Evaluation of the High Temperature Conversion of Plastic Particles after Injection into Blast Furnace Raceway Using CFD Simulations

Michael HARASEK, Christian JORDAN, Christian MAIER, Franz WINTER,
Institute for Chemical Engineering,
Christian Doppler Laboratory for Chemical Engineering at High Temperatures
TU Wien, Getreidemarkt 9/166, A-1060 Wien

Georg AICHINGER,
Siemens VAI GmbH & Co, Turmstraße 44, A-4031 Linz

Christoph FEILMAYR, Stefan SCHUSTER,
voestalpine Stahl GmbH, VOEST-ALPINE-Straße 3, Postfach 3, A-4031 Linz

The injection of plastic particles into the blast furnace raceway through tuyere lances was simulated with Computational Fluid Dynamics (CFD). The high speed conversion of plastic particles at high temperatures was investigated. Particle data obtained from ultimate and optical analysis combined with thermoanalytical data were used to accomplish a discrete phase model. Plug-flow reactor simulations on a CFD basis were performed to verify this model. The conversion of the particles, resulting temperatures as well as the formation of reducing species were studied.

1 Introduction

Alternative reduction agents are an important measure to reduce blast furnace operation costs. Examples for such reduction agents are oil, coal dust, natural gas, coke oven gas (COG, Andahazy et al. [2005, 2006]) and also recycling plastics. A big advantage of plastic particles is the saving of primary resources as coal and heavy oil.

At the moment, voestalpine Stahl utilizes oil and gas injections and trial operations regarding the plastic pellet injections are running. To determine the optimal operating conditions for plastic particle injections, computational fluid dynamic simulations are applied.

* Presented at AICHE Annual Meeting 2007 (4. - 9. 11. 2007, Salt Lake City) by Christian Maier
2 Geometry and physical boundary conditions

In this work one of the blast furnaces of voestalpine Stahl GmbH in Linz, Austria is considered. This blast furnace has a diameter of 12 m and a hot metal capacity of approximately 7500 t per day. In total 32 tuyeres are installed, commonly the reducing agent injections are done with heavy oil and tar products. Alternatively also plastic injections are possible. The plastic pellets are fed into the furnace using a pressurized air system. The blast temperature is 1220°C, the furnace is operated at a pressure of approx. 4.2 bar (gauge pressure), the hot blast amount is about 300000 Nm³/h (voestalpine Stahl [2007]).

The properties of the plastic particles can be found in table 1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>mean diameter</td>
<td>7 mm</td>
</tr>
<tr>
<td>mean density</td>
<td>300 kg/m³</td>
</tr>
<tr>
<td>composition</td>
<td>62% C, 9% H, 22% O, 7% ash</td>
</tr>
<tr>
<td>thermal conductivity</td>
<td>0.1 W/m.K</td>
</tr>
<tr>
<td>heat capacity</td>
<td>600 J/kg.K</td>
</tr>
<tr>
<td>emissivity</td>
<td>0.9</td>
</tr>
</tbody>
</table>

Table 1: Physical properties of the plastic particles.

3 CFD and Models

The first step for each CFD simulation is the discretization of the considered geometry. In this case, for the implementation of the full and simplified 3D geometries and the generation of the computational grid the preprocessor GAMBIT 2.3 (Fluent.Inc [2001-2006b]) was applied.

The CFD solver code used was FLUENT 6.3 (Fluent.Inc [2001-2006a]), a state of the art general purpose code with included post processing tools. FLUENT is based on finite volume discretization, for each finite control volume the physical balance equations are solved for momentum (Navier-Stokes-Equations), energy, mass (Continuity Equation) and species. Since some of the equations are highly nonlinear, an iterative solving procedure is applied\(^1\). One important feature of the CFD code is the possibility to include new models by utilizing “user defined functions” (UDFs), which were hooked into predefined interfaces of the solver\(^2\).

In total three different geometries were used:

- Tube reactor (plug flow reactor): A tube with a length of 40 m and a diameter of 0.34 m is used, the computational grid consists of 100000 cells.
- Simplified blast furnace geometry: A quarter of the lower part of a blast furnace is implemented using two symmetry planes (figure 1, left side), in total 350000 cells are used.

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\(^1\) All simulations were carried out using the cluster computers of the Vienna University of Technology, icp.zserv.tuwien.ac.at with a total number of 54 computing nodes - IBM p5-520/52A each with 2x CPU power5+ (1.9 GHz, 36MB L3 cache), 16 GB RAM, 1x 73 GB SCSI-HDD, 2x GbLan, InfiniBand HCA - OS: AIX 5L V5.3 or phoenix.zserv.tuwien.ac.at with approx. 150 CPU-cores - AMD Opteron 2,4-2,8 GHz 4-16 GB RAM.

\(^2\) In course of the simulations it was found that icp.zserv encountered severe problems with the User Defined Functions and the computing speed of cases with combustion model enabled was much lower than on the AMD platform.
Detailed blast furnace geometry: A segment of the lower part consisting of three tuyeres is implemented with periodic boundary conditions. In addition, the injection lances and the blast tube are implemented (figure 1, right side) also. In the center a conical section is separated to simulate the dead-man area. The segment is filled with 1.3 Million finite volume cells.

![Figure 1: left: simplified blast furnace geometry, right: detailed blast furnace geometry](image)

To ensure highest accuracy and performance all grids used for this work consist only of (unstructured) hexahedral elements. Also second or higher order discretisation schemes are applied for all equations.

All inlet boundaries are set to “mass flow inlets” (constant mass flow rate), all exit boundaries are set to “pressure outlet” (constant static pressure).

Following submodels of the FLUENT package were applied for an accurate description of the blast furnace:

- **Ideal gas**: The density of the gas phase is described using the ideal gas equation to account for the elevated absolute pressure in the furnace. Other properties of the mixture (thermal conductivity, heat capacity, viscosity) are calculated by ideal gas mixing rules based on data from VDI (Verein Deutscher Ingenieure; VDI-Gesellschaft Verfahrenstechnik und Chemieingenieurwesen [GVC]) and NIST (National Institute of Standards [2007]), if not available, kinetic theory approximations have been used.

- **Turbulent flow**: In this case the SST-ke-Model by Menter (Menter [1994]) is applied since it provided better convergence than the available ke-Models but required less computational power than RSM. The model has already been successfully applied to a wide range of technical flow problems (Jordan et al. [2005], Maier et al. [May 2008], Miltner et al. [2007]).

- **Combustion**: A simplified mechanism with only eight species (O₂, N₂, CO, CO₂, H₂, H₂O, C, heavy – oil) and fourteen global reactions (the most important are the forward and reverse Water gas shift, carbon combustion, oxidation of carbon monoxide, hydrogen combustion, methane steam reforming methane dry reforming and a combustion reaction for oil), has been constructed. To include turbulence interaction, the eddy dissipation concept (EDC, Magnussen [1981]) is used.
Radiation: Due to the high operating temperatures of the blast furnace process, radiation is a very important heat transfer mechanism. An appropriate model for radiation heat transfer, which can be applied for optically dense and transparent media is the discrete ordinates (DO) model (Mueller et al. [2005]). The radiation absorption and emissivity of the blast furnace interior (coke bed, gas phase) was described by using the weighted sum of grey gases (WSGG) approach (reference) with a modification to account for the porosity of the bed. This was necessary because heat transfer in the raceway was dominated by radiation, but on the other hand radiation had only a small effective reach in the porous media.

3.1 Raceway-Model

The modeling of the injection process into the raceway of a blast furnace requires a simple and sufficient description of the raceway geometry. Many approaches are known - most are based on experiments or multiphase CFD models (based on the Euler granular approach or using Discrete Element Models (DEM))(references!).

In this work a new approach has been implemented to find a suitable description of raceway form. The method is based on a spatially varying porous media, where the porosity and the pressure drop of the media are depending on the local gas velocity (figure 2 - porosity ramp sets on at the theoretical minimum fluidization velocity and ends at the terminal velocity of the average coke particles).

This way the raceway could be considered as a free gas jet into a dense solid bed, it is also assumed that there are no particles entrained into the raceway.

![Raceway model: ramp function for porosity](image)

3.2 Particle-Model

Plastic particles have a low thermal conductivity and the heat transfer rate in the raceway is extremly high. Thus it can be assumed, that the Biot-Number $Bi_{th} = \alpha \cdot \frac{d_p}{\lambda_{eff}}$ (d$_p$ particle diameter, $\lambda_{eff}$ thermal conductivity of the particle, $\alpha$ heat transfer coefficient) is high - the particle is non-isothermal. It can be assumed, that most of the heat transferred is utilized for the gasification of the plastic material and the core of the particle remains at a constant temperature. To analyze this behaviour of the plastic particles in the raceway experiments have been carried out. Only with laser pulses it was possible to simulate the high heat transfer rate which is expected in the raceway environment. The laser results showed that the assumption of the constant core temperature is correct (Lackner et al. [11-13 April, 2007]).
A particle gasification model simulating this behaviour has been programmed and included into the solver, the results of the experiment have been used for calibration purposes.

The discrete particle model (DPM) in FLUENT, which has been used for the mathematical treatment of the pellet injections, is based on an Euler-Lagrange procedure - dimensionless mass points are tracked in the flow domain with momentum and thermal interaction (Fluent.Inc [2001-2006a]). A sufficient number of particle tracks are evaluated statistically and the particle influence on the flow field is calculated - including the mass sources for the gasified components. The gasification process is implemented using a simple scheme based on Löffler et al. [2001]:

1. $C \rightarrow CH_4$ (if H is present), then
2. $C \rightarrow CO$ (if O is present), then
3. $H \rightarrow H_2O$ (if O is present), then
4. $C \rightarrow C_{gas}$ (if there is residual carbon), then
5. $H \rightarrow H_2$ (if there is residual hydrogen), then
6. $O \rightarrow O_2$ (if there is residual oxygen).

The plastic particles also interact with the the "wall" of the raceway (defined as a closed isosurface of a given porosity), it is assumed that the pellets are trapped on the coke surface when they hit it. The impact position is determined using a probability factor depending on the local porosity.

4 Plug flow reactor results

The plug flow reactor simulations have been used for validation of the user defined model code, especially for the user defined functions applied for the particle heating and gasification and subsequent combustion. Important model parameter for the simulations are listed in Table 2.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>tube length</td>
<td>40 m</td>
</tr>
<tr>
<td>tube diameter</td>
<td>0.34 m</td>
</tr>
<tr>
<td>wall temperature</td>
<td>2000 K</td>
</tr>
<tr>
<td>initial particle temperature</td>
<td>300 K</td>
</tr>
<tr>
<td>operating pressure</td>
<td>5 bar</td>
</tr>
<tr>
<td>inlet gas velocity</td>
<td>15 m/s</td>
</tr>
</tbody>
</table>

Table 2: Properties of the plug flow reactor simulation

The mass of a single 7 mm plastic particle plotted over the particle lifetime in the plug flow reactor is shown in figure 3. 99.9% of the mass have been gasified after approx. 1.15 s (for 6 mm diameter - 0.93 s; 8 mm diameter - 1.34 s), which is much longer than the residence time of the particle in the raceway - but agrees quite well with heat transfer estimations using a simple Nusselt-Correlation. This means that in practical operation most of the particles will impact on the raceway boundary.

The gasification rate of a particle stream of 0.025 kg/s can be found in figure 4.
Figure 3: Particle mass of a 7 mm plastic pellet heated in a plug flow reactor (oxygen rich atmosphere)

Figure 4: Contour plot of the gasification rate in kg/m³.s (oxygen rich atmosphere) - length of the reactor is scaled 1:25
5 Full geometry results

The resulting raceway form and the streamlines of the gas passing through the raceway using this model agree very well with recent data (see figure 5 compared to the figures of Selvarasu et al. [2007]) based on the Euler granular model. The length of the raceway results to approx. 0.5-0.75 m - the form varies slightly depending on the parameters used.

![3D-view of the simplified blast furnace model - path lines and surfaces of constant porosity (green: 0.5, red: 1.0)](image)

6 Future work

Using the detailed blast furnace geometry the effect of different injection amounts will be studied. Also important is the question, if the impacted plastic particles on the raceway boundary have any effect on the pressure drop and/or flow distribution. Furthermore there is a possibility to track coke particles remaining from the pellets which may are entrained into the bed.

7 Acknowledgement

The presented work of the CD-Laboratory for Chemical Engineering at High Temperatures at the Vienna University of Technology has been funded by the Christian Doppler Forschungsgesellschaft, Austria.

References


