1. Introduction

In an integrated metallurgical plant of the voestalpine Stahl, there are gases available from coke production and the basic oxygen furnace (BOF) process. Therefore, a project of utilization of these gases in the blast furnace is realized. In this process, they shall substitute alternative reducing agents like heavy oil, which are purchased from outside sources. Oil injection into the blast furnace has been practiced successfully to enhance the reduction process. The injection of reducing gases into the blast furnace results in a better flexibility of the energy network of an integrated metallurgical plant and the use of alternative reducing agents.

The gas considered in this work originates from coke production (coke oven gas, COG). It is injected with the hot blast into the blast furnace via tuyeres and is rich of species like H₂, CH₄ and CO. The combustion of this gas, taking place to some extent within the tuyeres, can lead to an overheating of these tuyeres and an oxidation of the gas lances, which is tried to advert. For this reason, a complete understanding of the conversion characteristics is very important. Calculations for gas injection are done by using both one and two lances, with the same volume flow in each case. These cases are compared with the case of oil injection. The aim of this work, compared to the previous work, is to study the effect of changing oil droplet diameters. Further parameters of the applied Rosin–Rammler distribution and the oil injection have been varied, to ascertain their effects on conversion. These parameters mainly were varied, because of the lack of relevant information like droplet diameter distribution or oil temperature at the point of injection.

In this work, theoretical considerations are made about combustion or the difference in conversion characteristics, respectively, between oil and gas injection. The following calculations are done by using computational fluid dynamics (CFD). It provides a detailed description of the oil and gas flow during the injection in the hot blast. Because of the high resource demanding flow calculation, a simplified model is used for the simulation of the ongoing chemical reactions. The simplest assumption is the thermodynamic equilibrium, which is based on the local composition of the gases and the local temperature. A further simplifying assumption is the neglect of coke in the model of the raceway.

To enhance the blast furnace process, the practice of injecting reducing agents into the blast furnace is used. In a metallurgical plant of the voestalpine Stahl, so far the injection of oil is practiced. The availability of gases like coke oven gas (COG) makes it possible to substitute reducing agents like heavy oil. The injection of gas and oil, respectively, shows different reaction characteristics and therefore different reducing conditions are obtained.

In this work, theoretical considerations are made about the different conversion characteristics of oil and gas. The calculations, done by using computational fluid dynamics (CFD), provide a detailed description of the oil and gas flow injected in the hot blast. For gas injection, the mixing of gas and blast and their conversion are considered in tuyere and raceway. For oil injection, additionally the evaporation of the oil droplets takes place.

The injection of gas with one lance shows an inhomogeneous distribution in temperature and velocity due to the high injection velocity compared to oil injection. For the injection of oil, evaporation of the oil droplets takes place and the gas formed reacts with the hot blast. There, the distribution of temperature, velocity and concentrations is more homogeneous than for gas injection. A variation of the oil droplet size injected shows for larger droplets (400 μm and more) an incomplete evaporation and distributions similar as for the gas injection.

KEY WORDS: blast furnace; gas injection; oil injection; modeling; simulation; combustion.
2. Basics

2.1. Plant Layout

The blast furnace considered is the HO 6 on the site of the voestalpine Stahl in Linz, Austria. This blast furnace has an output of about 2 400 t pig iron per day. Its diameter at the hearth is about 8 m. There are arranged 17 tuyeres uniformly distributed over the circumference of the blast furnace.

The main parts of the plant layout of blast furnace with gas injection are the mixing station, screw compressor, gas cooler, bustle pipe, injection lances and the pipes to connect these parts. In the mixing station, COG and gas from the basic oxygen furnace (BOF gas) are mixed according to the particular requirements of the process. In this work, only the injection of COG is considered. The process gas is conveyed via a screw compressor and a gas cooler to a bustle pipe, wherefrom it is directed to the tuyeres. In the case of heavy oil, it is also pumped under pressure to the bustle pipe and further to the oil injection lances, where it is injected into the tuyeres.

The injection of the reducing gas is done by using one gas lance or one oil lance per tuyere, respectively. The dimension of a gas lance is 22 mm in inner diameter with 1.5 mm wall thickness, whereas the inner diameter and wall thickness of an oil lance are 8.3 mm and 2.6 mm, respectively. The lances end 100 mm inside from the end of the tuyere. They are fixed on a pipe with a length of 860 mm. The tuyere itself has a slight conical orifice with a minimal diameter of 140 mm on its end and a length of about 575 mm.

2.2. Input Parameter

The oil injected in the blast furnace is usual heavy oil. Its elementary analysis and some physical properties are shown in Table 1. Further physical properties needed for calculations are listed in the FLUENT database.

In addition to these properties, input parameters like temperature or mass flow of oil and hot blast are required for calculation of heavy oil injection. The values of these parameters, listed in Table 2, are given only for one of the 17 tuyeres.

The composition of the used coke oven gas and its net calorific value is listed in Table 3. It can be seen that the principal constituents are H₂ and CH₄. The appointed input parameters valid for one tuyere can be seen in Table 4. The hot blast itself consists of hot air enriched with oxygen.

3. Modeling

The calculations have been done by means of computational fluid dynamics (CFD). For this, the commercial CFD code FLUENT 6.0 is used. Those resource needing simulations have been carried out using the central computer (sc.zserv.tuwien.ac.at) of the ZID (Zentraler Informatikdienst) of the Vienna University of Technology.

3.1. Building of the Geometry

At first, for CFD calculations it is necessary to build a geometry model. This is done by the preprocessor GAMBIT 2.0. In Fig. 1, the model of the tuyere with one gas lance and the raceway is shown. The dimensions of the lances and the tuyere are described in Chap. 2. The shape of the raceway is not really known, but it is convenient to build it as a cylinder with a length of 1 m and a diameter of about 0.5 m.
After having built the geometry, a mesh or grid has to be generated. This means that the geometry has to be divided into finite volumes. Because of the complex geometry, an unstructured hybrid mesh consisting of hexahedral and tetrahedral elements is generated. As the case may be, the mesh of the geometry consists between about 270,000 elements for oil injection and about 300,000 elements for gas injection.

3.2. Flow Modeling

The finite volume solver FLUENT 6.0\(^5\) solves conservation equations for mass and momentum for the flow in the tuyere/raceway region. Several physical models are added, according to the requirements of the flow.

One of these models is the realizable \(k-\varepsilon\) model for simulating the turbulence of the flow. It is assumed that it is an appropriate model for this application. A further description of the flow is the assumption of compressibility.

Irrespective of the physical models, conditions on the boundaries had to be set. These can be seen in Table 5. The values for mass flow inlet are shown in Tables 2 and 4. At the pressure outlet, the surrounding pressure is given with 0.24 MPa absolute. For walls, the default settings with adiabatic boundary conditions are used.

In the blast furnace, raceways are surrounded by a packed bed of coke. To accomplish the simulation in a reasonably realistic way around the raceway a layer as porous media is set with a thickness of 50 mm. This permeable media layer at the lower half is assumed to have a higher bulk density, equal to a packed bed with \(d_p=10\) mm and a porosity of \(\varepsilon=0.3\) at the upper part of the raceway. To assure the gas flow leaves the raceway through this upper part of the raceway the porous media layer at the lower half is assumed to have a higher bulk density, equal to a packed bed with \(d_p=5\) mm and \(\varepsilon=0.1\). The required parameters for calculation of the porous media are the permeability \(\alpha\) and the inertial loss coefficient \(C_2\). They are the result of the following equations.

\[
\alpha = \frac{D_p^2}{150} \cdot \frac{\varepsilon^3}{(1-\varepsilon)^2} ........................................................(1)
\]

\[
C_2 = \frac{3.5}{D_p} \cdot \frac{(1-\varepsilon)}{\varepsilon^3} .............................................(2)
\]

These equations are derived by use of the Ergun equation,\(^7\)

\[
\frac{\Delta p}{L} = \frac{150 \cdot \mu \cdot (1-\varepsilon)^3}{D_p^2} \cdot \frac{1.75 \rho \cdot (1-\varepsilon)}{D_p^2} \cdot \frac{\varepsilon^3}{\varepsilon^3} \cdot \frac{v_m^2}{\varepsilon} .............................................(3)
\]

so that

\[
\frac{\Delta p}{L} = \frac{1}{\alpha} \cdot \mu \cdot v_m + C_2 \cdot \frac{\rho}{2} \cdot v_m^2 .............................................(4)
\]

A further assumption concerning the raceway is the absence of any solid particles like coke.

3.3. Combustion Model

For combustion of the gas the equilibrium chemistry model FLUENT provides is used. This model requires that chemistry is fast enough so that thermodynamical equilibrium always exists. This equilibrium chemistry model is part of the probability density function (PDF) models. This kind of models first calculates chemical processes using a preprocessor (prePDF\(^5\)) before the flow is simulated. For the calculation of chemical equilibrium the Gibbs free energy is used, therefore no defined reaction mechanism or detailed chemical kinetic rate data is required. It is sufficient to define the important chemical species.

For gas combustion, these are the eight main species the gas and hot blast are composed of (which can also be seen in Table 3), the four radicals O, OH, H and HO\(_2\) as well as C(s) as solid soot particle. Furthermore, this model assumes that the reaction is mixing-limited and has a rigorous accounting of turbulence-chemistry interactions.

For combustion of the vapor released from the oil droplets by vaporization or boiling (see Chap. 3.4), the PDF model is used, too. The composition of the vapor is performed by an equilibrium calculation of PDF, using the atomic composition and enthalpy of heavy oil, which can be seen in Table 1. The calculation is done like the one for COG combustion.

3.4. Modeling of the Liquid Oil Phase

At oil injection liquid heavy oil flows through the lance into the tuyere. There the oil is dispersed by the flow of hot blast. Therefore, for simulation additional to solving transport equations for the continuous (gas) phase, the oil injection is modeled as a discrete second (liquid) phase. It follows the approach of Euler–Lagrange. This second phase consists of spherical particles (droplets) dispersed in the continuous phase. The solver computes the trajectories of these discrete phase entities, as well as heat and mass transfer to and from them. The coupling between the phases and its impact on both the discrete phase trajectories and the continuous phase flow is included. The dispersion of droplets due to turbulence in the fluid phase is predicted using the stochastic tracking model. It includes the effect of instantaneous turbulent velocity fluctuations on the droplet trajectories using stochastic methods.

The oil droplets are released at the front surface of the oil lance. For droplet size injected with one lance, a correlation equation to experimental results, given by Paloposki and Hakala\(^6\) is chosen (Eq. (5)). The mean diameter according to this equation amounts about \(d_p=200\) \(\mu\)m.

\[
d_p = 147 \cdot m_0^{0.186} .............................................(5)
\]

At the following calculations, the droplet diameter is varied in the range of 100 to 400 \(\mu\)m. Further, a droplet size distribution is assumed in analogy to the Rosin–Rammler size distribution method. It is based on the assumption that an exponential relationship exists between the droplet diameter \(d_p\) and the mass fraction of droplets with diameter greater than...
than \( d_p \) (Eq. (6)).

\[
Y_a = e^{-(s/d_p)'} \quad \text{......................................(6)}
\]

Other parameters for this distribution can be seen in Table 6.

For calculation of heat and mass transfer, the physical laws of heating, evaporation and boiling of the droplets are applied. While the droplet temperature is less than the vaporization temperature, the inert heating law according to Eq. (7) is applied.

\[
m_p \cdot c_p \cdot \frac{dT_p}{dt} = \alpha \cdot A_p \cdot (T_p - T_{\infty}) \quad \text{......................................(7)}
\]

When the temperature of the droplet reaches the vaporization temperature and continues until the droplet reaches the boiling point vaporization (Eqs. (8) to (14)) is initiated. There, the rate of vaporization is governed by gradient diffusion, with the flux of droplet vapor into the gas phase related to the gradient of the vapor concentration between the droplet surface and the bulk gas.

\[
n_i = k_d \cdot (c_{i,s} - c_{i,\infty}) \quad \text{..........................................(8)}
\]

The concentration of vapor at the droplet surface is evaluated by assuming that the partial pressure of vapor at the interface is equal to the saturated vapor pressure at the droplet temperature.

\[
c_{i,s} = \frac{P_{sat}}{R \cdot T_p} \quad \text{..........................................(9)}
\]

The concentration of vapor in the bulk gas is known from the PDF calculation.

\[
c_{i,\infty} = X_i \cdot \frac{P_\infty}{R \cdot T_\infty} \quad \text{..........................................(10)}
\]

The mass transfer coefficient in Eq. (8) is calculated from the Sherwood number, which is equated with a Nusselt correlation.\(^9,10\)

\[
Sh = \frac{k_d \cdot d_p}{D} \quad \text{..........................................(11)}
\]

\[
Sh = Nu = 2.0 + 0.6 \cdot Re_d^{1/2} \cdot Sc^{1/3} \quad \text{..........................................(12)}
\]

The vapor flux given by Eq. (7) becomes a source of species \( i \) in the gas phase. The mass of the droplet is reduced according to

\[
m_p(t+\Delta t) = m_p(t) - n_i \cdot A_p \cdot M_i \cdot \Delta t \quad \text{..........................................(13)}
\]

The droplet temperature is updated according to a heat balance that relates the sensible heat change in the droplet to the convective and latent heat transfer between the droplet and the continuous phase.

\[
m_p \cdot c_p \cdot \frac{dT_p}{dt} = \alpha \cdot A_p \cdot (T_p - T_{\infty}) + \frac{dm_p}{dt} \cdot h \quad \text{..........................................(14)}
\]

The heat transferred to or from the gas phase becomes a source respectively sink of energy during subsequent calculations of the continuous phase energy equation.

When the temperature of the droplet has reached the boiling temperature, the following equations predict the convective boiling of the discrete phase droplet.\(^11\)

\[
\frac{d(d_p)}{dt} = \frac{4 \cdot k_d}{\rho_p \cdot c_{p,\infty} \cdot d_p} \cdot (1 + 0.23 \cdot Re_d^{1/2}) \cdot \ln \left[ 1 + \frac{c_{p,\infty} \cdot (T_p - T_{\infty})}{h} \right] \quad \text{..........................................(15)}
\]

Throughout the boiling the droplet remains at a fixed temperature. Therefore, the next equation is derived by Eq. (14).

\[
\frac{dm_p}{dt} \cdot h = \alpha \cdot A_p \cdot (T_p - T_{\infty}) \quad \text{..........................................(16)}
\]

### 4. Results

#### 4.1. Gas Injection

In order to describe the combustion characteristics for gas injection with one lance the distribution of temperature and velocity is illustrated in Figs. 2 and 3. In front of these figures there can be seen a slice through the longitudinal...
axis of the gas lance and four cross sections through the raceway. In the background, a slice through the longitudinal axis of the tuyere is shown.

The distribution of temperature at gas injection, which can be seen in Fig. 2, shows a long drawn zone of cooler fuel gas, which is slightly bent up. Because of the high injection velocity (over 300 m/s), the gas flow is almost unmixed inside. At the surrounding area of this zone, where gas gets into contact with hot blast, combustion takes place (compare with Andahazy et al., 20053). Then, at the rear end of the raceway, the gas flow turns around and circulates within the raceway (Fig. 3). There, the higher temperatures arise up to 2 500°C due to slower velocity and better mixing of gas and blast.

In addition, the averaged concentrations of the gas species (mass flow weighted) leaving the raceway are shown in Table 7. It can be seen a high amount of H2O and low CO and CO2 concentrations. Furthermore, the temperature and velocity of the gas flowing out of the raceway are listed. These values are also mass flow weighted. For velocity, the voidage of the coke bed is not considered. About the whole gas is flowing through the upper part of the raceway into the coke bed. The area of this upper part is also given in Table 7.

4.2. Oil Injection

The results from the injection of oil differ from those of the gas injection in several aspects. The temperature distribution at the oil combustion with an average drop diameter of 200 μm representing the standard case like already mentioned in Chap. 3 is shown in Fig. 4.

The highest temperature is reached in the middle of the raceway and amounts about 2 600°C. Just at the beginning of the raceway, a cooler conus shaped temperature distribution can be obtained. The reason therefore can be attributed to the liquid state of aggregation oil is injected into the tuyere. About 120 mm after injection, the first droplets are evaporated and combustion takes place at the surrounding area of the conus of droplets, which can be seen on the higher temperatures in this area. The evaporation of droplets leads to the consumption of energy and therefore to lower temperatures in this conus. This energy consumption later is compensated by the heat of the combustion reactions.

At the end of this conus, oil droplets are evaporated completely (see also Fig. 5) and combustion takes place at maximum temperatures almost uniform over the whole cross-section. Figure 5 shows the in the raceway still existing oil drops in terms of their trajectories and their size. It can be seen that their greatest diameters are mostly in the middle of the inflowing oil stream.

The heating of the gas evaporated by the oil droplets in hot blast and the pyrolysis of hydrocarbons leads to an increase in volume and further to a velocity distribution illustrated in Fig. 6. It can be seen that the distribution is forking when the gas flow enters the raceway. For the injection of oil, a characteristic form becomes apparent which looks like the shape of a bowl. At the lower part where the flow hits the boundary defined to be less permeable, it slightly bends up towards the upper back part.

The gas leaving the raceway after conversion is specified in Table 8. The area denotes the upper part of the raceway
geometry nearly the whole gas is leaving through. Due to the composition of the gas leaving the raceway, it can be expected that conversion is nearly complete. The content of H₂ and CO can be explained by the high temperature of the out flowing gas flow of approximately 2300°C and its resultant equilibrium position. A further explanation can be the mixing processes of the fuel and the hot blast. A not considerable amount of oxygen from the hot blast is leaving the raceway along the boundary area near the tuyere.

The consequence of varying the inlet temperature of oil is studied first. This variation was accomplished in a range between 140 and 200°C and results in no significant changes of the obtained combustion characteristics. In addition, the changing of the boiling temperature of oil from 200 to 400°C has no consequences, too. Further variations are represented in the mean droplet diameter and the droplet size distribution by Rosin–Rammler. Calculated variations of the spread diameter for the Rosin–Rammler distribution can be neglected.

More important becomes the variation of the mean oil droplet diameter at the inlet. A lower mean diameter of 100 μm leads to approximately similar results like those of 200 μm. The gas flowing out of the raceway has an averaged temperature of 2304°C, which is just marginal higher than that at the standard case. Also the velocity amounts only 0.03 m/s more caused by the higher temperature. This higher temperature can be due to a higher degree of combustion, which is indicated by the lower mole fraction of CO and H₂. This let arrive the conclusion that the lower the mean droplet diameter the faster the gas is evaporated and the higher the degree of combustion and therefore the temperature and the gas velocity is.

Matters are quite different when higher mean droplet diameters are considered. The case where it amounts 300 μm does not show very significant changes compared to the standard case. When reaching a mean droplet diameter of 400 μm changes of the characteristics take place. Figure 7 shows the predominating temperatures in the raceway of this case under consideration of the Rosin–Rammler distribution. Most of the heat is generated at the lower part of the raceway due to better mixing of the gas with hot blast. For the upper raceway, a flow of non-evaporated oil droplets reaches to the end of the raceway still with droplet diameters up to 300 μm, which can be seen in Fig. 8. A part of the gas flow circulates in the raceway, which can be seen especially at its lower half where the porosity of the surrounding layer is smaller. (Fig. 9). The outcome of this is a mean temperature of 2075°C of the leaving gas flow and different mole fraction of the species, as listed in Table 8.

In order to show the influence of the utilization of a droplet size distribution on the conversion process, calculations for oil injection were carried out neglecting any size distribution. For mean droplet diameters up to 200 μm, no significant changes in results can be obtained. Results are different for mean droplet diameters of 300 μm. When

<table>
<thead>
<tr>
<th>Species [mole-%]</th>
<th>Mean droplet diameter [μm]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>100</td>
</tr>
<tr>
<td>H₂</td>
<td>0.24</td>
</tr>
<tr>
<td>H₂O</td>
<td>7.51</td>
</tr>
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<td>0.00</td>
</tr>
<tr>
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</tr>
<tr>
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</tr>
<tr>
<td>Velocity [m/s]</td>
<td>5.66</td>
</tr>
<tr>
<td>Area [m²]</td>
<td>1.03</td>
</tr>
</tbody>
</table>

Fig. 7. Temperature distribution [°C] for oil injection with dₚ=400 μm (2 slices through the longitudinal axes of tuyere (rear) and oil lance (front) and 4 cross sections through the raceway).

Fig. 8. Droplet size [m] and trajectories for oil injection with dₚ=400 μm (2 slices through the longitudinal axes of tuyere (rare) and oil lance (front) and 4 cross sections through the raceway).

Fig. 9. Velocity distribution [m/s] for oil injection with dₚ=400 μm (2 slices through the longitudinal axes of tuyere (rear) and oil lance (front) and 4 cross sections through the raceway).
using a droplet size distribution no oil droplets reach the rear boundary of the raceway due to evaporation. Neglecting the size distribution for droplets with mean diameters of 300 μm, most of them reach the rear boundary. This can also be seen for mean droplet diameters of 400 μm independent of droplet size distribution. The reason therefore is that assuming size distribution the smaller droplets evaporate earlier and increases temperature in a way that also leads to an earlier evaporation of the larger droplets.

In the cases where a minimum droplet diameter of 300 μm is assumed, oil droplets are entering the active coke zone, which is following the raceway. In this zone, the residual oxygen concentration still available in the gas decreases immediately due to the large coke surface and the high temperatures. Due to the small amount on oxygen available in this zone the oxidative decomposition of droplets, leaving the raceway becomes more and more repressed. In order to guarantee the total decomposition of the injected hydrocarbons, sufficient spraying of the oil is of high importance.

5. Conclusions

The gas injection with one lance shows a non uniform distribution of temperature and velocity. This is due to the high injection velocity of over 300 m/s. The gas flow reaches to the end of the raceway and burns there at temperatures of about 2500°C.

Considering the injection of oil, it is important to have a look on the oil droplets formed during the injection process into the blast. The following distribution of temperature, velocity and concentration for the gas leaving the raceway depends significantly on the size of the oil droplets. If there is assumed a Rosin–Rammer droplet size distribution up to droplet diameters of about 300 μm, the distribution profile of velocity and temperature looks like a bowl. This is due to evaporation of the droplets in the front region of the raceway. The oxidation of the gas released from the oil droplets predominantly takes place inside this profile. Therefore, it can be seen that in the raceway for oil injection a more uniform distribution is given than for gas injection. Thus, the gas produced from the oil leaves the raceway relatively uniformly distributed into the coke zone.

Droplets with mean diameters of about 400 μm and more do not evaporate completely inside the raceway and leave the raceway at its end. The same effect can be shown already for mean diameters of 300 μm without considering droplet size distribution. In these cases, temperature and velocity distributions are similar to those for gas injection.

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Nomenclature

\( A_p \) : Surface area of the droplet [m²]

\( c_s \) : Vapor concentration at the droplet surface [mol/m³]

\( c_p \) : Vapor concentration in the bulk gas [mol/m³]

\( c_p, \mbox{heat} \) : Heat capacity of the droplet [J/kg K]

\( c_p, \mbox{gas} \) : Heat capacity of the gas [J/kg K]

\( C_i \) : Inertial loss coefficient [1/m]

\( d_p \) : Diameter of the droplet [m]

\( D_D \) : Mean droplet diameter [m]

\( D \) : Diffusion coeff. of vapor in the bulk [m²/s]

\( D_p \) : Diameter of the particle in coke bed [m]

\( h_c \) : Latent heat [J/kg]

\( k_1 \) : Mass transfer coefficient [m/s]

\( k_i \) : Thermal conductivity of the gas [W/m K]

\( L \) : Depth of the porous media layer [m]

\( m_i \) : Oil mass flow [kg/s]

\( m_p \) : Mass of the droplet [kg]

\( M_i \) : Molecular weight of species \( i \) [kg/mol]

\( n_i \) : Spread parameter [–]

\( n \) : Molar flux of vapor [mol/m² s]

\( Nu \) : Nusselt number [–]

\( p_{o_p} \) : Operating pressure [Pa]

\( p_{o_n} \) : Saturated vapor pressure [Pa]

\( \Delta p \) : Pressure loss in porous media [Pa]

\( R \) : Universal gas constant [J/mol K]

\( Re_d \) : Reynolds number [–]

\( Sh \) : Sherwood number [–]

\( Sc \) : Schmidt number [–]

\( T_i \) : Temperature of the droplet [K]

\( T_r \) : Local temp. of the continuous phase [K]

\( \chi_i \) : Local bulk mole fraction of species \( i \) [–]

\( Y_c \) : Mass fract. w. diameter greater than \( d \) [–]

\( \alpha \) : Permeability of the porous media [m²]

\( \alpha_c \) : Convective heat transfer coefficient [W/m² K]

\( \varepsilon \) : Voidage [–]

\( \mu \) : Dynamic viscosity [Pa s]

\( \rho_p \) : Droplet density [kg/m³]

\( \nu_s \) : Superficial velocity [m/s]

\( \frac{d m_p}{d t} \) : Rate of evaporation [kg/s]

REFERENCES

1) T. H. Bürgler, G. Brunnbauer and A. Ferstl: Proc. of 3rd Int. Conf. on Science and Technology of Ironmaking, Steel Institute VDEh, Düsseldorf, Germany, (2003), 157.