Energy consumption in smelting reduction (SR) processes

(Consumo de energia em processo de redução direta (SR))

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Resumo

Ao contrário dos processos convencionais, onde são utilizados coque e hematita nos altos-fornos, combustíveis e minérios de ferro alternativos podem ser utilizados nos processos de fusão-redução, como carvão vegetal e finos de minérios de ferro a fim de produzir ferro esponja. . O uso dessas matérias-primas alternativas, através desses processos, pode amenizar os impactos ambientais e reduzir os custos de processos. Os conceitos da razão teórica de consumo de gás, a energia da redução do minério de ferro e os valores calóricos efetivos foram introduzidos primeiro. A razão de consumo de gás, na prática, e o consumo de gás, como unidade de redução na fusão-redução foram discutidos e calculados. A relação de carvão consumido e a variação da redução do minério de ferro no leito fluidizado também foram discutidos. A influência da pós-combustão no consumo de carvão no banho de minério no forno, como consumo de energia em diferentes combinações de quatro equipamentos foram calculados e discutidos.

Palavras-chaves: Fusão redução, consumo de energia, otimização de processo.

Abstract

In contrast, conventional processes use coke and hematite/sinter in the blast furnace, in SR processes, other alternative fuels and iron ore sources, like charcoal and fine iron ores, can be used to produce sponge iron. The use of these alternative sources, by SR processes, can reduce environmental impacts and lower production costs. At first, the concepts of the theoretical gas utilization ratio, the smelting heat of the iron ore and the effective calorific value of coal were introduced. Then, the reason for gas utilization ratio and its performance in the shaft as a reducer in the smelting process are discussed and calculated. The relationship between coal consumption and iron ore reduction in the fluidized bed are also discussed. Finally, the influence of post-combustion on coal consumption in an iron bath furnace are calculated and discussed.

Keywords: *Smelting reduction, energy consumption, process optimization.*

1. Introduction

The blast furnace is one of the most efficient reactors, and produces more than 95% of World's pig iron. However, it relies on metallurgical coke and charcoal as fuel, of which there is a worldwide shortage. Moreover, it requires agglomerated or lump feed, creates environment pollution and is more economically viable for plants with a capacity of more than 2 Mt. per year. These limitations have led to renewed interest in alternative methods of Iron making and the direct reduction method for solid sponge iron production of is the most successful, commercially. However, the economic advantages of liquid iron have led to the development of a different alternative known as the Smelting Reduction (SR) process (Fang, 2002; Gupta, 2005).

Since the 1980s, a number of SR processes have been developed, some of which have reached the pilot plant stage and only one, the COREX process, has been commercialized up to the year 2000. The advantages of SR processes, besides being hot metal production, are the use of non-coking coal instead of coal; the possible use of fine ores and pellets; and the reduction of costs? due to the smelting intensity (Kobayashi, 2001). However, the technology is yet to be improved with respect to energy consumption; to make the process more competitive with the existing ones (Delport et al., 1990, referenced Assis & Sampaio).

From the environmental point of view, these new processes are the best alternative for reducing waste production in this field. Most of them can use no coking coal, which is responsible for more than 70% of the existing sources in the world. Thus, it has been possible to replace part of coke making stage, which is polluting (Feng et al., 2004). Although fine ores, iron, and steelmaking wastes are used in the sintering and pelletizing processes, some plants are already able to achieve the product before these treatments. The COREX process doesn't need sinter to be part of the smelting components. Therefore the dioxins generated by sintering are avoided. Concerning fuels, the SR process can still make use of fuel gases and some oils in their reactions instead of coke (Hughes et al., 2001).

2. Materials and methods

2.1 Gas utilization ratio

The gas utilization ratio is an important parameter for the smelting reduction unit. It is the defining factor for the gas quantity needed by reduction unit.

There are several direct reduction devices that can be used for smelting reduction. The shaft and fluidized bed are the most practical and are usually selected by the smelting reduction designers.

The distribution of gas, ore and temperature in a shaft is continuous. This is the most important characteristic of the shaft. Hence the gas utilization ratio can be calculated by equilibrating the reducing reaction of FeO at 843 K (Fang, 1996) according to Equation 1:

$$\eta_t = (0.48 - 0.26 x_H)\frac{x - 1 + R_m}{\frac{1}{3} + R_m} \tag{1}$$

Where, η_t is the theoretical gas utilization ratio; x_H is the mol fraction of H_2 and H_2O in H_2, H_2O, CO and CO_2; x is the mol proportion of O and Fe in the iron ore; and R_m is the metallization degree of reduced product. The best iron ore for smelting reduction and direct reduction is hematite. Therefore x approximately equals 1.5. Let R_m equal 0.92, the simplified formula for the gas utilization ratio calculation follows Equation 2:

$$\eta = 0.544 - 0.295 x_H \tag{2}$$

The data from different industrial shafts have proved that the actual gas utilization ratio can be estimated using η_t. Figure 1 shows the relationship between η and x_H; where the line was calculated using Equation (2); BL is a pilot shaft

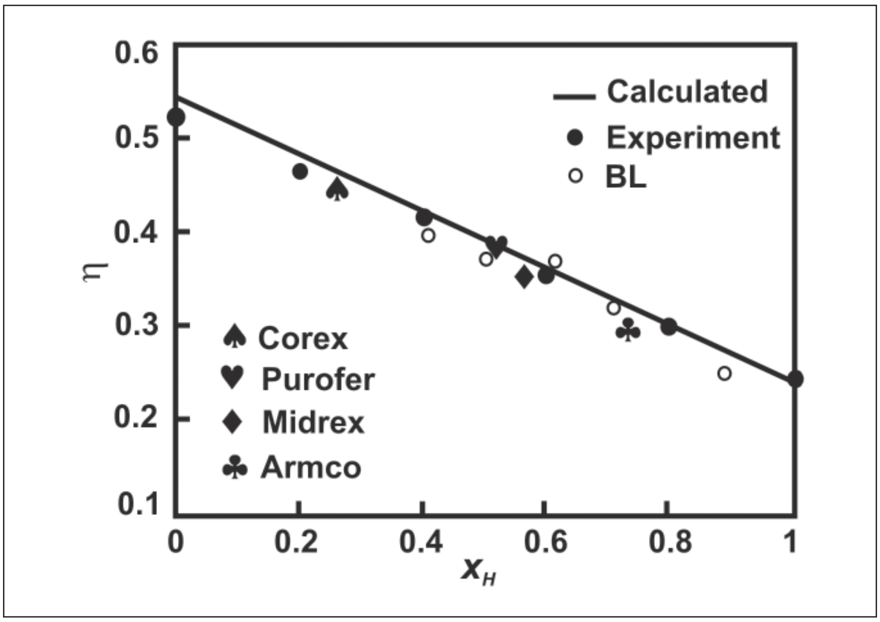

Figure 1 - Relationship between η and x_H.

process at Bao Steel in China and the experiment data was obtained from a simulating shaft in a laboratory (Fang, 2002). To a large extent, gas utilization depends on the physical and high temperature properties of pellets particularly the fines generation; i.e. permeability of the bed in the Reduction shaft. It should be mentioned that the ideal condition is considered in this picture. x_H is the mole fraction of H_2 and H_2O in H_2, H_2O, CO and CO_2 of whichever gas (Reducing or Top gas).

2.2 Smelting heat of iron ore

Smelting heat HS is the heat consumption necessary for iron ore smelting. It is intensively influenced by the metallization degree R_m of pre-reduced iron ore and can be calculated through heat balance. For R_m=1, it is considered that the calcinations of limestone and dolomite is 100%.

Let R_m=1 and calculate the heat consumption for smelting to get the first part of the smelting heat Q1 as a constant and calculate the second part of the smelting heat Q2 for reduction in the smelting furnace. An approximate formula for the smelting heat calculation with the form of a + b R_m can be obtained according to HS=Q1+Q2.

2.3 Effective calorific value and gas production from coal

The heat from coal combustion is marked as Q_t. It can be divided in two parts. One of them is gasification heat Q_g, which can be the gas's physical heat, decomposed heat, slag heat or other heat irrespective of smelting. The difference of Q_t and Q_g is the effective calorific value Q_e. Q_e is heat for smelting. Q_e in different smelting gasifiers for the same coal is different. The gas temperature in the smelting furnace as the combustion supporter has the greatest influences on Q_e. Industrial pure oxygen will be used as the combustion source in following discussion.

Reduction gas composition and quantity pg are mainly influenced by the C and H_2 contents of coal. An important parameter for gas is x_H. It has a great influence on gas utilization ratio.

3. Results

3.1 Reduction and smelting

The main reasons for using a reduction unit are to reduce and preheat the iron ore. Therefore the metallization degree and temperature of the reduced iron ore are main parameters of reduction.

The metallization degree of iron ore in the shaft can be over 90%, if the temperature of the iron ore is between 1073-1123 K. The temperature and utilization ratio of the reducing gas are dependent on x_H.

Gas temperature and x_H have an approximately linear relationship (Equation 3):

$$T_g = 814 + 262x_H \quad (3)$$

The reduced iron ore from the shaft contains about 712,000kJ of physical heat per ton hot metal.

The reduction in a fluidized bed is relatively easy. As mentioned above, iron ore can only be reduced to FeO to avoid a sticking problem. For one ton hot metal about 8.5 kmol of reducing gas is needed. The temperature limit for preheating is about 1,273 K. At a higher temperature, there is a risk of a liquid phase appearing in the fluidized bed. The reduced iron ore from a fluidized bed contains about 1,147,000 kJ of physical heat per ton hot metal (Gudenau, 1989).

A coal-fluidized bed is found in the COREX smelting? Gasifier, which is the only industrialized smelting furnace designed for SR processing. One of its features is a carbon-containing fluidized bed. Carbon gasification reaction can be carried out in the bed and effective temperature gradients can be formed in the furnace. Therefore, the gas temperature can be decreased. To avoid the appearance of coal tar, the gas temperature is commonly controlled at about 1373 K. Under this condition the effective calorific values of QLS, YQ and SF are separately 3670, 3132 and 1978 $J.g^{-1}$ with coal moisture of 5% and a gas oxidation rate of 1.3%.

There is no carbon-containing bed in an iron bath furnace. So it is impossible to control the gas temperature at a low level. In compensation, the post-combustion can be carried out in an iron bath furnace, which is impossible in a coal-fluidized bed. The effective calorific value of coal can be increased by post-combustion on a large scale. But the heat efficiency will be also decreased, due to the rising of the gas temperature.

4. Discussion

4.1 Energy consumption

Suppose that QLS coal and CVRD pellets are used. The energy consumption for the process with a combination of a shaft and a coal-fluidized bed can be calculated as follows (Kamijo et al., 2001).

The reducing gas consumption ($kmol.t^{-1}$) is (Equation 4):

$$M_g \approx \frac{8.542 + 17.125R_m}{\eta} \approx 18.02 + 36.13R_m \quad (4)$$

The combustion coal consumption ($kg.t^{-1}$) is (Equation 5):

$$M_{cl} \approx \frac{H_S - 712000}{Q_e} \approx 1735 - 1263R_m \quad (5)$$

The carbonized coal consumption ($kg.t^{-1}$) is about 53 $kg.t^{-1}$. About 1 kmol of gas can be produced with that.

The coal consumption is calculated based on Equation 6:

$$M_c = M_{cl} + 53 = 1788\text{-}1263R_m \qquad (6)$$

The gas production quantity (kmol.t^{-1}) can be determined by using Equation (7):

$$p_g = 0.0934M_{cl} + 1 = 163 - 118R_m \qquad (7)$$

Figure 2 shows the combination of reduction and smelting. M_g is increased with the rising of R_m and p_g is reduced by the rising of R_m. The two lines intersect at point O. At this point the produced reduction gas quantity in the smelting furnace just equals the gas quantity needed for the reduction unit. Therefore, energy consumption at this point reaches its lowest value.

According to point O, it can be calculated that the optimal R_{mo} is 94% and the coal consumption *Mc* equals approximately 600 kg.t^{-1}. If $R_m > R_{mo}$, the produced gas will be not enough for reduction. Some gas must be used circularly. If $R_m < R_{mo}$, excess gas will be produced. In these two cases the energy consumption will be increased. Therefore point O is the optimal operating state and coal consumption at O is also optimal, although it may not be the lowest.

If the HS is too high or the Q_e too low, point O may not exist or R_{mo} is over the attainable value for the industrial shaft. Under this condition a lot of gas (in excess) will be produced. The coal consumption will be as high as 1,400kg.t^{-1}, although a high R_m over 95% will be used.

The best way to decrease the coal consumption in this case is to use a smelting coal with higher effective calorific value or an iron ore with lower smelting heat.

The combination of a fluidized bed and an iron bath furnace has other regulations. Post-combustion can effectively increase the effective calorific value of the smelting coal. The first problem for a high post-combustion rate is the temperature of the gas. Another main factor for limiting the increase in the post-combustion rate is the reducing gas's requirement. To reduce iron ore to FeO about 8.5 kmol of reducing gas is needed for 1-ton hot metal. Thinking on this requirement and the temperature, a value of about 0.45 is perhaps a suitable limit for the post-combustion rate.

Figure 3 shows the relationship of coal consumption and post-combustion rate for the combination of a fluidized bed and an iron bath using QLS coal and CVRD pellets, most likely to be fine ore. The coal consumption is much higher than that of the combination with the shaft and coal fluidized bed. But fine ore can be directly used by this combination. The coal consumption can be compensated to a certain scale in this way.

Fluidized bed (FB), shaft (S), coal fluidized bed smelting furnace (FSF) and iron bath converter (IBC) can be arranged in 4 different combinations. Taking the reclaiming rate of the chemical heat in gas as 100% and that of the physical heat as 80%, energy consumption of the different combinations can be calculated as in Table 1.

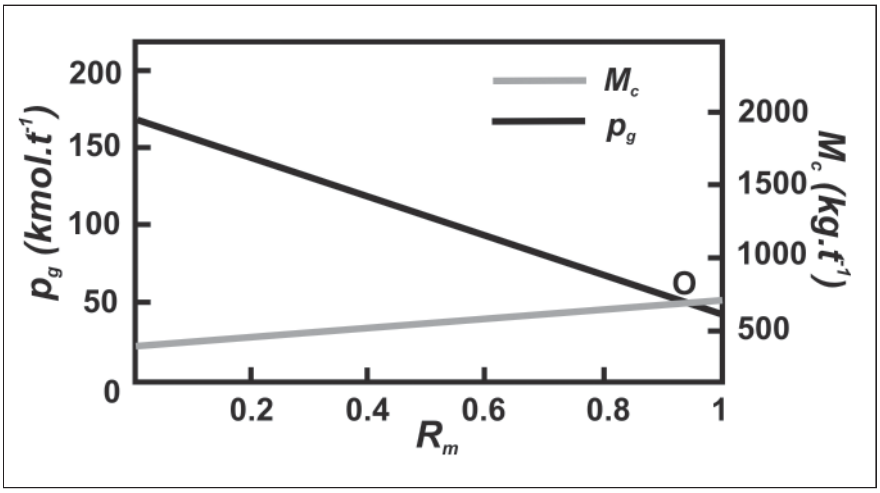

Figure 2 - Combination of reduction and smelting.

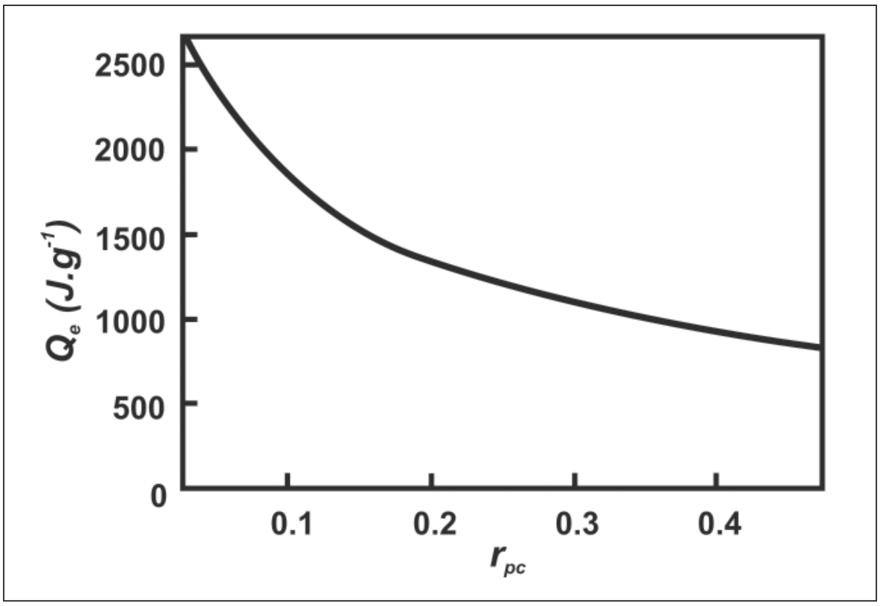

Figure 3 - Influence of r_{pc} on Q_C.

The energy consumption of the shaft and iron bath combination is the largest. That is to say that a high post-combustion rate is needed when using an iron bath as the smelting unit. The energy consumption of the fluidized bed and coal fluidized bed combination is very large. The main problem is that the reduction degree is too low. A high degree of metallization is needed when using a coal-fluidized bed.

An important difference between the fuels used for smelting reduction and in the blast furnace is their effective calorific value. The effective calorific value for smelting reduction is mostly much lower than that of metallurgical coke. Table 2 shows the effective calorific values of some smelting coals.

Figure 4 is the relationship between standard coal consumption M_{cs} and Q_e using the coals shown in Table 2 and the CVRD pellets for the COREX process.

In the area of lower Q_e, the coal consumption reduces quickly with the rising of the effective calorific value. As Q_e increases from 1000 to 2000 J.t^{-1}, 800kg of standard coal will be reduced. The influence is much weaker in the area of high effective calorific value. The lowest coal consumption appears at an effective calorific value of about 2750 J.g^{-1}. If the effective calorific values rise further, even if the real coal consumption decreases, the standard coal consumption will increase on a small scale.

The important thing for COREX is to find coal with a high effective calorific value and make sure this coal is the major part of the smelting coal, which can be a mixture of coals. Take such coal as main part; suitable smelting coal can be mixed up. When usingUsing smelting coal with a suitable effective calorific value, the energy consumption and the quantity of excess gas in excess will be decreased from present state in on a great scale.

It should also be pointed out too that the coal consumption depends to a large extent on the operating parameters and also depends on the coal's physical and high temperature properties like

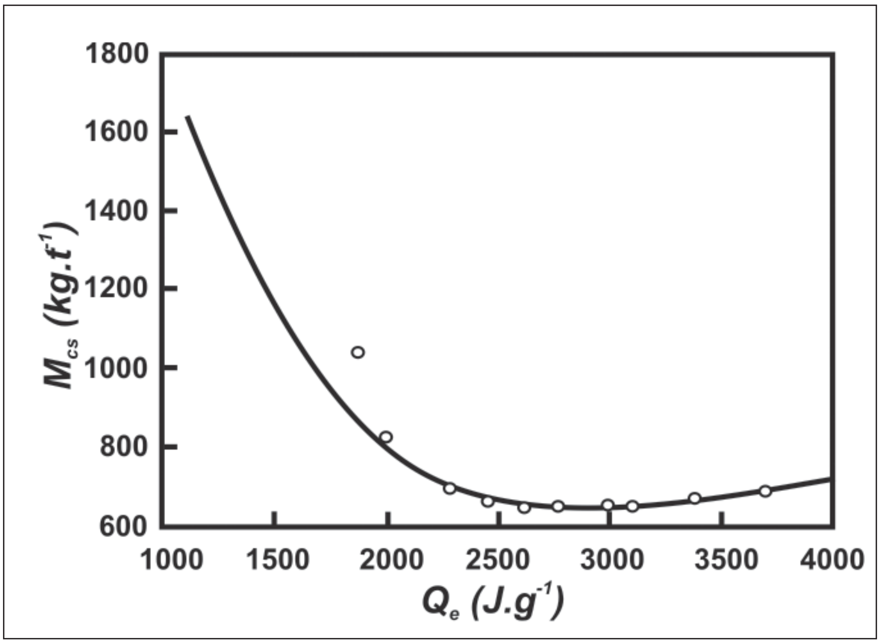

Figure 4 - Influence of Q_e on coal consumption.

Table 1 - Energy consumption of the different processes (GJ.t^{-1}).

Combination	Coal	Oxygen	Ore	Gas (chem.)	Gas (phy.)	Sum
S+FSF	19.65	2.30	3.01	-8.01	-0.75	16.20
S+IBC (r_{cp}=0)	89.15	10.43	0	-60.47	-8.52	30.59
FB+FSF	58.55	6.85	3.01	-41.88	-3.21	23.32
FB+IBC (r_{cp}=0.4)	35.89	6.40	0	-13.94	-6.95	21.40

Table 2 - Effective calorific values of some coals (GJ.t^{-1}).

Nr.	1	2	3	4	5	6	7	8	9	10	11
Q_e	3,670	3,400	3,132	2,922	2,782	2,620	2,440	2,332	1,978	1,854	1,005

thermal decrepitating index, coal char CSR, CRI, similar to Coke CSR and Coke CRI for the blast furnace (Delport, 1990).

5. Conclusions

1. The selection of coal and iron with suitable effective calorific value and smelting heat is very important for reducing the energy consumption of smelting processes using a shaft and coal-fluidized bed combination.
2. A high reduction degree is needed for smelting reduction with a coal-fluidized bed as the smelting unit. Otherwise the energy consumption will be very high.
3. A high post-combustion rate is necessary for an iron bath furnace.
4. For the process with large amount of excess gas, the reclaiming rate of the gas's physical heat must be increased. Otherwise the energy consumption will not be acceptable.

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