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STATIC MODEL STUDY ON THE CHARACTERISTICS OF COKE OVEN GAS DOME INJECTION IN COREX MELTER GASIFIER

Coke oven gas (COG) dome injection in COREX melter gasifier is recognized as one of effective method to reduce the amount of solid fuel used for gasification. In this work, a static model was developed to study the characteristics when COG is injected from dome. The critical bosh gas and critical fuel rate in COREX melter gasifier under different melting rate and coke rate were discussed. The amount of COG injection from dome under the critical fuel rates was studied. The results shows that when the heat of bosh gas reaching the critical value, the decrement of fuel rate decreases with the increase of melting rate and increases with the increase of coke rate. Under the critical fuel rate, the total volume of COG increases with the increase of melting rate and coke rate. After the COG injection, the amount and reduction capacity of the generator gas can meet the needs of reduction in shaft furnace. The findings of this work can be used as a theoretical basis to guide plant operations for COG injection.

Keywords: Coke oven gas injection, COREX melter gasifier, fuel rate, static model

1. Introduction

At present, more attention is attracted to global warming and CO_2 emission from coal-fired industries such as power plant and steel industry. In the latter, the BF-BOF process is the dominant steel production route, and the blast furnace, one of the sectors of the traditional BF-BOF process, occupies the most energy consumption and CO_2 emission, which account for over 50 and 70% of the total steel industry, respectively [1,2]. For these reasons, various new technologies in ironmaking process are developed in recent decades to reduce energy consumption and CO_2 emission [3-7]. Among these technologies, COREX, a smelting reduction process, is regarded as a cost-efficient and environmental-friendly process, which produces hot metal from iron ore and coal. The COREX-3000 process, which is the largest plant with a design production capacity of 1.5 million tons of hot metal per year, has realized industrial scale production at Baosteel in China [8,9]. However, with the large-scale of equipment and increasing of reactors volume, COREX-3000 involved in some technical problems [10], which directly restrains the competitiveness of the whole process. In order to reduce the product cost, one COREX-3000 module in Baosteel, Shanghai was moved to Basteel, Xinjiang for utilizing local coal resources. Owing to the COREX process in Xinjiang is adjacent to the traditional blast furnace ironmaking plant [11], the surplus coke oven gas (COG) in the ironmaking plant can be used by the COREX process to reduce solid fuel consumption and thus cut down costs.

Melter gasifier is the key reactor of COREX process. The hot DRI along with partially calcined fluxes from the shaft furnace are discharged to the top of the melter gasifier in solid state. Solid fuel is fed into the melter gasifier and oxygen is blown through the tuyeres, which gasifies the coal and generates reducing gas and heat. The hot reducing gas rises and transfers its sensible heat to the semi-coke bed, providing the need for slag/metal separating and other chemical reactions. Generally speaking, the two main functions of the melter gasifier are melting and gasification. Besides, it should be pointed out that the most innovative feature of the melter gasifier is the secondary injection system installed in dome zone. Collected dust is returned to the melting gasifier through the dust burner arranged above the semi-coke bed to combustion with auxiliary oxygen [12,13]. Therefore, on the premise of providing heat and realizing the slag/metal melting, part of the gasification function can be replaced by injecting reducing gas from the secondary injection system. Predictably, COG injection from dome in COREX melter

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gasifier is recognized as one of feasible measures to decrease the fuel rate through reducing the amount of fuel for generating reducing gas.

Blast furnace operation with COG injection has become one of the important research focusses in the word [14-16]. For example, the combustion reactions in the tuyere [17] and the characteristics of blast furnace raceway [18] with COG injection are studied. The effects of COG with oxygen enrichment injection into blast furnace on CO_2 emission, theoretical flame temperature, direct reduction rate and so on are investigated through the heat and mass balance calculation [19,20]. Multi-fluid model is developed to study the inner characteristic of blast furnace operation with COG injection [21]. Furthermore, a blast furnace process of COG injection together with top gas recycling through tuyere injection and/or shaft injection has been mathematically simulated [22]. These works are useful for understanding COG injection in blast furnace, whereas the difference between a blast furnace and a COREX process makes it impossible for the latter to draw experience directly from COG injection in a blast furnace. Recently, the characteristics of COG injection from tuyere in a COREX melter gasifier were investigated by Wu et al. [23]. The authors also developed a static model to study the COG dome injection for adjusting dome temperature [24]. However, so far, the effect of COG injection from dome on fuel rate has not been studied, particularly the critical fuel rate in COREX melter gasifier with COG injection.

In this work, a static model was developed to study the characteristics of COG dome injection. The critical bosh gas was firstly calculated, and then the extremity fuel rates in COREX melter gasifier under different melting rate and coke rate were discussed. The amount of COG dome injection under the critical fuel rates was studied. Finally, the influence of COG dome injection on the composition of reducing gas was also discussed. This work could lay theoretical basis and technological support for control and optimizing the COREX process with COG injection.

2. Static model and computation method

2.1. The overall static model

The consumption of raw material (iron ore, fuel, and flux) in the static model can be calculated based on the three balance equations (Fe, C, and binary basicity (R_2)). The slag amount can be calculated through the slag balance equation and is determined by the amount of quartz and other gangue materials. Details about the input items of the static model can be found in our previous works [23,24]. The balance equations of Fe, C, R_2 and slag are shown:

$$\sum_i m_i \times w_{\mathrm{Fe}_i} = m_{\mathrm{HM}} \times w_{[\mathrm{Fe}]} + m_{\mathrm{slag}} \times w_{(\mathrm{FeO})} \times 56/72 \tag{1}$$

$$\sum_i m_i \times w_{\mathrm{C}_i} = m_{\mathrm{HM}} \times w_{[\mathrm{C}]} + \\ + \left(V_{\mathrm{CO}} + V_{\mathrm{CO}_2} + V_{\mathrm{CH}_4}\right) \times 12/22.4 \tag{2}$$

$$R_2 = m_{\mathrm{CaO}} / m_{\mathrm{SiO}_2} \tag{3}$$

$$m_{\mathrm{slag}} = \left(\begin{array}{l} m_{\mathrm{CaO}} + m_{\mathrm{SiO}_2} + m_{\mathrm{Al}_2\mathrm{O}_3} + m_{\mathrm{MgO}} + \\ + m_{\mathrm{CaS}} + m_{\mathrm{P}_2\mathrm{O}_5} + m_{\mathrm{MnO}} + m_{\mathrm{TiO}_2} \end{array}\right) \Big/ \left(1 - w_{(\mathrm{FeO})}\right) \tag{4}$$

where, i is the raw materials including coal, coke, iron ore, dolomite, limestone and quartzite; m_i denotes the mass of raw materials for producing 1 t hot metal, kg; $w_{\mathrm{C}i}$ and $w_{\mathrm{Fe}i}$ respectively represent the mass fraction of C or Fe in raw material i; m_{HM} is the mass of hot metal, which is 1 t in this study; m_{slag} is the mass of slag, kg; $w_{[\mathrm{C}]}$ and $w_{[\mathrm{Fe}]}$ denote the mass fraction of C or Fe in hot metal, %; $w_{(\mathrm{FeO})}$ denotes the mass fraction of FeO in slag, %; V_{CO}, V_{CO_2}, V_{CH_4} represents the volume of CO, CO_2 and CH_4 in export gas for producing 1 t hot metal, respectively, m^3/t; m_j (j = CaO, SiO_2, $Al_2O_3 \cdots$) represents the mass of j in slag, kg.

Through solving the balance equations of C, H, O, and N in shaft furnace and melter gasifier after the raw material consumption is received, the volume and composition of top gas in each furnace can be obtained. For heat balance, energy conservation in the pre-reduction shaft furnace and melter gasifier is calculated. The heat balance equations are solved by calculating the "heat income" from input materials and heat from carbon consumption. "heat output" includes the heat taken away by the top gas and the absorption heat of direct reduction. On the other hand, the heat balance of the whole COREX process is investigated.

2.2. Critical bosh gas

In order to meet the demand of mass, momentum and heat transfer between gas and solid phase in the high temperature zone of the lower part of the melting gasifier, the amount of bosh gas should not be too low. The higher the heat of bosh gas, the more energy is transferred to the burden, and the larger the heat income of the hearth zone. According to the income and output of the material in the packed bed of melter gasifier, when the fuel decreases, the amount of carbon burned in the tuyere decreases, causing the combustion heat and the volume of bosh gas decrease. The reducing of the heat of bosh gas leads to the decrease of the heat of burden (slag and metal), which causes the decrease of heat income of hearth zone. Based on the practical production experience, the temperature of hot metal and slag should not be lower than 1500°C and 1550°C, respectively. Therefore, in this work, the critical bosh gas is obtained when the temperature of hot metal and slag leaving the packed bed are 1500°C and 1550°C, respectively. Besides, the temperature of reducing gas leaving the top of packed bed is assumed as 850°C, which is 50°C higher than the solid temperature. In the raceway zone, the heat income is coke sensible heat, combustion heat and sensible heat of slag and melter. The heat output is sensible heat of gas, sensible heat of slag and melter and the heat loss. With the increase of melting rate, the amount of oxygen increases resulting an increase of combustion heat. While the sensible heat of slag and melter of heat income decreases due to the decrease of residence time of burden in packed bed. On the other hand, the amount of reducing gas leaving the raceway increases with the increase of melting rate. Therefore, the temperature of the reducing gas leaving the raceway varies with the change of melting rate, but the change is not significant. In this work, the temperature of the reducing gas leaving the raceway is assumed as 3500°C, which is closed to the value in previous work [25]. Schematic diagram of the condition of the packed bed zone in gasifier melter is shown in Fig. 1.

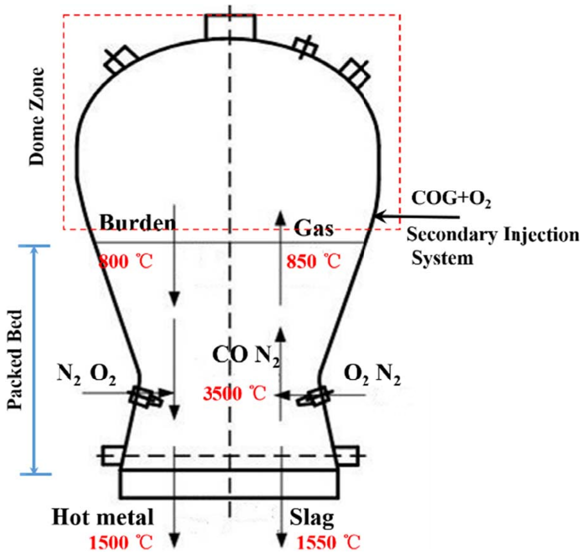

Fig. 1. Schematic diagram of packed bed in COREX gasifier melter

On the basis of the overall COREX process model, the results of composition of the slag and hot metal can be obtained as the boundary condition of the packed bed, and the composition of generator gas are used as the boundary condition of the dome zone. After calculating the dome zone, the composition of reducing gas leaving the packed bed can be obtained.

Based on the zoned static model, the critical volume of the bosh gas to meet the heat demand is 670.71 Nm^3/t, and the corresponding bosh gas heat is 4413.16 MJ/t.

3. Results and discussion

3.1. Model validation

In order to validate the reliability of the model, the results of this model were compared with the results from plant data for slag basicity, as shown in Fig. 2(a). It can be seen that the predicted slag basicity matches well with the actual values. The maximum difference between predicted and actual values is 8% for the slag basicity in the range of 1.18 to 1.38. Fig. 2(b) shows the comparison of calculated and actual export gas volume. The results show the similar tendency and the predicted value are basically consistent with the actual data. These agreements verify the applicability of the present static model for predicting the characteristics of COG injection from dome.

3.2. Critical fuel rate

In order to clarify the effect of COG injection from dome on fuel rate, the initial fuel rate under different melting rate is firstly investigated. Fig. 3 shows the relationship between melting rate and fuel rate. In practice, some coke or semi-coke are added to increase the permeability of the packed bed in COREX melter gasifier. From the inset of Fig. 3, the melting rate is negatively correlated with the fuel rate through fitting the practice production data. All data are collected from Basteel practice production values. The relationship is obtained through fitting and can be described as y =1272.98-2.21x, where y denotes the fuel rate; x represents the melting rate. The standard error of the slope and intercept of the equation is 0.2 and 27.6 respectively. Based on this relationship, effect of coke rate on fuel rate is shown in Fig. 3. In the following work, for each melting rate, the influence of coke rate will be discussed under the condition that the coal is replaced by coke without changing the total fuel carbon content. With the increase of coke rate, the fuel rate decreases. The largest fuel rate is 1020 kg/t when the melting rate is 140 t/h and the coke rate is 150 kg/t.

Fig. 4 shows the effect of melting rate on the heat of bosh gas under different coke rates. Under the same coke rate, the heat

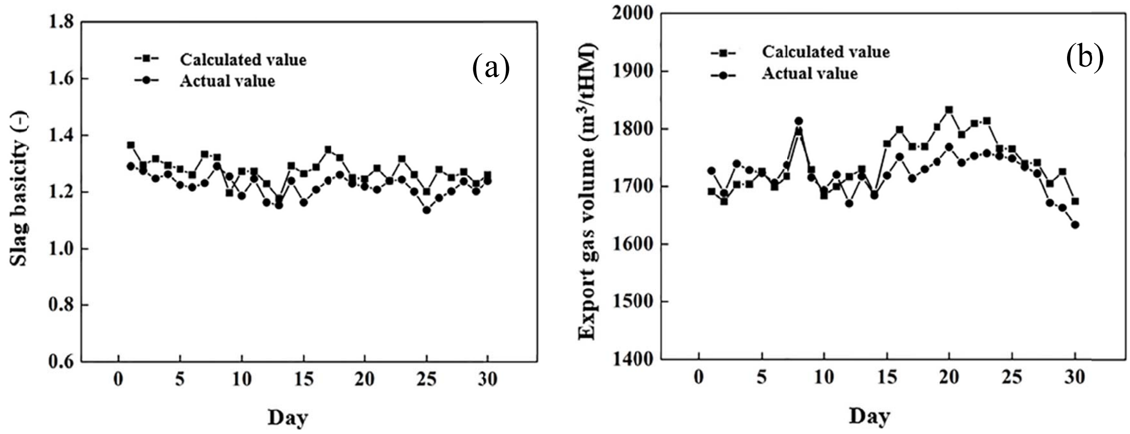

Fig. 2. The comparison of actual and predicted values (a) slag basicity; (b) export gas volume

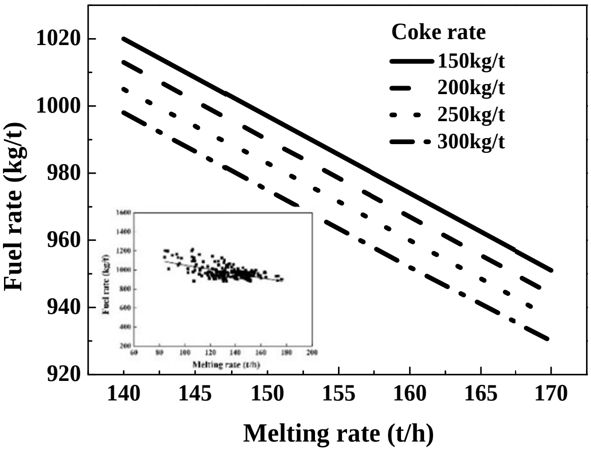

Fig. 3. Relationship between melting rate and fuel rate

of bosh gas decreased when the melting rate increased. The main reason for this is that with the increase of melting rate, the fuel rate is reduced, as shown in Fig. 3. The fuel consumption per hot metal decreases and the heat in melter gasifier reduces, leading to a drop of bosh gas energy. From Fig. 4, it can be seen that the heat of bosh gas increases with the increase of coke rate. This is attributable to the moisture and volatile matter amount in coke being lower than coal, demanding less heat. Besides, it should be pointed out that the heat of bosh gas under different melting rates is higher than the critical bosh gas heat, which means that the fuel rate can be reduced without affecting the heat demand of the gasifier melter.

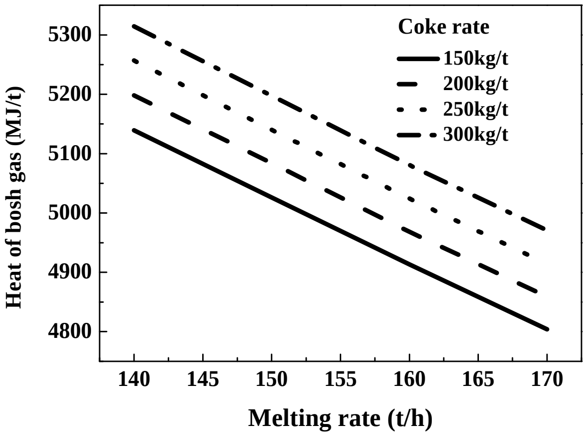

Fig. 4. Effect of melting rate on the heat of bosh gas under different coke rates

Fig. 5 shows the decrement of fuel rate under different melting rates when the bosh gas reaching the critical value. The decrement of fuel rate corresponds to the heat of bosh gas. Under low melting rate and high coke rate, the heat of bosh gas is higher and therefore the decrement of fuel rate is also larger. While under high melting rate and low coke rate, the minimum decrement of fuel rate is only 52 kg/t. Detail of fuel structure under the critical condition is shown in Table 1. In the following study, the dome temperature and volume of generator are calculated under the critical fuel rates.

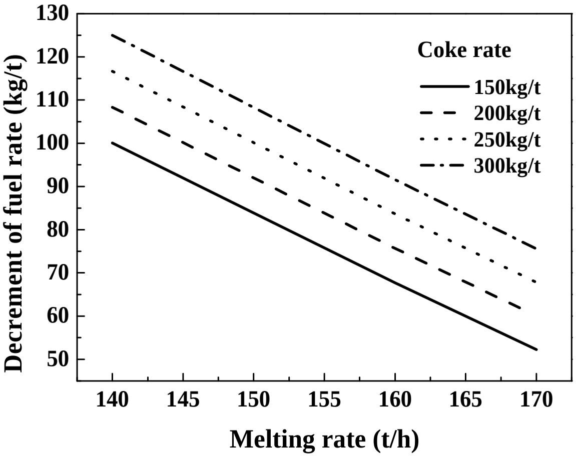

Fig. 5. Decrement of fuel rate under different melting rate

TABLE 1

Fuel structure under critical bosh gas condition (Unit: kg/t)

Melting rate Coke rate	140 t/h	150 t/h	160 t/h	170 t/h
150 kg/t	919.96	913.12	906.29	898.75
200 kg/t	904.64	897.99	891.33	883.97
250 kg/t	888.32	882.85	876.38	869.20
300 kg/t	873.00	866.72	860.43	854.42

Under critical fuel rate, the dome temperature and volume of generator gas in COREX melter gasifier are shown in Fig. 6. Fig. 6(a) shows the variation of dome temperature with melting rate. Since the heat can meet the normal smelting demand in the lower part of COREX melter gasifier, the heat of reducing gas rising from the lower part to the upper is not much different. Therefore, the dome temperature is mainly affected by the decomposition of coal and the amount of reducing gas. Under the conditions of low melting rate and low coke rate, the lump coal is used more and the dome temperature is lower due to the influence of decomposition heat. While under the conditions of high melting and high coke rate, the dome temperature is relatively high. From Fig. 6(a), it can be seen that the lowest dome temperature is 1002°C and the highest temperature is 1041°C, which are lower than the 1050°C required by the dome zone. Therefore, it is necessary to adjust the dome temperature.

Fig. 6(b) shows the volume of generator gas under critical fuel rate. Under the conditions of low melting rate and coke rate, due to the high use of lump coal, the amount of generator gas is relatively higher, and the largest volume is 1655 Nm^3/t. However, under high melting rate and coke rate conditions, due to the use of lump coal, the lowest volume of generator gas is only 1521 Nm^3/t. In this work, the metallization degree of iron ore in the shaft furnace is assumed as 60%, denoting that the required amount of reducing gas in shaft furnace should be 1530.54 Nm^3/t [24]. From the aspect of making full use of energy and saving raw materials, it seems that it is the optimum status when the volume of generator gas from melter gasifier equals the volume of reducing gas required by the reduction shaft. But this is not the actual situation. The temperature of the generator

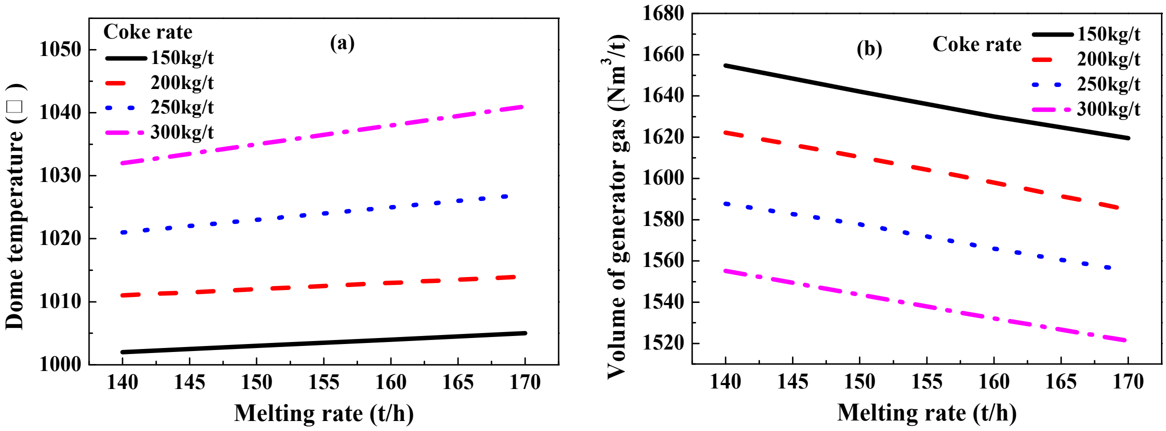

Fig. 6. Dome temperature (a) and volume of generator gas (b) under critical fuel rate

gas is 1050°C. However, the reducing gas for the shaft should be around 850°C for getting a smooth running of reduction shaft. It means a part of cooling gas should be added to the generator gas to decrease the gas temperature. The ideal optimum volume of generator gas should equal the sum of the volume of cooling gas and reducing gas. In this work, the volume of cooling gas is determined by the amount of heat released by the generator gas decreasing from 1050°C to 850°C, dividing the change of cooling gas temperature. The ideal optimum volume of generator gas is 1730 Nm^3/t.

3.3. COG dome injection

Since the dome temperature and volume of generator gas are not meet the production demand under critical fuel rate, COG injection from dome at room temperature can be adopted to adjust the dome temperature and supplement the volume of generator gas. The proportion of CO, CO_2, N_2, H_2 and CH_4 in the COG is 7%, 2%, 5%, 58% and 28%, respectively. The volume of COG dome injection for adjusting the dome temperature is shown in Fig. 7. As the dome temperature is generally lower than the appropriate one (1050°C), as shown in Fig. 5, the COG injection from dome is used for combustion. For low melting rate and coke rate conditions, the volume of COG is relatively large, up to 51 Nm^3/t level. While for high melting rate and coke rate conditions, the amount of COG is small, and the minimum injection volume is about 6 Nm^3/t.

Fig. 8 shows the volume of generator gas after COG injection. The volume of the generator gas is larger compared with the volume of generator gas before COG injection such as that shown in Fig. 6(b). The maximum value can reach 1734.5 Nm^3/t, and the lowest value is 1530.1 Nm^3/t. Comparing with the ideal optimum volume of generator (1730 Nm^3/t), the amount of generator gas after COG injection at a melting rate of 140 t/h and coke rate of 150 kg/t, satisfies the need of reduction in shaft furnace. While the volume of generator gas under other conditions is insufficient, which needs to be further adjusted.

The deficiency of the generator gas is supplemented by continue injecting COG from the dome zone, and supplemented with appropriate oxygen for temperature control, thereby achieving the purpose of satisfying the operation requirements of shaft furnace. Fig. 9 shows the volume of COG injection from dome for adding reducing gas. The volume of COG varies from 11 Nm^3/t to 180 Nm^3/t. With the increase of melting rate and coke rate, the amount of COG injection increases. Especially for the condition with a melting rate 170 t/h and coke rate 300 kg/t, the maximum injection can reach 180 Nm^3/t. The total amount of

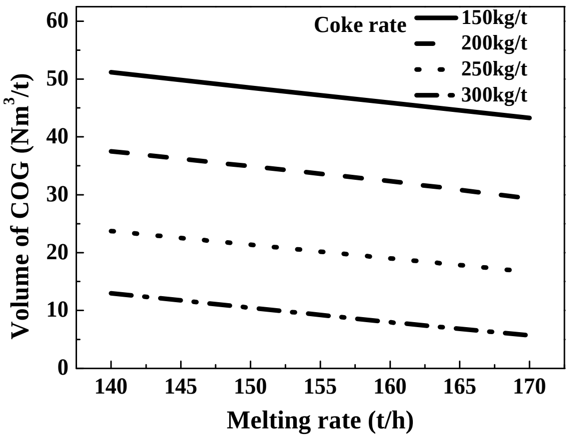

Fig. 7. The volume of COG injection from dome for adjusting dome temperature

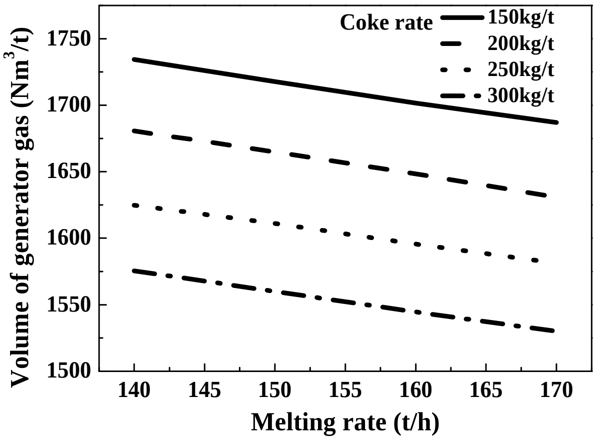

Fig. 8. The volume of generator gas after COG dome injection

COG injection used for temperature control and supplementing reducing gas is shown in Fig. 10. It can be seen from Fig. 10, with the increase of melting rate and coke rate, the total volume of COG increases. Although the amount of COG injection for temperature adjustment decreases with the melting rate and the coke rate increase, the volume of generator is lower due to the high melting rate and high coke rate, and the amount of COG used for gas supplement is more. Therefore, the high melting rate requires a large amount of COG injection at a high coke rate. The maximum amount of COG injection is 185.4 Nm^3/t. After the COG injection, the volume of the generator gas can meet the needs of reduction in shaft furnace.

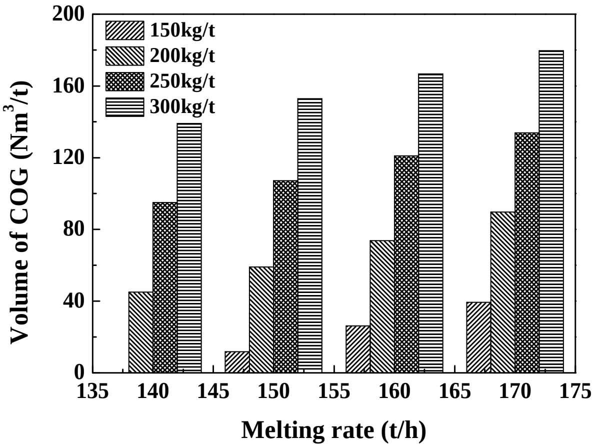

Fig. 9. The volume of COG injection from dome for adding reducing gas

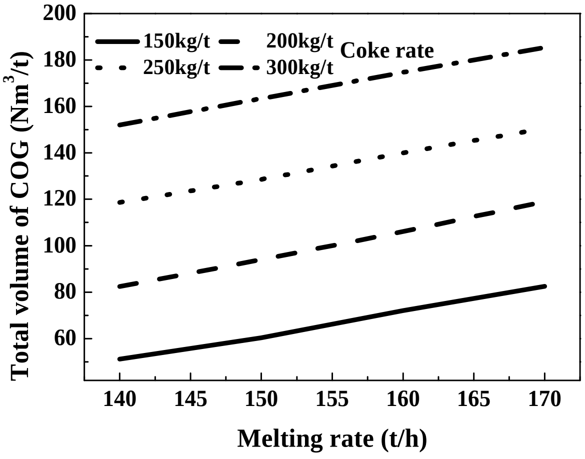

Fig. 10. Total volume of COG injection from dome

The volume fraction of generator gas after COG injection under the melting rate 160 t/h is shown in Fig. 11. When the coke rate decreases from 300 kg/t to 150 kg/t, the volume fraction of CO increases from 61.5% to 67.6%, but the H_2 volume fraction decreases from 22% to 19.2%. The main reason is due to the COG is injected for decomposition under high coke rate and for combustion under low coke rate. Further, the amount of the injected COG is especially higher in high coke rate condition. Therefore, with decreasing of coke rate, the volume fraction of H_2 and CH_4 decrease. Besides, the reduction capacity of the generator gas after COG injection under different coke rates is close to that in the basic case [24], which is suitable for reduction in shaft furnace.

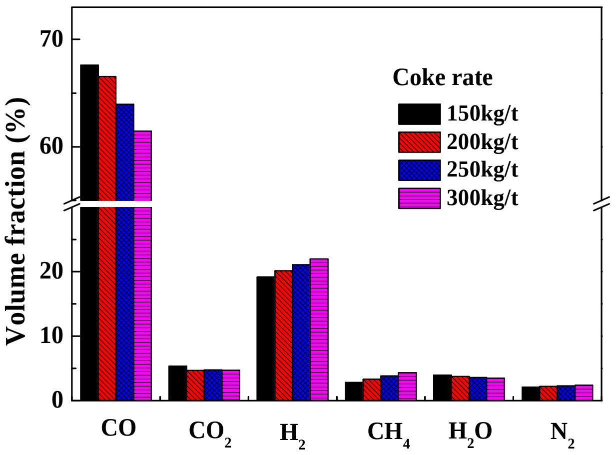

Fig. 11. Volume fraction of generator gas after COG injection at the melting rate 160 t/h

4. Conclusions

The characteristics of COG dome injection in COREX melter gasifier for reducing fuel rate were investigated by means of a static model. Based on the calculation, the critical fuel rate and the amount of COG injection were studied. The following conclusions could be drawn:

(1) Based on the premise that the temperature of hot metal, slag and reducing gas leaving the top of packed bed are 1500°C, 1550°C and 850°C respectively, the model calculates that the critical volume of the bosh gas is 670.71 Nm^3/t, and the corresponding bosh gas heat is 4413.16 MJ/t.

(2) When the heat of bosh gas reaching the critical value, the decrement of fuel rate decreases with the increase of melting rate and increases with the increase of coke rate.

(3) Under the critical fuel rate, with the increase of melting rate and coke rate, the dome temperature increases while the volume of generator gas decreases. Since the dome temperature and volume of generator gas could not meet the production demand, COG was injected from dome to control the dome temperature and supplement the volume of generator gas.

(4) With increasing of melting rate and coke rate, the volume of COG injection for temperature adjustment decreases, but the volume of COG used for gas supplement increases. As the amount of COG used for gas supplement is more, the total volume of COG increases with the increase of melting rate and coke rate. After the COG injection, the amount and reduction capacity of the generator gas can meet the needs of reduction in shaft furnace.

Acknowledgements

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