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REVIEW

Review on improving gas permeability of blast furnace

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Abstract
Blast furnace ironmaking process is the most mature and highly effective process for producing liquid iron. Blast furnace is a gas–solid and gas–solid–liquid countercurrent reactor, and maintaining gas permeability is the precondition of smooth production. Therefore, improving the gas permeability throughout the blast furnace remains a hot issue which is concerned by many metallurgical scholars. According to the research results of many scholars, the dominant factors influencing the gas permeability of different locations in the blast furnace (locations are distinguished according to the morphology change of the burdens) were reviewed. And the strategies for improving the gas permeability of different locations in the blast furnace were summarized based on these dominant influencing factors, such as suppressing the low-temperature reduction degradation of sinter in the lump zone, improving the indirect reduction degree and suppressing the interaction between different burdens. It is hoped to provide both theoretical and practical values for guiding the blast furnace so as to improve smooth operation and smelting efficiency.

Keywords Ironmaking · Blast furnace · Gas permeability · Location

1 Introduction

Blast furnace ironmaking process is the crucial foundation of ironmaking and steelmaking industry, which provides the main raw material for converter steelmaking and a part of raw material for electric arc furnace steelmaking to save electricity [1–5]. In addition, blast furnace also produces cast iron and iron alloy, such as Fe–Mn alloy to meet the demands of some special applications [6].

Blast furnace is a gas–solid and gas–solid–liquid countercurrent reactor. Upward flowing gas is generated in raceway through combustion of coke and coal, while iron ore and coke move downward. From top to bottom, iron ore is reduced gradually. Undergoing softening and melting, liquid iron and slag pass through coke bed to enter into hearth. The poor gas permeability of blast furnace leads to less amount of reducing gas going through ore bed, which will result in the situation that the reduction in iron ore is more dependent on direct reduction and cause more fuel consumption. Moreover, due to poor gas permeability, the pressure difference of blast furnace increases, resulting in difficulty in smooth operation. Therefore, gas permeability of blast furnace is still a hot issue in blast furnace ironmaking research. In this paper, the main factors influencing the gas permeability of blast furnace were systematically elaborated, as well as the improvement methods, hoping to give a reference for current ironmaking research and operation.

2 Permeability of lump zone

2.1 Effect of low-temperature reduction degradation of sinter

The lump zone of blast furnace can be regarded as a solid burdens packed bed, and pressure drop of gas passing through lump zone can be evaluated by Eqs. (1) [7] and (2) [8]:

$$-\frac{\Delta P}{\Delta L}=\frac{150\mu(1-\varepsilon)^2 v_s}{\varepsilon^2 D_p^2}+\frac{1.75\rho(1-\varepsilon)v_s^2}{\varepsilon^2 D_p} \qquad (1)$$

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$$\frac{\Delta P}{\Delta L} = \frac{\Delta P_1}{\Delta L} + \frac{\Delta P_2}{\Delta L} = \frac{72\mu\tau(1-\varepsilon)^2 v_s}{\varepsilon^3 D_p^2} + \frac{3\tau(1-\varepsilon)\rho v_s^2\left(\frac{3}{2}+\frac{1}{\beta^4}+\frac{5}{2\beta^2}\right)}{4\varepsilon^3 D_p} \quad (2)$$

where $\Delta P/\Delta L$ is the pressure drop per unit height of packed bed; $\Delta P_1/\Delta L$ is the pressure drop caused by tortuousness per unit height of packed bed; $\Delta P_2/\Delta L$ is the pressure drop caused by pore-throat rate per unit height of packed bed; μ, ρ and v_s are viscosity, density and velocity of gas, respectively; ε is the voidage of packed bed; D_p is average particle diameter; and τ and β are tortuousness and pore-throat rate, respectively, governed by the voidage of packed bed. According to the equations, pressure drop in lump zone is mainly determined by the properties of burden particles.

Sinter is one of the main raw materials for blast furnace ironmaking, and its mass ratio is between 50% and 85% in China. The main phases of sinter include Ca_2SiO_4, olivine, acicular calcium ferrite (SFCA), magnetite and hematite. The reduction in sinter causes degradation, which will generate powder of ores, resulting in voidage decrease. Most metallurgists considered that the reduction in hematite is the main cause of low-temperature reduction degradation [9–13]. Because different mineral phases possess different shrinkage coefficients, during cooling process, inner stress is generated in sinter, and many cracks appear in sinter as stress is released. When hematite is reduced to magnetite, volume expansion happens due to crystal transition, which will increase inner stress and cause cracks extension, eventually leading to reduction in degradation of sinter. Due to specific structure and mineral-phase composition, low-temperature reduction degradation mainly happens in sinter [9]. In blast furnace, this phenomenon often occurs in low-temperature lump zone, most seriously between 500 and 550 °C, bringing two negative effects: (1) The generated powder ores were partly blown out from the top of blast furnace along with gas, decreasing the utilization rate of ore; (2) the remaining powder ores clog voids of burden bed and cause voidage decrease, resulting in an increase in pressure difference.

Several methods were executed to prevent low-temperature reduction degradation of sinter. Spraying $CaCl_2$ solution on sinter surface or improving MgO content in sinter proved to be effective [14–16]. When spraying a proper amount of $CaCl_2$ solution on sinter surface, Cl^- reacted with Fe_2O_3 to increase Fe–O bond energy, which could be demonstrated by the red-shift to high frequency of Fe_2O_3 characteristic absorption peak in infrared spectrum analysis. Increase in Fe–O bond energy restrained the reduction of Fe_2O_3 to Fe_3O_4 at low temperature, avoiding stress-induced cracks and cracks extension caused by crystal transformation. It needs to be noted that spraying excessive $CaCl_2$ resulted in a sharp decrease in sinter reducibility and Cl^- could cause equipment erosion. MgO was introduced into sinter materials to form $[Mg_{1-x}, Fe_x]O\cdot Fe_2O_3$ during sintering, which inhibited crystal transformation of hematite, refraining the low-temperature reduction degradation of sinter. Low content of MgO had no effect on SFCA formation, and it inhibited the reduction in sinter at low temperatures [17–19]. However, high MgO content made SFCA amount decrease and olivine phase increase in sinter, which deteriorated the reducibility of sinter [20–22]. Al_2O_3 was beneficial to SFCA formation; however, high Al_2O_3 led to high liquid-phase viscosity, increased glass phase in sinter and weakened the strength of sinter [23, 24].

2.2 Interface resistance between alternating layers in lump zone

Iron-bearing feed and coke with different sizes are charged into blast furnace alternately, forming interface layer with low voidage, as shown in Fig. 1. Thereby, the effect of interface on the gas permeability of blast furnace is unneglectable. Liu et al. [25] studied the interface phenomenon of lump zone, and the results showed that when improving gas flow rate or interface layer thickness, the overall pressure drop and interface pressure drop all increased. Coke layers thickness reduction also resulted in the deterioration of permeability. Pressure drop through interface layer constituted the majority of pressure drop of burden layers [25].

The pressure drop equation that described interface layer is given as Eq. (3). Combining with pore-throat equation, it could predict the total pressure drop of lump zone

$$\frac{\Delta P}{\Delta L} = 1.43\left(\frac{\mu}{D_p\rho v_s}\right)^{-0.864}\left(\frac{\phi}{n}\right)^{-1.58} \quad (3)$$

where ϕ is the bed voidage; and n denotes the interface numbers.

In summary, the permeability of lump zone can be improved by suppressing low-temperature reduction degradation of ore and reducing interface of ore and coke. Lump zone is above cohesive zone and dripping zone, and

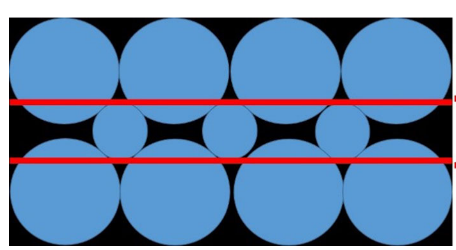


Fig. 1 Schematic illustration of interface layer

no liquid phase exists in this zone; therefore, it is relatively easy for the gas to pass through it. In cohesive zone and dripping zone, under the action of high temperature and reduction, iron-bearing feed begins to soften and deform, liquid iron and slag are generated, and the gas permeability declines sharply. The impact factors and rules are quite different from those of lump zone.

3 Permeability of cohesive zone

3.1 Softening and melting properties of iron-containing burdens

Cohesive zone is comprised of cohesive layers and coke layers, possessing the poorest gas permeability. In general, the ratio of gas permeability of cohesive layer, ore layer and coke layer is 1:4:52 [26], that is, the resistance of cohesive layer to gas is several times greater than that of other layers.

With the increase in temperature and reduction phenomenon, iron-containing burden began to soften and melt, eventually forming cohesive zone with the lowest permeability in blast furnace. Factors that affected the softening and melting behavior of iron-containing burdens include gangue-phase composition and reducibility of burdens. Normally, the softening and melting properties of basic burden are better than those of acid burden, which is attributed to the following reasons [27–38]: (1) The reducibility of basic iron-containing burden is better than that of acid burden; (2) the melting point of gangue phase of basic iron-containing burden is higher than that of acid burden. Basic sinter has a high porosity and high content of Ca^{2+} and Mg^{2+}, which can thus adsorb the reducing gas, contributing to better kinetic conditions of reduction than acid burden. This allows basic sinter to acquire more iron phase than acid pellet or lump under the same reduction conditions, thus enhancing the resistance to deformation of sinter. For sinter with high basicity, the gangue phase mainly forms Ca_2SiO_4 during reduction process. However, for acid burden, often referring to acid-oxidized pellet, reducibility is worse than that of basic sinter. A dense iron layer is generated on the surface of acid pellet, preventing reducing gas from entering inside the pellet. Besides, silica (SiO_2) reacts with FeO to produce Fe_2SiO_4 during reduction process. Low melting point phase formation exacerbates the deformation of acid burden, leading to the deterioration of the permeability of burden layers.

Considering the negative effect of acid pellets on permeability, the proportion of pellets in burden is limited. Acid pellet has high TFe; therefore, low pellet proportion leads to the decrease in the TFe of blast furnace burdens, which is unfavorable to energy saving and production efficiency. In order to overcome the poor softening and melting properties and improve the proportion of pellets, many scholars attempted to prepare the pellets by adding MgO and denoted it as MgO pellet. Practice has proved that the reducibility of MgO pellet is better than that of traditional acid pellet. This is attributed to the fact that MgO addition increases the porosity of pellet and Mg^{2+} enhances the ability of adsorbing reducing gases, thereby improving the kinetic conditions of reduction. Furthermore, the softening and melting properties of MgO pellet become better; nonetheless, the reasons have not been elucidated yet. According to previous research [39], two reasons are widely recognized. The first is the improvement in the reducibility of MgO pellet. The second is the contribution of added MgO to a higher melting point of the gangue phase.

3.2 Interaction among different burdens

In cohesive zone, interactions occur among different iron-containing burdens, which significantly affects the gas permeability of cohesive zone. The studies on interaction are mainly based on the CaO–SiO_2–FeO slag system [27–32, 35–38]. Figure 2 shows the interaction among different burdens. Figure 2a exhibits the microscopic morphology of lump ore, and the main phase of lump ore is Fe_2SiO_4. Figure 2b displays the microscopic morphology of sinter, and the main phase of sinter is Ca_2SiO_4. Figure 2c shows the morphology of interface between sinter and lump ore. A new phase ($CaSiFeO_4$) appears at the interface of sinter and lump ore. Equations (4)–(6) describe these reactions, being consistent with the CaO–SiO_2–FeO phase diagram shown in Fig. 3

$$2FeO + SiO_2 = 2FeO \cdot SiO_2 \tag{4}$$

$$2CaO + SiO_2 = 2CaO \cdot SiO_2 \tag{5}$$

$$CaO + FeO + SiO_2 = CaO \cdot FeO \cdot SiO_2. \tag{6}$$

Temperature, chemical composition, microstructure, metallurgical properties and contacting condition are main factors which influence the interaction. Among these factors, reduction degree of burden before softening and melting provides an integrated reflection of chemical composition, metallurgical properties and operating condition. Scholars have studied the effect of reduction degree on interaction [32–36, 38]. Figures 4 and 5 demonstrate that with the increase in reduction degree of burdens, the interaction between burdens is suppressed. Iron phase inhibits the mutual contact of different gangue phases, thus preventing the formation of low melting point phase. This explains why some blast furnaces under special operating conditions acquire better permeability, such as oxygen

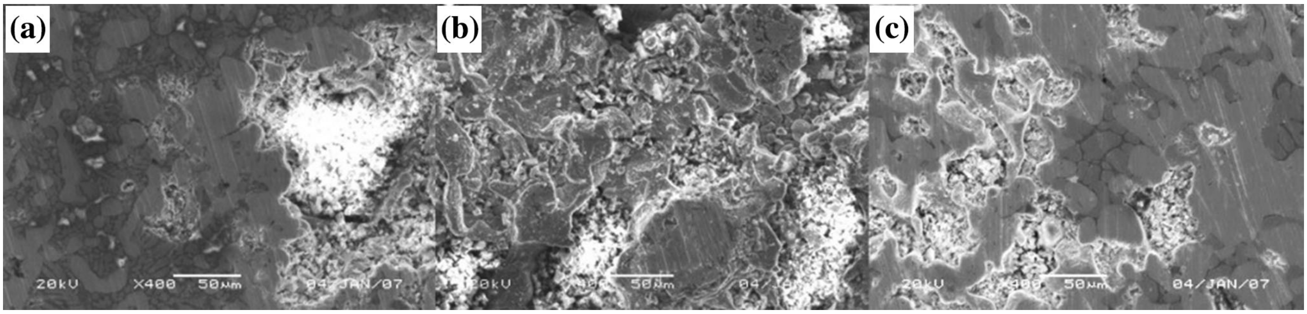


Fig. 2 SEM micrographs of lump ore (**a**), sinter (**b**) and interface between sinter and lump ore (**c**) [27]

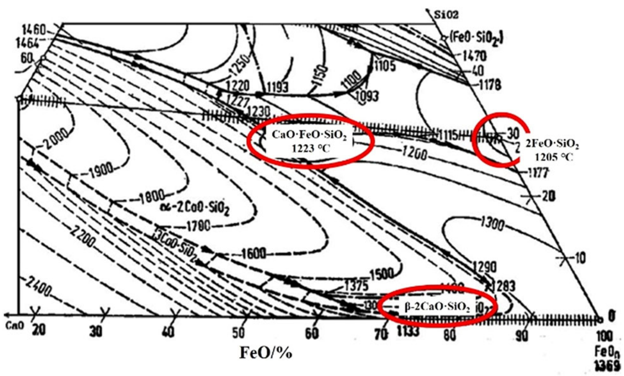


Fig. 3 Phase diagram of CaO–SiO_2–FeO [27]

blast furnace, hot reducing gas injection and utilization of metallized burden [40–45].

The effect of temperature on interaction is presented in Fig. 6. Clearly, increase in temperature leads to the violent progress in the interaction. The low basicity lump ore easily forms liquid phase first at high temperature to promote mass transportation. Concerning the chemical composition, according to phase diagrams of CaO–SiO_2–Al_2O_3 and CaO–SiO_2–Al_2O_3–FeO, addition of Al_2O_3 leads to the decrease in the melting points of CaO–SiO_2 and CaO–SiO_2–FeO systems and improvement in the liquid-phase ratio, in particular, in low basicity range. In contrast, MgO addition increases the melting points of CaO–SiO_2 and CaO–SiO_2–FeO systems, which is beneficial for reduction in liquid phase at low temperature. In other words, addition of MgO requires higher temperature for obtaining same liquid-phase ratio, which is advantageous for obtaining a low position and thin cohesive zone and improving permeability of cohesive zone.

In short, the interaction among different iron-bearing burdens causes premature appearance of molten slag. Notably, this unexpected phenomenon reduces the voidage of ore layer and deteriorates the gas permeability of cohesive zone. Therefore, the interaction among different burdens should be suppressed.

3.3 Influence of burden arrangement

Theoretically, the iron-bearing burdens with different properties can be charged into blast furnace under different arrangements: layer by layer, mixed arrangement and longitudinal arrangement, as shown in Fig. 7. Burden arrangement affects the procedure of softening and melting of iron ore, thus showing the difference of permeability in cohesive zone. Ishii et al. [46] prepared sponge balls with different liquid contents to represent pellet and sinter, respectively, and studied the influence of arrangement of iron-containing burdens on gas permeability. The layered

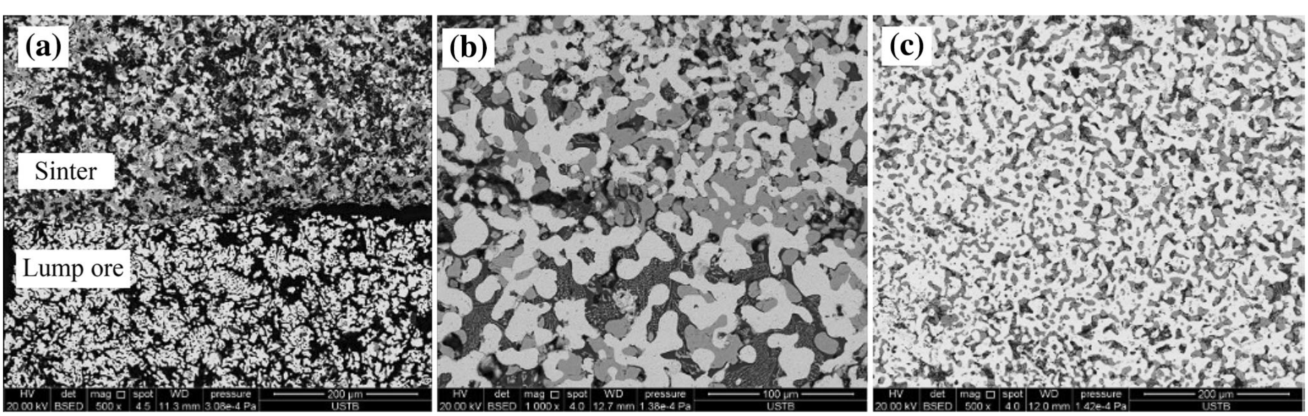


Fig. 4 Interface of interaction at reduction degree $R = 60\%$. **a** Shrinkage of 10%; **b** shrinkage of 30%; **c** shrinkage of 60% [36]

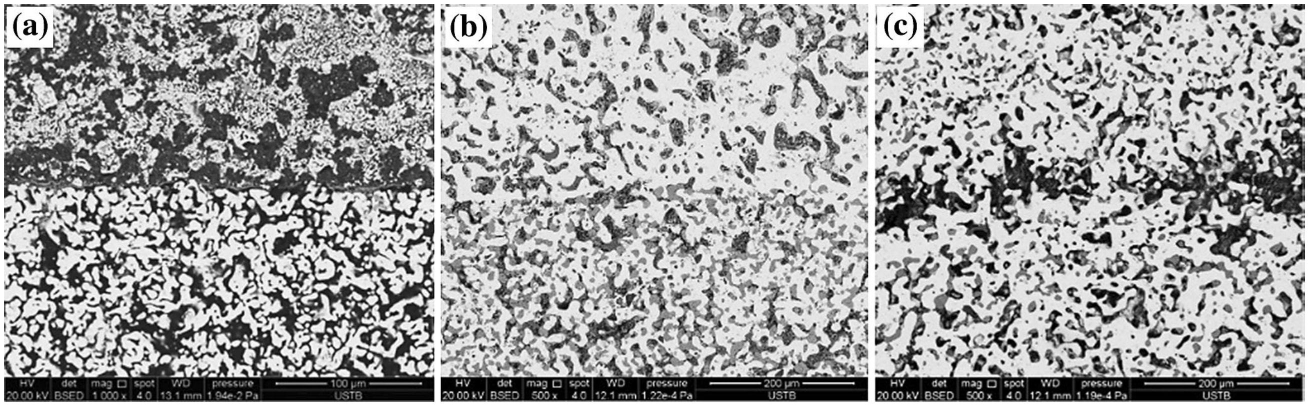


Fig. 5 Interface of interaction at R = 90%. **a** Shrinkage of 10%; **b** shrinkage of 30%; **c** shrinkage of 60% [36]

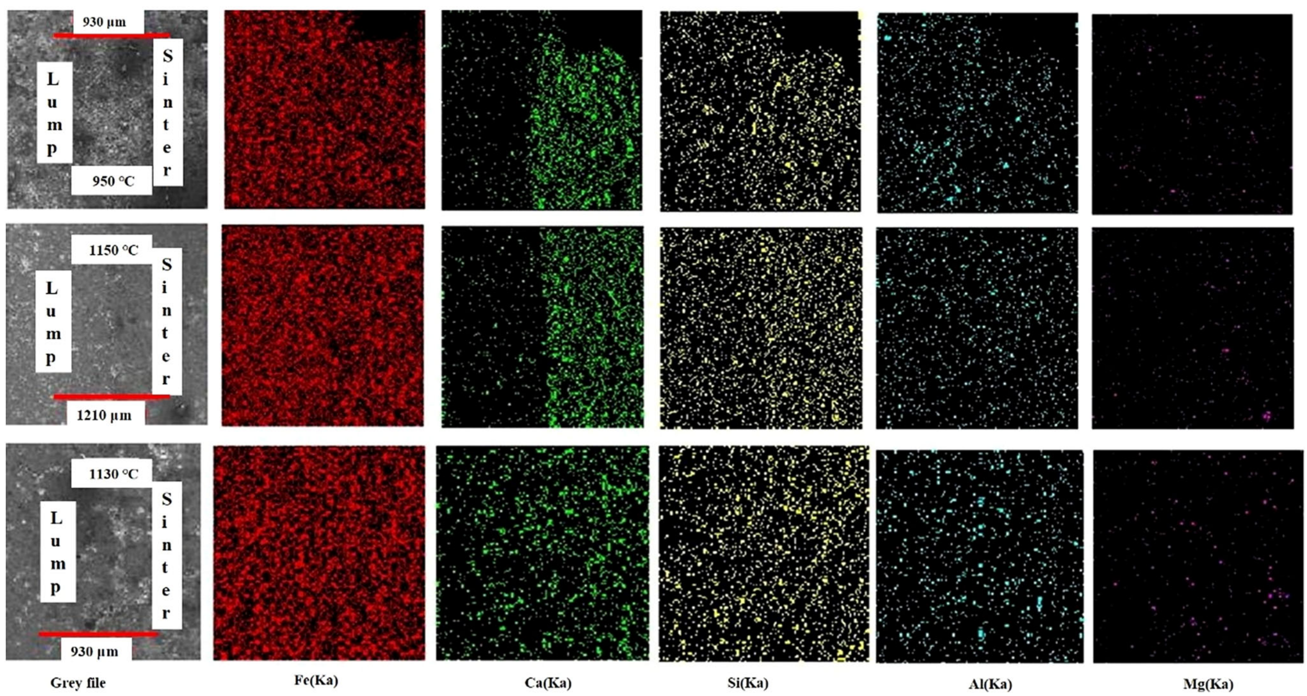


Fig. 6 Elemental distributions of contacting surface at different temperatures [29]

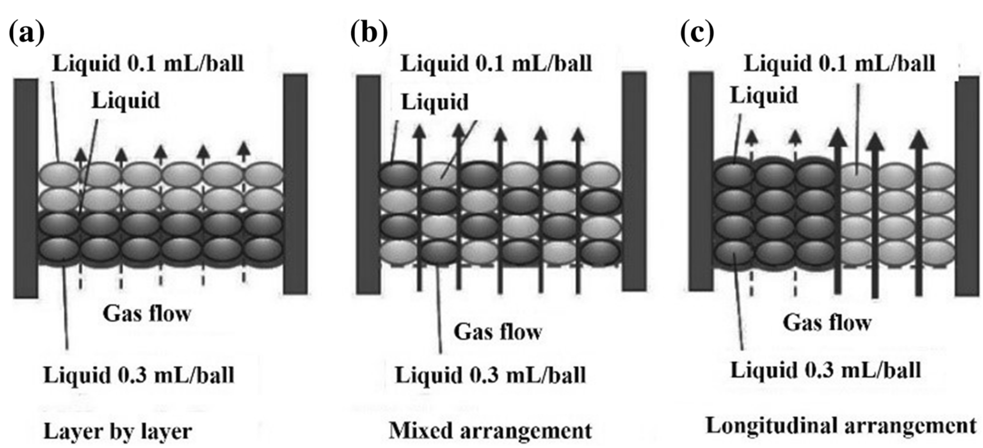


Fig. 7 Schematic illustration of different arrangements of furnace burdens [46]

arrangement of sinter and pellet was the most detrimental to permeability of cohesive zone. According to this research, mixed arrangement and longitudinal arrangement allowed gas flow passages to be opened due to the support of sinter, and the permeability of cohesive zone was improved.

Although the above-mentioned cold simulation experiment could acquire some meaningful results, it only focused on the effect of amount of liquid phase on permeability, while ignoring the effect of interaction on liquid-phase generation. The promoting role of interaction on liquid-phase generation has been clarified in Sect. 3.2. The liquid-phase generation was found to be unfavorable for the permeability because the liquid phase blocked the voids of burden layers. In actual blast furnace production, arrangement mode shown in Fig. 7b was the most unfavorable for permeability of cohesive zone, and arrangement mode presented in Fig. 7a was the most advantageous. Mixed arrangement increased contacting areas of different burdens, thus accelerating the interaction. As a result, more liquid phases were generated before dripping. Combined with the analysis of interaction of different burdens, a new model describing the effect of iron-containing burdens arrangement on cohesive zone was developed. Figure 8 provides the schematic illustration of softening and dripping process under condition of taking interaction of different burdens into account. The symbol I in Fig. 8 indicates the mixing degree of different burdens. When $I = 0$ (corresponding to Fig. 8a), the interaction proceeds from top to bottom. With the increase in I, the interaction area expands, resulting in an increase in liquid phase before dripping, and the permeability of cohesive zone deteriorates.

Besides the effect of iron-bearing burden arrangement, coke charging mode also played an unneglectable role in determining the permeability of burden layers. Mu et al. [47] studied the effect of ore–coke mixed charging on the permeability of burden layers. According to their research, ore–coke mixed charging was beneficial to reduce the maximal pressure difference of burden layers and improve the permeability because the coke in burden layers acted as skeleton to improve the voidage of cohesive zone. Central coke charging technology is another special coke charging mode which has been widely applied in current blast furnace operation to ensure smooth operation. The central coke charging reduces the ore/coke ratio in the central narrow area, being beneficial to open central gas stream and form an inverted V-shaped cohesive zone, which helps to distribute the gas flowing up without inter-disturbance compared to V-shaped and W-shaped cohesive zones, improving the gas permeability. At the same time, lack of iron ore in central area reduces the dissolution of central coke during moving down process; therefore, the particle size and strength of coke are protected in central deadman and hearth, which makes the central area of the hearth more active, and the gas, liquid slag and iron pass through the coke layer more easily, reducing the erosion of the hearth caused by the circulation of molten iron [26, 48–50]. There are two ways to open central gas stream and decrease pressure difference of blast furnace: (1) narrow platform and deep funnel mode, and (2) wide platform and shallow funnel mode. Mode (1) is proper for the coke with large particle size, taking full advantage of good rollability of large particles to realize central segregation of large size coke and improving gas permeability of center of blast furnace. For the coke not large enough, adopting central coke charging can decrease ore/coke ratio in center to form

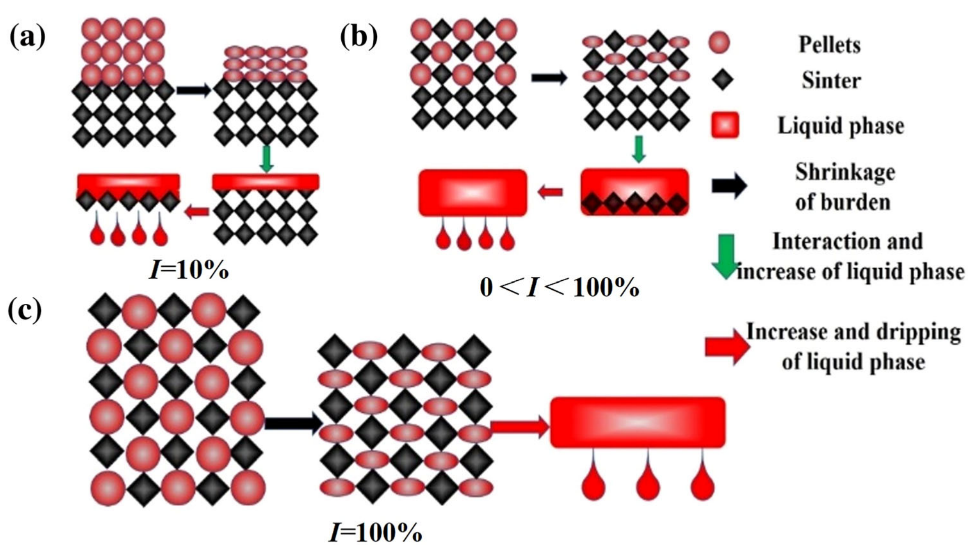


Fig. 8 Schematic illustration of influence of burden arrangement on cohesive zone

burden surface distribution as mode (2) and increase gas permeability of center. Usually, the proportion of central coke does not exceed 15% [48]. In recent years, some blast furnace operators think that although the central coke charging technology has an advantage in smooth operation, it reduces the gas utilization rate and increases the fuel rate. Thereby, some Chinese steel companies are trying to cancel the central coke charging gradually [51, 52]. In the authors' opinion, central coke charging or not should be determined by possessed materials conditions. Reckless cancelation of central coke disregarding the poor burden conditions may destroy the smooth operation of blast furnace.

3.4 Permeability of cohesive zone under special operating conditions

Metallized burdens, such as scrap, direct reduced iron (DRI) and hot briquetted iron (HBI), have been used in blast furnace ironmaking in some steel companies. Utilization of metallized burden could significantly improve productivity and save fuels. Kaushik and Fruehan [42, 43] found that the utilization of DRI and HBI improved the gas permeability of cohesive zone, and the chemical compositions of DRI and HBI are listed in Table 1. These metallized burdens exhibited high TFe and metallization rate, which reduced the low melting point of the gangue phase, led to the melting of slag and inhibited the interaction [32–36, 38].

There were different opinions on the effect of metallized burden on permeability of cohesive zone [45]. Table 2 summarizes the chemical composition of the metallized burden, which deteriorated the gas permeability of the cohesive zone. Table 2 presents that the metallized pellets had higher gangue content; therefore, the gangue phase in the metallized pellets interacted with the sinter and oxidized pellets, causing an increase in liquid gangue phase before dripping; as a result, the voidage decreased and the gas permeability deteriorated. Therefore, the metallization rate, gangue-phase content and gangue-phase composition of the metallized burdens should be considered comprehensively.

Oxygen blast furnace and hot reducing gas injection have received significant attention with the objective of reducing energy consumption and carbon emission in blast furnace ironmaking. The industrial tests in trial blast furnace demonstrated that the gas permeability of cohesive zone was improved under the conditions of oxygen blast furnace and reducing gas injection [40, 41]. Table 3 and Figure 9 show the simulation of softening and melting behavior of burden in oxygen blast furnace under laboratory conditions. The softening zone became wider and the melting zone became narrower due to high reduction degree of burden before softening, which improved the permeability of burden layers [53].

Table 1 Chemical composition of metallized burdens used by Kaushik and Fruehan [42, 43]

Chemical composition/wt.%							
Burden	TFe	MFe	FeO	SiO_2	S	C	Metallized ratio/%
DRI	92.3	88.1	5.14	1.3	0.002	2.01	85.50
HBI-1	94.6	88.0	8.16	1.0	0.010	0.01	93.03
HBI-2	92.9	86.4	8.06	1.7	0.050	1.15	93.00

3.5 Mechanism of molten burdens penetrating into coke layer

Molten iron and slag penetrated into coke layer, blocking voids and enhancing resistance of gas passing through the bed. Japanese scholars studied softening, melting and penetrating behavior of slag in coke bed [54]. Molten slag penetrated into coke bed regardless of the liquid-phase ratio of slag, as shown in Fig. 10.

The penetration of slag was determined based on the wettability between slag and coke. Therefore, at a fixed coke rate, reducing liquid-phase amount prior to penetrating into coke layer should be the effective way to improve the permeability of cohesive zone. In other words, ideally, it was expected that the liquid phase immediately penetrated into coke layer as soon as it was generated. Improvement in reducibility of iron-bearing burden and enhancement in reduction atmosphere of blast furnace helped to achieve "immediate penetration into coke layer as burdens melted". Specific methods that favored the desired process included utilization of MgO pellet, reasonable arrangement of iron-containing burdens and special processes such as above-mentioned oxygen blast furnace, hot reducing gas injection and utilization of metallized burden.

Table 2 Chemical composition of metallized pellet deteriorating permeability [45]

Chemical composition/wt.%							
TFe	MFe	FeO	SiO_2	CaO	MgO	Al_2O_3	Metallized ratio/%
66.61	51.55	15.50	4.41	11.13	2.21	2.55	77.39

Table 3 Characterized value of softening and melting of burdens under traditional blast furnace (TBF) and oxygen blast furnace (OBF) conditions [53]

Experiment	$T_{10\%}$/K	T_s/K	ΔT_B/K	T_d/K	ΔT_M/K	ΔT_{SM}/K	ΔP_{max}/Pa	S/(kPa K)
Sinter/TBF	1508	1738	230	1811	73	303	2342.2	118.54
Sinter/OBF	1497	1737	240	1801	64	304	1911.0	103.73
Pellets/TBF	1376	1581	205	1718	137	342	3263.4	379.96
Pellets/OBF	1300	1718	418	1731	13	431	1117.2	8.15
Mixed burdens/TBF	1411	1596	185	1687	91	276	2861.6	215.82
Mixed burdens/OBF	1440	1688	248	1703	15	263	1813.0	19.84

$T_{10\%}$ Temperature at which shrinkage of burdens layer is 10%; T_s temperature at which burdens layer is steeply rising; T_d dripping start temperature; ΔT_B softening temperature range of burdens, $\Delta T_B = T_s - T_{10\%}$; ΔT_M softening temperature range of burdens, $\Delta T_M = T_d - T_s$; ΔT_{SM} cohesive zone interval, $\Delta T_{SM} = T_d - T_{10\%}$; ΔP_{max} maximum differential pressure; S permeability index, $S = \int_{T_s}^{T_d} (\Delta P_{max} - \Delta P_T)dT$; ΔP_T differential pressure at temperature T

4 Gas permeability of dripping zone

4.1 Effect of coke bed

The pressure drop of gas passing through dripping zone and deadman can be calculated by using Eq. (7). For coke bed, increasing particle size of coke, increasing voidage of coke bed and decreasing retention of slag and iron in coke bed are beneficial to dwindle the pressure drop of dripping zone

$$\frac{\Delta P}{\Delta L} = K_1 \frac{1 - \varepsilon_c + h_z}{d^2} \rho v_s + K_2 \frac{1 - \varepsilon_c + h_z}{d(\varepsilon_c - h_z)^3} \rho v_s^2 \tag{7}$$

where K_1 and K_2 are dimensionless coefficients; h_z denotes the retention amount of slag and iron; ε_c is the voidage of packed coke bed; and d is the harmonic mean diameter of average particle size of coke and average diameter of droplets.

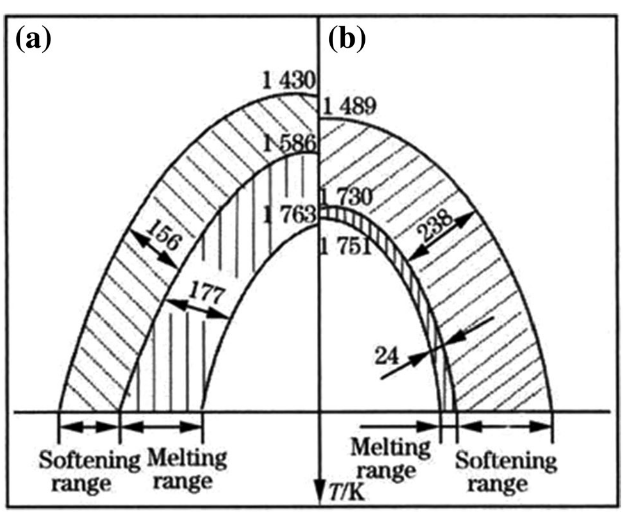


Fig. 9 Temperature range of softening and smelting under different process conditions. **a** Traditional blast furnace; **b** oxygen blast furnace [53]

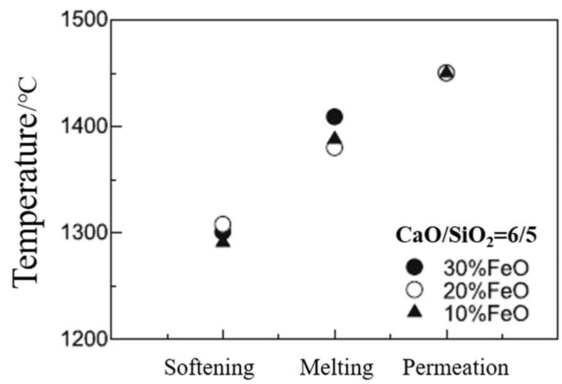
Coke was the only solid phase in the part below the cohesive zone, and its size distribution significantly affected the voidage, and further the gas permeability. The reactions of coke in the blast furnace included volatilization, direct reduction, carburization, dissolution and combustion. Volatilization occurred in lump zone, and it had almost no effect on the strength of coke. In the cohesive zone, gasification dissolution reaction of coke occurred violently. The gasification dissolution reaction of coke can be described in terms of Eqs. (8) and (9) as follows:

$$C(s) + CO_2 = 2CO \tag{8}$$

$$C(s) + H_2O(g) = CO + H_2 \tag{9}$$

The gasification dissolution reaction caused a decrease in the strength and size of the coke during descending process, resulting in deterioration of gas permeability of the coke bed in the lower portion of the blast furnace. Many scholars studied the gasification dissolution reaction of coke and proved that the loss of coke strength caused by H_2O was lower than that by CO_2 [55–63]. CO_2 reacted with coke and easily merged the original small pores into large ones, which destroyed the skeleton of coke. However, the dissolution reaction with H_2O only increased the tiny pores of coke. In the traditional blast furnace ironmaking process, the proportion of H_2 was very low; thus, the gasification and dissolution of coke were mainly caused by CO_2. Noteworthy, when H_2O:CO_2 was increased to 5:5 even to 7:3, the synergistic action of two dissolution reactions accelerated the gasification of coke [61]. For high hydrogen-enriched reduction operations, such as injection of natural gas and coke oven gas even pure hydrogen injection, the decrease in coke strength caused by the dissolution of CO_2 appeared to be reduced, and the effect of H_2O had to be taken into account.

In cohesive zone and dripping zone, liquid slag destroyed coke strength and decreased coke diameter



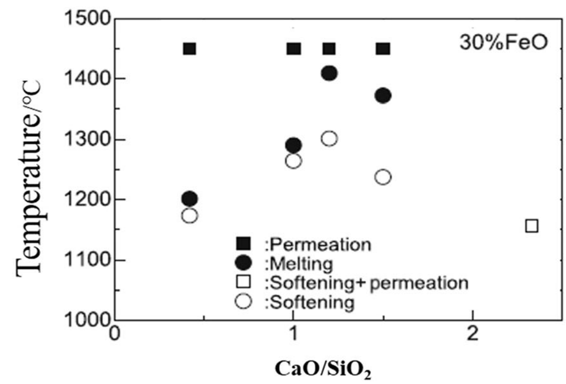


Fig. 10 Melting state of slag and temperature in coke bed [54]

through dissolution reaction. Experiments of coke dynamic dissolution in FeO-containing molten slag showed that FeO content of slag, temperature and dissolution time exhibited positive relationship with weight loss rate of coke, corresponding to the diameter of coke [63]. The dissolution time was the most remarkable impact factor for coke dissolution, followed by FeO content and temperature. Adjustment in smelting parameters or improvement in quality of materials could weaken dissolution reaction of coke. For instance, in oxygen blast furnace, FeO content in the initial slag decreased owing to high reduction potential of gas, thus reducing coke dissolution reaction. Furthermore, dissolution time was reduced because of shrinkage of smelting period in oxygen blast furnace. The above-mentioned changes of FeO content in the initial slag and dissolution time permitted the coke to maintain strength and particle size in dripping zone. Moreover, harmful elements such as potassium, sodium, lead and zinc accelerated the degradation of metallurgical properties of coke, resulting in smaller particle size of coke.

4.2 Effect of slag property on gas permeability

Slag properties play an important role in retention amount of slag in coke bed. A cold simulation test verified that the static retention (Hs) increased with the increase in viscosity and surface tension of liquid phase [64]. Increasing density of liquid phase could dwindle retention amount, indicating that the liquid phase retained in coke bed was mainly slag in real blast furnace. The effect of factor on strength was ranked in the following order: density > surface tension > viscosity. Comparing flow behavior of slag through coke bed with that of iron indicated that the retention of slag was more sensitive than that of iron. Gas flow increased by 5%–10% and the corresponding slag retention increased by 20%–30% [65]. Accordingly, optimization of slag composition to obtain good slag properties was not only the demand of guaranteeing pig iron quality, but also the effective method for improving the permeability of dripping zone due to decreasing retention amount. Undoubtedly, reducing slag amount through increasing iron grade of iron-bearing burdens directly impacted retention amount of slag in dripping zone.

4.3 Effect of unburned coal powder on gas permeability

Pulverized coal injection (PCI) is the most effective measure to decrease fuel cost of ironmaking. With PCI increasing, the pulverized coal cannot burn out in raceway. Many theoretical and experimental studies proved that the accumulation of unburned coal powder occurred in the blast furnace when PCI exceeded a certain value [66–68]. A two-dimensional model experimental study indicated that the unburned coal powder mainly gathered in the area where the velocity of gas flow was slow or flow direction changed [69]. The accumulation of a fair amount of unburned coal powder in coke bed will lead to the decreased voidage and increased pressure difference. However, a small amount of unburned coal powder can improve the gas permeability of the coke bed. If unburned coal powder content in slag is less than 9%, the viscosity of slag decreases and the fluidity increases, which is beneficial to reduce the retention of slag in the coke bed. Moreover, unburned coal powder reacts with CO_2, H_2O and FeO in preference to coke, and the coke is protected, enhancing the skeleton role. Of course, the maximum amount of unburned coal powder is expected to be just consumed by reducing reaction. Over this amount, the coal powder will be discharged from blast furnace through dust, causing the waste of fuel.

5 Gas permeability of hearth

Hearth is an important area in the lower part of the blast furnace, where the overwhelming majority of gas is produced. Therefore, influence of the gas permeability of this part on the production and smooth operation of the blast furnace cannot be ignored. The particle size and strength of coke and the properties of slag significantly affect the gas permeability of the hearth. The post-reaction strength of coke determines the voidage of deadman in hearth, and lower post-reaction strength results in poorer gas permeability. Firstly, under the huge load of upper burden, the coke with low post-reaction strength crushes and wears to form the dense deadman, and the voidage decreases. Secondly, in raceway, the high-speed rotary coke with low post-reaction strength rubs the fixed coke bed to produce a large amount of coke breeze, which enters the coke bed to block the voids, further deteriorating the gas permeability, causing the development of edge gas flow and shrinking the campaign life of blast furnace.

As mentioned above, the property and volume of slag determine the retention amount in coke bed. Low iron grade of ore indicates more slag volume and high retention amount in coke bed. A high Al_2O_3 content or irrational MgO/Al_2O_3 ratio in slag leads to an increase in viscosity of slag, increasing the retention amount as well. More seriously, when the temperature of hearth is low, the fluidity of hot metal weakens, finally leading to an inactive state, even accumulation in hearth. The smooth operation of blast furnace is destroyed, worsening the blast furnace indexes and bringing potential safety hazard.

6 Conclusions and prospects

Improving the permeability of blast furnaces is a hot issue concerning research on the blast furnace ironmaking. Impact factors on the permeability of different zones of blast furnace and improvement methods are summarized in this review.

For lump zone of blast furnace, suppressing low-temperature reduction degradation of ore and reducing interface layer could effectively improve the permeability of lump zone. However, the improvement in permeability in lump zone was limited for overall blast furnace because the pressure drop in blast furnace mainly occurred in the cohesive zone.

Increasing thickness of coke split could improve the permeability of cohesive zone. In contrast, low coke rate operation and batch weight limitation prevented further improvement in permeability by thickening coke layer. Increasing the permeability of soft-melting ore layer should be a radical solution. Improvement in reducibility of ore and enhancement in reducing atmosphere of blast furnace could decrease FeO content of the initial slag, improving softening and smelting properties. Use of MgO pellet, adjustment of arrangement of iron-containing burdens and taking special processes into account (oxygen blast furnace, hot reducing gas injection, and metallized burden) were also effective methods, which helped to achieve "immediate penetration and passing through coke layers as burdens melted", thus improving the permeability of cohesive zone.

Increasing coke size and quality, reducing carbon dissolution reaction with CO_2 and H_2O, decreasing FeO content of the initial slag and controlling harmful element loads below acceptable level favored coke bed to maintain a large voidage in dripping zone. Lowering surface tension and viscosity of slag through chemical composition optimization could decrease the retention of slag in coke layer, thus improving the permeability of dripping zone.

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