Gas Permeability Assessment of the Cohesive Zone in the Blast Furnace

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Abstract. A mathematical model is proposed for assessing the gas permeability of the cohesive zone in the blast furnace. The gas permeability is improved by increasing the intensity of the axial gas flux and introducing coke nuts in the ore layer. This is important in introducing intense pulverized-coal injection.

For the stable and highly productive operation of a blast furnace it is necessary to provide good gas permeability of the blast furnace charge. To improve gas permeability of the coke bed, the coke must undergo screening with the release of 25-40 mm fraction, rarely more than 80 mm, to achieve the optimal size of skip coke. To increase gas permeability of the lens of ore, the iron-bearing materials (mainly sinter and pellets) in several cases also are subjected to a second or a third screening to remove small fraction (less than 5 mm) [1].

Researchers have always been interested in the determination of gas permeability of the solid material layer. Between the middle of the 19th century to the beginning of 20th century when the equation for the assessment of gas permeability was being developed and clarified, the iron ore part of the blast furnace charge appeared as a dense lump iron ore, so in the process of equation development only the porosity of the layer was taken into account. During the next stage (1930-1950), when sinter and pellets started to be used in blast furnace production it became obvious that the porosity of these materials should also be considered in the equation. There are research data which mention that the determination of gas differential pressure in porous materials (for example a layer of coke or sinter) in comparison with the calculated differential as per the Darcy-Weisbach equation (where the material is taken as nonporous) gives a significant - up to 10-30 % - measure of inaccuracy [2]. This difference, by F. F. Kolesanov, is connected to the fact that the exclusion of the porosity of lumps from the calculation led to significant differences of calculated data vs. experimental data, and the materials were taken as denser (that is without taking the porosity into account) to simplify the calculation. In the beginning of the 21st century the staff of Donetsk National Technical University led by S. L. Yaroshhevskiy suggested to use instead of “porosity” the indicator of “equivalent porosity” which takes into account not only the porosity of the layer, but also the porosity of the material taking into account the volume of the pores available for gas passage [3].

However, the strongest resistance to gas passage (up to 50 % from the general differential pressure in a blast furnace) is given by the zone of plastic condition – the cohesive zone. Between 1970 and 1980 under the guidance of G. Gudenau there was research done on the behaviour of the materials in the cohesive zone and the influence of the shape of the cohesive zone on the gas permeability in a blast furnace. Based on the research G. Gudenau regarded that the cohesive zone is a group of interchanging
inclined layers of softened iron ore charge and coke. It was generally hypothesised that gas passes only through batch structure, and the ore layers of the softened charge are fully impermeable [4-6]. Besides, it is supposed that the cohesive zone is limited by the temperature of the beginning and the end of the softening of ore materials [7].

One of the possible ways to increase gas permeability of the lens of ore in the “dry” zone and in the cohesive zone is the integration of coke nut or coke into the iron ore layer. Under the guidance of V. I. Loginov there were extensive studies of the assessment of the influence of coke integration into the iron ore material on the blast furnace process. It was found that when mixing the entire mass of the loaded coke with the sinter compared to the normal loading system (in layers) the gas dynamic conditions of melting change and the heat-mass exchange and physical-chemical processes are activated. It is noted that when mixing the entire mass of coke with the sinter in the cohesive zone “…the areas of ore materials, which are in plastic condition, in this case will be better treated with gas and the resistance of the zone will be lower” [8].

As the laboratory studies showed, the gas permeability of the zone of softened iron ore materials improves when the coke is integrated at the temperatures typical for the cohesive zone. So, in [9] sinter of size 10-15 mm or the mix of sinter and coke was loaded into a crucible and they put the crucible into a heating oven. They imitated the load onto the materials layer by a load block at the cohesive zone layer. They injected the mix of CO, CO₂ and N₂ into the working environment, which is close to the chemical composition of gas in the cohesive zone. It is showed that in the range of temperatures 1400-1800 K the integration of coke significantly improves gas permeability of sinter in the cohesive zone: maximum decrease of gas differential pressure in sinter was observed at the integration of coke in the amount of 10 % (Figure 1).

![Figure 1. The change of gas differential pressure in the cohesive zone when integrating coke into sinter in the amount of 0 % (1), 5 % (2) and 10 % (3) [9].](image)

Coming from the mentioned above a relevant objective is an analytical study of gas permeability in the cohesive zone when integrating lump fuel into the ore layer.

The objective of this study is to assess the gas permeability of the cohesive zone when integrating coke nuts into the ore layer, including when using the technology of pulverized coal injection system (PCI) into the blast furnace hearth.

Based on the literature data about the softening and melting of recovered iron ore materials we understand that the cohesive zone is limited by the temperatures of the beginning and the end of softening. In the calculations we supposed that the cohesive zone is Λ-shaped, and the base of the cohesive zone is supported by the walls of the blast furnace belly. For the study we chose the shape of the zone Λ-shape because it provides the best gas permeability of a blast furnace especially when injecting PCI in high quantities. We took the height of the cohesive zone (H₀) as equal to the height of the belly H₆ to simplify
the calculation (Figure 2). Over the top border of the cohesive zone there is a “dry” zone of blast furnace charge; under the bottom one is the mix of coke with melt of the ore part of the charge with overflowing slag and hot iron.

By mixing the entire mass of loaded coke with ore materials before loading into a blast furnace [8] there is reduced control over the gas passage and it complicates the process of the arrangement of mixing a high amount of coke with ore materials. That’s why we think it is reasonable to mix only a part of coke or coke nut with ore materials: it preserves the possibility to control gas passage in a blast furnace while improving gas permeability of ore layers in the “dry” zone and in the cohesive zone.

The existing hypothesis formulated by G. Gudenaus concerning the impermeability of the ore layer in the cohesive zone contradicts several facts. Firstly, in the “dry” zone (before the cohesive zone) the ore structures are permeable enough due to high equivalent porosity. But in the cohesive zone, in connection to the shrinkage of the iron ore layer, there is a reduct ion in the equivalent porosity of the layer. However, upon that there might be residual equivalent porosity of the ore layer. It can be permitted that through the ore layer in the cohesion zone some part of gas will pass, so the ore layer will become permeable. Secondly, at high temperatures in the cohesive zone (around 1200°C, that is at the border of the belly zone) in the lens of ore there might be a build-up of fluid melt which will partially flow to the zone located below, that is the batch structure. It will lead to some increase of porosity of the ore layer in the cohesive zone and consequently, to the increase of gas permeability of the ore structure. This assumption regarding the increase of gas permeability when a part of melt overflows was mentioned in [10]. Besides, the authors of [11] while developing a model for the assessment of gas permeability of the blast furnace charge supposed that in case of the integration of coke into the iron-bearing material in the cohesive zone the ore layer becomes permeable for gas.

Coming from that we can suppose that the ore structures are partly gas permeable and to improve the accuracy of calculation these factors must be considered in the methods of calculation of gas permeability of the cohesive zone. In our opinion, this improves the accuracy of calculation. In connection to that in this study we made an attempt to assess the gas permeability in the cohesive zone while integrating coke nut into the ore part of the charge while increasing the consumption of PCI with the regard to the assumed gas permeability of the ore structure.

As per the scheme (Figure 2) the height of the excess of the cohesive zone over the border of the belly was determined by the formula, m
\[ KN = DN \cdot \tg \left( 90^\circ - \frac{\beta}{2} \right), \]

(1)

where \( \beta \) is the angle in the top of the cohesive zone in degrees.

The length of gas passage through batch structure or through the layer of ore material \( PM \) can be determined by geometry based on the similarity of triangles. In the triangle \( PMF \) the side \( FM \) is known (taken as equal to the height of the melt \( AD \)) and two angles \( \angle PFM = \beta/2; \angle PMF = 90 - \alpha_W \) (where \( \alpha_W \) – is the inclination angle of batch structures and ore layers to the horizon). Besides, these data allow us to determine the side \( PM \) by the formula, m

\[ PM = FM \cdot \frac{\sin(\beta/2)}{\sin(180 - \beta/2 - (90 - \alpha_W))}. \]

(2)

The length of the generatrix of the cone can be computed by the formula

\[ DK = \sqrt{DN^2 + KN^2}, \]

(3)

where \( DN \) is the radius of the melt in m.

The thickness of the layer of coke and ore component (or the mix of the ore component and injected coke nut) was assessed based on their quantity in the charge considering their position on the melt layer.

To determine the volume of the gas passing through the batch and ore structures it is necessary to assess the lateral area of the cohesive zone. Considering the earlier assumption regarding the shape of the cohesive zone it will have cone shape. Then the lateral area of the cohesive zone (Figure 2) taking into account formula (3) can be assessed by the formula, m²

\[ S = \pi \cdot DN \cdot DK. \]

(4)

We think that gas passage through batch and ore structures is distributed proportionally to the surface areas of coke \( S_c \) and ore \( S_o \) structures for gas passage and also the porosity of the coke and the ore layer in the cohesive zone. Upon that we need to consider two factors for the cohesive zone:

- the decrease of surface area for gas passage in ore structures because of the softening and partial melting of the ore layer (layer shrinkage);
- the reduction of the surface area for gas passage in coke bed due to frequent scarifying and degradation of coke.

Based on the laboratory data the shrinkage of sinter upon softening and partial melting is 22-26 \% [12, 13]. By the data of [14] ore melt can flow into batch structure in the volume of up to 0.08 m³/m³. Considering the factors specified above we take the residual equivalent porosity of coke in the cohesive zone (the volume and, consequently, the height of the coke layer on the level of the bottom of the shaft of the furnace do not change) as equal to \( \varepsilon_{rco} = 0.42 \) m³/m³.

The surface area of coke bed \( S_c \) and lens of ore \( S_o \) was assessed by the formulas, m²

\[ S_c = S \cdot \frac{h_c}{h_c + h_o - (1 - \Delta V)}; \]

(5)

\[ S_o = S \cdot \frac{h_o - (1 - \Delta V)}{h_c + h_o - (1 - \Delta V)}; \]

(6)

where \( h_c \) and \( h_o \) are the heights of coke beds and lenses of ore respectively in m; \( \Delta V \) is the shrinkage of the ore layer (ore structures) in the cohesive zone as a unit fraction.

The initial equivalent porosity of the ore layer was determined considering the equivalent porosity of the sinter and pellets by the formula
\[ \varepsilon_{beg}^{por} = \varepsilon_{eq}^{s} \cdot \%_{s} + \varepsilon_{eq}^{p} \cdot \%_{p}, \]  
(7)

where \( \varepsilon_{eq}^{s} \) and \( \varepsilon_{eq}^{p} \) are the equivalent porosities of the sinter and pellets in m\(^3\)/m\(^3\); \( \%_{s} \) and \( \%_{p} \) are the fractional proportions of sinter and pellets in the charge as a unit fraction.

The residual equivalent porosity of the ore layer (ore structures) without the injection of coke nut was assessed by the formula, m\(^3\)/m\(^3\)

\[ \varepsilon_{res}^{por} = \frac{\varepsilon_{beg}^{por} - \Delta V}{(1 - \varepsilon_{beg}^{por}) + (\varepsilon_{beg}^{por} - \Delta V)}. \]  
(8)

The residual equivalent porosity of the ore layer considering the injection of coke nut was determined by the formula, m\(^3\)/m\(^3\)

\[ \varepsilon_{res}^{sym} = \varepsilon_{res}^{por} \cdot \%_{por} + \varepsilon_{res}^{nut} \cdot \%_{nut}, \]  
(9)

where \( \varepsilon_{res}^{nut} \) is the residual equivalent porosity of coke nut in the lens of ore in the cohesive zone in m\(^3\)/m\(^3\); \( \%_{o} \) and \( \%_{nu} \) are the fractional proportions of ore materials and coke nut as unit fractions.

The fraction of the surface area of batch structure for gas passage (the fraction of gas passing through batch structure) was assessed by the formula

\[ Q_{c} = \frac{S_{c} \cdot \varepsilon_{res}^{c}}{S_{c} \cdot \varepsilon_{res}^{c} + S_{o} \cdot \varepsilon_{res}^{sym}}. \]  
(10)

Then the fraction of gas passing through the ore structure is assessed by the difference

\[ Q_{o} = 1 - Q_{c}. \]  
(11)

The quantity of the hearth gas which is formed in the bottom part of a blast furnace was determined by the formula, m\(^3\)/s

\[ V_{HG} = \frac{P_{day} \cdot V_{HG}^{o}}{24 \cdot 60 \cdot 60}, \]  
(12)

where \( V_{HG}^{o} \) is the discharge of hearth gases for 1 tonne of hot metal in nm\(^3\)/t of hot metal; \( P_{day} \) – is the daily performance of the furnace, t / day.

Then the amount of gases which pass through the cohesive zone taking into account the temperature and the pressure was assessed by the formula, m\(^3\)/s

\[ V_{HG}^{l} = V_{HG} \cdot \frac{\varepsilon_{av}^{CS} + 273}{273} \cdot \frac{p_{0}}{p_{b}}, \]  
(13)

where \( \varepsilon_{av}^{CS} \) is the average temperature in the cohesive zone in °C, it is taken as equal to the average value between the temperature of the end and the beginning of the softening of ore materials; \( p_{0} \) and \( p_{b} \) are the absolute values of the atmospheric pressure and blast respectively, kPa.

The velocity of gas passage through batch structure was determined by the formula, m/s

\[ U_{0} = \frac{V_{HG}^{l} \cdot Q_{o}}{S_{c} \cdot \varepsilon_{res}}. \]  
(14)

The influence of the injection of fuel additives on the coke rate was assessed by the formula, kg / t of hot metal
where \( C_0 \) is the coke rate with the initial iron content in the charge Fe_0 (\%), absence of PCI, but with the same high temperature of blasting and other parameters of blast furnace melting in kg/t of hot metal; PCI is the flow rate of PCI in kg/t of hot metal; Fe is the percentage of iron content in the charge during a base period.

The gradient of the gas temperature was determined by the formula, K/m

\[
a_f = \frac{T_{se} - T_{sb}}{H_{cz}},
\]

where \( T_{sb} \) is the absolute temperature of the beginning of softening in K; \( T_{se} \) is the absolute temperature of the end of softening in K; \( H_{cz} \) is the height of the cohesive zone in m.

The calculation of the absolute pressure in the cohesive zone was assessed by the formula [14], kPa

\[
p = \left[ \frac{p_0^2}{\sin \alpha_w} \left( \frac{1 - \epsilon_{res}^e}{\epsilon_{res}^e} \right) \right] \frac{p_0 \cdot \rho_g \cdot U_0^e}{T_0 \cdot F} \left( T_{sb} \cdot H_{cz} + \frac{a_f \cdot H_{cz}^2}{2} \right),
\]

where \( p_0 \) is the gas pressure on the border of the charge and the belly in Pa; \( f \) is the specific resistance; \( d_e \) is the equivalent (harmonic mean) diameter of the lumps of coke in the cohesive zone in m; \( F \) is the factor of the shape of a lump; \( T_0, p_0 \) are the normal absolute temperature and pressure \( (T_0 = 273 \text{ K}, p_0 = 101 \text{ kPa}); \rho_g \) is the normal density of gas, kg/m³.

Then the differential gas pressure in the cohesive zone can be determined by the formula, kPa

\[
\Delta p_{cz} = p - p_r.
\]
injection of coke nut in the volume of 0 - 30 % into the ore layer will help to increase the gas fraction passing through the ore layer from 6.9 to 36.1 %.

Table 1. The determination of the main sizes of the cohesive zone for the conditions of the blast furnace of 1719 m³ capacity.

| Indicators                                      | The angle in the top of the cohesive zone β |
|------------------------------------------------|--------------------------------------------|
|                                                | 60°  | 90°  | 120°                        |
| 1. The height of the cohesive zone excess over the border of the belly, m | 8.8  | 5.1  | 2.9                         |
| 2. The length of the gas passage through batch (ore), m | 1.0  | 1.5  | 2.2                         |
| 3. The length of the generatrix of the cone, m | 10.2 | 7.2  | 5.9                         |
| 4. The surface area of the side surface of the cohesive zone, m² | 163.4| 115.4| 94.5                        |

A series of calculations was done to assess the gas permeability of the cohesive zone while injecting coke nut into the ore layer in the amount of up to 30 % at low (β=120°), medium (β=90°) and high (β=60°) intensity of the axial gas flow. Figure 3 shows that when increasing the fraction of coke nut from 0 to 30 %, loaded into the iron ore part of the charge, with different intensity of the axial gas flow the differential gas pressure decreases by 17.5-18.6 %. Besides, changing the intensity of axial gas flow from low to high (angle β in the top of the cohesive zone reduces from 120 to 60°) will lead to the reduction of the resistance to gas passage from 33-40 to 11.4-14 kPa (2.9 times).

Besides, a series of calculations was done to assess the gas permeability of the cohesive zone for the conditions specified above and the PCI in the amount up 250 kg/t of hot metal. Figure 4 (a) shows that while increasing the consumption of PCI from 0 to 250 kg/t of hot metal and zero consumption of coke nut the differential gas pressure in the cohesive zone increases from 40 to 55.8 kPa (or by 39.5 %). To keep the base value of the differential gas pressure while increasing the consumption of PCI one of the compensating measures can be the increase of the consumption of coke nut mixed with the iron ore part of the charge. So, for example, at low intensity of gas passage to keep the base value of the differential gas pressure, equal to 40 kPa, and the increase of the consumption of PCI up to 150 kg/t of hot metal the consumption of coke nut should be about 30 % (Figure 4 (a)). At high intensity of gas flow the differential gas pressure with the consumption of PCI up to 250 kg/t of hot metal will be significantly lower than the base value of the differential gas pressure (40 kPa) (Figure 4 (b)).
Conclusion
The calculations of gas permeability are made based on the assumption that ore structures are impermeable to gas. The analysis of the literature data and the calculations show that in a blast furnace ore structures in the cohesive zone, as a rule, are permeable to gas, which significantly influences the distribution of gas flow. Up until now the method of calculated determination of gas permeability of ore structures in the cohesive zone is not fully perfected. In this study we suggested a method of calculated determination of gas permeability of the cohesive zone, which considers the influence of the loading of coke nut into the ore layer.

As a main statement we take that the ore structure in the cohesive zone is permeable for gas. Besides, the developed method of assessment allows us to determine the gas permeability in the cohesive zone when changing a range of technological parameters of blast furnace melting.

Changing the intensity of the axial gas flow in a blast furnace to a higher one will help to stretch out the height of the cohesive zone over the border of the belly and to improve the gas permeability of the cohesive zone. We assessed the influence of different intensity of the axial gas flow in the cohesive zone while injecting coke nut into the ore layer. It showed that when a blast furnace is operating with skip coke prepared by fractional composition and with the injection of coke nut into the iron ore part of the charge in the amount of up to 30% the transfer from low intensity of axial gas flow to the high one will help to improve the gas permeability of the cohesive zone by 2.9 times. This measure is quite relevant especially in case of assimilation of blast furnace melting with the high consumption of PCI.

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