The State of the Art and Future Perspective of Intelligent Blast Furnace Ironmaking

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Abstract. In a BF-BOF steel plant, the blast furnace ironmaking is the kernel step whose energy consumption, pollutants emission and production cost share are all the highest. Any small improvement of blast furnace efficiency implies great social and economic benefits. Artificial intelligence has contributed to the improvement of blast furnace process and will do it even better, i.e. realizing a higher and higher efficiency within a longer and longer period of time. This paper described our achievement in the field of artificial blast furnace ironmaking and made a comparative analysis against some other BF AI systems applied in Chinese steel industry, showing our system was superior in respect to availability, accuracy and return on investment. Future research topics have been proposed for promoting the development of artificial intelligent BF technology.

Brief Introduction of Blast Furnace Ironmaking Process

Basic Principles of the Process

The insight of a blast furnace is shown in Fig. 1.

Figure 1. Schematic diagram of the blast furnace ironmaking process.

Solid burden materials, i.e. iron-bearing materials, coke and fluxes, are charged in batches from the furnace top and formed a layered stock column, slowly moving downwards. Gases, which are produced at the tuyeres by combustion of hot blast and coke, contain CO, H\textsubscript{2} and N\textsubscript{2}, and move upwards through voids of the stock column.

Transfer of mass, heat and momentum between gases and burden materials takes place and, as a result, hot metal and slag are produced, which are periodically tapped out from the hearth. Waste gases move out through the uptakes at the furnace top.
Basic Features of the Process

*High temperatures*: hot metal=1350~1550°C, molten slag=1400~1600°C, hot blast= 950~1350 °C, theoretical flame temperature=2000~2500 °C.

*High pressures*: pressure at the outlet of blower =0.3~0.55MPa, furnace top gas pressure = 0.15~0.30MPa.

*Huge production capacity*: volumetric productivity=2.0~3.1 t/m³•d (large furnaces), 3.0~5.0 t/m³•d (small furnaces), the world maximum blast furnace: Effective volume =6000m³ (South Korea), Daily throughput=13000 t.

*Ceaseless pattern of operation*: wishing the furnace continuously run for a period of time as long as possible.

*Complexity of process mechanism*: Human cognition on the coupling transfer phenomena of mass, heat and momentum between gas, solid, liquid and fines is very limited.

Energetically Improving the Blast Furnace Process Efficiency is a Demand of This Era

The share of hot metal production cost accounts for 70~75% of crude steel production cost. Theoretical lower limit of carbon consumption≈ 414kg/tHM, equivalent coke consumption ≈465 kg/tHM, Minimum CO₂ emission≈1519 m³/tHM. Five percent higher than the lower limits for a BAT (Best Available Technology) furnace and 13.54% higher than the lower limits for Chinese blast furnaces, leaving a great space for improvement in economy and CO₂ emission mitigation in China. In 2017, Chinese blast furnace hot metal production was 710.76 Mt, accounting for 60.50% of the world blast furnace hot metal production, see Fig. 2[1].

![Figure 2. Overview of Chinese and world iron production: (a) The production of blast furnace iron in China and world; (b) The growth rate of blast furnace iron production and its share in the world blast furnace iron production.](image)

Difficulties of Blast Furnace Process Control

Among all processes in a steel plant, the blast furnace is the most difficult, due to

1. The very complex mechanism and continuous operation mode in a very long term
2. Non-linearity, large lag and there exist periodical fluctuations
3. Information asymmetry, i.e. some important process information missing, the precision of measured data frequently is not up to grade
4. Highly depending on human intelligence and there exist four problems as follows: a) the vigor and ability of operators are limited, it is hard to avoid false positives and false negatives take place when facing as many as tens of hundreds of measured data, and they cannot work efficiently and permanently (24×7×365); b) it’s hard to reach agreement between human experts on the cognition and approach of a same blast furnace event; c) the resource of high-level human blast furnace experts is scarce in the industry; d) the resource of high-level human blast furnace experts is scarce in society and their service charge is very high
5. A variety of cost-reducing and efficiency-increasing measures add the difficulties, these measures consist of using the most economic burden materials by making every effort, pursuing a
stability and efficiency for the whole iron making system, prolonging the service life of the blast furnace as much as possible, etc.; it is hard to find an appropriate balance between use of economic burden materials, long campaign life and the goal of maintaining a long-term high-efficient smooth running

**Why the Application of Intelligent BF Ironmaking Brings Benefits**

**AI will Realize Breaking out in BF Ironmaking**

Analysis shows that manufacture industry, education, financial and health care are the four sectors in which Artificial Intelligence will realize breaking out because of their great growing space and high dependence on human experience and knowledge. Blast furnace ironmaking, a sector of manufacture industry, will be greatly impacted by AI.

The position of a blast furnace operating expert is equivalent of a lawyer in the financial sector, or a specialist of pathological section diagnosis of cancer in the healthcare industry, very scarce and very highly paid. It is urgent to mitigate the dependence on them via the application of big data and AI technologies.

**Goal and Roles of Intelligent BF Ironmaking**

Goal: Promote the whole operating level of a blast furnace and assist in realization of long-period high efficient smelting

Definition of long-period: the time interval when the specific requirement of high efficient smelting is fulfilled is as long as possible

Definition of high efficient smelting: the fuel rate is lower, the company’s requirements for hot metal quality are met, the company’s requirement for hot metal throughput is met, pig iron cost is lower, pollutants emission is lower, campaign life of the furnace is longer, resources adaptability is high

The specific roles of intelligent BF ironmaking:

1. Alleviate operators’ routine work and assist them in holding the historical, the present and the future situations of BF in time, fully and accurately
2. Detecting earlier all kinds of abnormalities in the process or in the shop, figuring out standardized treatment recommendations so that to avoid burning extra coke and resulting in repeated fluctuations of furnace state
3. Assist in the improvement of BF production due to more blast can be blown, as the result of a higher furnace smooth running level and an improved relationship between pressure and volume of blast, on the one hand, and that it is possible to precisely judge the BF operating point and to estimate the blast volume limit, providing a support of optimal decision making for the thermal, slagging, raw materials qualities regimes
4. Improve the safety and prolong the attended time of BF equipment including the furnace bottom and hearth
5. Promote the adaptability of BF to the variation in natural resources in respect to supply, quality and price of iron ores, coke and coal for injection
6. Eliminate severe abnormalities and accidents and thus avoid casualties, materials losses and cost for outside experts
7. Assist in formulating and optimizing all kinds of BF operational regimes through integrating theoretical models such the burden distribution model, coal injection model, holistic BF model and so on

**The State of the Art of Intelligent BF Ironmaking**

**The Main Existing Important AI BF Systems in the World**

SACHEM: France: A process control system for blast furnaces and related technologies; the project is aided by the E.C.S.C; the Sachem technical solution is proposed by Alstom Drives and Control
Comparison between Shaogang BF ES and the Other Systems

Basis for comparison: not primarily the number of models, especially mechanism models, but its roles played in blast furnace operation guidance

Key points: Availability, Effectiveness in the judgment of furnace heat and furnace state and economic and social benefits generated by the system application

A. High availability

High Availability refers to that the system is able to routinely run in a long period of time (months, years or even the whole campaign life), providing service for operators and other related personnel of BF operation.

Actual performance of Shaogang BF ES: it was commissioned in No. 8 BF of 3200m$^3$ September 2012 and had run routinely by the end of 2015, lasting three years and four months$^{[2-4]}$, and the reason of service stoppage: the MES was rebuilt due to the incorporation of Shaogang into Baosteel, as a result, the database that supported the BF ES was out of action.

To compare with the following systems:

(1) Operational platform-type Blast Furnace Expert Systems, Wugang Baosteel
   ES of No. 1 BF (2200m$^3$): executed normally for about four years (2004-11 to 2008-12)$^{[5]}
   ES of No. 5 BF (3200m$^3$): executed normally for about two years (2010-1 to 2011-12)$^{[6]}

(2) ES of Pangang BF No. 1 (1200m$^3$) (imported from VAI)
   It executed routinely 2003 ~ 2005, lasting three year$^{[7]}

(3) ES of Taisteel 4747 m$^3$ BF (imported from VAI)
   As introduced to the authors by the company, this system was discarded after only 15 days test-running

(4) ES of of Nangang 2500m$^3$ BF (imported from Rotaruukki, Finland, and VAI)
   It was reported that this system was put into operation at the end of March, 2009$^{[8]}$, but no performance data was provided. According to Mr. Liangyong Xiong of this company, this system was completely unusable

(5) ES of a Gary Work BF, US Steel (imported from VAI)
   According to Dr. Yongfu Zhao of this company, this system was discarded after only 15 days test-running

(6) ES of Guofeng No. 1 BF (University of Science and Technology, Beijing)
   This system was commissioned 10 Dec. 2012$^{[9,10]}$, but no information on performance was presented

B. High accuracy

High Accuracy refers to high precision of diagnosis and forecast results of kernel modules, i.e. the furnace heat model and the abnormal states model, providing accurate information to operators for judging, predicting and controlling BF states and formulating appropriate regulating schemes of operational regimes

[a] Inspection of role in furnace heat control

As seen in Fig. 3$^{[4]}$, after the commission of Shaogang BF No. 8 expert system, hot metal [Si] decreased (from about 0.45% down to about 0.40%) with smaller variation; fuel rate was decreased (from about 515 kg/tHM to about 495 kg/tHM) with smaller variation.

The excellent application effects in a long period of time fully demonstrated the high accuracy and reliability of the furnace heat model and it really played a guiding function for furnace heat regulation by operators

In comparison with the operational platform-type Blast Furnace Expert Systems, Wugang
Baosteel, the use ratio of furnace heat prediction and control models was only 30~40%, see Table 1.

Figure 3. Comparison of furnace heat and fuel rate before and after the Expert System commission.

Table 1. Check list of furnace heat control function of the operational platform-type Blast Furnace Expert Systems, Wugang Baosteel [11].

<table>
<thead>
<tr>
<th>No.</th>
<th>Component</th>
<th>Development content</th>
<th>Usage [%]</th>
<th>Situation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Research</td>
<td>Operation</td>
</tr>
<tr>
<td>4</td>
<td>Furnace heat control system</td>
<td>High temperature zone heat balance model</td>
<td>80</td>
<td>60</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Furnace heat prediction model</td>
<td>90</td>
<td>40</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Furnace heat control expert system</td>
<td>70</td>
<td>30</td>
</tr>
</tbody>
</table>

Note: Usage: assessment of service condition; Users of the system: include developers, operators and managers; State: whether it covers all modes and states of the specific problem?

No information in respect to the effect for furnace heat prediction and control of Pansteel BF No. 1 was presented.

The BF ES of Taisteel and Nansteel never normally ran.

As for Guofeng No. 1 BF ES, from 2013-04-16 0:00 to 2013-04-17 0:00 the predicted furnace heat and the measured furnace heat agreed well [9], and the agreement rate reached 98.6% [10]. But how to calculate the agreement rate was not introduced.

[b] Inspection of role in furnace smooth running

Table 2 lists the situation of gas distribution and smooth running during 2012-8 to 2012-12 [4]. After the ES was commissioned, the number of slipping and channeling was decreased from 20 to zero while the blow-down rate was decreased from 1.68% to 0.86%, the magnitude of decrease being 48.8%.

Table 2. The smooth running situation of BF No. 8

<table>
<thead>
<tr>
<th>Time</th>
<th>Slip [no./month]</th>
<th>Channeling [no./month]</th>
<th>Slag crust falling off, [no./month]</th>
<th>Blow down rate [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2012.08</td>
<td>12</td>
<td>8</td>
<td>15</td>
<td>1.68</td>
</tr>
<tr>
<td>2012.09</td>
<td>4</td>
<td>2</td>
<td>19</td>
<td>1.49</td>
</tr>
<tr>
<td>2012.10</td>
<td>2</td>
<td>1</td>
<td>6</td>
<td>1.11</td>
</tr>
<tr>
<td>2012.11</td>
<td>1</td>
<td>0</td>
<td>2</td>
<td>0.31</td>
</tr>
<tr>
<td>2012.12</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0.86</td>
</tr>
</tbody>
</table>

Compared to Pansteel BF No. 1 ES:

As reported by the company [7], “Especially under the unfavorable condition of supply tension of raw materials resources and frequent change in raw materials quality during recent years (2013~2015), through the application of the blast furnace expert system, the stability of production was greatly improved, the occurrence of furnace hanging and slipping remarkably decreased, the blast furnace realized a good situation of higher throughput promoted by stable production and higher benefits promoted by stable production.”
Unfortunately, no specific information on furnace smooth running improvement was presented. For all other BF expert systems mentioned in this paper, no information on furnace smooth running improvement was mentioned in the literature.

C. High return on investment

High Return on investment refers to the return on investment of the expert system, i.e. the ratio of benefits (including economic as well as social benefits) generated by system commission to system cost.

The application certificate issued by Shaogang shall prevail: the system was put into normal operation September 2012, BF productivity was increased from 2.18 t/m³•d till 2.427 t/m³•d, comprehensive coke rate was decreased from 495 kg/t to 474 kg/t by 21 kg/t, bringing about a considerably economic benefit: estimating according to the condition in 2012, 28.9×10⁴ ton hot metal was additionally produced every year, 5.95×10⁴ ton fuel was saved annually. The resultant annual economic benefit reached 10645.27×10⁴ RMB and annual CO₂ emission was reduced by 18.55×10⁴ ton.

Assuming the contribution ratio of AI and human intelligent is 50% each, the economic benefit created by the intelligent blast furnace expert system is about 5322.635×10⁴ RMB per year while CO₂ emission mitigation was 9.275×10⁴ ton.

The techno-economic indices of Pansteel No. 1 BF before and after the application of the expert system are presented in Table 3 [7].

<table>
<thead>
<tr>
<th>Year</th>
<th>Pig iron throughput [×10⁴ t]</th>
<th>Productivity [t/m³•d]</th>
<th>Comprehensive coke ratio [kg/t]</th>
<th>Blast temperature [°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2001</td>
<td>90.8</td>
<td>2.396</td>
<td>586</td>
<td>1093</td>
</tr>
<tr>
<td>2003</td>
<td>109.7</td>
<td>2.754</td>
<td>574</td>
<td>1173</td>
</tr>
<tr>
<td>2004</td>
<td>100.3</td>
<td>2.512</td>
<td>-</td>
<td>1184</td>
</tr>
<tr>
<td>2005</td>
<td>104.4</td>
<td>2.609</td>
<td>578</td>
<td>1170</td>
</tr>
</tbody>
</table>

Compared to 2001, in 2005 Pansteel No. 1 BF of 1280m³ additionally produced 13.6×10⁴ ton pig iron and the combined coke ratio was decreased by 8 kg/tHM. In consideration of the difference in furnace size, the benefit in terms of production improvement of Pansteel No. 1 BF ES and Shaogang No. 8 BF ES are comparable, in terms of coke ratio saving, however, the benefit of Shaogang No. 8 BF ES is 2.625 times of Pansteel No. 1 BF ES.

**Future Study Topics of Intelligent Blast Furnace Ironmaking**

As described above, the authors have made a great progress in the intelligent blast furnace ironmaking field, but the road to success is still long and hard in consideration of the following expectation for this AI technology:

1. Assist to materialize optimal balance between pig iron production, fuel consumption and furnace campaign life, and consistently improve the efficiency of the blast furnace
2. Prolong as much as possible the period of high efficiency

Some future study topics have been proposed by the authors aiming at the above mentioned requirement:

1. To establish a knowledge-atlas suitable for all kinds of the system application scenarios by using AI and big data technique and to figure out expert proposals for operational regimes regulation focused on all kinds of blast furnace working modes including blow-in, blow-out, oxygen-stop, PCI-stop, slow-wind blowing, emergent blow-down, scheduled blow-down and so on
2. To develop a BF optimized burdening model with the support of artificial logistics technique by using the ANN and optimization techniques, meeting the requirement of specific blast furnaces
3. To develop a blast furnace decision-making support system for guiding the thermal, slagging, blowing and charging regimes on the basis of the BF optimized burdening model and the lower furnace gas dynamics model
(4) To actively get involved in project initiation and development for measurement technology, especially for monitoring the variation in moisture content of pellets, lump ores, landed sinter and coke, the temperature and chemistry of hot metal during cast, trajectory of charged materials at the furnace top and the formed burden layers structure, corroded condition of the furnace hearth, accumulated volume of slag and hot metal in the hearth and so on.

(5) The combination of loading method for solid burden materials (ores, coke and fluxes) as well as gaseous materials (blast plus pulverized coal) is together called top-and-bottom regulations, which is the most difficult operational practice to handle and optimize. It is urgent to apply the real-time data measured by the advanced advices in some blast furnaces, including in-burden probe, furnace top multi-radar measurement system, infrared tuyere lenses and so on, for improving the top-and-bottom regulations through developing and applying some relevant theoretical and AI models.

(6) To study in depth the dynamical features and to grasp the intrinsic variation rules by utilizing big data technique.

(7) In order to adapt to special requirement of the blast furnace process that no state of catastrophe out of control takes place and to solve the difficulty of once an existing control approach is built-up, it will become static and unchangeable, which is unable to meet the requirement of control for the blast furnace with the feature of complexity and polytropism. It has to research and utilize the intensified intelligent technique, introducing human effect or cognition models into the intelligent system.

Among above mentioned study topics, the authors already have a considerable working basis for the second, the third, and the fifth.

References


