Co-injection of Noncoking Coal and Natural Gas in Blast Furnace

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The most radical method for saving coke in ironmaking is to inject gaseous, liquid and solid substitutes into the blast furnace (BF) hearth by means of tuyeres. Use of one or another type of auxiliary fuel depends on the ratio of their prices, their deposits and the peculiarity of the technology.

This paper presents the basic theoretical proposals of a technology for the simultaneous injection by tuyeres of natural gas (NG) and pulverized coal (PC) with any ratio up to complete exception of one of them. A laboratory study has been carried out of the thermal decomposition and gasification of different types of coals. Determination has been made of the softening temperature and melting temperature of the ash of these coals. These temperatures play an important role in optimizing the tuyere assembly design, raceway processes and slag regimes. The factors which determine the oxidizing potential of the raceway have been established.

A study has been made of the comparative estimation of NG and PC and the compensation rates for BF operational conditions with simultaneous injection ranges of 0–100 m³/THM NG and 0–200 kg/THM PC, at a flame temperature of 1950–2150°C and maintaining other blast and burden parameters constant. The rates automatically compensate the changes in temperature and the thermal and oxidizing potential in the raceway.

This technology and tuyere assembly design are successfully used at two BFs.

KEY WORDS: ironmaking; blast furnace; natural gas; pulverized coal; auxiliary fuel injection; compensation rate.

1. Introduction

Ferrous metallurgy continues to be one of the most power-consuming industries. The specific energy requirements for steelmaking in some EC countries are as follows (Gigajouls per metric ton of crude steel)1,2): Finland 17.9, France 20.0, Germany 17.6, Netherlands 17.3, Spain 14.3, Sweden 18.0 and United Kingdom 19.4. Ironmaking is the most power-consuming process in ferrous metallurgy, being responsible for almost one half of the total fuel consumption. The rate of fuel in the cost price of pig iron is 30–35% due to the high price of coke.

There are many ways to save coke, the most radical method being to use gaseous, liquid and solid substitutes. All of these fuels are introduced into the hearth of the furnace through the tuyere apparatus, except coke which is charged on the top. About 40 or 50 substitutes of coke are known, but only natural gas (NG), coke oven gas (occasionally), fuel oil and pulverized coal (PC) are used on an industrial scale.

BF operation technology with NG has been developed in the USSR and was first applied in 1957 at Dneprropetrovsk Steel Plant and in 1959 at Donetsk Steel Plant (DSP), Ukraine.3) This technology calls for practically no capital investment or special equipment (except for the station for gas pressure reduction and gas distribution control) and provides a considerable decrease in coke consumption. Due to these advantages, in the late 1980s and early 90s 112 BFs of total of 133 in the former USSR operated with NG.4) They consumed more than 11 × 10⁶ m³ of NG per year. Average consumption of NG was 70–100 m³/THM. More than 70 BFs in USA and Canada also operated with NG in the 1970s.5) In Europe the application of NG has never become widespread.6,8)

In the 1970s, fuel oil injection technology was widely used in Germany, Japan, France, USSR and the USA.7,8) But since the oil crisis the use of fuel oil has decreased considerably. Nevertheless, fuel oil was injected in Spain until 1995. Some BFs, for instance in the United Kingdom and in Finland, continue to operate with fuel oil injection to the present.9)

Research work and industrial experimentation with pulverized coal injection (PCI) began in the early 1960s in USA,10) China11) and Ukraine.4) The first European commercial complex for PC preparation and injection was built in 1980 at DSP, Ukraine.12,13) Since then there has been an intensive expansion of PCI technology. At present about 100 complexes operate in Europe, Asia and America. The last 2 PCI complexes were installed
in 1996 and 1997 in two new BFs constructed in Gijon, Spain.

Use of one or another type of fuel additive depends on ratio of prices of NG, fuel oil and PC, their deposits and the peculiarity of the technology. Besides, the co-injection of two kinds of fuel can provide some technological benefits; for instance, co-injection of oil and PC in US Steel Gary Works' No. 13 BF provided additional coke savings and an increase in productivity.14)

Technology and equipment for the simultaneous use of NG and PC in ironmaking with any ratio up to complete exception of one of them have been successfully developed over many years at 2 BFs in Ukraine, permitting a cut in the coke rate of 30% and more.

In this paper the basic theoretical proposals of this technology, tuyere assembly design and furnace operating experience and its use are given.

2. Natural Gas Combustion

2.1. Basic Principles of Natural Gas Combustion Theory

The combustion of NG is referred to as a series of chain reactions, a theory of which was suggested by Semyonov.15) Pyrolysis of NG occurs involving active centres. The scheme of the thermal destruction of methane, the principal component of NG, can be described as follows:

\[
\begin{align*}
2\text{CH}_4 & \rightarrow 2\text{CH}_2 + \text{H}_2 \\
\text{CH}_3 - \text{CH}_3 & \leftrightarrow 2\text{CH}_2 + \text{H}_2 \\
\text{ethane} & \\
\text{CH}_2 = \text{CH}_2 & \leftrightarrow 2\text{CH} + \text{H}_2 \\
\text{ethylene} & \\
\text{CH} \equiv \text{CH} & \leftrightarrow 2\text{C} + \text{H}_2 \\
\text{acetylene} &
\end{align*}
\]

At thermal oxidizing, the pyrolysis oxidation of intermediate products takes place simultaneously with the destruction of methane15):

\[
\begin{align*}
\text{CH}_4 & \rightarrow \text{CH}_3 + \text{H} \\
\text{H} + \text{O}_2 & \rightarrow \text{OH} + \text{O}
\end{align*}
\]

Further there are two alternatives:

variant 1

\[
\begin{align*}
\text{CH}_3 & \rightarrow \text{CH}_2 + \text{H} \\
\text{CH}_2 & \rightarrow \text{CH} + \text{H} \\
\text{CH} + \text{OH} & \rightarrow \text{CO} + \text{H}_2
\end{align*}
\]

variant 2

\[
\begin{align*}
\text{CH}_3 + \text{OH} & \rightarrow \text{CH}_3\text{OH} \\
\text{CH}_3\text{OH} + \text{O} & \rightarrow \text{HCHO} + \text{H}_2\text{O} \\
\text{HCHO} & \rightarrow \text{CO} + \text{H}_2
\end{align*}
\]

In the end, a carbon monoxide and a molecule of hydrogen are formed. The final products of further oxidation at high temperature are CO₂ and H₂O.

Table 1. Composition of gas mixture generated by reaction

\[
\text{CH}_4 \leftrightarrow \text{C} + 2\text{H}_2. \quad (\text{vol}%)\]

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>CH₄</th>
<th>H₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
<td>96.90</td>
<td>3.10</td>
</tr>
<tr>
<td>400</td>
<td>86.16</td>
<td>13.84</td>
</tr>
<tr>
<td>500</td>
<td>62.53</td>
<td>37.47</td>
</tr>
<tr>
<td>550</td>
<td>46.69</td>
<td>53.37</td>
</tr>
<tr>
<td>600</td>
<td>31.68</td>
<td>68.32</td>
</tr>
<tr>
<td>700</td>
<td>11.07</td>
<td>88.93</td>
</tr>
<tr>
<td>800</td>
<td>4.41</td>
<td>95.59</td>
</tr>
<tr>
<td>1000</td>
<td>0.50</td>
<td>99.50</td>
</tr>
<tr>
<td>1100</td>
<td>0.20</td>
<td>99.80</td>
</tr>
</tbody>
</table>

Methane, like other saturated hydrocarbons, is unstable against heat. It decomposes upon heating16):

\[
\begin{align*}
2\text{CH}_4 & \leftrightarrow \text{C}_2\text{H}_2 + 3\text{H}_2 \\
\text{CH}_4 & \leftrightarrow \text{C} + 2\text{H}_2 \\
6\text{CH}_4 & \leftrightarrow 2\text{C}_2\text{H}_2 + 9\text{H}_2
\end{align*}
\]

Analysis of the equilibrium constants for these reactions and data from Table 1 testifies that methane decomposes completely at a temperature above 100°C.17)

High temperature, relatively low pressure (some atmospheres) and the presence of catalysts (newly-reduced iron, coke) favour char generation. These conditions exist in the tuyere cavity and in the lower part of the BF (except for the raceway). To suppress char generation it is necessary to provide a good mixing of the NG with the blast as well as its oxidation by oxygen before NG can decompose into carbon and hydrogen.

2.2. Natural Gas Mixing and Combustion in the Blast Furnace Tuyeres

To avoid local supercooling of the hearth and char generation, it is first of all necessary to provide uniform NG distribution around the furnace periphery and good mixing with blast. The NG jet is introduced in the tuyere cavity perpendicularly to the blast stream, at a certain angle to it, and sometimes in the opposite direction in order to improve mixing.

In the absence of any control, NG is distributed between the tuyeres extremely unevenly. NG variation and blast consumption occur in opposite directions: the more NG, the less blast and vice versa. A particular cause of blast volume decrease upon an increase in NG consumption is the rise in the volume of gases generated. Therefore upon the fluctuation of NG consumption through a given tuyere, the NG/blast ratio will fluctuate even more considerably. The flame temperature decreases at the tuyeres with a higher NG/blast ratio, which leads to an increment in slag viscosity, incompleteness of NG combustion with char generation, and worsening of melting products drainage.

To avoid these negative changes in the BF operation it is necessary to use an automatic control system of NG and blast consumptions. NG burning starts in the tuyere cavity and the degree of its development is determined by the completeness of NG and blast mixing.

Results of industrial tests with the aid of probing of the hearth with a water cooled tube18) showed that at NG/blast < 1.2 penetration of the main body of the NG
jet to the tuyere axis is not achieved. A jet with approximately 70% CH₄ is located in the upper zone of the tuyere. At NG/blast > 1.2 penetration of the main body of the NG jet to the tuyere axis is achieved.

The degree of NG oxidation (CO + CO₂)/(CH₄ + CO + CO₂) rises moving away from outlet point, but does not exceed 50% (at relatively low rate of NG and blast with 25% O₂). Obviously, the presence time of NG in the tuyere (less than 0.004–0.005 s) is not long enough for ignition.

### 3. Research of Coal Dust Behaviour upon Heating

A theory of coal combustion was developed in the papers of Zeldovich, Knorre and other authors. PC gasification processes in BF and ironmaking technology using PC injection have been thoroughly investigated, published and discussed by specialists during the last 10–15 years. Granular coal injection has also been studied.

This chapter presents the results of laboratory research of separate stages of coal thermal decomposition and gasification and its ash melting, which have been carried out by the authors in the National Metallurgical Research Centre (CENIM). Chemical analyses and the ash contents of the studied coals, which are injected in BFs in the Ukraine and Spain or recommended for injection, are given in **Tables 2** and **3**.

Donbass is a PC from the concentrate of a lean coal from the Donbass basin and for a long time has been injected into the hearth of BFs at Donetsk Steel Plant (DSP) in the Ukraine. Guasare coal is used for PC preparation and injection in 2 new BFs in Gijon, Aceria Corporación Siderúrgica in Spain. Prodeco, Logan and Welch coals can also be used for PC preparation and injection in BFs in Spain.

#### 3.1. Investigation of Mechanism and Kinetics of Coal Thermal Decomposition and Burning

The results of chemical analyses (Table 2) testify that the volatile matter (VM) content in Prodeco and Guasare coals is almost 3 times as high as in Donbass coal. Ash content is equal to 5.5–9% for coals used in the BFs of Spain and 11% for Donbass. Donbass coal also has a higher sulphur content.

Thermal decomposition of coals has been studied on the thermal analysis instrument at a heat of up to 1 000°C in an inert atmosphere. Some results of these investigations are shown in **Table 4**. The end of the coal thermal decomposition process practically comes at 850°C. Maximum intensity of thermal decomposition is noticed in the range of 400–600°C. Total mass loss upon thermal decomposition depends on the VM content. This dependence is linear till 30–35% VM (Fig. 1).

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**Table 2.** Chemical analysis of coals. (wt%)

<table>
<thead>
<tr>
<th>Components</th>
<th>Donbass</th>
<th>Guasare</th>
<th>Logan</th>
<th>Welch</th>
<th>Prodeco</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fixed carbon</td>
<td>75.7</td>
<td>75.22</td>
<td>58.6</td>
<td>75.5</td>
<td>52.65</td>
</tr>
<tr>
<td>VM</td>
<td>13.1</td>
<td>37.35</td>
<td>34.1</td>
<td>16.7</td>
<td>38.15</td>
</tr>
<tr>
<td>Ash</td>
<td>11.2</td>
<td>5.43</td>
<td>7.3</td>
<td>7.7</td>
<td>9.21</td>
</tr>
<tr>
<td>Moisture</td>
<td>1.1</td>
<td>2.08</td>
<td>1.4</td>
<td>0.8</td>
<td>4.99</td>
</tr>
</tbody>
</table>

**Table 3.** Coal ash composition. (wt%)

<table>
<thead>
<tr>
<th>Components</th>
<th>Donbass</th>
<th>Guasare</th>
<th>Logan</th>
<th>Welch</th>
<th>Prodeco</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO₂</td>
<td>51.42</td>
<td>55.54</td>
<td>53.55</td>
<td>50.50</td>
<td>63.5</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>29.46</td>
<td>23.24</td>
<td>29.85</td>
<td>27.64</td>
<td>16.5</td>
</tr>
<tr>
<td>Fe₂O₃</td>
<td>9.00</td>
<td>10.59</td>
<td>7.56</td>
<td>10.50</td>
<td>6.3</td>
</tr>
<tr>
<td>CaO</td>
<td>2.19</td>
<td>0.92</td>
<td>2.13</td>
<td>2.78</td>
<td>4.5</td>
</tr>
<tr>
<td>MgO</td>
<td>1.16</td>
<td>1.10</td>
<td>1.5</td>
<td>1.17</td>
<td>3.5</td>
</tr>
<tr>
<td>SO₃</td>
<td>0.30</td>
<td>0.036</td>
<td>0.16</td>
<td>1.15</td>
<td>1.0</td>
</tr>
<tr>
<td>Na₂O</td>
<td>0.96</td>
<td>0.44</td>
<td>0.20</td>
<td>0.79</td>
<td>1.18</td>
</tr>
<tr>
<td>K₂O</td>
<td>3.36</td>
<td>2.38</td>
<td>1.97</td>
<td>2.04</td>
<td>0.90</td>
</tr>
</tbody>
</table>

**Table 4.** Mass loss at coal thermal decomposition burning. (wt%)

<table>
<thead>
<tr>
<th>Type of Coal</th>
<th>Atm</th>
<th>Heat rate, °C</th>
<th>Temperature range, °C</th>
<th>Total mass loss, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Donbass</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>air</td>
<td>1000</td>
<td>1.53</td>
<td>60-120</td>
<td>95.91</td>
</tr>
<tr>
<td>600</td>
<td>1.50</td>
<td>3.50</td>
<td>120-420</td>
<td>93.56</td>
</tr>
<tr>
<td>N₂</td>
<td>1000</td>
<td>0.92</td>
<td>420-600</td>
<td>93.58</td>
</tr>
<tr>
<td>600</td>
<td>0.97</td>
<td>1.94</td>
<td>600-820</td>
<td>93.58</td>
</tr>
<tr>
<td>Guasare</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>air</td>
<td>1000</td>
<td>1.78</td>
<td>60-120</td>
<td>99.92</td>
</tr>
<tr>
<td>600</td>
<td>1.67</td>
<td>6.96</td>
<td>120-420</td>
<td>98.66</td>
</tr>
<tr>
<td>N₂</td>
<td>1000</td>
<td>2.26</td>
<td>420-600</td>
<td>97.23</td>
</tr>
<tr>
<td>600</td>
<td>2.24</td>
<td>4.73</td>
<td>600-820</td>
<td>95.58</td>
</tr>
<tr>
<td>Logan</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>air</td>
<td>1000</td>
<td>1.66</td>
<td>60-120</td>
<td>99.22</td>
</tr>
<tr>
<td>600</td>
<td>1.67</td>
<td>5.56</td>
<td>120-420</td>
<td>97.62</td>
</tr>
<tr>
<td>N₂</td>
<td>1000</td>
<td>2.17</td>
<td>420-600</td>
<td>91.05</td>
</tr>
<tr>
<td>600</td>
<td>2.12</td>
<td>5.43</td>
<td>600-820</td>
<td>89.65</td>
</tr>
<tr>
<td>Welch</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>air</td>
<td>1000</td>
<td>1.26</td>
<td>60-120</td>
<td>98.97</td>
</tr>
<tr>
<td>600</td>
<td>1.12</td>
<td>8.23</td>
<td>120-420</td>
<td>96.94</td>
</tr>
<tr>
<td>N₂</td>
<td>1000</td>
<td>1.31</td>
<td>420-600</td>
<td>95.35</td>
</tr>
<tr>
<td>600</td>
<td>1.22</td>
<td>9.32</td>
<td>600-820</td>
<td>93.11</td>
</tr>
<tr>
<td>Prodeco</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>air</td>
<td>1000</td>
<td>5.05</td>
<td>60-120</td>
<td>98.54</td>
</tr>
<tr>
<td>600</td>
<td>3.89</td>
<td>9.00</td>
<td>120-420</td>
<td>97.56</td>
</tr>
<tr>
<td>N₂</td>
<td>1000</td>
<td>5.78</td>
<td>420-600</td>
<td>92.63</td>
</tr>
<tr>
<td>600</td>
<td>4.94</td>
<td>5.28</td>
<td>600-820</td>
<td>91.57</td>
</tr>
</tbody>
</table>

**Fig. 1.** Dependence of mass loss on volatile matter.
Burning of PC from different coals has been studied on the thermal analysis instrument in an air atmosphere at a variable heating rate (Table 4). Figure 2 shows the thermal analysis of Guasare coal carried out in an air atmosphere (Fig. 2a) and a nitrogen atmosphere (Fig. 2b) at a heating rate of 1 000°C/h. These figures are used to elaborate the data presented in Table 4.

An analysis of the derivative charts obtained allows the PC combustion process to be divided into several stages. The first stage involves the evolution of the moisture contained in the coal dust. This process finishes at 110–200°C, depending on the heating rate and coal grade. In the second stage chemisorption occurs. In the third stage VM is evolved. This process proceeds in the range of 330–600°C. The fourth stage consists of coke residue combustion. It ignites at 550–620°C and finishes burning at 730–880°C. At the end of coke residue combustion a further decrease in sample mass takes place, which can be explained by the final combustion of carbon trapped in the ash.

The combustion characteristics of the different types of coals have been studied in a previous paper.\textsuperscript{38}

\subsection*{3.2. Coal Ash Properties}

The content and physical properties of coal ash play an important role in optimizing the design of the tuyere apparatus, raceway processes and the slag regime. The effect of ash softening and melting characteristics on the above parameters is explained as follows.

The temperature of coal particles and the gaseous phase around them increases from the value of blast temperature, at the PC outlet point from lance into tuyere cavity, to the value of flame temperature during coke residue burning in the raceway.

At a greater distance between the tuyere nose and the point of the PC lance outlet, a higher blast temperature or an increasing level of coal grinding, the temperature of PC particles and gaseous phase at the tuyere nose becomes higher. If the PC ash softening temperature is approximately equal to the temperature within the tuyere cavity, ash melting and sticking on the inner surface of tuyere is possible.

Therefore it is necessary to take into account that moving the PC lance position away from the tuyere nose improves PC combustion conditions due to a longer presence time of PC particles in the tuyere apparatus, but with the danger of the occurrence of ash sticking. From the viewpoint of tuyere apparatus exploitation conditions, PC delivery to the tuyeres is more advisable than into the blowpipe.

Melting of ash proceeds in a temperature range characterized by 4 points: initial deformation temperature (IT), softening temperature (ST), hemispherical temperature (HT) and fluid temperature (FT). The process of PC ash softening and melting has been studied using a device with a furnace which provides a maximum temperature to 1650°C at heating rate of 8°C/min. The process occurs in a controlled atmosphere of 3l/min argon. The test is carried out in accordance with the ASTM standard.\textsuperscript{39}

Five identical triangular pyramids (cones) of a sample of pulverized coal, 15 mm in height and 6 mm in width, are placed in the furnace, positioned on a tray on a revolving pedestal. As the temperature rises, and with the assistance of a video system, the equipment records information about the transformations which take place in each of the five cones. At the end of the test a graphic record is obtained of the height and width variations which occur in each of the five cones during the test (Fig. 3). At the same time a printout is obtained of the temperatures at which the following four representative points occur:

\begin{itemize}
\item IT = Initial deformation temperature. The temperature at which the first rounding of the apex of the cone occurs.
\item ST = Softening temperature. The temperature at which the cone has fused down to a spherical lump in which the height is equal to the width at the base.
\item HT = Hemispherical temperature. The temperature at which cone height = 1/2 cone width.
\item FT = Fluid temperature. The temperature at which the fused mass has spread out in a nearly flat layer with a maximum height of 1.6 mm.
\end{itemize}

Table 5 gives the results of investigations of the ash melting process for the studied coals. Analysis of the
Table 5. Deformation, softening and melting temperature of coal ash.

<table>
<thead>
<tr>
<th>Coals</th>
<th>FT deformation</th>
<th>ST softening</th>
<th>FT melting</th>
</tr>
</thead>
<tbody>
<tr>
<td>Donbass</td>
<td>1269</td>
<td>1468</td>
<td>1497</td>
</tr>
<tr>
<td>Guasare</td>
<td>1354</td>
<td>1407</td>
<td>1494</td>
</tr>
<tr>
<td>Logan</td>
<td>1300</td>
<td>1455</td>
<td>1491</td>
</tr>
<tr>
<td>Welch</td>
<td>1324</td>
<td>1447</td>
<td>1468</td>
</tr>
<tr>
<td>Prodeco</td>
<td>1254</td>
<td>1269</td>
<td>1384</td>
</tr>
</tbody>
</table>

results obtained testifies that the deformation and softening of Donbass coal start at about 1270 and 1470°C respectively, and the melting temperature is 1500°C. With the injection of this coal, no sticking on the tuyere's inner surface was observed. This is explained by 2 reasons: the relatively low blast temperature (1100°C) and the short presence time of PC particles in the tuyere cavity due to the short distance between the lance tip and tuyere nose (310 mm) at DSP.

Guasare coal has ash which begins to deform at 1350°C. Ash softening occurs at 1400°C and melting at 1500°C. The PC lance introduces in the blast stream also close to the tuyere base (at 360 mm). The blast temperature at BF-B Gijon in 1997 was 150–1170°C.

This tuyere design and technological parameters provide the outlet of PC particles in the raceway before the start of ash melting.

Logan and Welch coals, from the viewpoint of ash properties, can also be recommended for PC injection.

Prodeco coal has a considerably lower ash softening and melting temperature. When introducing PC into the blast stream at a temperature of about 1200°C, the temperature in the tuyere cavity increases above 1300°C. In this case, ash can stick to the inner surface of the tuyere apparatus, and this can cause problems in the BF operation.

4. Co-firing of Pulverized Coal and Natural Gas in the Blast Furnace

4.1. Factors to Determine the Oxidizing Potential of the Raceway

The consumption of injected auxiliary fuels into BFs, from the viewpoint of their complete combustion in the raceway, is limited by the oxidizing potential of hearth. Its value is given by the oxygen excess coefficient in the raceway, determined by the equation:

\[ \alpha = \frac{(C_0 V_{bl} + S_1 V_1 + S_2 V_2) \omega}{m S_1 + n S_2} , \]  

where \( \alpha \): oxygen excess coefficient (—);
\( C_0 \): rate of carbon in coke burnt in front of the tuyere (kg/kgHM);
\( S_1 \): NG consumption (m³/kgHM);
\( S_2 \): PC consumption (kg/kgHM);
\( V_{bl} \): blast volume (m³/kg C₆);
\( V_1, V_2 \): blast volume (m³/kg NG) and (m³/kg PC) respectively;
\( \omega \): oxygen content in blast (—);
\( m \): theoretical oxygen consumption for combustion of 1 m³ NG (m³);
\( n \): theoretical oxygen consumption for combustion of 1 kg PC (m³);

The coefficient \( m \) is calculated by the equation:

\[ m = 2(CH_4) + 3.5(C_2H_6) + 5(C_3H_8) + \cdots , \]  

where \( CH_4, C_2H_6, C_3H_8 \cdots \) corresponding to methane, ethane, propane and other components in NG, (—).

The coefficient \( n \) is calculated by the equation:

\[ n = 1.8667C^* + 11.2H^* , \]  

where \( C^* \) and \( H^* \) are the content of carbon and hydrogen in PC, (—).

The lowest theoretically permissible value of \( \alpha \) is 1.0. Since complete mixing of the injected fuel with the blow is impossible to maintain, in practice the minimum value of \( \alpha \) is 1.25–1.30. According to Eq. (1) the oxidizing potential of the hearth depends on the oxygen concentration in the blast as well as the NG and PC consumption.

It is possible to increase the oxidizing potential of the raceway by means of higher oxygen enrichment in the blast. The necessary increment in oxygen concentration in this case is determined from the equation:

\[ \Delta \alpha = \frac{(m S_1 + n S_2)}{V_{bl}} \Delta \omega , \]  

where \( \Delta \alpha \): increment of oxygen content in blast (—);
\( V_{bl} \): actual blast volume (m³/kgHM);
\( \Delta \omega \): increment of \( \alpha \) value required (—).

The results of calculations which have been carried out for a wide range of combined blast parameters show that to increase \( \alpha \) by 0.1 an increment of the oxygen concentration by 1.5–4.0% is needed.

At a constant oxygen concentration in the blast, the oxidizing potential of the raceway can be maintained or changed by controlling the ratio of NG and PC consumption, according to the equation:

\[ \Delta S_2 = -\frac{m}{n} \Delta S_1 . \]  

where \( \Delta S_2 \): increment of PC consumption (kg/kg HM), \( \Delta S_1 \): increment of NG consumption (m³/kg HM).

Analysis of relationship (5) testifies that to maintain the oxidizing potential, a PC consumption change by 10 kg should be accompanied by a change in NG consumption in the opposite direction by 7–8 m³.

4.2. Comparative Estimation of NG and PC and the Compensation Rate

The main difference between NG and PC consists of the quantity of combustible components—carbon and hydrogen. The ratio \( C/H \) = 3–5 for NG and 5–25 for coals. A result of the low value C/H for NG is the high wastes of heat for dissociation of hydrocarbon compounds, a large volume of combustion products, and a
relatively low flame temperature. PC requires 2~4 times less heat expense for its preparation for combustion.

Auxiliary fuel injection affects not only the oxidizing potential of the raceway but also the heat, gasodynamical and slag formation regimes of BF operation. Figure 4 shows that NG changes the main parameters of the process more considerably than PC. Figure 4 shows one variant of calculation using the complex method of BF parameter determination developed by Ramm.40) Depending on the fuel composition and technological conditions of melting, the flame temperature decreases by 300~400°C per 100 m³ NG and by 70~170°C per 100 kg PC. The direct reduction rate (i.e. reduction of iron oxides by solid carbon) decreases by 15~20% per 100 m³ NG and 2~6% per 100 kg PC. The bosh gas volume increases at the burning of 1 atom of carbon in NG or PC by 70% or 10~25% respectively, compared to the combustion of one atom of carbon in coke.

The compensation rate of PC by NG, considering the effect of auxiliary fuels on the oxidizing potential of the hearth as well as on the heat, gasodynamical and other regimes of BF operation, depends to a large extent on the composition of the fuels and technological conditions.

Figure 5 shows that PCI allows at different values of NG decrease in the flame temperature range of 1950~2150°C to change BF productivity and coke consumption in a wide range (96~106% and 104~68% respectively). It permits the possibility of choosing the technological regime according to the market situation.

Compensation rates were calculated for BF operation conditions with ranges of NG 0~100 m³/THM (0~7000 m³/h) and pulverized low ash lean coal 0~200 kg/THM at a flame temperature in the range 1950~2150°C and keeping other blast and burden parameters constant. Two variants of compensation rates have been calculated: (1) for maximum productivity (line a); (2) for minimum coke consumption (line b). From Fig. 5 it can be seen that the first variant is achieved when the compensation rate of PC by NG makes from 1.0 (point a₁) to 0.55 m³/kg (point a₂). In this case productivity rises up to 106% and coke consumption decreases down to 93~76%. The second variant is achieved when the compensation rate is equal to 0 (point b₁) and 0.2 m³/kg (point b₂). In this case an additional decrement of coke by 3~8% occurs, but productivity decreases down to 96~93%. Under real conditions the compensation rate of PC by NG is in the range (0.2~0.5) m³/kg.

Under technological conditions of DSP 170 kg/THM, PC provides maintenance of the flame temperature at 2150~2200°C with the complete exception of NG. This regime permits a decrease in the coke rate to 76% and an increase in productivity up to 106%; the compensation rate makes up to 0.57 m³/kg.

When putting BFs and DSP into a technology with oxygen enrichment in the blast needed for the intensification of the process, it was necessary to determine the kind of fuel (PC or NG) which better accompanies oxygen delivery. For that purpose 4 variants of BF operation were calculated. Analysis of the calculation results (Table 6) shows that under the considered
Table 6. BF operation parameters at different relationship between NG and PC consumption.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Base period</th>
<th>I</th>
<th>II</th>
<th>III</th>
<th>IV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Auxiliary fuel consumption:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PC (kg/tHM)</td>
<td>0</td>
<td>0</td>
<td>120</td>
<td>120</td>
<td>120</td>
</tr>
<tr>
<td>NG (m³/tHM)</td>
<td>92</td>
<td>160</td>
<td>29.0</td>
<td>25.0</td>
<td>23.4</td>
</tr>
<tr>
<td>Oxygen concentration in blast (%)</td>
<td>21.0</td>
<td>8000</td>
<td>8000</td>
<td>4300</td>
<td>2600</td>
</tr>
<tr>
<td>Proces oxygen volume (m³/h)</td>
<td>0</td>
<td>0</td>
<td>8.2</td>
<td>8.2</td>
<td>22.3</td>
</tr>
<tr>
<td>Coke consumption (kg/tHM)</td>
<td>537</td>
<td>480</td>
<td>378</td>
<td>493</td>
<td>417</td>
</tr>
<tr>
<td>Decrease of coke consumption (%)</td>
<td>10.6</td>
<td>29.6</td>
<td>8.2</td>
<td>8.2</td>
<td>22.3</td>
</tr>
<tr>
<td>Total fuel consumption (kg/tHM)</td>
<td>617</td>
<td>641</td>
<td>624</td>
<td>619</td>
<td>608</td>
</tr>
<tr>
<td>Change of total fuel consumption (%)</td>
<td>3.89</td>
<td>1.13</td>
<td>0.32</td>
<td>1.46</td>
<td></td>
</tr>
<tr>
<td>Productivity (%)</td>
<td>100</td>
<td>115.6</td>
<td>114.6</td>
<td>107.3</td>
<td>102.5</td>
</tr>
<tr>
<td>Cost price (%)</td>
<td>100</td>
<td>102.3</td>
<td>94.6</td>
<td>96.2</td>
<td>95.0</td>
</tr>
</tbody>
</table>

Fig. 6. Compensation rates of PC by NG at different oxygen content in blast.

conditions a variant with simultaneous injection of PC and NG in equal rates (50:50%) is the most efficient. On the basis of the calculations a nomogram of compensation of PC by NG at different oxygen concentrations in blast has been constructed (Fig. 6).

Figure 6 shows the ways to maintain the optimum technological parameters under concrete technological conditions of DSP BF s for changing blast parameters. An example: a BF has operated at PC = 100 kg/tHM, NG = 75 m³/tHM and 22.5% O₂. To increase the PC rate to 200 kg/tHM it is possible for instance:

(a) to decrease NG consumption to 45 m³/tHM keeping O₂ constant;
(b) to raise the O₂ content almost to 26% keeping NG constant.

To increase the O₂ content in the blast to 26% it is possible:

(a) to raise NG consumption to 105–110 m³/tHM;
(b) to raise PC consumption approximately to 190 kg/tHM;
(c) to raise NG consumption approximately to 90 m³/tHM and PC consumption to 140 kg/tHM.

4.3. Devices for Introduction of Auxiliary Fuels into the BF

The efficiency of BF operation with auxiliary fuel injection depends on the reliability and technological suitability of the devices for its delivery into furnace. These devices operate at high temperature, large temperature gradients and abrasive wear by moving solid substances. They are to maintain:

− good mixing of the injected fuel with the hot blast and sufficient residence time of powder particles in the hot blast stream for its preparation for combustion in the raceway;
− visual monitoring of the tuyere apparatus and the raceway through the peep sight;
− duration of performance not less than without auxiliary fuel injection;
− keeping required conditions of tuyere apparatus service.

Figure 7 shows a tuyere assembly design developed for the simultaneous delivery of 2 kinds of fuel. Special lances for NG and PC delivery are introduced into the tuyere body. NG is introduced into the upper part of the tuyere perpendicularly to the blast stream through a lance with...
an inner diameter 25 mm. For a more even distribution of the blast oxygen in the tuyere cross section for NG and PC burning, the tuyere is introduced into the lower part of the tuyere through the lance with an inner diameter 25 mm also. To maintain a good mixing, PC is also delivered perpendicularly to the blast jet and closer to the tuyere axis (at a distance of about 60 mm from the tuyere wall). The distance between the tuyere nose and the lance tip is greater for the PC lance than for the NG lance, since for preparation of PC to burning more time is necessary.

Industrial exploitation of the described device over a long period of time at DSP has proven its technological suitability and pretty high longevity. Its serial production is mastered.

In recent years a tuyere assembly device with an additional lance for process oxygen delivery has been developed in order to improve PC combustion. In this case the tuyere apparatus has a minimum of 5 lances (or more at double water cooling), which decrease its strength and makes service more complicated, especially when it needs to be replaced. We have developed the method which makes it possible not only to eliminate the above mentioned disadvantages but also to simplify the control of the technological regime with the simultaneous injection of NG and PC.

It consists of pneumatic transportation of PC by NG. PC is usually transported with air, nitrogen or flue gases. If NG is used as PC transporting agent only one lance will be necessary for fuel delivery. An increase in PC consumption is achieved by raising its concentration in the dust laden gas stream due to the decrease in transporting gas volume. To decrease PC consumption a reverse action is needed. In both cases change in temperature, heat and oxidizing potential of the raceway being compensated automatically in accordance with given above compensation rates.

4.4. Controlling the Thermal State in the BF

Auxiliary fuels injected into the hearth of the BF can be used to control the thermal regime, which is characterized by the pig iron composition (particularly silicon content) and its temperature.

A disadvantage of the control of the thermal state of a BF "from the top" (e.g. by the coke rate in the burden) consists of the considerable time delay due to the movement of the charge materials down the furnace and the inertia of the thermal processes. A high quality of control is therefore not achieved. A control action "from the top" must be combined with actions "from the bottom", which are practically free of transport delay.

Among the methods of controlling the thermal state of a BF "from below" the most economical and efficient, besides adjustment of blast humidity, is to change the auxiliary fuel consumption.

To create a control system for the BF thermal state using a control action "from below", the dynamics of the BF process with respect to the probable control relations were analysed in a previous paper.

The influence of NG on pig iron silicon content and its temperature is of a complicated nature. Thus an increase in NG consumption at the first stage leads to a decrease in hearth heat. After a certain time a secondary effect, consisting of a rise in the hearth heat, begins to appear in connection with the change in the course of reduction processes in the furnace. Thus an increase in NG consumption affects the thermal state of the BF hearth in stages and finally raises the pig iron silicon content. The fuel effect of controlling the pig iron silicon content by changing the NG consumption is achieved after 14–16 h (Fig. 8a).

The complicated nature of the transient process when the NG consumption is changed is particularly associated with the decomposition of hydrocarbons and the formation of a large quantity of hydrogen. It makes it difficult to use this fuel addition for the operational control of the furnace hearth heat.

NG injection and PC injection were measured separately. When the NG rate (20 m³/tHM) was changed, the initial NG value was 60–80 m³/tHM. When the PC rate (20 kg/tHM) was changed the initial PC value was 70–90 kg/tHM. The Si content in pig iron was 0.6–0.9 %.

PC, which is similar in chemical composition to coke, does not bring about any substantial changes in the composition or quantity of tuyere gases; a change in its consumption therefore influences the thermal state according to a less complicated law. The equation of the transient process of a change in the pig iron silicon content, with a change in PC consumption, can be presented in the form:

$$\Delta Si = 0.085 \Delta S_2 \left[ 1 - \exp \left( - (i - 0.5)/3.5 \right) \right]$$

where:

$$\Delta Si$$ = variation in pig iron silicon content (%),

$$\Delta S_2$$ = variation in the PCI rate (kg/tHM),

i = time from the moment of a change in PC consumption (h).

Equation (6) and Fig. 8b testify that the complete control effect is achieved after 7–9 h.

The highly dynamic nature of PC in combination with the relatively simple transient process predetermines its advantage when the thermal state of the BF hearth has to be operationally controlled.

On this basis a local automated control system for maintaining BF hearth heat conditions by changing the
PC rate has been developed.\textsuperscript{45} The system is realized using microcomputers and has been operating successfully for several years at DSP. It has proven high reliability, simplicity of maintenance and accuracy of obtained results. The average Si and S content in pig iron has decreased from 0.95 to 0.85\% and from 0.035–0.037 to 0.030–0.032\% respectively. The fluctuation of Si and S has decreased from 0.25–0.27 to 0.20\% and from 0.015 to 0.010\% respectively. The operation of the system provides as a result additional coke savings of 4–5 kg/THM.

4.5. Results of the BF's Operation Using Two Kinds of Fuel

Ironmaking with simultaneous injection of NG and PC into the hearth with the enrichment of the hot blast with process oxygen has been adopted at 2 BFs DSP. The parameters of their operation during some particular periods have been published in previous papers.\textsuperscript{4,46} The parameters of the BFs operation using the given technology, generalized for 5 years, are as follows.

Oxygen concentration in the blast has been 24.0–25.5\%. Total consumption of injected fuels has been 150–180 kg/THM, in particular NG 80–90 m\(^3\)/THM and PC 70–100 kg/THM. The coke/coal replacement ratio has been about 0.9 kg/kg and the coke/NG replacement ratio about 0.8 kg/m\(^3\), which allowed a decrease in coke consumption down to 400 kg/THM. The quality of the charge materials did not change. The productivity of the BF remained at the initial level. The intensity of melting by carbon has decreased down to 0.75–0.80 t/(m\(^3\) \cdot 24 h) due to the decrease in the coke rate and void of burden.

The slag volume has been 380–420 kg/THM when the rate of pellets in the burden was 30–40\%. The optimization of slag composition (increase in MgO and decrease in Al\(_2\)O\(_3\)) and the development of special measures for removing alkalis in the slag, made it possible to produce a qualitative pig iron with an average content of S=0.030\% and Si=0.75\% at slag basicity CaO/SiO\(_2\)=1.23–1.28.

The direct reduction rate (\(r_d\)) was 25–30\%, the remaining share of iron monoxide being reduced by the gases CO and H\(_2\). The carbon monoxide utilization rate, which is determined by top gas composition, \(\eta = 100\text{CO}_2/(\text{CO}_2 + \text{CO})\), equaled 38–40\%.

The flame temperature in the raceway remained in the range 1950–2050\(^\circ\)C due to the maintenance of optimal compensation rates of PC, NG and O\(_2\).

Since 1996 NG use in Ukraine became less profitable. Because of this, NG consumption was decreased to 0–20 m\(^3\)/THM, PC being gradually increased to 150–170 kg/THM. The above determined compensation rates of PC by NG were applied there. The sinters/pellets ratio in the burden was changed from 60/40 to 40/60; the blast temperature was decreased from 1100 to 1000\(^\circ\)C; moisture in the blast is till now approximately 10 g/m\(^3\) and the flame temperature is about 2100\(^\circ\)C.

5. Conclusions

(1) The PC combustion process includes stages of evolution of moisture, chemisorption, escape of VM and coke residue combustion. The total mass loss upon coal destruction is directly proportional to the VM content till 30–35\% VM, then this dependence takes on an exponential character.

The content and properties of coal ash, in particular the process of ash melting, play an important role in optimizing the design of the tuyere apparatus and the slag regime. From the viewpoint of tuyere apparatus operating conditions, PC delivery to the tuyeres and the use of coals with a high ash softening temperature is advisable.

(2) The compensation rate of PC by NG has been determined considering the effect of the auxiliary fuel on the oxidizing potential in the raceway and the heat, gasodynamical and slag formation regimes of BF operation. This value is 0.2–0.5 m\(^3\)/kg, depending on the fuel composition and technological conditions. On this basis a flexible technology using two kinds of auxiliary fuel has been developed. The ratio of injected fuels can be changed up to full exception of one them.

(3) Auxiliary fuels can be used to control the thermal state in the BF. A local automated control system for maintaining BF hearth heat conditions by changing the PC rate has been developed, and has been operating successfully for several years.

(4) Ironmaking with simultaneous injection of NG and PC into the hearth with the enrichment of the blast with oxygen has been adopted at two BFs. The total consumption of auxiliary fields is 150–180 kg/THM at 24.0–25.5\% O\(_2\) in the blast.

Prolonged industrial exploitation of tuyeres with lances for simultaneous injection of NG and PC has proven longevity and technological suitability.

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REFERENCES

6) European Blast Furnace Committee, Performance Data for Sinter Plants and Blast Furnaces, Middlesborough, United Kingdom, (1998).
7) S. Griffin: Steel Times, 208 (1980), No. 5, 354.
15) N. Semenov: Chain Reactions, Goshizdat, Moscow, (1934).
40) A. N. Ramm: Modern Blast Furnace Process, Metallurgiya, Moscow, (1980), 204.

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