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COMBINED INJECTION OF PLASTIC PARTICLES AND HEAVY FUEL OIL INTO A BLAST FURNACE RACEWAY – DETAILED CFD ANALYSIS

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Abstract. *Auxiliary reducing agents like oil, tar, pulverized coal, natural gas, coke oven gas and waste plastics are injected into the blast furnace to decrease the coke rate. CFD methods have been used to simulate the injection of plastics into the blast furnace raceway at blast furnace A at voestalpine Stahl GmbH, Linz (Austria).*
Based on this CFD model for plastic particle injection reported earlier an extended model is being developed. The new model makes use of the capability to predict the raceway shape based on a new porous media approach avoiding the high computational effort of a full eulerian multiphase formulation and incorporates also a simplified reaction mechanism for calculation of the high temperature conversion of the injected materials. In addition to that code to handle the injection of multicomponent droplets like heavy fuel oil and tar has been incorporated. Boundary conditions for the new model are set using process data from voestalpine Stahl in Linz (Austria).
It is also necessary to provide suitable boundary conditions and physical properties for each of the involved materials. Since the availability of high temperature material data is sparse, measurements for thermal conductivity and heat capacity of the coke used at the simulated blast furnace have been carried out. Thermal conductivity was analyzed using a direct approach measuring the thermal diffusivity of a cylindrical coke bed heated at constant temperature. Heat capacity was measured using a drop calorimeter.

1 INTRODUCTION

Basing on a CFD model for plastic particle injection published by the authors [1] an extended simulation model is developed. The new model makes use of the capability to predict the raceway shape using a new porous media approach. This allows to avoid the high computational effort of a full Eulerian multiphase formulation and incorporates a simplified reaction mechanism for calculation of the high temperature conversion of injected materials. In addition the ability to handle the simultaneous injection of multicomponent droplets like heavy fuel oil and tar has been incorporated.

2 CFD GEOMETRY AND BOUNDARY CONDITIONS

2.1 Geometry and operational data of the blast furnace

One of the blast furnaces (BF "A") of voestalpine Stahl GmbH in Linz, Austria is considered in this contribution [2]. The blast furnace has a bosh diameter of 12 m, a working volume of 3125 m³ and a hot metal capacity of approximately 7800 - 8800 t per day. In total 32 tuyéres are installed, combined injections of various reducing agents are possible. At the site heavy fuel oil, tar and plastic pellets [3, 4] are commonly used. The plastic pellets are fed into the furnace using a pressurized air transport system, heavy fuel oil injection utilizes coaxial two-phase lances that are fed with steam. The average blast temperature is 1220°C, the furnace is operated at a hot blast pressure of approximately 4.2 bar (gauge pressure), the hot blast amount (including additional oxygen) is about 320000 Nm³/h.

The geometry section implemented for this work is shown in Figure 1. The detailed geometry includes not only the blast furnace walls, tuyéres and the hot blast pipes, but also the injection lances for the alternative reduction agents.

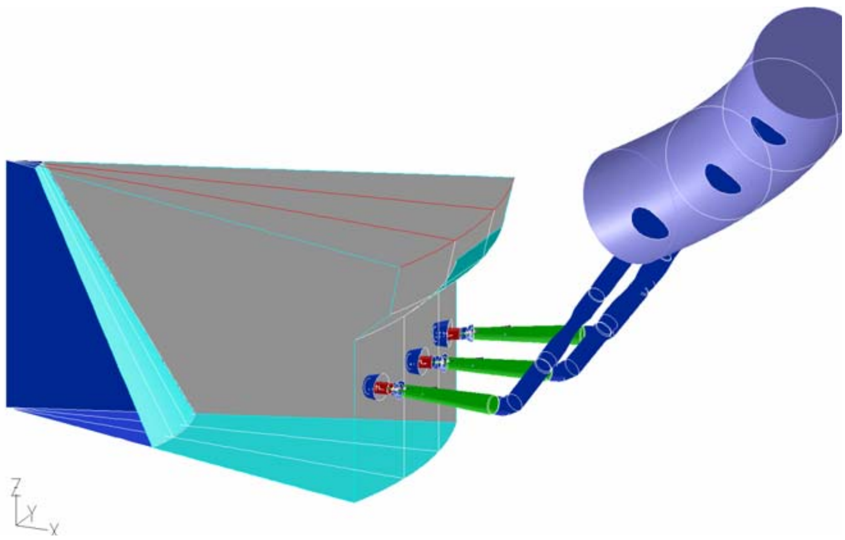

Figure 1: Detailed blast furnace geometry – simulated section in the lower part of the furnace featuring three of 32 tuyéres and also includes the hot blast pipes.

2.2 Material Properties

All CFD simulations require suitable boundary conditions, which can be achieved from the simulated process (see section 2.1). Other important inputs are the material properties of the present fluid and solid phases. Figure 2 gives an overview of the necessary data for this calculation and the appropriate source.

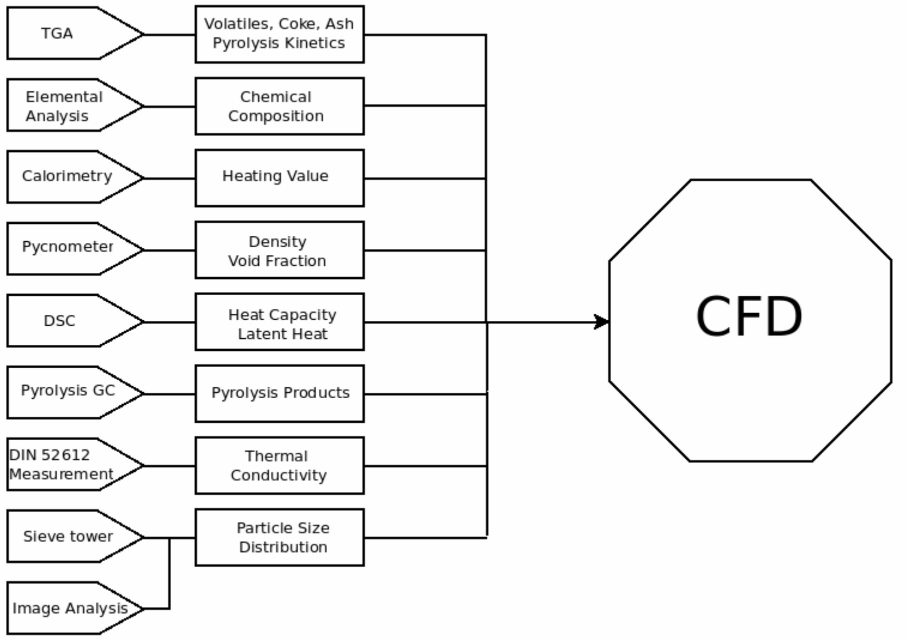

Figure 2: Detailed blast furnace geometry – simulated region.

The gas phase has been considered as an ideal gas, gas thermal conductivity, heat capacity and molecular viscosity are assumed to follow an ideal gas mixing law of the components (O_2, N_2, CO, CO_2, H_2, H_2O, C_{solid}, fuel-oil), species data taken from [5, 6] . Table 1 summarizes the material data for the alternative reduction agents, plastic particles and heavy fuel oil, used in this simulation. Both, the plastic particles and the heavy fuel oil droplets are simulated using a lagrangian discrete particle model (DPM). The reaction kinetics of the plastic particles has been measured using TGA and a laser ablation experiment to cover the high temperature conversion [7, 8]

Component	parameter	Value
plastic particles	mean equivalent diameter D_p	7 mm
	Mean density (particles)	600 kg/m³
	chemical composition	62% C / 9 % H / 22 % O / 7 % ash traces of halogens (Cl, F)
	thermal conductivity k_p	0.1 W/m.K
	specific heat capacity	600 J/kg.K
	optical emissivity	0.9
heavy fuel oil - water emulsion	chemical composition	88 % C / 12 % H
	water content	10 %
	droplet diameter (model assumption)	0.2 mm

Table 1. Physical properties of the injected material (from [9])

A suitable reaction mechanism consisting of 15 gas phase and surface reactions has been set up [10]. Turbulence and radiation have also been considered using standard models available in the CFD code. The radiation model required several extensions implemented as user defined code: A custom WSGG (weighted sum of grey gases) approach [9] accounts for the presence of hydrogen and carbon monoxide and also takes care of the optical properties of the coke bed.

To ensure proper boundary conditions for the particle and droplet reactions within the raceways also the surrounding coke bed has to be characterized. Important parameters for the solid coke are the thermal conductivity and the specific heat capacity. Since these material properties are strongly temperature dependent and also vary with particle shape and size as well as with the composition, direct analysis of the material charged to the considered blast furnace is required.

The mechanical behaviour of the coke bed within the blast furnace (porosity and fluid dynamic resistance) has been treated using a simplified raceway model, which considers the void fraction to be a linear function of the velocity [1, 10]. The linear relationship is bounded by the minimal fluidization velocity and the terminal sinking velocity of an average coke particle of the bed.

3 HEAT CAPACITY

Measurements of the heat capacity of the coke have been done using a drop calorimeter. This calorimeter has been constructed according to [11] - a sample of the material is heated to a known temperature using an insulated tubular oven and dropped into a dewar vessel containing a certain amount of water. The temperature of the water is monitored before and during the dropping process, the raise in temperature and the known heat capacity of the liquid are used to calculate an averaged heat capacity for the temperature range of T_{water} to T_{oven}. Repeating the experiment at different oven temperatures enables to calculate a temperature dependent heat capacity.

4 THERMAL CONDUCTIVITY

4.1 Treatment of thermal conductivity

Typically - also in the CFD code FLUENT [12] - estimates of the effective thermal conductivity of a granular bed are calculated using simple combinations of heat conduction resistances (solids and voids accoring to the global porosity) in serial or parallel as suggested by [13 or [14]. Other authors like in [15] give more sophisticated equations considering 2D or 3D structures of solids surrounded by fluid phase. The drawback of these methods is the assumption of perfect geometries or the need of experimental data or estimations of the contacting region of the solid grains, which also depends on the particle size distribution. Since these parameters are hardly available in free literature a direct measurement of the effective thermal conductivity was chosen.

4.2 Measurement of thermal conductivity

The measurement approach for the thermal conductivity is based on the “log experiment” of [16] to calculate the thermal diffusivity of a homogeneous sample in a tubular containment which is heated in an environment of constant temperature. This experiment relies on a set of simple boundary conditions, constant initial sample temperature and constant temperature of the surrounding. This can be easily fulfilled by using a sufficiently long cylindrical tube filled with the considered granular material placed in an oven with controlled heating. A Fourier transformed form of a simplified energy balance is applied for calculation of the thermal diffusivity. From this the thermal conductivity can be computed using the known density of the sample and the heat capacity measured previously.

To avoid coke oxidation and reaction during the experiment the setup was flushed using inert gas, e.g. nitrogen, when high temperatures have been applied. To get a better estimate of the measurement error and to collect more information on the applied measurement methods, CFD simulations of the experimental setup are to be carried out. Figure 3 provides an overview of the geometry.

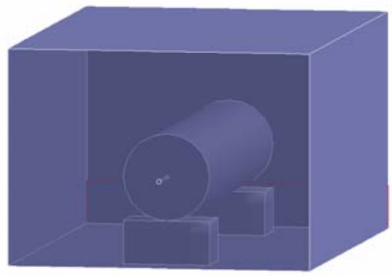

Figure 3: To conduct thermal conductivity measurements a cylinder containing the material has been placed into a furnace running at constant temperature.

5 SIMULATION RESULTS

As a primary result of the CFD simulation, pressure and velocity distributions within the selected region can be found. Also the contours of the gas species and reaction rates can be calculated for the base case. As example, Figure 4 shows the gas phase velocity magnitude at a cross section of the blast furnace (symmetry plane of the middle raceway). Because of the raceway model the solid coke phase (considered as a porous media) is removed near to the tuyére creating a raceway. Within this raceway volume further reactions are considered, e.g. oxidation of fuel oil and pyrolysis of injected particles.

Figure 5 gives an example of the carbon dioxide mass fraction. As it can be seen the maximum occurs at the raceway boundary because of the contact of the blast oxygen with the coke bed. In the coke layer surrounding the raceway, the carbon dioxide is reduced to form carbon monoxide which is required to operate the blast furnace according to the Boudouard equilibrium. This behaviour is confirmed also by the temperature distribution depicted in Figure 6.

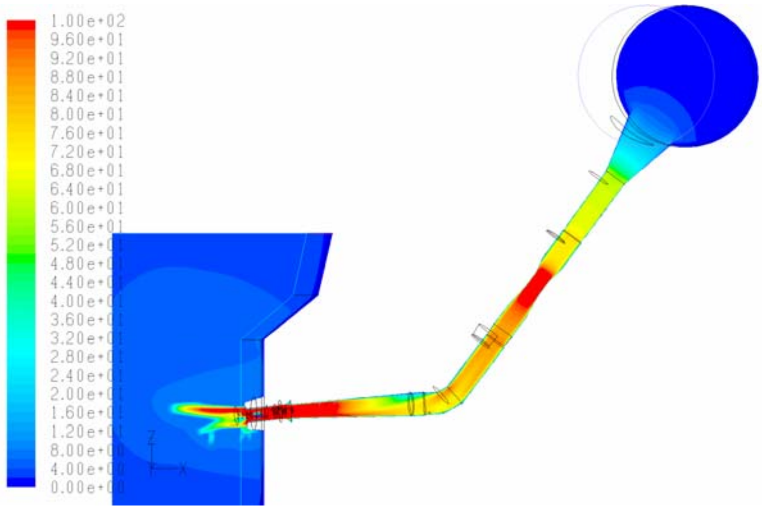

Figure 4. Gas velocity magnitude in m/s in the symmetry plane of the middle raceway section

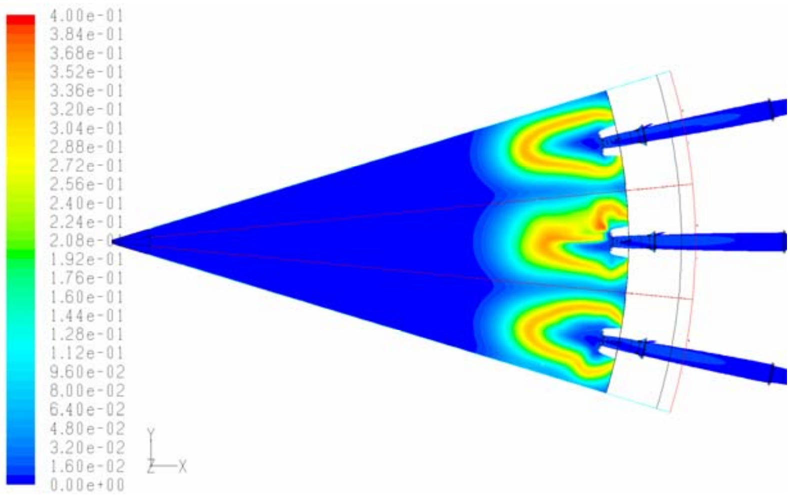

Figure 5. Plane surface in tuyére level – mass fraction of carbon dioxide

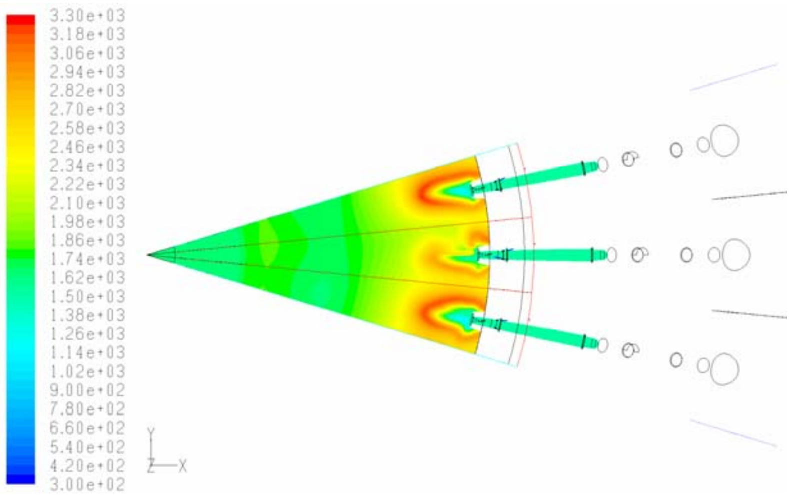

Figure 6. Plane surface in tuyére level – absolute temperature in K

Figure 7 shows the DPM tracks of the simultaneous injection of plastic particles (injection lance pointing upwards from the lower right side; green-yellow) and heavy fuel oil (lance pointing downwards from the upper right side; blue). It can be seen, that the smaller fuel oil droplets evaporate after only a short distance, the much bigger (6-8 mm) plastic particles shrink during the travel time but may reach the raceway boundary. The impacted plastic particles react until they are completely decomposed.

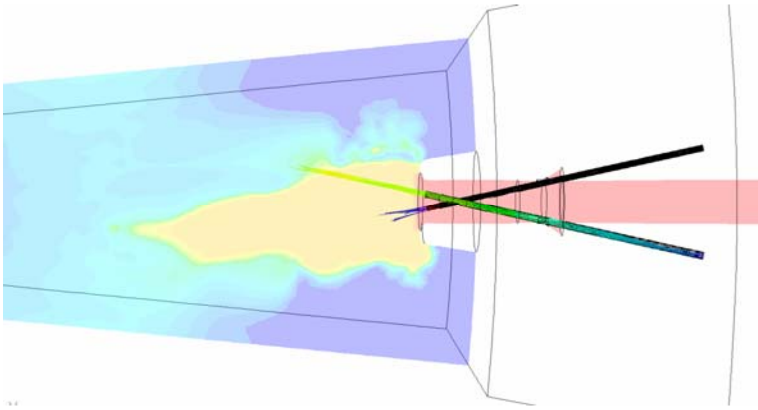

Figure 7. Simultaneous injection of particles (green-yellow, injection point lower right side, pointing upward left – slow reaction) and heavy fuel oil (dark blue, upper right side – rapid evaporation). Shape of the raceway at injection level in the background.

6 CONCLUSIONS AND FURTHER WORK

A CFD model for simulating the plastic pellet injection into a blast furnace raceway was successfully implemented. Using this model the conversion of plastic particles at high temperatures and high heat flux rates could be investigated. Particle data obtained from ultimate and optical analysis combined with thermoanalytical data were used to adjust a discrete phase model. Moreover a new modeling approach to calculate the raceway shape was implemented. The results agree well with published simulation data using other models and with the practical experience of the blast furnace operators. The modelling allows to give additional insight into the conversion process.

With further simulations using the detailed blast furnace geometry the effect of different injection amounts will be studied in more detail. Also important problems like if the impacted plastic particles on the raceway boundary have any effect on the pressure drop and/or flow distribution, or if coke particles remaining from the pellets are entrained into the bed could be addressed.

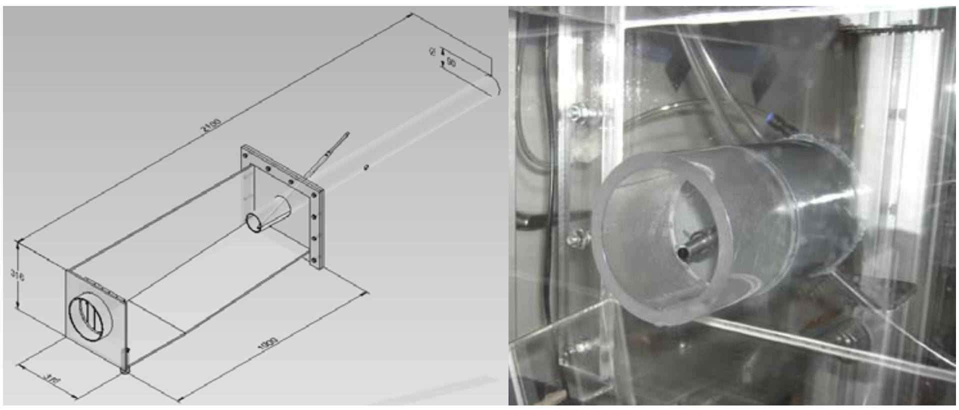

Figure 8. Overview – lab scale test rig for PIV measurements

To improve the model parameters for the heavy fuel oil spray and evaporation, a lab scale test rig of one tuyére section was be constructed (Figure 8). PIV (Particle Image Velocimetry) measurements and high speed camera techniques will be used to estimate the mean droplet diameter of the liquid spray and initial velocity in the downscaled model. Characteristic dimensionless numbers (especially the Reynolds number and the Ohnesorge number) are used to calculate the corresponding parameters in the full scale blast furnace at operating conditions.

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