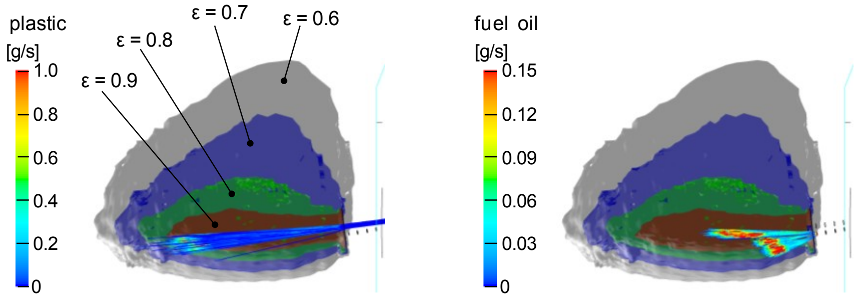

Figure 8: Tracks of injected auxiliary reducing agents, coloured by mass release rates. Iso-surfaces, coloured by local coke bed void fraction ε, defining the shape of the raceway cavity.

5. Conclusions and Outlook

A multiphase model describing the conditions in the vicinity of the tuyères of a blast furnace was developed and successfully validated for a number of processes. The model also incorporates the description of dispersed phases, representing injected auxiliary reducing agents.

Model development was done in conjunction with experimental work to gain data for validation purposes as well as to define boundary conditions for CFD simulations. Future work will include the extension of the width of parameter variation for heterogeneous coke reactions, aiming for higher temperatures (CO_2 gasification) and also other gasification agents (e.g. steam gasification) by conducting thermogravimetric analysis.

The model predictions for the blast furnace process will be used to support the optimisation procedure for injection of auxiliary reducing agents, aiming at a decrease of the environmental impact of iron production via the blast furnace route and also at the further improvement of plant efficiency and economics.

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