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Development of a Blast Furnace Model with Thermodynamic Process Depiction by Means of the Rist Operating Diagram

Andreas Spanlang*[a,b], Walter Wukovits[b], Bernd Weiss[c]

[a]K1-MET GmbH Metallurgical Competence Center, Stahlstrasse 14, 4020 Linz, Austria
[b]TU Wien, Institute of Chemical Engineering, Getreidemarkt 9/166, 1060 Vienna, Austria
[c]Primetals Technologies Austria GmbH, Iron- and Steelmaking Technology and Innovation – Direct Reduction, Turmstrasse 44, 4031 Linz, Austria
andreas.spanlang@k1-met.com

Despite the fact that alternative processes such as Corex® and Finex® have already been established on industrial scale, the blast furnace route continues to be the most important process used to produce pig iron. Due to its importance, a variety of models of the blast furnace process have been developed in the past decades. In addition to this, a well-established analogue representation of blast furnace operation is given by the Rist operating diagram.
The target of this work is to create a comprehensive blast furnace model in the simulation platform of gPROMS ModelBuilder®. Based on elemental assignments and empirical component distribution correlations, the blast furnace process is depicted by means of a black box model. The thermodynamic process boundaries are analysed in a Rist sub-model. Furthermore, an additional sub-model is used to calculate the adiabatic flame temperature in front of the blast furnace tuyeres. This modelling concept enables the description of interdependencies between the main blast furnace process, raceway conditions as well as overall thermodynamic process conditions within a single mathematical model.
A detailed analysis of the model behaviour under varying coke substitution scenarios was carried out. The achieved simulation results demonstrate the applicability of the developed model for simulation of the blast furnace process under a wide range of operation conditions. The model also provides the means for simulation of different blast furnace route setups which allow for further optimisation regarding process efficiency, fuel consumption and environmental emissions of the blast furnace process.

1. Introduction

The blast furnace process is the most important iron making process worldwide. It has been in use for centuries and is still being developed in order to increase efficiency as well as productivity. In addition to this, development of alternative iron making processes, so called smelting reduction processes, started in the 1970s. Main target of these efforts was to derive process routes capable of producing pig iron (hot metal) at low capacity using non-coking coal directly thereby reducing environmental emissions (Flickenschild et al., 2012). Theoretically such processes would be independent of energy intensive raw material beneficiation carried out in sinter and coking plants. As of today, only the Corex® and the Finex® smelting reduction processes were established on industrial scale.
Driven by economical as well as ecological reasons, blast furnace iron making significantly advanced in the past decades as well. Due to the introduction of numerous technological improvements such as higher blast temperatures, elevated top gas pressure levels, enhanced burden distribution and sinter quality as well as the injection of hydrocarbons like coal, oil and natural gas, the overall reducing agent demand was successfully reduced to levels below 500 kg/t hot metal (Lüngen and Yagi, 2012). These developments contribute to the competitive efficiency of modern blast furnaces. Worldwide market shares of over 99 % in recent years confirm that the blast furnace route remains the primary process for the production of hot metal (Spanlang, 2015).

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A schematic overview of the blast furnace process is illustrated in Figure 1. Alternating layers of coke and iron oxide bearing burden are charged at the top of the furnace while hot blast enters the furnace through multiple tuyeres. This hot blast then gasifies coke and other hydrocarbons generating hot reducing gas which mainly consists of CO, H_2 and N_2. The hot reducing gas ascends through the furnace and is responsible for the reduction, heating and smelting of the descending burden producing hot liquid metal and slag. The remaining reducing gas leaves at the top of the furnace and can be reused for other purposes such as heating of coking plants or hot blast stoves. In summary, the blast furnace process can be characterized as a counter current, multi-phase heat and mass exchange reactor. Oxygen is removed from oxidic burden constituents and transferred to an ascending hot reducing gas phase which in turn transfers heat to the descending burden and coke (Geerdes et al, 2009).

Both the sensible heat as well as chemical reduction potential (through reducing gas) required for blast furnace process, are provided by the gasification of coke and hydrocarbons inside the raceway in front of blast furnace tuyeres. A way to characterize the conditions in the raceway is by means of the raceway adiabatic flame temperature or RAFT (Peacey and Davenport, 1979). This adiabatic temperature is a theoretical concept and commonly considered in practice as an empiric parameter for stable blast furnace operation (Geerdes et al, 2009).

Due to the importance of the blast furnace process a large number of different mathematical models has been developed in the past decades. These include statistical models, thermodynamic models as well as kinetic-dynamic models. While statistic models are based on long term analysis of operation data, thermodynamic and kinetic models are based on mass and energy balances as well as chemical reaction kinetics (Bogdandy and Engell, 1967). All of these types of models are still being used in today’s iron making industry.

Another way of characterising blast furnace operation is provided by means of the Rist operating diagram (see Figure 2). It is based on plots of reduction data of a lab-scale blast furnace (Rist and Bonnivard, 1962) and has been developed to a full-fledged analogue diagram in the following years. The distinctive feature of this operating diagram is the graphical representation of balances of carbon, oxygen and hydrogen through an operation line. These elements are involved in the formation and utilization of the reducing gas mixture in a blast furnace (Rist and Meysson, 1967). In addition to this, the equilibrium conditions of involved indirect iron oxide reduction reactions are taken into consideration by means of an equilibrium line (Babich et al., 2008).

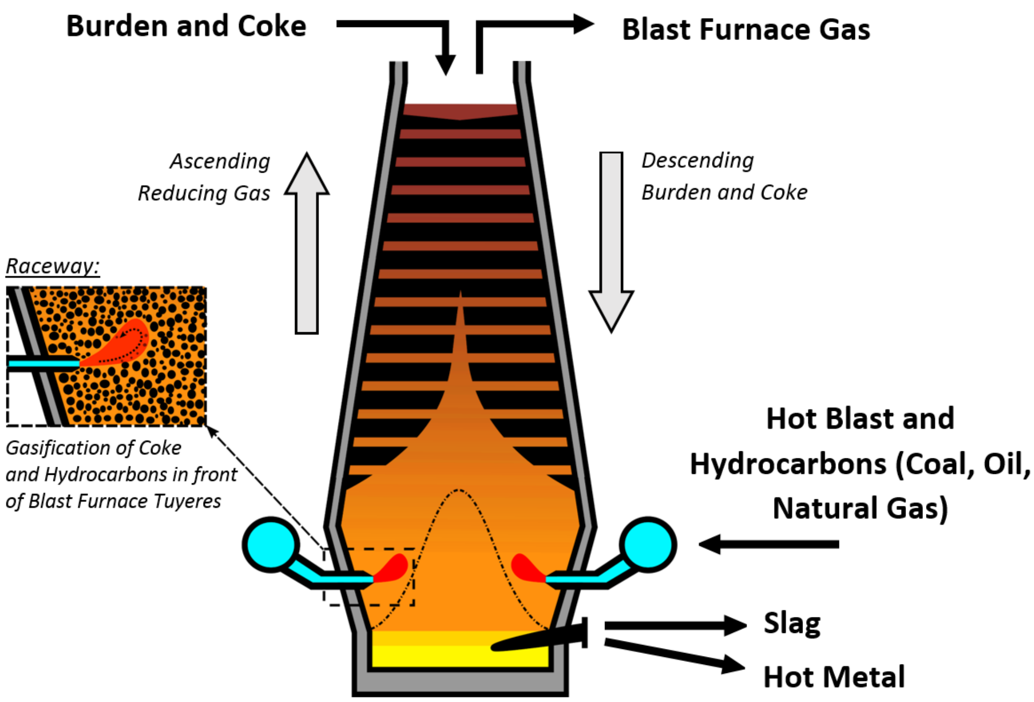

Figure 1: Blast furnace process overview

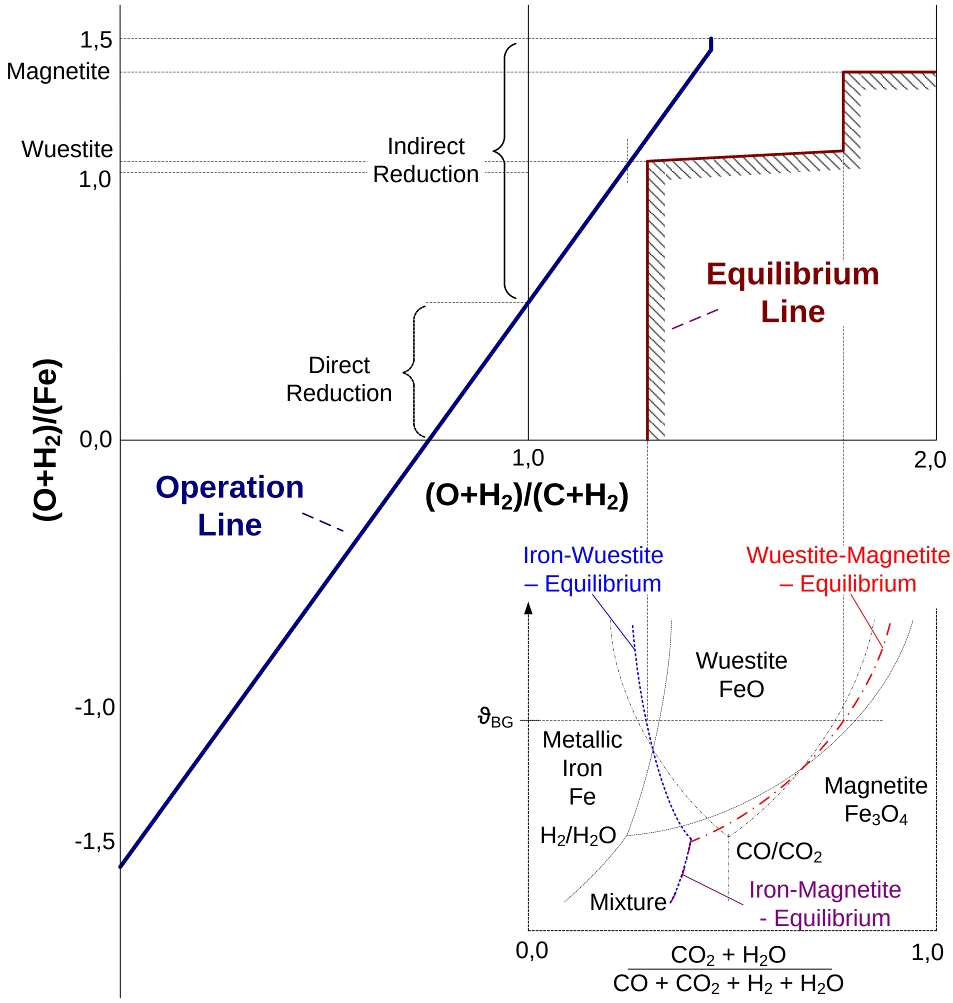

Figure 2: Example of a Rist operating diagram

2. Modelling

The blast furnace model consists of three distinct sub topologies or calculation layers. The task of the main sub topology layer is the depiction of the material flows of the blast furnace process. The chemical and physical conversions which are responsible for the transformation of burden, coke, hot blast and injectants into blast furnace gas, slag and hot metal are implemented through the use of a black box model. In recent years, multiphase equilibrium calculation routines have already been developed for the comparable melter gasifier model in gPROMS® (Almpanis-Lekkas et al. 2014). However, due to observed deviations regarding manganese and silicon contents in hot metal and slag, this approach was rejected for the blast furnace model. Hence, empiric elemental assignments and distribution coefficients of affected elements are used for an implicit implementation of blast furnace conversions and reactions. In order to form the required internal structure of the main calculation layer, a combination of different sub models is required. The connection between the sub models is established by material streams which are intended to represent material flow regimes occurring in the blast furnace process (see Figure 3). The solid material streams are each connected to splitter models which are used for the implementation of dust separation. The main solid material streams are mixed with other gaseous and liquid input streams in a mixer model before being directed to the black box sub model. The output streams of this black box model are blast furnace gas, slag and hot metal. Prior to leaving the system, the produced blast furnace gas is mixed with the collected solid dust stream.
The second calculation layer is used to investigate the gasification conditions at the blast furnace tuyeres. This task is assigned to the adiabatic flame temperature sub model. The third calculation layer is used to determine the overall thermodynamic conditions of the blast furnace process by making use of a specifically developed Rist sub model.

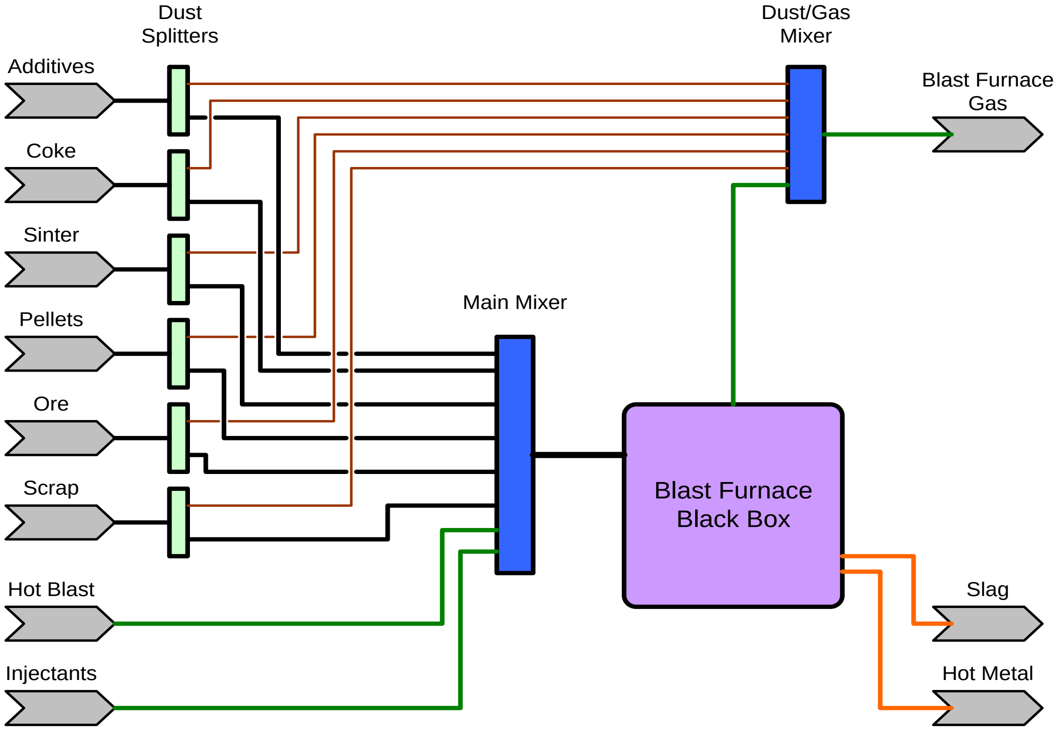

Figure 3: Main sub topology layer of the blast furnace model

The adiabatic flame temperature sub model is used for the calculation of the RAFT. It can be derived by means of empiric formulas or very accurately from adiabatic mass and heat balance calculations (Geerdes et al, 2009). The model presented in this work is based on the latter approach. Complete gasification under adiabatic conditions is performed with the hot blast and injectants entering the system boundary of the theoretical blast furnace tuyeres. The temperature of the resulting gas is equal to the RAFT.
The Rist sub model is required to construct the Rist operating diagram. Assuming ideal behaviour, it serves as the graphical representation of blast furnace operation. This includes depiction of the influences of varying operation parameters such as blast temperature, burden pre-reduction as well as injection of hydrocarbons on the blast furnace process (Rist and Meysson, 1967). Thereby it is possible to use this analogue model for interpretation and comprehension of different operation scenarios while it also allows qualitative prediction of thermochemical changes in a blast furnace (Kundrat, et al., 1991).
The material flow information required for the calculation of RAFT and Rist operating diagram is not provided through the use of sub topology material streams but means of mathematical equations. Thus no specific sub topology is required. In general, the tasks of the calculation layers are carried out in parallel on the same hierarchical level as illustrated in Figure 4. All three layers add up to an overall sub topology of the blast furnace model. Due to this combined modelling approach, the results of the adiabatic flame temperature sub model and the Rist sub model are indirectly excreting influence on the mass and energy balance of the black box model. Therefore, the interdependencies between blast furnace process, RAFT and thermodynamic conditions can be described within the single mathematical model of the blast furnace unit operation model.

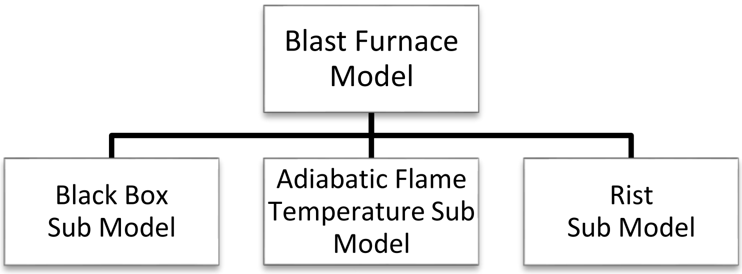

Figure 4: General hierarchy of the blast furnace model

3. Simulation Results

The developed model has successfully been validated against plant data as well as established calculation tools. In addition to this, several parameter and input variation scenarios have been investigated including pre-reduced iron carrier usage and natural gas injection (Spanlang, 2015). The simulation presented in this work illustrates the effects of coke substitution by means of hydrogen injection. A necessary assumption for this scenario is constant thermodynamic efficiency which is expressed by a constant horizontal approach of the Rist operation line to the wustite equilibrium. Depending on operating conditions, the blast furnace gas temperature can range from 100 °C to 230 °C (Lüngen and Yagi, 2012) In this particular case, it is specified with 150 °C. Based on this, the injection of H_2 is increased from 0 to 200 m^3 (STP) / t (HM).
The overall simulation results of this variation are given in Figures 5 – 7. It can be observed in Figure 5 that the specific amount of coke required for the process drops from 455 to 401 kg/t hot metal. Moreover, the specific amount of hot blast also decreases from 952 to 889 m^3 (STP) / t hot metal. This effect is explained by a shift in the reduction mechanisms in the blast furnace which is caused by hydrogen injection. Since solid carbon is exchanged by gaseous H_2, highly endothermic direct reduction with solid carbon is partially replaced by less endothermic indirect reduction with H_2. Therefore, the input of energy-rich hot blast has to be reduced in order to ensure constant blast furnace gas temperature. Figure 6 illustrates calculated process outputs. A minor change can be observed for the specific slag production rate with a decrease from 222 to 217 kg/t hot metal. In addition to this, the CO_2 equivalent emissions decrease from 1,428 to 1,259 kg/t hot metal which is equal to a reduction of approximately 12 %. Both effects are linked to the decreasing coke mass flow which supplies both carbon and slag forming components to the blast furnace process. A drop from 2,300 to 2,022 °C is visible for the RAFT which is explained by the decreasing supply of hot blast and the increasing hydrogen injection rate.

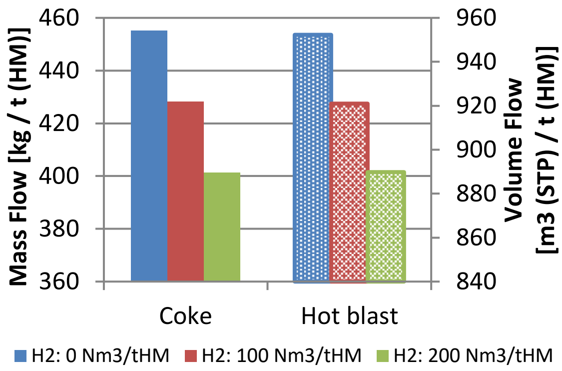

Figure 5: Calculated input variations

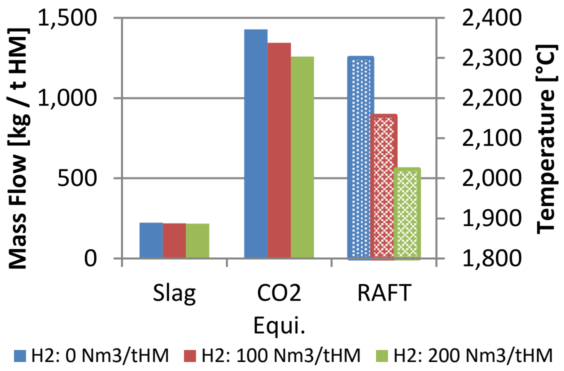

Figure 6: Slag and CO_2 equivalent output, RAFT

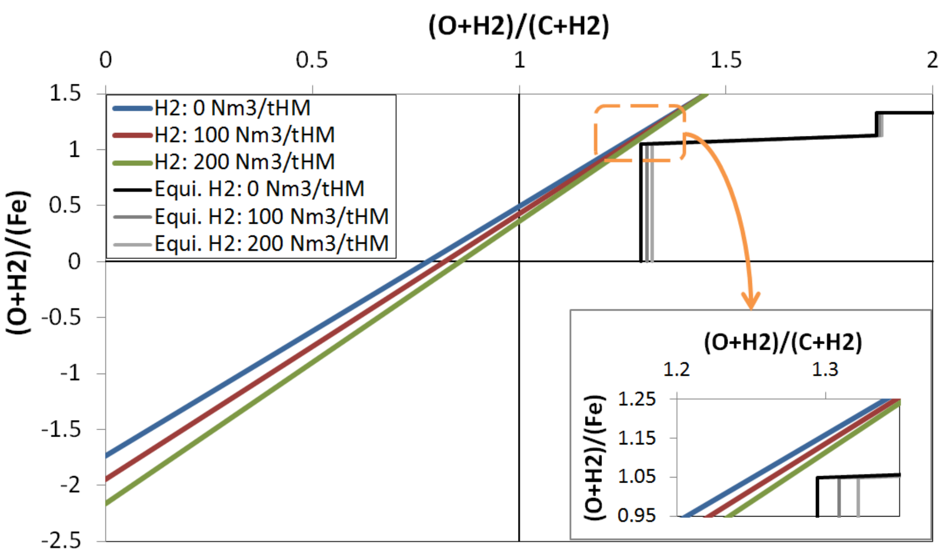

Figure 7: Rist operating diagram

Figure 7 depicts the corresponding Rist operating diagram of this simulation. The gradient of the operation line is decreasing with increasing hydrogen injection. This can be translated to a decreasing reducing agent demand of the process which is in line with the observed decrease of CO_2 equivalent emissions. Furthermore, a drop of direct reduction percentage can be observed which corresponds to the shift in the reduction mechanisms from carbon to hydrogen.

4. Conclusions and Outlook

The model described in this work links the basic mass and energy balances of the blast furnace with an additional model for the raceway adiabatic flame temperature as well as an analogue process description offered by the Rist operating diagram. This allows for a variety of possible applications including verification and benchmarking of existing as well as predictive simulation of new blast furnace process set-ups. Moreover, it is possible to study alternative process scenarios like usage of pre-reduced iron carriers or low-emission scenarios like natural-gas or hydrogen injection. The results presented in this work demonstrate the considerable potential of such theoretical approaches to reduce CO_2 emissions of blast furnace processes.
Due to the flexibility offered by the gPROMS® simulation platform, application of the developed model is not limited to the blast furnace only. In future the model can be used in combination with models of coking plants, sinter plants, hot blast stoves and basic oxygen furnaces in order to simulate integrated steel plants. This would offer the ability for comprehensive optimization and may lead to increased process efficiency, reduced environmental emissions as well as increased cost effectiveness.

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