Reducing Ability of CO and H$_2$ of Gases Formed in the Lower Part of the Blast Furnace by Gas and Oil Injection

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Gases formed in the raceway by injection of reducing agents into the tuyere affect the blast furnace process in several ways. Energy set free by conversion in the raceway helps the melting of the burden and has beneficial effects on reaction kinetics. The formation of CO and H$_2$ helps to save blast furnace coke. The aim of this work is to study effects of the gases formed after the injection of coke oven gas (COG) and heavy oil into the tuyere of a blast furnace and after conversion in the raceway when entering the active coke zone. For this reason a gas conversion simulation is developed including description of the zones of the lower blast furnace part. The cases studied have the same melting rate at which the injection of COG is accomplished with one and two lances while those of oil is studied with one lance. The simulation predicts that the available amount of species for the reduction of iron ore and the reduction potential is similar for the studied reducing agents COG and heavy oil. Evaluating the potential to save coke a theoretical exchange ratio of 0.84 can be determined for comparable cases in terms of the same reduction progress so that the same consumption of coke has to be expected if no difference between the agents exists.

KEY WORDS: blast furnace; modeling; simulation; reducing potential; gas conversion; coke rate.

1. Introduction

The blast furnace is the dominating process for producing liquid iron even though recently many new alternative iron-making technologies have been developed. Many investigations are done since years to improve efficiency and reduce operating costs and environmental effects of the blast furnace process. While the processes happening in the upper part of the furnace are already well known the lower part is still an area of great research. The great demand on liquid iron nowadays and rising prices of raw materials make it necessary to improve the blast furnace process in terms of utilization of byproducts of other processes and also wastes. The injection of reducing agents like pulverized coal, heavy oil, coke oven or natural gas and plastics helps to save coke. This reduction of the coke consumption can be due to the formation of CO and H$_2$ as reducing species and also the production of heat required for the melting process. The major heat consuming reactions occur above 1 000°C in the lower part of the furnace. Highly endothermic reactions like the calcinations of limestone, the direct reduction of wustite and other metal oxides, the fusion of metal and slag and many more increase heat requirement suddenly.

In this work the effects of two injected reducing agents, namely coke oven gas (COG) available from the coke production and heavy oil are studied in terms of their ability to save blast furnace coke. The formation of reducing species in the bosh belly area and the effects of species and temperature on the reduction kinetics and the cohesive zone are evaluated with the help of a developed model implemented into a simulation.

While Computational Fluid Dynamics (CFD) simulations can provide a detailed description of the conversion characteristics in the raceway and its completeness, it is not appropriate for statements about effects of gases in the bulk of the inner lower part of the furnace. For this reason a gas simulation tool is developed using the programming language Fortran 90 and the developing environment Compaq Visual Fortran. This simulation includes a model for the description of processes happening in the lower, inner part of the blast furnace.

Initial point for the simulation tool are the gases leaving the raceway after the injection of the reducing agents into the tuyere. The simulation includes the most important homogeneous, heterogeneous and heterogeneous catalyzed reactions for the implementation of blast furnace chemistry. Influences like those of the active coke zone or the cohesive zone are modeled to provide are more realistic description.

The simulation ends when the thermal reserve zone which occupies about 70% of the shaft volume appears in terms of very close temperatures of gas and burden. These temperatures show that the heat exchange in the lower zone is completed.

While previous model studies mostly result in temperature zones located in the furnace also dependent on radial
position, this work results in a mean temperature over a cross section of the blast furnace. The obtained results should be in agreement with the theory of a typical S-shaped temperature curve\(^{2}\) to ensure suitable conclusions.

The main advantage of the model developed is the comparison of injected reducing agents in terms of their coke consumption and the reduction potential which can be accomplished with simplified model assumptions.

### 2. Modeling

The COG injection is accomplished with one and two gas lances in the tuyere while that of oil only is done with one lance. The conversion characteristics of the reducing agents in the raceway already are studied in detail\(^{3,4}\) using computational fluid dynamics (CFD). The formation of reducing species in the raceway and the completeness of the conversion which can be limited by mixing of reductant and oxygen is of great importance for the temperatures existent in the raceway. These temperatures can lead to loss of contact material of the lances in the tuyere when reached in front of the raceway. The composition and the net calorific values of coke oven gas (COG) are listed in Table 1. In Table 2 the parameters for oil are listed in which a mean diameter of the oil droplets of 200 \(\mu\)m\(^{5}\) was used in the CFD calculations.\(^{3,4}\) These CFD calculations make it possible to take a look inside of the raceway where measurement is difficult due to high temperatures predominant.

The gases leaving the raceway after the COG injection and the injection of oil which are listed in Table 3 enter the active coke zone of the furnace and are used for this reason as starting point for the simulation.

### 2.1. Gas Conversion Simulation

The simulation is realized as a plug flow reactor (PFR). The position of the assumed PFR, the whole the raceway leaving gas volume flows through, is shown below in Fig. 1. The numbers denote the modeled zones in the simulation.

The zones modeled concern the active coke zone (Zone 1) where the remaining oxygen content of the gas is consumed. Zone 2 represents the cohesive or melting zone. Above the melting zone (Zone 3) all burden is solid. The flows in the gas conversion simulation can be seen in Fig. 2. To draw the outlines of the different zones solid temperatures are chosen as boundaries for modeling. On the basis of a tapping temperature of about 1 450°C the solid/liquid temperature on raceway level is said to amount constantly 1 500°C. This is the solid temperature where all simulations, independent of the reducing agent, start. The reduction of iron ore is considered in zone 2 and 3 because it is said to be finished at a solid temperature of 1 370°C. At this temperature nearly no wustite is left in practice.

In the dead man or active coke zone the bulk consists of spherical particles of 100% carbon with a diameter of 2 cm and therefore has a voidage of 0.4. The liquid materials consisting of liquid iron and slag flow downwards to the bosh and thereby take half of the free volume available. For this reason an effective voidage of 0.2 for the upward to the blast furnace top flowing gas exists. The zone is assumed to end at a solid/liquid temperature of 1 375°C.

Above the dead man the bulk is considered as liquid spherical particles of slag and hot metal and solid particles of coke. The reduction reactions are said to be finished at approximately 1 370°C like already mentioned above. Due the fact that the simulation only considers the lower part of the furnace and is calculated from the gas side, a small starting amount on wustite has to be predetermined which is the same for all simulations. This assumed predominant condition has to be taken under consideration when examining the simulation results in terms of the reduction potential. The reduction potential as result is given as the amount
of wustite in the iron containing flow, more precisely the percentage of iron existent as FeO. These values represent the amount on wustite the particular gas is able to reduce to hot metal within the simulation height. It is not representing the amount available under real conditions. A higher reduction potential in reality would result in an earlier, at greater heights, finished reduction while at the simulation a higher amount on wustite is still available for reduction.

The melting zone ends at a solid temperature of 1250°C. This ensures the start at approximately 1150°C which fit the melting temperature of pig iron containing 4.5% carbon. Furthermore slag starts to melt at approximately 1200°C which is equivalent to the melting point of wollastonite (CaO · SiO₂).

It is generally known that the greatest pressure loss occurs in the melting zone. A typical pressure loss can be seen in Fig. 3 together with the theoretical assumed temperatures predominant in the blast furnace. For this reason a pressure loss of 1 bar is defined during this zone. A constant pressure of 2.4 bar as initial value for the gas entering the bosh belly area can be traced back to the CFD simulations in the raceway done in a previous work.

As thermodynamic data for the liquid state of aggregation of pig iron and slag, measured values are used provided by industry. These values are assumed to be constant for the liquid state because no temperature dependency is available. For the solids the data of wollastonite is taken for the description of slag and for pig iron those of pure iron and carbon are used. Those pure materials cannot describe exactly real conditions in the furnace, therefore they are decreased by 25% after several tries.

The physical properties of the gas side are calculated in terms of density, viscosity and thermal conductivity. For the calculation of the thermal conductivity the approach of Wassilijewa for diluted gas mixtures at pressures below 10 bar is applied. The coefficient λᵢⱼ is defined by Mason and Saxena.

\[ \lambda_m = \sum_{i=1}^{n} \sum_{j=1}^{n} y_i \cdot \lambda_i \cdot \sum_{j=1}^{n} y_j \cdot A_{ij} \]  

\[ A_{ij} = \left[ 1 + \left( \frac{\mu_i}{\mu_j} \right)^{\frac{1}{2}} \right]^{1/4} \left[ \frac{M_i}{M_j} \right]^{1/4} \]  

Fig. 1. Temperature and melting zone after the injection of COG with one lance.

Fig. 2. Mass flows and temperature boundaries in the gas conversion simulation tool.

Fig. 3. Assumed temperature progression profile for the bosh belly area of a blast furnace.
\( \lambda_m \): thermal conductivity of the mixture [W/m K]
\( \lambda_i \): thermal conductivity of species \( i \) [W/m K]
\( y_{ij} \): molar fraction of the species \( i, j \) [-]
\( A_{ij} \): coefficient of the species pair \( i \) and \( j \) [-]
\( \mu_{ij} \): dynamic viscosity of the species \( i, j \) [Pa s]
\( M_{ij} \): molecular mass of species \( i, j \) [g/mol]

Between the counter-current moving phases of gas and solid the heat transfer (3) takes place.

\[
\dot{Q} = \alpha \cdot a \cdot \Delta T \quad \text{(3)}
\]

\( \dot{Q} \): heat flow [W]
\( \alpha \): heat transfer coefficient [W/m² K]
\( a \): area available for heat transfer [m²]
\( \Delta T \): temperature difference [K]

For the calculation of the Nusselt number (4) an approach of Akiyama⁸ is used measured especially for counter current flow reactors like the blast furnaces. The approach looks similar to those of Ranz⁹,¹⁰ including other parameters.

\[
\text{Nu} = \frac{\alpha \cdot d_p}{\lambda} = 2.0 + 0.39 \cdot \text{Re}_{p}^{1/2} \cdot \text{Sc}_{p}^{1/3} \quad \text{(4)}
\]

Nu: Nusselt number [-]
Sc: Schmidt number [-]
Re: Reynolds number based on particle diameter [-]
d: diameter of the particle [m]
\( \lambda \): thermal conductivity [W/m K]

It is generally known that theoretical calculated heat transfers often do not fit experimental results. This can be seen at several reports of discrepancies for the calculated values under usage of Gnielinski¹¹,¹² for fixed bed heat transfer. Some of them are summarized by Kunii and Suzuki;¹³ Martin¹⁴ explained this phenomenon by a model assumption of Schlunder¹⁵ who expects the gas not to flow homogeneous through the bed material but forms channels resulting in different voidages for sectors of the whole bed. Because of accomplished experimental results¹⁶ heat transfer is reduced compared to theoretical calculations to 2.5–5% depending on the fraction of liquid burden.

For the description of the chemical interaction a set of decisive reactions which can be seen in Table 4 are implemented into the simulation. These reactions include not only homogeneous gas and heterogeneous reactions of gas and coke but also those for the reduction of wustite.

The heat of the homogeneous reactions is assigned to the gas side while those of the heterogeneous and the heterogeneous catalyzed are assigned to the solid side. The exact view of the flow and the heat transfer can be seen in Fig. 4. The heat loss is considered to be on the solid side. This guarantees a higher heat content of the gas compared to the stock and therefore ensures adequate heat transfer which is important under real conditions.

While under ideal conditions the temperature remains constant during the melting process in the simulation a heat distribution on the material flows makes a more realistic temperature prediction possible. The transferred heat is distributed over the three available materials slag, the iron containing flow and coke corresponding to their surface fractions.

The injection and its characteristics are listed in Table 5 for the injection of COG and oil per furnace and per tuyere.

The simulations each contain the flows of one blast furnace tuyere. Both injection tasks are characterized by a melting rate of 2 400 t H.M./d for a blast furnace. As initial values for the simulation the results of the CFD calculations

| Table 4. Implemented reactions in the simulation tool. |
|------------------------------------------------------|
| No. | Reaction | Type            |
|-----|----------|-----------------|
| 1   | \( \text{C} + \text{H}_2\text{O} \rightarrow \text{CO} + \text{H}_2 \) | Heterogeneous   |
| 2   | \( \text{C} + \text{CO}_2 \rightarrow 2 \text{CO} \) | Heterogeneous   |
| 3   | \( \text{C} + 2 \text{H}_2 \rightarrow \text{CH}_4 \) | Heterogeneous   |
| 4   | \( \text{C} + (1+\gamma) \text{O}_2 \rightarrow (1+\gamma) \text{CO} + \gamma \text{CO}_2 \) | Heterogeneous   |
| 5   | \( \text{CO} + \text{H}_2\text{O} \rightarrow \text{CO}_2 + \text{H}_2 \) | Heterogeneous-catalyzed   |
| 6   | \( \text{CO} + \text{H}_2 \rightarrow \text{CO}_2 + \text{H}_2 \) | Homogeneous   |
| 7   | \( \text{CO} + \frac{1}{2} \text{O}_2 \rightarrow \text{CO}_2 \) | Homogeneous   |
| 8   | \( \text{H}_2 + \frac{1}{2} \text{O}_2 \rightarrow \text{H}_2\text{O} \) | Homogeneous   |
| 9   | \( \text{CH}_4 + 2 \text{O}_2 \rightarrow \text{CO}_2 + 2 \text{H}_2\text{O} \) | Homogeneous   |
| 10  | \( \text{CH}_4 + \text{H}_2\text{O} \rightarrow \text{CO} + 3 \text{H}_2 \) | Homogeneous   |
| 11  | \( \text{FeO} + \text{H}_2 \rightarrow \text{Fe} + \text{H}_2\text{O} \) | Homogeneous   |
| 12  | \( \text{FeO} + \text{CO} \rightarrow \text{Fe} + \text{CO}_2 \) | Homogeneous   |

| Table 5. Gas and Blast composition in mol% and net calorific value. |
|--------------------------------------------------|
| COG                      | Oil                      |
| Hot blast                | Hot blast                |
| Volume [Nm³/h]           | 93000                    | 98000                    | 5765 |
| Mass [kg/h]              | 119135                   | 125500                   | 7382 |
| Temperature [°C]         | 1150                     | 1150                     | 1150 |
| Oxygen hot blast         |                          | 24900                    | 25960        | 1527 |
| [Nm³/h]                  | 24900                    | 2092                     | 37060        | 2180 |
| Hot metal (HM)           |                          | 24900                    | 25960        | 1527 |
| Melting rate [t/h]       | 100                      | 100                      | 5.88         | 5.88 |
| Temperature [°C]         | 1500                     | 1500                     | 1500         | 1500 |
| Injection [Nm³/h]        | 12500                    | 375                      | --           | --   |
| [kg/h]                   | 5030                     | 296                      | 6700         | 394  |
| Injection specific       | [Nm³/t H.M.]             | 125                      | 7.4          | --   |
| [kg/t H.M.]              | 50                       | 2.9                      | 67           | 3.9  |
3. Results and Discussion

3.1. COG Injection

The COG injection is realized with one and two gas injection lances per tuyere. The temperature curves for the injection with one lance can be seen in Fig. 5. The temperature difference at the start of the simulation amounts 551°C. The temperature curves of solid and gas decrease approximately with the same gradient until the melting zone is reached after 1.3 m. This first 1.3 m all burden, slag and iron, except the coke of the dead man is liquid. When the melting zone which is indicated by a solid temperature of 1375°C is reached, the burden starts to solidify.

In the melting zone the transferred heat from the gas phase to the solid is divided and assigned to the burden materials proportionate. This leads to slightly converging of the curves and to an approximately constant remaining solid temperature in the zone where slag as well as liquid iron hardens.

The melting zone has a length of 1.95 m. After 3.25 m when the end of this zone is reached all burden is solid. The temperature difference of the phases then amounts about 280°C. After the melting zone the temperatures converge in such a way that the conclusion of a reached isothermal zone can be drawn. The isothermal zone normally lies around 1000°C in a blast furnace. Compared to the typical assumed temperature characteristics in the lower part of the furnace (Fig. 3) for stable conditions the obtained results seem to fit quite well. Nevertheless the predicted end temperature of the simulation is too high amounting approximately 1130°C for the injection of COG with one lance.

CO and 11.0% H₂) retains until the end of the simulation. Only at greater heights and a rising reduction potential of more than about 8% the fraction of CO rises slowly. This circumstance can be due to temperatures higher than 1000°C and proportionally small conversion rates of wustite because of small available amounts. Higher conversion rates like mentioned will effect an adjustment for the benefit of CO because of coke and oxygen of wustite pass into the gas phase, leading to an increase of the mole fraction of CO.

The second injection case is those of COG with two gas lances. The resulting temperature curves for this case can be seen in Fig. 7. Due to a somewhat higher conversion rate of the injected reducing agent in the raceway (Table 3) the difference of the phase temperatures amounts with 635°C more than in the case of one lance. The higher conversion rate is indicated by a higher resulting gas temperature as well as by higher fractions on reaction products like CO₂ and H₂O.

The higher temperature difference in the beginning causes the temperature curves to decrease with a higher gradient. The melting zone is reached after 1.05 m and its length is with 1.48 m about 25% shorter than at the injection with one lance.

The reduction potential of 7.45% wustite in the iron containing flow is predicted by simulation after a height of 6 m. This is less than at the injection with one lance and can be ascribed to the lower average solid temperature during the simulation which is implemented in the reaction kinetics of the reduction.
In this case the simulation also predicts the same equilibrium composition of the gas after a negligible height like at the other COG injection. The simulation end temperature also is too high for the isothermal zone but with 1110°C is less than those with one gas lance.

### 3.2. Injection of Heavy Oil

At the calculation of the gas conversion after the injection of heavy oil under usage of the standard parameters of the simulation some points have to be taken into consideration. The temperature of the gas leaving the raceway at the oil injection amounts with 2293°C about 150°C more than at the injection of COG. Under real conditions a higher temperature of the gas in the lower part will result in a higher temperature of the burden at the raceway level while the simulation predicts a constant temperature of 1500°C of slag and liquid iron because of the average tapping temperature.

In Fig. 8 the result with the standard simulation parameters can be seen. The melting zone has a length of 1.25 m and starts after 0.91 m. This high gradient of the decreasing gas and solid curve can be explained again by the difference in the beginning. The predicted reduction potential amounts 5.06% wustite in the iron containing flow. Because of the difference of approximately 30% between the length of the melting zones of the injection of COG with one lance and the oil standard case problems arise when comparing the reduction potential. Actually a higher gas temperature has to result in a higher reduction potential due to its effect on the reaction kinetic. Another crucial point influencing the reduction kinetic is the predominant pressure in the reactor.

When the temperatures decrease with a higher gradient, the melting zone is reached at lower reactor heights and becomes smaller. Therefore assuming a constant loss on pressure of 1 bar a lower pressure is predominant at smaller heights. This has bad effects on the reaction kinetics. Because equilibrium composition of the gas is already reached and the kinetic of gas reactions is very fast this effect can only be seen at the reduction potential.

Actually a smaller cohesive zone will result in a lower pressure loss under real conditions. For this reason once a lower loss on pressure of 0.7 bar is defined after alignment with the injection of COG with one lance. The obtained result looks similar to those with the greater pressure loss but the simulation predicts a reduction potential of 10.14% wustite in the iron containing flow. This potential is approximately the same like for the injection of COG with one lance.

### 3.3. Evaluation of the Results and Discussion

The simulation model seems to describe the residual conversion until it is completed in the active coke zone only insufficient. This can be obtained at the injection of COG with one and two lances. Although the same amount of COG is injected under same volume flows the differences of the temperatures leaving the raceway of about 100°C do not have an influence on the behavior of the curves in the beginning of the simulation. For this reason only CFD results should be used in the simulation where the conversion is nearly complete.

The results of the predicted reduction potential for COG and heavy oil after a simulation height of 6 m are listed in Table 6. These results show that at great differences of the melting zone length it is important to take the loss on pressure into consideration.

A theoretical exchange rate between COG and oil can be deducted from the needed coke input of the simulations because there is the same melting rate for the injected agents assumed under real conditions. Therefore the input and output flows of the simulation reactor height of 6 m are listed in Table 7 to Table 8 for the cases studied.

A theoretical exchange rate can be determined using the two comparable cases of COG injection with one lance and

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**Table 6.** Predicted simulation reduction potential in terms of wustite content in iron containing flow at a reactor height of 6 m.

| Injection | COG | Oil |
|-----------|-----|-----|
| Pressure loss | 1 bar | 2 lances | 1 bar | 0.7 bar |
| Reduction potential | 10.0% | 7.5% | 5.1% | 10.1% |

**Table 7.** Input flows for cases studied.

| Injection | COG | Oil |
|-----------|-----|-----|
| Pressure loss | 1 bar | 1 | 1 | 0.7 |
| CO | [kg/h] | 1272 | 505 | 2700 | 2700 |
| CO₂ | [kg/h] | 6657 | 7965 | 18074 | 18074 |
| H₂ | [kg/h] | 78 | 18 | 24 | 24 |
| H₂O | [kg/h] | 10924 | 11448 | 6200 | 6200 |
| O₂ | [kg/h] | 20290 | 19135 | 15667 | 15667 |
| N₂ | [kg/h] | 83955 | 83943 | 88199 | 88199 |
| radicals | [kg/h] | 996 | 1149 | 1328 | 1328 |
| sum | [kg/h] | 124172 | 124163 | 132192 | 132192 |
| Fe | [kg/h] | 85527 | 87924 | 89250 | 85374 |
| FeO | [kg/h] | 12172 | 9112 | 7395 | 12376 |
| Fe₂O₃ | [kg/h] | 0 | 0 | 0 | 0 |
| C in coke | [kg/h] | 28526 | 28373 | 24429 | 25908 |
| Coke | [kg/h] | 32200 | 32027 | 27575 | 29245 |
| slag | [kg/h] | 24000 | 24000 | 24000 | 24000 |
the injection of oil with a loss on pressure of 0.7 bar. These two cases approximately have the same reduction potential and therefore in the simulation theoretical the same need for coke should be expected if no difference between these reducing agents exists.

With the factor 1.2 for the exchange of oil to coke resulting from practical experience the calculation listed in Table 9 can be laid down. The difference of the coke input between COG and oil can be turned in an amount on oil equivalent using the factor 1.2. Regarding the injected amount of reducing agent for both cases and considering the oil equivalent on the oil side a theoretical exchange rate can be calculated. In Fig. 9 the graphical illustration of the exchange rate can be seen using the values of injected reducing agent and the oil equivalent of the coke difference for each case.

The resulting exchange rate for heavy oil to COG amounts 0.84.

| Table 8. Output flows for cases studied. |
|----------------------------------------|
| OUTPUT | COG | Oil |
| Injection | 1 lance | 2 lances | 1 lance |
| Pressure loss [bar] | 1 | 1 | 1 | 0.7 |
| CO [kg/h] | 6515 | 6430 | 6434 | 6694 |
| CO₂ [kg/h] | 0 | 0 | 0 | 0 |
| H₂ [kg/h] | 1299 | 1309 | 717 | 716 |
| H₂O [kg/h] | 0 | 0 | 0 | 0 |
| O₂ [kg/h] | 0 | 0 | 0 | 0 |
| N₂ [kg/h] | 8395 | 8394 | 8819 | 8819 |
| sum [kg/h] | 15040 | 14956 | 15326 | 15585 |
| Fe [kg/h] | 95000 | 95000 | 95000 | 95000 |
| C in H.M. [kg/h] | 5000 | 5000 | 5000 | 5000 |
| slag [kg/h] | 24000 | 24000 | 24000 | 24000 |

| Table 9. Output flows for cases studied. |
|----------------------------------------|
| COG | Oil |
| Coke input [kg/1 H.M. | 322 | 292 |
| Coke difference between COG and Oil [kg/1 H.M. | 30 | 0 |
| Oil equivalent of the coke difference (CD) [kg/1 H.M. | 25 | 0 |
| Reducing agent injected [kg/1 H.M. | 50 | 67 |
| Adjustment of injected agents with CD [kg/1 H.M. | 50 | 42 |
| Exchange rate [-] | 1 | 0.84 |

4. Conclusions

Oil and coke oven gas (COG) are very effective injectable reducing agents for the blast furnace. The reduction potential of the gas formed in the raceway at the simulation can be expressed by the FeO content in the iron containing flow. The highest reduction potential in the simulation is predicted for COG injection with one lance on the condition that the same end pressure is reached independent of the height of the melting zone. Under operating conditions a smaller melting zone reduces the pressure loss. The higher predominant absolute pressure on this part has a beneficial effect on the reduction potential due to the higher partial pressures of the reducing species which can be found in the reduction kinetics. This effect becomes apparent for the oil case at the attempt of defining once a higher end pressure. The simulation then predicts approximately the same reduction potential for the injection of oil as for the studied COG injection with one lance. This aligns with the nature of the compared injections in terms of the same melting rate in reality. Similar considerations have to be made for the injection with two lances.

Looking at the available gas species it was obtained that the residual oxygen is consumed very fast when carbon is present. The equilibrium composition of the reducing gas is reached immediately and remains nearly constant during simulation. The mole fraction of H₂ at the injection of COG is higher, CO is only a bit lower than in the case of heavy oil injection. The higher molar flow of the gas formed during the injection of oil can not compensate this occurrence.

Compared to COG, heavy oil provides a higher amount of carbon which can consume oxygen from the hot blast. With a mass balance of the two reducing agent flows from the simulation, it is possible to derive a theoretical exchange rate for COG to heavy oil. This rate amounts approximately 0.84 for comparable cases in terms of the same amount of FeO in the iron containing flow.

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