MATERIAL BALANCE IN A BLAST FURNACE, WHEN REPLACING COKE WITH COAL DUST

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ABSTRACT

The paper presents the technology for the preparation and burning of coal dust in the blast furnace, as well as the material balance, - without and with the injection of coal dust. On the basis of the comparative analysis, measures are proposed to replace the amount of coke with coal dust in the range of 0.8 - 1 coke / CDI.

KEYWORDS: blast furnace, coke, injection of coal dust (CDI), material balance

1. Introduction

In advanced ironmongery, the development of this process has grown since 1983, so over 100 plants currently consume 20 million tons of energy per year, replacing 19 million tons of coke. Current research is directed towards optimizing the coke/coal dust replacement ratio so that this ratio remains in the range of 0.9 ÷ 1.1 kg coke / kg of coal, being very dependent on the type of coal and especially the way it is prepared. Thus, in the European Union there is currently a brew of approx. 180 kg CD/t p.i., at a consumption of 320 kg coke/t p.i.

The efficiency of the use of auxiliary fuels consists of the price difference from coke and the high coke replacement coefficient 0.8 - 0.9. This coefficient depends on the blast furnace operating conditions, the calorific value of the auxiliary fuels, and the energy consumption required to feed the blast furnace.

The ArcelorMittal Steel Galati plant is equipped with a CDI1 preparation unit and a distribution and injecting transmission installation at the blast furnace, a plant made at the highest level of the current technology, having a capacity of 70 tons coal dust/h and 560,000 tons/year, and can save between 400,000 and 500,000 tons of coke per year.

2. Objectives

The aim is to reduce the consumption of coke from the blast furnace load by infusing the coal dust:
- on the short term, reducing energy costs per ton of pig iron by reducing coke consumption;
- on the medium and long term, the reduction in the share of coke ovens, sections with high pollutant potential and the recovery or replacement of which have a high cost price.

This involves the use of quality materials for blast furnace loading, agglomerated coke, coal, and intensification of the coal dust burning process at the tuyeres, reducing the proportion of carbonaceous residue left off and adequate equipment with computational techniques.

3. Theoretical considerations

The theoretical study of the combustion of pulverized coal in the burning area in front of the tuyeres blows shows the importance of maintaining a sufficiently large and stable cavity.

The most important steps, which describe the carbon dioxide combustion process in the air, are the following:

\( \textbf{a) Combustion chemical reactions.} \) In order for the combustion process to occur it is necessary for the oxygen atoms to reach the reaction front and the reaction products to be removed in the atmosphere (Figure 1).

Under the high temperature of the burning area in front of the wind gullies, 70-80% of the coal dust mass is consumed in the process as follows:

- volatile materials react in gaseous phase:

\[
\begin{align*}
\text{C}_\text{(s)} + 0,5 \text{O}_2 & \rightarrow \text{CO}_\text{(g)} \quad \Delta H = < 0 \quad \text{Exoth.} \\
\text{H}_2 + 0,5 \text{O}_2 & \rightarrow \text{H}_2\text{O} \quad \Delta H = < 0 \quad \text{Exoth.}
\end{align*}
\]
Fig. 1. Carbon burning in front of the tuyere

- in cases of oxidant deficiency, carbon dissociation (carbon black) can also be formed. The carbon residue suffers a heterogeneous reaction:

\[ \text{C}(s) + 0.5 \text{O}_2(g) \rightarrow \text{CO}(g) \quad \Delta H = < 0 \quad \text{Exoth.} \quad (2) \]

\[ \text{C}(s) + \text{CO}_2(g) \leftrightarrow 2\text{CO}(g) \quad \Delta H = > 0 \quad \text{Endoth.} \]

- coke is subject to a heterogeneous combustion reaction similar to coal residue:

\[ \text{C} + \text{O}_2(g) + \text{N}_2(g) \leftrightarrow \text{CO}_2(g) + \text{N}_2(g) \quad \Delta H = < 0 \quad \text{Exoth.} \quad (3) \]

\[ \text{C} + \text{CO}_2(g) \leftrightarrow 2\text{CO}(g) \quad \Delta H = > 0 \quad \text{Endoth.} \]

\[ \text{C}(s) + \text{H}_2\text{O}(g) \rightarrow \text{CO}(g) + \text{H}_2(g) \quad \Delta H = > 0 \quad \text{Endoth.} \]

Since the reaction takes place in the presence of excess carbon at a high temperature, the carbon dioxide is reduced by the Bell-Boudouard reaction (Figure 2) or loss of carbon monoxide solution (eq.3).

**Fig. 2. Bell-Boudouard diagram**

### b) Transfer of reaction products from the ash surface to the volume of the gaseous phase

The CO flow at the ash-atmosphere interface is determined with the relation:

\[ F_{(CO)} = 4\pi r_0^2 \cdot K_d^{CO} \cdot C[X_{CO}^\alpha - X_{CO}^\nu] \quad (4) \]

Similarly, the CO$_2$ flow is calculated by:

\[ F_{(CO_2)} = 4\pi r_0^2 \cdot K_d^{CO_2} \cdot C[X_{CO_2}^\alpha - X_{CO_2}^\nu] \quad (5) \]

Where:

- $r_0$ - radius of spherical coal;
- $K_d^{CO}$, $K_d^{CO_2}$ - transfer mass constant of CO/CO$_2$ in the volume of the gaseous phase;
- $X_{CO}^\alpha$, $X_{CO}^\nu$ - the molar fraction of CO/CO$_2$ at the surface of the ash coke turned into ash;
- $X_{CO_2}^\alpha$, $X_{CO_2}^\nu$ - The molar fraction of CO/CO$_2$ in the volume of the gaseous phase.

**Fig. 3. Pulverized coal reactions in the raceway**

The main parameters influencing the burning rate of the coal dust, at the blast furnace tuyeres are:
- granulometry or specific surface area of the CDI;
- degree of enrichment in oxygen;
- the type of coal;
- chemical composition of coal;
- the excess of air or oxygen;
- air temperature;
- air humidity;
- the temperature of the flame;
- the gas composition profile of the combustion zone (the maximum CO$_2$ tuyere);
- running of the blast furnace.

**c) Blast furnace material balances.** The material balance must always be accompanied by an indication of the area of the installation to which the balance sheet relates. The mass balance is calculated for all components involved in the process (Figure 4), and is defined as:

- the mass of materials entering the system;
- the mass of materials leaving the system.

**Fig. 4. Mass balance**
The calculation is based on the mass balances considering all injectors with the following assumptions:
- the oxygen in the coke composition can be neglected in comparison with the O₂ content of the blowing air;
- the reducing gas in the tank does not contain free oxygen, this means that all the available oxygen is reacting in front of tuyere gullies to form CO₂;
- the downstream gas from the blowpipe area does not contain CO₂, if carbon oxides are formed as a result of the various carbon dioxide reduction reactions, it is immediately converted to CO as a result of the Bell - Boudouard reaction.

In the area of direct reduction there are only oxides reduction reactions with carbon. This means that H₂ reacts with oxides in the area of indirect reductions. All the H₂ content in the blast furnace comes from the scaling area, the difference being consumed and converted to H₂O in the area of indirect reductions.

The percentage of indirect CO₂ reductions is defined as the ratio between the amount of CO₂ generated from indirect reduction reactions and the sum of the amounts of CO₂ and H₂O formed by indirect reduction reactions and the amount of CO formed from direct reduction reactions.

\[ RI_{CO_2} = \frac{CO_{2\text{direct}}}{CO_{2\text{indirect}} + CO_{\text{direct}} + H_2O_{\text{indirect}}} \]  \hspace{1cm} (6)

The percentage of indirect reductions that form H₂O is defined as the ratio between the amount of H₂O formed by indirect reduction reactions and the sum of the amounts of CO₂ and H₂O formed by indirect reduction reactions and the amount of CO formed by direct reduction reactions.

\[ RI_{H_2O} = \frac{H_2O_{\text{indirect}}}{CO_{2\text{indirect}} + CO_{\text{direct}} + H_2O_{\text{indirect}}} \]  \hspace{1cm} (7)

Mass balances allow for the calculation of the amount of CO produced by direct reduction reactions and the amounts of CO and CO₂ produced by the direct reduction reactions.

### 4. Method of research

The calculation of the material balance for two assumptions, respectively, without the CD insufflations with (1) and (2) the operation of the blast furnace with the insufflations of the coal dust. If the determination of the substitution ratio of coke with coal dust is not sufficient, the technical analysis is necessary, and knowledge of the elemental chemical composition of coal is also necessary. The calculation is complex and iterations can be applied in its deployment. Some empirical relationships are also considered.

The chemical composition of pig iron, coke and coal dust are given in tables 1-3.

#### Table 1. The chemical composition of pig iron

<table>
<thead>
<tr>
<th>FAK2</th>
<th>Fe</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Ti</th>
</tr>
</thead>
<tbody>
<tr>
<td>%</td>
<td>94.34</td>
<td>4.10</td>
<td>0.40</td>
<td>1.1</td>
<td>0.1</td>
<td>0.03</td>
<td>0.14</td>
</tr>
</tbody>
</table>

#### Table 2. The chemical composition of coke

<table>
<thead>
<tr>
<th>C</th>
<th>H</th>
<th>N</th>
<th>S</th>
<th>A</th>
<th>Wc0</th>
<th>Slag</th>
<th>VM</th>
<th>H2</th>
<th>[kJ/kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>86.8</td>
<td>0.40</td>
<td>0.60</td>
<td>0.50</td>
<td>10.30</td>
<td>4.00</td>
<td>0.195</td>
<td>1.65</td>
<td>17566</td>
<td></td>
</tr>
</tbody>
</table>

#### Table 3. The chemical composition of coal dust

<table>
<thead>
<tr>
<th>C</th>
<th>H</th>
<th>N</th>
<th>S</th>
<th>A</th>
<th>Wc0</th>
<th>Slag</th>
<th>VM</th>
<th>H2</th>
<th>[kJ/kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>75.55</td>
<td>5.11</td>
<td>1.40</td>
<td>0.70</td>
<td>6.55</td>
<td>1.25</td>
<td>0.134</td>
<td>34.02</td>
<td>26883</td>
<td></td>
</tr>
</tbody>
</table>

The balance material of the blast furnace process for 1000 kg pig iron is shown in Figure 5. The coke rate is settled as 340 kg/t of pig iron, the metallic cargo rate is 1600 kg/t of pig iron, the volume of top gas is about 1 500 Nm³/h, the output slag from the bottom of the furnace is 275 kg, the amount of injected coal dust is 169 kg/t of pig iron and the produced pig iron is 1000 kg.

![Figure 5. Balance material for 1000 kg pig iron](image)

- The amount of carbon that burns to CO₂ (gf):
  \[ C_{(CO_2)} = CO_{\text{red}} \cdot \frac{M_{\text{C}}}{22.4} = 213.01 \text{ [kg C]} \]

- The amount of carbon that burns at CO (gf):
  \[ C_{(CO)} = (CO_{\text{gas}} - CO_{\text{v}}) \cdot \frac{12}{2.44} = 132.55 \text{ [kg C]} \]

- Air preheats temperature:
  \[ T_{air} = t_{pa} + 60 \cdot \frac{120}{1016.8} \cdot 100 = 1290^\circ C \]
The preheating temperature of the air is considered at 1000 – 1060 °C and of the coal dust at 60 °C.

- Humidity of tuyere blowing through the tuyere:

\[ G_{air_{tu}} = W_{air} \cdot \frac{M_{H_2O}}{22.4} = 11.66 \text{ [kg } H_2O] \]

**Carbon balance**

The amount of carbon combustion (burnt) in the tuyere \((C_{hu})\) is determined as the difference between the amount of carbon introduced into the blast furnace and the amount of carbon consumed for combustion, reduction, casting, Bell - Boudouard reaction. Total carbon introduced into blast furnace with fuels:

\[ C_{hu} = \langle C \rangle - [C] - C_{rd} = 281,59 \text{ [kg carbon]} \]

- carbon coke:

\[ C_k = k_t \cdot \frac{\%C_{ck}}{100} = 293.52 \text{ [kg carbon]} \]

\[ k_t = (100 - W_k) \cdot k_h = 336.6 \text{ [kg carbon]} \]

- carbon with coal dust (CDI):

\[ C_{CDI} = CDI_i \cdot \frac{\%C_{CDI}}{100} = 129.78 \text{ [kg carbon]} \]

- total carbon introduced into the blast furnace:

\[ \langle C \rangle = C_k + C_{CDI} = 423,30 \text{ [kg carbon]} \]

- carbon direct oxide reduction is given in Table 4:

**Table 4. Reducing carbon oxides**

<table>
<thead>
<tr>
<th>Oxide</th>
<th>Reaction</th>
<th>( C_{carbon} )</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO2</td>
<td>SiO(_2)+2C=Si + 2CO</td>
<td>( C_{SiO2} )</td>
<td>6.00</td>
</tr>
<tr>
<td>MnO</td>
<td>MnO + C=Mn+CO</td>
<td>( C_{MnO} )</td>
<td>2.18</td>
</tr>
<tr>
<td>P(_2)O(_5)</td>
<td>P(_2)O(_5)+5C=2P + 5CO</td>
<td>( C_{P2O5} )</td>
<td>1.45</td>
</tr>
<tr>
<td>FeO</td>
<td>FeO + C=Fe +CO</td>
<td>( C_{FeO} )</td>
<td>90.97</td>
</tr>
<tr>
<td>(C_{rd}=C_{Si}+C_{Mn}+C_p+C_{Fe})</td>
<td></td>
<td>(=100,60)</td>
<td>100.00</td>
</tr>
</tbody>
</table>

The total amount of iron that is reduced and turns into pig iron is:

\[ [Fe] = 1000 \cdot 10 \cdot \sum \text{oXide} = 94.01 \text{ [kg } Fe] \]

where:

- \([Fe]\) - is the total iron, into the pig iron [kg/\(\text{t}_{\text{pig-iron}}\)];
- \(R_d\) - rate of direct reduction (\(R_d=55\%\), \(R_d=45\%)\).

Carbon balance is given in Table 5 and also is illustrated in Figure 6.

**Table 5. Carbon balance**

<table>
<thead>
<tr>
<th>Inputs</th>
<th>Outputs</th>
<th>Value</th>
<th>[%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>(C_k)</td>
<td>(C_{CDI})</td>
<td>293,520</td>
<td>69,340</td>
</tr>
<tr>
<td>(C_{pig-iron})</td>
<td>(C_{rd})</td>
<td>41,100</td>
<td>9.710</td>
</tr>
<tr>
<td>(C_{air})</td>
<td>(C_{rd})</td>
<td>129,780</td>
<td>30,660</td>
</tr>
<tr>
<td>(C_{pig-iron})</td>
<td>(C_{rd})</td>
<td>100,610</td>
<td>23,760</td>
</tr>
<tr>
<td>Total 423,300</td>
<td>Total 423,300</td>
<td>100,00</td>
<td>66,530</td>
</tr>
</tbody>
</table>

**Fig. 6. Carbon balance**

**Hydrogen balance**

Hydrogen is introduced into the blast furnace by the humidity in the air injected through the tuyere vents, the hydrogen brought from the volatile matter of coal dust \(CDI\) and the coke volatile matter \(v_k\):

\[ H_{t} = H_{(air)_{tu}} + H_{(v)_{ck}} + H_{(v)} = 7.98 \text{ [kg } H] \]

- the amount of hydrogen introduced into the blast furnace with the inspired air (Table 6), (eq. 3):

\[ H_{(air)_{tu}} = C_{hu} \cdot \frac{\%H_{air}}{\%O_{air}} \cdot \frac{2M_{H_2}}{22.4} = 2.250 \text{ [kg } H] \]

**Table 6. Air composition [%]**

<table>
<thead>
<tr>
<th>(O_2)</th>
<th>(H_2)</th>
<th>(N_2)</th>
<th>(W)</th>
<th>(p_w) [kg/m(^3)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>21,184</td>
<td>0,995</td>
<td>77,82</td>
<td>1,00</td>
<td>1,293</td>
</tr>
</tbody>
</table>

- the amount of hydrogen brought by volatile matter from coke \((v_k)\):

\[ v_k = k_h \cdot \%(v)(k) = 5.554 \text{ [kg } v_k] \]

\[ H_{(v)_{ck}} = v_k \cdot \%H_v = 1.764 \text{ [kg } H] \]

- the amount of hydrogen brought with the volatile matter from the coal dust \((v_{CDI})\):

\[ v_{CDI} = CDI \cdot \%(v)(CDI) = 57.5 \text{ [kg } v_{CDI}] \]

\[ H_{(v)_{CDI}} = v_{CDI} \cdot \%H_v = 3.966 \text{ [kg } H] \]

To determine the minimum \(H_2\) theoretical amount required for \(Fe_2O_3\) reduction to iron, at a temperature typically considered as 900 °C, under the conditions of a countercurrent reactor, we can keep to the following scheme:

\[ \begin{align*}
3Fe_2O_3 + H_2 &= 2Fe_3O_4 + H_2O & \text{Zone I.} \\
2Fe_3O_4 + 2H_2 &= 6FeO + 2H_2O & \text{Zone II.} \\
6FeO + 6H_2 &= 6Fe + 6H_2O & \text{Zone III.}
\end{align*} \]

From the total amount of hydrogen \((H)\) introduced into the blast furnace at indirect reductions
takes 40 ÷ 50%, the rest is the blast furnace gas (45%): 

\[ H_{\text{lad}} = (45\%) \cdot H_f = 3.910 \text{ [kg} H\text{]} \]

The amount of hydrogen in the blast furnace: 

\[ H_{\text{gas}} = H_{\text{lad}} + H_f - H_{\text{lad}} = 4.070 \text{ [kg} H\text{]} \]

The calculated data for hydrogen balance are given in Table 7 and also schematically represented in Figure 7.

**Table 7. Hydrogen balance**

<table>
<thead>
<tr>
<th>Inputs</th>
<th>Outputs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value</td>
<td>[%]</td>
</tr>
<tr>
<td>2,250</td>
<td>28,190</td>
</tr>
<tr>
<td>1,764</td>
<td>22,110</td>
</tr>
<tr>
<td>3,966</td>
<td>49,700</td>
</tr>
<tr>
<td><strong>Total 7,980</strong></td>
<td><strong>100,00</strong></td>
</tr>
</tbody>
</table>

**Fig. 7. Hydrogen balance**

**Carbon dioxide balance**

According to the principle of transformation succession, the reduction of iron oxide (Fe₂O₃) is achieved in more stages. The lower iron oxide (FeO) is stable only at temperatures above 572 °C, and the reduction of iron oxides takes place as follows:

\[
\begin{align*}
\text{Fe}_2\text{O}_3 & \rightarrow \text{FeO} \\
\text{Fe}_2\text{O}_4 & \rightarrow \text{Fe} \quad T > 572^{\circ}\text{C} (11) \\
\text{Fe}_2\text{O}_3 & \rightarrow \text{Fe} \quad T < 572^{\circ}\text{C} (12)
\end{align*}
\]

The distribution and degree of oxidation of Fe and Mn in the blast furnace are given in Table 8.

**Table 8. The distribution and degree of Fe and Mn oxidation in the blast furnace**

<table>
<thead>
<tr>
<th>Material</th>
<th>Fe_{tot}</th>
<th>FeO</th>
<th>Mn_{ox}</th>
<th>Mn_{oxO}</th>
<th>MnO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sinter</td>
<td>690,24</td>
<td>586,67</td>
<td>103,53</td>
<td>4,31</td>
<td>4,31</td>
</tr>
<tr>
<td>Ore Fe</td>
<td>280</td>
<td>280</td>
<td>-</td>
<td>1,5</td>
<td>1,5</td>
</tr>
<tr>
<td>Ore Mn</td>
<td>7,98</td>
<td>7,98</td>
<td>-</td>
<td>16,81</td>
<td>16,81</td>
</tr>
<tr>
<td>Ash coke</td>
<td>8,66</td>
<td>8,66</td>
<td>0,105</td>
<td>-</td>
<td>0,105</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>986,88</td>
<td>874,65</td>
<td>112,19</td>
<td>22,72</td>
<td>22,62</td>
</tr>
<tr>
<td>Pig iron</td>
<td>981,88</td>
<td>874,65</td>
<td>107,19</td>
<td>12,72</td>
<td>-</td>
</tr>
<tr>
<td>Slag</td>
<td>5,0</td>
<td>5,0</td>
<td>10</td>
<td>9,9</td>
<td>0,105</td>
</tr>
</tbody>
</table>

* corresponding to 55-65 % Fe in the agglomerate

a) Amount of carbon dioxide resulting from the indirect reduction of metal oxides:

- the amount of oxygen resulting from the reduction of iron oxides, Fe₂O₃ are given in Table 9.

**Table 9. The amount of oxygen resulting from the reduction of iron oxides, Fe₂O₃**

<table>
<thead>
<tr>
<th>Oxide by Fe</th>
<th>Oxygen resulting from reduction (Fe₂O₃)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fe</td>
<td>Oxygen, [kg]</td>
</tr>
<tr>
<td>Fe₂O₃→FeO</td>
<td>874,65</td>
</tr>
<tr>
<td>FeO→FeO</td>
<td>874,65</td>
</tr>
<tr>
<td>FeO→Fe</td>
<td>112,19</td>
</tr>
<tr>
<td><strong>Total 389,546</strong></td>
<td></td>
</tr>
</tbody>
</table>

**: - Fe₂O₃ → 0,429 kgO₂/kgFe₁FeO+Fe₂O₃  
- FeO → 0,286 kgO₂/kgFe₂O₃  
0,429 - 0,286 = 0,143 kgO₂/kgFe₁FeO+Fe₂O₃→FeO

b) CO₂ from volatile materials:

\[ CO_{2,\text{vol материалах}} = \text{m}_{\text{ volunteers}} \cdot \frac{22,4}{\text{M} \text{CO}_{2}} = 9,253 \text{ [Nm}^{3} \text{CO}_{2}] \]

- total carbon dioxide from indirect reduction is:

\[ CO_{2,\text{непосредно}} + CO_{2,\text{воздух материалах}} = 397,622 \text{ [Nm}^{3} \text{CO}_{2}] \]

**Table 10.**

<table>
<thead>
<tr>
<th>Indirect reduction with CO (eq. 10, 11)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fe₂O₃→FeO</td>
</tr>
<tr>
<td>125,074 - 20,198 (red. H) = 104,388</td>
</tr>
<tr>
<td>FeO→Fe</td>
</tr>
<tr>
<td>234,406+30,066 = 173,067</td>
</tr>
<tr>
<td>Total oxygen, Ox_{tot} = 104,388+173,067 = 277,406</td>
</tr>
</tbody>
</table>

- the carbon dioxide obtained from the indirect reduction (eq. 5), results from the following calculation:

\[ CO_{2,\text{непосредно}} = \frac{2,224}{\text{M} \text{CO}_{2}} = 388,367 \text{ [Nm}^{3} \text{CO}_{2}] \]

- the carbon dioxide resulting from the indirect reduction of manganese oxide is:

\[ Mn_{2}O_{3} + CO = 2 MnO + CO_{2} \]

\[ CO_{2,\text{непосредно Mn}} = \frac{2,224}{\text{M} \text{MnO}} = 9,253 \text{ [Nm}^{3} \text{MnO}_{2}] \]

- total carbon dioxide from indirect reduction is:

\[ CO_{2,\text{непосредно Mn}} + CO_{2,\text{непосредно}} = 397,622 \text{ [Nm}^{3} \text{CO}_{2}] \]

b) CO₂ from volatile coke materials are:

\[ CO_{2,\text{v кокс}} = k_{v} \cdot \frac{V_{k}}{100} \cdot \frac{22,4}{\text{M} \text{CO}_{2}} = 1,425 \text{ [Nm}^{3} \text{CO}_{2}] \]

- CO₂ from volatile CDI materials:

\[ CO_{2,\text{v CDI}} = k_{v} \cdot \frac{V_{CDI}}{100} \cdot \frac{22,4}{\text{M} \text{CO}_{2}} = 6,058 \text{ [Nm}^{3} \text{CO}_{2}] \]

d) CO₂ in blast furnace gas there are:

\[ CO_{2,\text{gas}} = 397,622 + 1,425 + 6,058 = 405,105 \]

\[ G_{CO_{2}} = \frac{28}{22,4} = 506,381 \text{ [kg} CO_{2}] \]
The calculated data for carbon dioxide balance are given in Table 11 and also schematically represented in Figure 8.

**Table 11. Carbon dioxide balance [Nm³ CO₂]**

<table>
<thead>
<tr>
<th>Inputs</th>
<th>Value</th>
<th>[%]</th>
<th>Outputs</th>
<th>Value</th>
<th>[%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂_red</td>
<td>397,622</td>
<td>98,154</td>
<td>CO₂_gas</td>
<td>405,105</td>
<td>100</td>
</tr>
<tr>
<td>CO₂_c</td>
<td>1,425</td>
<td>0,351</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CO₂_cons</td>
<td>6,058</td>
<td>1,495</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>405,105</td>
<td>100,00</td>
<td><strong>Total</strong></td>
<td>405,105</td>
<td>100,00</td>
</tr>
</tbody>
</table>

**Fig. 8. Carbon dioxide balance**

**Carbon monoxide balance**

a) CO resulted from direct reduction reactions is from direct reduction of FeO to Fe (eq. 6); it is allowed a proportion of 46% from FeO → Fe and for 92,73% Fe in pig iron:

\[
CO_{Fe} = 170,62 \text{ [Nm}^3\text{ CO]} 
\]

Carbon monoxide resulted from direct reduction of oxides is given in Table 12.

**Table 12. Carbon dioxide from direct reduction**

<table>
<thead>
<tr>
<th>Oxide</th>
<th>Reaction</th>
<th>( f \text{ Nm}^3\text{ CO}_2 )</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO₂</td>
<td>SiO₂ + 2C = Si + 2CO</td>
<td>CO₅\text{Si} = 6,40</td>
<td>64</td>
</tr>
<tr>
<td>MnO</td>
<td>MnO + C = Mn + CO</td>
<td>CO₅\text{Mn} = 4,68</td>
<td>46</td>
</tr>
<tr>
<td>P₂O₅</td>
<td>P₂O₅ + 5C = 2P + 5CO</td>
<td>CO₅\text{P} = 32,51</td>
<td>28</td>
</tr>
<tr>
<td>FeO</td>
<td>FeO + C = Fe + CO</td>
<td>CO₅\text{Fe} = 170,62</td>
<td>22</td>
</tr>
<tr>
<td></td>
<td>CO₂_red = 214,21 \text{(100)}</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

b) From the burning of carbon to the tuyere (eq. 6):

\[
CO_{c} = C_{c} \cdot \frac{22,4}{12} = 525,635 \text{ [Nm}^3\text{ CO]}
\]

c) From volatile matter of coke:

\[
CO_{c,k} = k \cdot \frac{\%C}{\%CO} \cdot \frac{22,4}{100} = 1,64 \text{ [Nm}^3\text{ CO]}
\]

d) Carbon monoxide consumed at indirect cuts:

\[
CO_{cons} = CO_{c,red} = 397,62 \text{ [Nm}^3\text{ CO]}
\]

From the amount of carbon monoxide obtained, the amount of monoxide required to carry out the reduction reactions decreases.

Total carbon monoxide in the blast furnace gas is:

\[
CO_{gas} = CO_{r,dir} + CO_{b}\text{n} + CO_{me} - CO_{cons} = 343,81 \text{ [Nm}^3\text{ CO]}
\]

\[
G_{CO_{gas}} = CO_{gas} \cdot \frac{28}{22,4} = 429,77 \text{ [kg CO]}
\]

The calculated data for carbon monoxide balance are given in Table 13 and also schematically represented in Figure 9.

**Table 13. Carbon monoxide balance [Nm³ CO]**

<table>
<thead>
<tr>
<th>Inputs</th>
<th>Value</th>
<th>[%]</th>
<th>Outputs</th>
<th>Value</th>
<th>[%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO_{r,dir}</td>
<td>214,210</td>
<td>28,889</td>
<td>CO_{cons}</td>
<td>397,620</td>
<td>53,624</td>
</tr>
<tr>
<td>CO_{b}\text{n}</td>
<td>525,635</td>
<td>70,890</td>
<td>CO_{g}</td>
<td>343,865</td>
<td>46,375</td>
</tr>
<tr>
<td>CO_{r,k}</td>
<td>1,640</td>
<td>0,221</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>741,485</td>
<td>100,00</td>
<td><strong>Total</strong></td>
<td>741,485</td>
<td>100,00</td>
</tr>
</tbody>
</table>

**Fig. 9. Carbon monoxide balance**

**Nitrogen balance**

a) Oxygen blown on blast furnace blasts:

\[
O_{2\text{air}} = C_{b}\text{n} \cdot \frac{22,4}{2 \cdot 12} = 262,817 \text{ [Nm}^3\text{ O}_2]\]

The amount of nitrogen brought by the air:

\[
N_{2\text{air}} = O_{2\text{air}} = \frac{77,82}{21,184} = 965,466 \text{ [Nm}^3\text{ N}2]\]

b) Coke volatile nitrogen

\[
N_{\text{vC}} = k \cdot \frac{\%\text{vC}}{100} \cdot \frac{\%\text{N}_2}{100} \cdot \frac{22,4}{28} = 0,732 \text{ [Nm}^3\text{ N}2]\]

c) Nitrogen from coal dust:

\[
N_{\text{CDI}} = CDI \cdot \frac{\%\text{CDI}}{100} \cdot \frac{\%\text{N}_2}{100} \cdot \frac{22,4}{28} = 0,647 \text{ [Nm}^3\text{ N}2]\]

Total nitrogen in blast furnace gas:

\[
N_{\text{gas}} = N_{\text{air}} + N_{\text{vC}} + N_{\text{CDI}} = 966,845 \text{ [Nm}^3\text{ N}2]\]

\[
G_{N} = N_{\text{gas}} \cdot \frac{28}{22,4} = 1208,556 \text{ [kg N}_2]\]
The calculated data for nitrogen balance is given in Table 14.

Table 14. Nitrogen balance \( Nm^3_{N_2} \)

<table>
<thead>
<tr>
<th>Inputs</th>
<th>Value</th>
<th>[%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>( N_{2\ air} )</td>
<td>965,466</td>
<td>99,857</td>
</tr>
<tr>
<td>( N_{2\ vkg} )</td>
<td>0,732</td>
<td>0,076</td>
</tr>
<tr>
<td>( N_{3\ DCI} )</td>
<td>0,647</td>
<td>0,067</td>
</tr>
<tr>
<td>Total</td>
<td>966,845</td>
<td>100,00</td>
</tr>
</tbody>
</table>

The volume of air blowing is:

\[
V_{air} = \frac{O_{2\ tu} \cdot 100}{21,184} = 1240,639 \ [Nm^3\ air]
\]

5. Conclusions

The blasting of the pulverized coal is made in order to reduce the consumption of coke, the replacement of liquid fuels and natural gas, the increase in economic efficiency and the improvement of environmental conditions.

The worldwide trend is to continuously decrease the specific consumption of coke in the blast furnaces. Thus, in the European Union there is a current of approximate 180 kg CDI/t of pig iron, consumption of 320 kg coke/t of pig iron.

The efficiency of CDI technology is determined by the amount of CD injecting and the coke - CD replacement index obtained.

Iron production in ArcelorMittal Galati uses a modern injection of coal dust plant with a nominal capacity of 70 t CD/h or approx. 560,000 t CD/year.

For all periods of operation with the CDI, the replacement index is set at acceptable, of 0.8 \(\div\) 1 kg coke/kg CD. The main problem to be resolved remains the increase of the CDI above the apparent critical level to that corresponding to the rated capacity of the installation. Regime characterized by temperature air at 1060 °C the enrichment of the air in oxygen by 2% and the maintenance of the same air humidity at the injection of 100 kg/t of pig iron resulted a specific coke consumption of 434 kg/t of pig iron, replacement, \(E = 0.87\ \text{kg coke/kg CD}\), which also takes into account the influences of the measures that condition CD injection.

In many cases, however, there is a ceiling for acceptance of blast furnace CDI at 130 - 160 kg CD/t of pig-iron levels and practically coke specific consumption remains at relatively high rates of over 400 kg/t reflecting the existence of technological reserves recovered:

a) general measures to optimize the entire technological flow (the quality of the raw materials, the agglomerate, the pellets, the coke, the parameters of the elaboration process, including the distribution of the load and the gas distribution, the increase of the computerization of the process) of technological coke consumption in reference mode (no auxiliary fuels), roughly equal to the total fuel requirement under CDI conditions.

b) combustion intensification measures CDI:

- optimization of \(O_2\) enrichment level of the insulated air;
- optimization of constructive and insufflation parameters of \(O_2\) through lances;
- optimization of CDI burning parameters (O/C ratio, granulation, humidity, temperature and flame);
- reducing the possibilities of forming black and black fume in sewage plants;
- use of coal mixtures with different VM content that are easier to grind and have a lower heat dissipation.

References

[1]. ***, Documentation of ArcelorMittal Galati.
[2]. Xingu Ming, Possibility of Combustion Blast furnace Operation with Oxygen, University of Michigan, Mechanical Engineering, p. 3-2.
[3]. Harting W., et al. Measures to increase blast furnace productivity, Stahl und Eisen, Germany, nr. 6/2015.