Journal of Iron and Steel Research, International 24 (2017) 608—616

Contents lists available at ScienceDirect

Journal of Iron and Steel Research, International

journal homepage: www.chinamet.cn

Numerical analysis of carbon saving potential in a top gas recycling oxygen blast furnace

Xue-feng She[1,*], Xiu-wei An[2], Jing-song Wang[1], Qing-guo Xue[1], Ling-tan Kong[1]

[1] State Key Laboratory of Advanced Metallurgy, University of Science and Technology Beijing, Beijing 100083, China
[2] Qingdao Special Steel Company Limited, Shandong, Qingdao 266409, Shandong, China

ARTICLE INFO

Key words:
Blast furnace process
Direct reduction degree
Carbon consumption
Direct reduction
Carbon saving potential
Oxygen blast furnace

ABSTRACT

Aiming at the current characteristics of blast furnace (BF) process, carbon saving potential of blast furnace was investigated from the perspective of the relationship between degree of direct reduction and carbon consumption. A new relationship chart between carbon consumption and degree of direct reduction, which can reflect more real situation of blast furnace operation, was established. Furthermore, the carbon saving potential of hydrogen-rich oxygen blast furnace (OBF) process was analyzed. Then, the policy implications based on this relationship chart established were suggested. On this basis, the method of improving the carbon saving potential of blast furnace was recycling the top gas with removal of CO_2 and H_2O or increasing hydrogen in BF gas and full oxygen blast. The results show that the carbon saving potential in traditional blast furnace (TBF) is only 38—56 $kg \cdot t^{-1}$ while that in OBF is 138 $kg \cdot t^{-1}$. Theoretically, the lowest carbon consumption of OBF is 261 $kg \cdot t^{-1}$ and the corresponding degree of direct reduction is 0.04. In addition, the theoretical lowest carbon consumption of hydrogen-rich OBF is 257 $kg \cdot t^{-1}$. The modeling analysis can be used to estimate the carbon savings potential in new ironmaking process and its related CO_2 emissions.

1. Introduction

In recent years, the importance of minimizing carbon dioxide emissions in the steel industry has emerged as a critical concern in helping to slow down the rate of global warming. Several joint research projects, such as the Ultra-low CO_2 Steelmaking (ULCOS) in Europe, have been proposed to develop technologies that limit energy consumption and greenhouse gas emissions from steel plants. The new blast furnace iron production process is one of the key development technologies that emerges from these joint projects, which addresses the problems associated with energy consumption. Traditional blast furnace (TBF) was developed more than one hundred years ago. Theoretically, the consumption of carbon in this type of traditional process is close to its lowest value[1]. However, the disadvantages of the TBF ironmaking process, such as long production cycle, high energy consumption, high pollutant emission, and a massive high quality coke that is converted to low quality gas, have become increasingly obvious primarily owing to the shortage of coal and the limits being imposed on carbon dioxide emission and other metallurgical pollutants. According to statistics compiled in 2015, the average fuel ratio for a blast furnace (BF) in China is 450—500 $kg \cdot t^{-1}$[2]. Fuel consumption in blast furnace iron production is high and further achieving carbon savings and low CO_2 emissions from the blast furnace process is extremely urgent. Therefore, it is very strategically important to further reduce the quantity of carbon consumed in the ironmaking process.

As proposed by Pamm[3], the influence of direct reduction on the carbon consumption in blast furnace has a huge impact on the process. This was aptly illustrated by Pamm in his plot of carbon consumption and degree of direct reduction[3]. The use of carbon in the blast furnace as well as the potential for carbon savings and the direction for research in reducing carbon consumption can be intuitively observed from the data in Pamm's work. However, there are considerable limitations in the traditional relationship between carbon consumption and de-

* Corresponding author. Ph.D.; Tel.: +86-13811569346, +86-10-82376018.
E-mail address: *shexuefeng@ustb.edu.cn* (*X. F. She*).

Received 19 September 2016; Received in revised form 21 February 2017; Accepted 24 February 2017
Available online 15 June 2017
1006-706X/

gree of direct reduction, because only the FeO reduction of iron oxides is calculated. In fact, several reduction reactions including both Fe_2O_3 and Fe_3O_4 occur in a blast furnace. In addition, the use of pulverized coal injection technology sharply increases the hydrogen contentin the reducing gases. However, the influence of the hydrogen content on carbon consumption is not considered in the traditional relationship, so that the total carbon consumption in an actual blast furnace is not reflected in Pamm′s assessment.

With this background in mind, a new technology called the oxygen blast furnace (OBF) iron production process has emerged overtime and has been perfected for several decades. This process is characterized by an increase in the reduction potential of the blast furnace gas[4], so that the level of direct reduction can be significantly reduced to less than 0.1[5,6]. At present, the oxygen blast furnace ironmaking process has been investigated using high-temperature tests[7-9] and numerical simulations[10-13]. However, few researchers have addressed the potential for energy saving in the blast furnace by investigating the relationship between the degree of direct reduction and carbon consumption. Furthermore, the same relationship in the OBF has not been established yet.

In this study, the intent was to analyze energy consumption in Chinese steel works by using a newly developed relationship chart that describes carbon consumption and degree of direct reduction in the process based on the excess coefficient of the reduction reactions. This relationship should effectively reflect the actual situation in a blast furnace operation. Moreover, two ways of carbon saving in BF were investigated; one was recycling the top gas with removal of CO_2 and H_2O, and the other was hydrogen-rich oxygen blast furnace. Some policy implications were proposed based on the analysis of the relational chart describing energy consumption.

2. Carbon Consumption Theory of TBF

2.1. *Carbon consumption of direct reduction on minor elements*

There are three factors that affect the carbon consumption in a blast furnace: (i) carburization of pig iron and reduction of minor elements; (ii) reduction of iron oxides, which includes direct reduction and indirect reduction; and (iii) production of heat to meet the temperature requirements of blast furnace process. The carbon consumption of a blast furnace is determined from the production of 1 t hot metal. It is assumed that the reduction of Fe_2O_3 to Fe_3O_4 and Fe_3O_4 to FeO is accomplished by CO, which is part of the indirect reduction. The chemical composition of hot metal was provided by Laiwu Iron and Steel Ltd. in China as shown in Table 1. Table 1 shows that the carbon consumption from the carburization of the hot metal is 41.4 kg · t^{-1} and the carbon consumption by the reduction of minor elements (Si, Mn and P) can be calculated using Eq. (1).

$$C_{Si,Mn,P}=12/28w_{[Si]}+12/55w_{[Mn]}+60/62w_{[P]}=(12/28\times0.5+12/55\times0.15+60/62\times0.08)/100\times1000=5.43\ kg\cdot t^{-1} \quad (1)$$

where, $C_{Si,Mn,P}$ is the carbon consumption on direct reduction of minor elements per ton hot metal, kg · t^{-1}; and $w_{[Si]}$, $w_{[Mn]}$, and $w_{[P]}$ are the mass fractions of Si, Mn, and P in hot metal, respectively, %.

Table 1
Chemical composition of hot metal from a major iron and steel company in China (wt.%)

Fe	Si	S	P	Mn	C	Total
95.10	0.50	0.03	0.08	0.15	4.14	100.00

Currently, the chemical composition of hot metal in the steel industry is quite consistent. Thus, the two main factors that control the carbon consumption in a blast furnace are the reduction of iron oxides and heat required to melt the constituents.

2.2. *Effectiveness of hydrogen as reducing agent*

The technology of pulverized coal injection is widely used in blast furnace technology to decrease the rate of coking. The hydrogen contained in the coal is used in the process of reducing the iron oxides, which decreases the overall carbon consumption in the process. However, the utilization of the available H_2 is extremely limited by the balance of CO, CO_2, H_2 and H_2O in the chemistry of the process. Previous research[14] has reported that the utilization rate of H_2 in the TBF is about 30%−50%. However, more than 80% of the available H_2 can participate in reduction reactions in a blast furnace, which directly replaces carbon and participates in FeO reduction.

The assumptions used for calculations of hydrogen utilization were: (1) the utilization rate of H_2 is 40% and it is used exclusively in the reduction reaction of FeO; (2) in the smelting process in China′s large steel works, the amount of pulverized coal injection is maintained as 150 kg · t^{-1}, in which the H_2 content is 4% (mass percent). Then, the degree of reduction of H_2 for reducing FeO was calculated as follows:

$$r_{H_2}=w_{coal}\varphi(H_2)\times0.4\times56/2\times1/w_{[Fe]}=150\times0.04\times0.4\times56/2\times1/951=0.07 \quad (2)$$

where, r_{H_2} is the degree of FeO reduction by H_2, %; w_{coal} is the amount of pulverized coal injection for each ton of hot metal, kg · t^{-1}; $\varphi(H_2)$ is the