Energy Efficient Technology to Produce Hot Metal from Titania-Magnetite Ore

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Agenda

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- Influence of iron content increase
- Improvement in gas utilization and intensity of operation
- Influence of sinter granulometry on BF intensity of operation and overall carbon rate
- Influence of PCI rate on BF intensity of operation and overall carbon rate
- Reduction in hot metal titanium
- Conclusions
Introduction

• Reduction in fuel consumption and increase in productivity of blast furnace are the most important factors of profitability of hot metal production.

• Reduction or retarding of titanium carbides and titanium nitrides formation during titania-magnetite ore smelting is the most effective way to increase energy efficiency of the blast furnace process.

• Nizhne-Tagilskiy metallurgical combine (NTMK), Ural Federal University and Hatch investigated the phenomena of titania-magnetite ore processing in blast furnace and developed practical measures to improve energy efficiency of the process.

• Increase in total iron content in metallic burden, improvement in carbon monoxide utilization and reduction in heat losses are the main factors to improve energy efficiency of blast furnace process.
Introduction

• Previous studies revealed that intensive operation of blast furnace could be achieved by implementing the following measures:
  – maximum possible top pressure
  – optimize slag composition
  – use of special fluxes such as iron flux
  – optimize distribution of ore load at the furnace top
  – optimize raw material granulometry
  – optimize the combination of coke, PCI and natural gas injection depending on coke, supplemental fuels and metallic burden qualities.

• The overall carbon rate, which is the combined contribution of coke and supplemental fuels, is proposed as the parameter for energy efficiency estimation.

• Analysis of the influence of all above measures to increase intensity of blast furnace operation and reduce the overall carbon rate is presented in this paper.
Introduction

- Nizniy Tagil Iron & Steel Works, Russia (NTMK) is an integrated Iron & Steel plant, which incorporates cokemaking, blast furnace operation, BOF steelmaking, rolling and other auxiliary processes.
- NTKM’s metallic burden base is Kachkanar titania-magnetite ore which also contains vanadium.

<table>
<thead>
<tr>
<th>NTKM Metallic Burden Chemical Composition, %</th>
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<tbody>
<tr>
<td>BF Burden</td>
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<tr>
<td>----------</td>
</tr>
<tr>
<td>Sinter</td>
</tr>
<tr>
<td>Pellets</td>
</tr>
<tr>
<td>Iron flux</td>
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<tr>
<td>BF burden</td>
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</table>
Introduction

• Specific of blast furnace operation producing vanadium containing hot metal is the presence of titania in a burden. Titanium solubility in hot metal is limited and various titanium refractory compounds and titanium oxides are formed in the furnace hearth.

• Titanium nitrides and titanium carbides increase the melt viscosity, melt residence time in a reducing atmosphere and as a result increase losses of metal to slag, deterioration of the hearth operation, problem with metal and slag tapping and loss of tuyeres.

• NTMK’ more than 40 year experience in processing of titania-magnetite ore and production of vanadium containing hot metal allows to develop the major principles of effective blast furnace operation with high titania load:
  – minimization of melt residence time in the blast furnace hearth
  – rigid rules on hearth’s thermal condition
  – rigid taping schedule
  – rigid requirements for burden quality and burden preparation
  – optimal hearth design
  – addition of manganese ore to destruct titania carbides and nitrides

• Deviation from equilibrium conditions as far as possible
Iron Content Increase

• It is well known that iron content increase leads to reduction in slag yield, which is accompanied by the reduction in specific coke rate.

• This also leads to the reduction in density of slag flow in a coke packing (per m² of coke packing).

• As a result the porosity of the material column in area of slag movement is increased, pressure drop is reduced and more air could be injected into the furnace for productivity increase.

• If there is no reserve of gas-dynamics in the upper part of the blast furnace, the wind could not be increased.

• Then the overall pressure drop would be reduced, and the intensity of blast furnace process will remain the same.
Iron Content Increase

• The results of mathematical modeling which took into account the relationship between the quality of raw materials and pressure drop in upper and slag zones of a blast furnace showed the following:
  • sinter porosity should be increased by 0.02 (from 0.36 to 0.38) when iron content is increased by 1% to maintain the same reduction in pressure drop of the upper zone as in the slag zone of blast furnace. In this case wind rate and the intensity of blast furnace operation could be increased.

• Increase in total iron content also leads to an increase in FeO in the primary slag, which is accompanied by the reduction in slag melting temperature.
SiO$_2$-Al$_2$O$_3$-FeO slag melting temperature as a function of FeO content

Stable accretion on low stack, belly and bosh staves could be formed when slag’s FeO content is below 30%. With an increase in metallic burden total iron content, the fraction of gangue materials reduces, while the FeO content, which depends on extend of indirect reduction, increases.
FeO content in primary slag as a function of FeO fraction reduced by direct reduction
Influence of Fe content and CSR on intensity of operation and equivalent carbon rate reduction

• With Fe content increase in metallic burden by 1%, the same amount of FeO would remain in primary slag if the fraction of FeO direct reduction would be reduced by 0.02. The conditions of gas movement in the cohesive zone will remain the same.

• Increase in CSR is an important tool to stabilize the gas-dynamics of the bottom part of the furnace. The modeling of melt filtration through the coke packing in the cohesive zone allowed the following conclusion: coke CSR should be increased by 2% for each percent of the metallic burden Fe content increase to maintain the same conditions for the melt movement (the base CSR value was 60%).

• In summary, increase in metallic burden Fe content to reduce the equivalent carbon rate and increase intensity of blast furnace operation requires an increase in porosity of metallic burden (particularly sinter), increase in extend of indirect reduction and improvement in coke CSR value.
Improvement in gas utilization and operation intensity

• The “shrinking core” model of iron oxide reduction was used to evaluate the possibility of improving the CO utilization in titania-magnetite blast furnace. According to this model degree of CO utilization and material residence time in a reduction zone are linked by equation (1):

\[
\Delta \eta_{CO} = \frac{\eta_{CO}^E}{\eta_{CO}} \cdot \frac{k \cdot e^{k \cdot \tau}}{(e^{k \cdot \tau} - 1)} \cdot \Delta \tau \quad . \quad (1)
\]

• Here \( \eta_{CO}^E \) – equilibrium degree of CO utilization; \( \eta_{CO} \) - actual degree of CO utilization.

• An increase in \( \eta_{CO}^E \) and \( \eta_{CO} \) difference increases the influence of residence time by \( \Delta \eta_{CO} \). The equilibrium degree of CO utilization, \( \eta_{CO}^E \), depends on the extent of solution loss (Boudouard) reaction \( C + CO2 = 2CO \), which depends on the pressure at the bottom part of blast furnace.

• It was shown in past publications that there is no reserve to increase the top pressure at NTMK-EVRAZ BF. Therefore, the optimization of burden material granulometry, usage and increase in PCI and natural gas rates are the major factors for increasing \( \Delta \eta_{CO} \).
Improvement in gas utilization and intensity of operation – sinter granulometry

- The extent of indirect reduction very much depends on thermodynamics and kinetics of the process.
- The rate of metallic burden reduction is a function of the particle size.
- Core shrinking models assume spherical shape of the particles at all stages of the reduction process. The particles enter into reduction reaction with initial radius $r_0$, density $\rho_0$ and mass $m_0$.
- The rate of reduction reaction ($\omega$) is defined by equation (2):
  \[
  \omega = \frac{\Delta m}{\Delta t} = kS,
  \]
  \(2\)
- where $k$ is the reaction rate constant, which is a function of pressure, temperature and gas composition; $\Delta m$ is the amount of reduced ore; $\Delta t$ is the reduction time and $S$ is the interface area between metallic and oxide phases.
Improvement in gas utilization and intensity of operation – sinter granulometry and kinetic model

- The initial rate of reduction could be estimated based on the following equation:
  \[ f = \frac{k}{(r_0 \rho_0)} t. \]  
  (3)

- According to equation (3) the rate of reduction increases with decrease in radius of the particles and increase in residence time.

- The average initial radius of particles could be estimated as
  \[ r_0 = \sqrt[4]{\frac{S}{\pi}} \]
  where  
  \[ S = \sum g_i \cdot \frac{d_i}{d} \cdot (1 - \varepsilon) \]
  and \( g_i \) is a fraction of particle with diameter \( d_i \) and \( \varepsilon \) is the voidage of the layer of material.

- Kinetic model clearly states that smaller iron ore particles are better for more productive blast furnace, i.e. greater intensity of operation and less heat loss. However, this contradicts the gas-dynamics requirements specifically material column permeability to gas flow.
Improvement in gas utilization and intensity of operation – sinter granulometry and resistance

• The gas permeability could be estimated by Ergon equation:

\[ \Delta P = \lambda \cdot \frac{h}{d_E} \cdot \frac{1 - \varepsilon}{\varepsilon^3} \cdot \frac{T}{T_0} \cdot \frac{P_0}{P} \cdot \rho_0 \cdot \frac{w_0^2}{2} \]

• Here \( h \) is the burden layer height; \( d_E \) is the particle equivalent diameter; \( w_0 \) is the gas flow velocity at the empty cross-section of the furnace at normal conditions.

• Part of Ergon Equation \( \Delta P_{Burden} = \frac{1}{d_3} \cdot \frac{1 - \varepsilon}{\varepsilon^3} \) was used as gas-dynamics resistance parameter

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Relative rate of reduction and gas-dynamic resistance as a function of +40 mm fraction of sinter

- ▲ - gas-dynamics resistance; * - reduction rate
Relative rate of reduction and gas-dynamic resistance as a function of -5 mm fraction of sinter

\[ R^2 = 0.9667 \]

\[ R^2 = 0.9036 \]

\( \Delta \) – gas-dynamics resistance; \( \bullet \) – reduction rate
Influence of sinter granulometry

- Increase in sinter fraction +40 mm by 1% reduces the rate of reduction by 4.5% and gas-dynamics resistance by 3%.
- While the reduction in sinter fraction -5 mm by 1% increases both the rate of reduction and gas-dynamics resistance by 9%.
- Similar trials and calculations were carried for the complete elimination of +40 mm fraction and reduction in +25 mm fraction.
- It was found that the best conditions to increase the extent of indirect reduction with respect to sinter granulometry and porosity are to maintain the fraction of -5 mm in sinter below 6% and +25 mm fraction below 10%.
PCI rate

• Increase in residence time of metallic burden in the indirect reduction zone of blast furnace is another way to improve CO utilization.

• Increase in PCI rate is accompanied by an increase in ore load (kg metallic burden/kg of coke), reduction in specific coke consumption and increase in metallic burden fraction in indirect reduction zone of the furnace and increase in it’s residence time.

• Mathematical modeling revealed that the reduction of specific coke rate by 100 kg/thm leads to improvement in gas utilization by 1- 2%.
Influence of PCI rate - degree of CO utilization as PCI rate function
Influence of PCI rate on CO utilization

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Periods of BF operation</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>2012</td>
<td>January -June 2013</td>
</tr>
<tr>
<td>Production, thm/day</td>
<td></td>
<td>6 795.4</td>
<td>6 895.5</td>
</tr>
<tr>
<td>Specific productivity, thm/m³/day (WV)</td>
<td></td>
<td>3.59</td>
<td>3.63</td>
</tr>
<tr>
<td>Coke rate, kg/thm</td>
<td></td>
<td>406.8</td>
<td>355.6</td>
</tr>
<tr>
<td>Natural gas rate, Nm³/thm</td>
<td></td>
<td>132.8</td>
<td>91.3</td>
</tr>
<tr>
<td>PCI rate, kg/thm</td>
<td></td>
<td>0</td>
<td>82.8</td>
</tr>
<tr>
<td>Overall carbon rate, kg/thm</td>
<td></td>
<td>429</td>
<td>428</td>
</tr>
<tr>
<td>Oxygen in blast, %</td>
<td></td>
<td>29.9</td>
<td>30.3</td>
</tr>
<tr>
<td>Top gas temperature, °C</td>
<td></td>
<td>101</td>
<td>116</td>
</tr>
<tr>
<td>$\eta_{CO}$, degree of CO utilization, %</td>
<td></td>
<td>49.6</td>
<td>50.2</td>
</tr>
</tbody>
</table>

With increase in PCI rate, the overall carbon consumption is reduced. Analysis of the actual operating data and results of mathematical modeling show that the intensity of blast furnace operation increases with reduction in overall fuel rate.
Influence of intensity of blast furnace operation

• It is well known that the increase in intensity of blast furnace operation reduces heat loss.

• While the increase in operation intensity leads to an increase in the volume of metallic burden in the zone of indirect reduction, and reduces the individual particle residence time in this zone.

• All these factors could lead to reduction in CO gas utilization and increase in heat requirements for direct reduction.

• Therefore, reduction in overall carbon consumption with simultaneous increase in blast furnace intensity of operation could be achieved by the reduction in heat loss, charging of small diameter metallic burden particles and coke to furnace periphery, the formation of stable accretion on stack, belly and bosh walls and low FeO content in primary slag.
Relationship between overall carbon rate and intensity of blast furnace operation

![Graph showing the relationship between specific overall carbon rate and daily production.](image-url)
Reduction in hot metal titanium

• The effect of overall carbon rate on reduction of titania in the bottom part of blast furnace was estimated based on results of mathematical modeling [1, 3] and were confirmed by analysis of actual operating data:
  • titanium content in hot metal reduces with reduction in overall carbon rate/with intensity of blast furnace operation increase/PCI rate increase/coke rate reduction, since all these four parameters linked to each other.
  • The thermal conditions of the bottom part of blast furnace also reduce titania, which become apparent in relationship between titanium and silicon content in hot metal.
  • Reduction in specific coke consumption is accompanied by the attenuation of the coke layers and reduction in time of contact between titania and carbon content of coke which in turn moves the reduction process further away from the equilibrium conditions.

• All of this confirms that process kinetics plays a crucial role in titania reduction, and the formation of titanium carbides and titanium nitrides.
Effect of overall carbon rate on titania reduction

![Graph showing the effect of overall carbon rate on titania reduction. The x-axis represents the overall carbon rate in kg/thm, ranging from 420 to 455. The y-axis represents the Ti content in hot metal, ranging from 0.12 to 0.20. Points on the graph indicate an increasing trend as the carbon rate increases.]
Conclusions

• The overall carbon rate is an effective parameter and a good indication of the effectiveness of blast furnace operation.

• Reduction in overall carbon rate could be achieved by increase in intensity of blast furnace operation, improvement in CO utilization, increase in Fe content in metallic burden, improvement in coke CSR, optimization of sinter granulometry and porosity, charging of smaller metallic burden particles to the furnace periphery and the formation of stable accretion on the walls of the low stack, belly and bosh.

• Titanium content in hot metal reduces with the reduction in overall carbon rate.

• Optimal ratio of PCI to natural gas as supplemental fuels is very important for achieving the best blast furnace performance with changing in raw materials quality.
Acknowledgements

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Thank you.

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