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Change in coke characteristics in a low-movement coke bed of blast furnaces

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Зміна характеристик коксу в коксовому шарі з низьким рівнем руху доменних печей

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Abstract. *The question of the appropriateness of using the archaic term "tooterman" in relation to the relatively immobile coke mass in the lower part of blast furnaces was raised. For the first time, an attempt was made to summarize information about changes in coke characteristics depending on its location in local MCM zones, for which a conditional division of the MCM into three interdependent but functionally different parts: the upper central superheater (feeding), the middle part between the air blast and cast iron nozzles (working), and the lower part located in the sump (MKM working zone). The conditions for the use of coke in local parts of the MCM were comprehensively considered. New data about the increase in melting intensity on the size of the living part of the MCM has been extracted. It has been shown that the very changes in the intensity of smelting are done to ensure the life of the tuyere part by heating with coke. It is shown by comparing the structure of the MCM of two Japanese blast furnaces cooled during operation that working at a reduced smelting intensity leads to the degeneration of the stable axial zone of low-mobility materials above the tuyere horizon, thereby changing the conditions for preliminary coke heating and its supply to the lower parts of the MCM. The known mechanism of coke piece destruction by liquid metal flowing past them with carbonization of the latter needs to be clarified, since liquid slag formed on the tuyeres during oxidation of Fe, Si, Mn, and P components of cast iron also moves through the sub-tuyere coke mass, The restoration of these oxides requires additional consumption of coke carbon. Based on the generalization of research data and theoretical principles of the blast furnace process, the sequence of coke combustion processes in the MCM sub-bed array is proposed. The mechanism of erosive influx onto the coke massif, which is located in the zone of intense molten flow, has been clarified. It is shown that in this array, there is not one process of coke consumption for metallurgical reactions, as previously thought, but three. The influence of MCM "survivability" on the technical and economic indicators of smelting has been assessed.*
Keywords: *blast furnace process, toterman, sump, coke mass, smelting intensity, coke, erosion, graphitization, structure.*

Анотація. *Було порушено питання про доцільність використання архаїчного терміна «перегрівач коксу» стосовно відносно нерухомої коксової маси в нижній частині доменних печей. Вперше було зроблено спробу узагальнити інформацію про зміни характеристик коксу залежно від його розташування в локальних зонах ГКМ, для чого було проведено умовний поділ ГКМ на три взаємозалежні, але функціонально різні частини: верхній центральний перегрівач (живильний), середня частина між повітряним дуттям та чавунними соплами (робоча) та нижня частина, розташована в зумпфі (робоча зона ГКМ). Комплексно розглянуто умови використання коксу в локальних частинах ГКМ. Отримано нові дані про збільшення інтенсивності плавлення від розмірів живої частини ГКМ. Показано, що самі зміни інтенсивності плавлення здійснюються для забезпечення терміну служби фурмової частини шляхом нагрівання коксом. Порівнянням структури МВМ двох японських доменних печей, охолоджуваних під час експлуатації, показано, що робота зі зниженою інтенсивністю плавки призводить до дегенерації стабільної осьової зони малорухливих матеріалів над фурменним горизонтом, тим самим змінюючи умови попереднього нагрівання коксу та його подачі до нижніх частин МВМ. Відомий механізм руйнування шматків коксу рідким металом, що протікає повз них, з карбонізацією останнього потребує уточнення, оскільки рідкий шлак, що утворюється на фурмах під час окислення Fe, Si, Mn та P компонентів чавуну, також рухається через підфурменну коксову масу. Відновлення цих оксидів вимагає додаткової витрати коксового вуглецю. На основі узагальнення дослідницьких даних та теоретичних основ доменного процесу запропоновано послідовність процесів горіння коксу в масиві підшару МВМ. З'ясовано механізм ерозійного напливу на коксовий масив, який розташований у зоні інтенсивного розплавленого потоку. Показано, що в цьому масиві існує не один процес споживання коксу на металургійні реакції, як вважалося раніше, а три. Оцінено вплив «живучості» МСМ на техніко-економічні показники плавки.*
Ключові слова: *доменний процес, тотерман, відстійник, коксова маса, інтенсивність плавки, кокс, ерозія, графітизація, структура.*

Introduction. In multi-ton ferrous metallurgy, coke is essentially an indispensable component of blast furnace charge. And while its functions as a heat carrier and source of carbon monoxide reducing agent can be partially replaced by blowing in hydrocarbons, its physical functions cannot be replaced due to the thermal stability of the lump. The ability of coke to retain its lumpiness close to the blast furnace hearth allows the creation of a movable frame of materials and ensures the flow of reduction, melting, and accumulation processes at different temperature levels.

Particularly difficult operating conditions for coke occur in the lower high-temperature zone of the blast furnace, where only one coke remains in a solid state during normal furnace operation. Depending on the specifics of the mechanical processes, this zone is divided into three parts. The upper zone between the cohesion zone at the top and the conical part of the axial zone of low-mobility materials (OZMM – term by V.G. Druzhkov, 1982) on the side and the furnace hearths at the bottom was named the active coke zone by E. Bepler and colleagues [1] (**Fig. 1**). V.P. Puzanov and V.A. Kobelev (2012) gave this complex spatial figure another name: "counterflow coke nozzle." The second part includes a very specific zone of furnace hearths, and the third part includes a coke toterman extending from the OZMM down to the tongs [1].

The immobile coke mass under the mobile zone, submerged in molten slag and cast iron, is commonly referred to as a coke deadman [1-3], which is not entirely correct in terms of the use of this term. The term "deadman" came from the practice of operating blast furnaces, when, as a result of certain technological violations, a "dead" monolith of solidified melts and coke formed on the hearth. Under normal conditions of the blast furnace process, the coke mass located under the active coke zone is a gas-permeable formation, as evidenced by the powerful emission of blast furnace gases when blowing out the cast iron tap at the end of the smelting process, drainage capacity, and limited mobility relative to the hearth or the horizon of the air blast pipes.

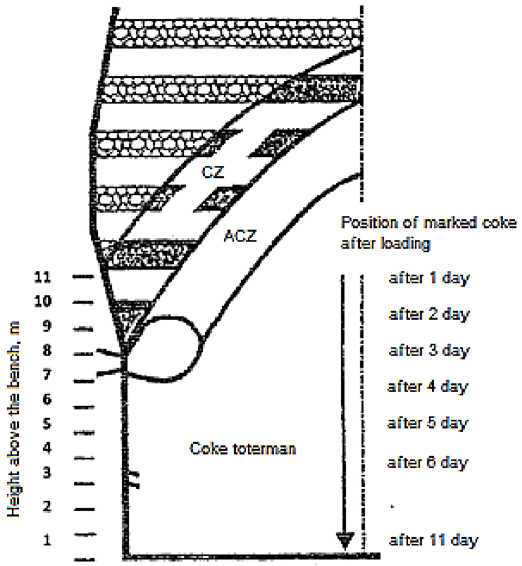

Fig. 1. Diagram of coke movement in blast furnace No. 1 at the Schwelgen plant and names of characteristic zones in its lower part E. Beppler et. al [1]: CZ – cogesion zone; ACZ – active coke zone

Therefore, when considering issues related to the operation of the lower part of blast furnaces, it is proposed to replace the terms "totherman" and "coke totherman," which do not correspond to the essence of the processes occurring in the aforementioned part, with the terms "low-mobility coke mass" (LCA) and "low-mobility coke charge" (LMC), or even "low-mobility coke frame." Given the difference in the processes occurring at different heights of the low-mobility coke mass, we believe it is advisable to divide it into characteristic zones from top to bottom: the upper superheater (OZMM), the middle sub-furnace between the horizons of the furnaces and cast iron nozzles, and the lower sub-nozzle located in the sump. This division makes it possible to consider the functional purpose of each part more specifically and, with the help of the results of modern research, to consider the behavior of coke in the MCM structure from new perspectives. This is prompted by fundamental changes in the profiling of blast furnaces, which have led to an increase in both the height of the furnace and the depth of the sump [4], which has significantly affected the operational characteristics of coke within the specified profile elements.

Analysis of recent studies and publications. The beginning of active research into the condition of coke along the height of the charge column is associated with the dismantling of blast furnaces that were frozen in operation [5]. Analysis of the contents of three Japanese blast furnaces showed that, regardless of the quality of the coke used and the technology used to conduct the process, the size of the coke decreased during the process of lowering it from the tuyere into the hearth, and the smaller the initial size of the coke, the greater the decrease.

The second pattern identified was a sharp thinning of the coke structural grid due to increased pore formation in the low-mobility coke mass below the air blast horizon. Subsequently, with the advent of sophisticated research tools, a number of studies [6-9] appeared that more thoroughly illuminated the behavior of coke in specific areas of its use**.**

In cores taken from the air blast horizon, the characteristics of coke that determine its metallurgical value were studied, both in the blast zone and in the upper part of the MCM [6, 7]. These are the strength of coke at different levels of smelting intensification [7], the distribution of fine fractions along the furnace radius, and the ability of coke to resist aggressive factors such as gasification, alkali content, etc. [6].

Modern methods for studying the microstructure of the phase and elemental composition of coke samples taken from the MCM between the tuyere and nozzle horizons were used in the study [8]. These are X-ray diffraction (XRD analysis), energy dispersive X-ray spectroscopy (EDS analysis), and electron microscopy.

The authors [9] used X-ray structural analysis to evaluate the degree of graphitization of coke collected from the blast furnace sump, which allowed them to determine the average carbon stacking height (L_C), the interlayer distance d_{002}, and the number of neps $n_H = L_C/d_{002}$. The use of a scanning electron microscope and spectroscopy made it possible to study the interface between coke and cast iron and to determine the phases in the coke pores, both captured and newly formed.

Given the importance of the topic, the results of individual studies will be reviewed, analyzed, and, where possible, supplemented.

The purpose of the work to determine the functional purpose of the components of the low-mobility coke mass of blast furnaces using the results of leading studies and, from this perspective, to examine the behavior of coke in specific locations.

Research results and discussion. In accordance with the division of the low-mobility coke mass into three characteristic parts, the main material of the article is also divided into corresponding blocks.

The superstructure central part of the MCM. The superstructure part is a kind of channel for supplying coke to its superstructure immovable array, on the condition of which the operation of the blast furnace will largely depend. In turn, the satisfactory performance of the feeding function of this part depends on the organization of the coke vent in the center of the furnace and the maximum possible preservation of the properties of coke at the entrance to the MCM. Experience has shown that, in principle, blast furnaces can operate with any form of cohesion zone and differences in the method of feeding the MCM from above. However, with a purely peripheral furnace stroke and feeding of the sub-furnace working coke mass with degeneration of the central one, only small-volume furnaces could operate. There are known cases of operation of such furnaces, in particular, DP No. 1 of the Yenakiieve Metallurgical Plant with a *V*-shaped cohesion zone and the absence of an over-furnace cone-shaped part of the MCM (I.D. Balon et al., 1984).

The main reason for the possibility of smelting with a degenerate super-furnace part of the MKM was the small radius of the furnace, half of which was the length of the furnace hearth. Due to this design difference in small furnaces, coke was heated to the required temperatures not above the furnaces, but at their horizon. Powerful furnaces have a significant difference between the length of the furnace radius and the length of the tuyere hearth, so without preheating the coke above the tuyeres, normal furnace operation is impossible.

To analyze the behavior of coke in the feeding part of the coke oven battery, the results of studies on blast furnaces No. 3 and No. 4 of Chine Steel (Taiwan) were used, where coke samples were taken at the level of air tuyeres using samplers with a diameter of 200 and 300 mm. During the experiments, the strength of the selected coke samples was determined using a drum used to measure CSR [7].

In the further analysis, we divided the furnace radius, along which the samples were taken, into two parts: the first part, from the air blast pipes to the 2 m mark, represented the blast pipe cavity together with the “bird's nest” of fines, the second – between the 2 and 4 m marks in the direction of the center of the furnace – the axial zone of the low-mobility super-tundish array.

Researchers [7] found a significant difference in the nature of changes in coke strength along the radius of the furnace depending on the injection of pulverized coal fuel (PCF) and its absence on the coke bed. In the case of PFP injection, curves with minimum strength in the furnace zone and maximum strength shifted to the center of the furnace were observed (**Fig. 2, a**, **Fig. 2, b**). The researchers explained the appearance of maximum strength values by the blowing of the surface of coke pieces with a blast jet, a weakened gasification reaction, and physical abrasion, as a result of which the latter showed a higher drum test. In turn, the practically unchanged strength of coke without coal injection over a distance of 4 m was explained by the high degree of coke replacement in the tuyeres.

The latter argument can be partially agreed with by comparing the graphs in **Fig. 2**, in and **Fig. 2, d**. Indeed, coke samples using coal-free technology lost SiO_2 much more slowly than those using coal.

However, the decisive difference in the nature of changes in coke strength lies elsewhere – in the temperature and thermal regime of the furnace and in the structure of the low-mobility coke masses in it, which is determined not only by the injection of fuel additives or their absence. To illustrate this argument, **Fig. 3** shows the structures of the charge column frozen in operation in Japanese blast furnaces No. 1 at the Amagasaki plant [10] and No. 1 at the Hirohata plant [11] (**Fig. 3**).

The performance indicators of these furnaces and the volumes of slow-moving coke mass elements determined by us [12] are presented in **Table 1**. Since Japan used high-quality imported blast furnace raw materials at that time, coke and iron ore materials in both furnaces were of similar quality. The main difference in the blast furnace process strategy was the choice of priority. At DP No. 1 Amagasaki, maintaining a high ore load and moderate smelting intensity resulted in high smelting efficiency, with a specific fuel consumption of only 451 kg/t of pig iron.

High smelting efficiency (53.2 t/m2/day) at DP No. 1 Hirohata was achieved by increasing the smelting intensity, but with a significantly higher specific fuel consumption (542 kg/t of pig iron).

Table 1 - Performance indicators for frozen blast furnaces and quantitative characteristics of their low-mobility coke beds according to data from [10-12]

Indicators	Plant, furnace number	
	Amagasaki, No. 1	Hirohata, No. 1
Diameter of the horn, m	6	7,8
Useful volume, m^3	721	1407
Specific productivity, $t/m^2 \cdot day$	48,8	53,2
Fuel consumption (coke + fuel oil), kg/t	451	542
Ore load on coke	3,57	3,12
Melting intensity per fuel used I_P, $t/m^3 \cdot day$	0,854	0,979
Volume of coke mass, m^3/% of useful furnace volume in profile elements:		
- horn	100 / 13,9	235 / 16,7
- shoulders	40 / 5,5	133 / 9,5
- steaming	-	133 / 9,5
- mine	-	23 / 1,6
Total coke mass volume, m^3/%V_{cor}	140 / 19,4	391 / 27,8

An analysis of the information presented in **Fig. 3** allows us to draw certain conclusions about the effect of smelting intensity on the formation of the charge column. As the intensity increases, the following changes occur:

1) the height of the overburden part of the low-mobility coke mass increases;

2) the total volume of the coke mass increases;

3) the number of windows in the plastic zone increases and, accordingly, the gas permeability of the critical zone increases;

4) the circumferential unevenness in the formation of cohesion zones and the immobile coke mass increases or is eliminated.

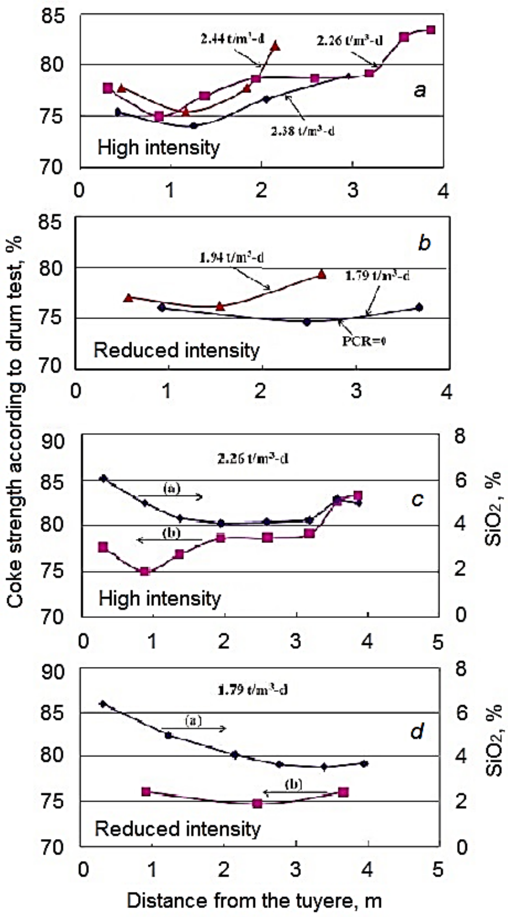

Fig. 2. Change in coke strength along the radius of the furnace DP No. 3 and 4 of the CSC company (Taiwan) depending on high (a, c) and low (b, d) melting intensity per specific productivity, as well as on the SiO_2 content in coke samples according to data [7]: PCR = 0 means cessation of pulverized coal fuel injection

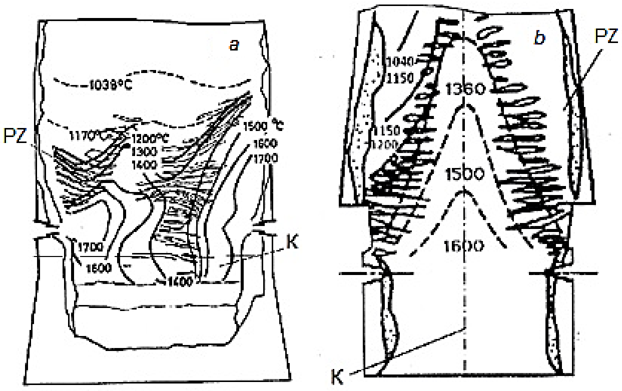

Fig. 3. Forms of the plastic zone and low-mobility coke mass in the frozen blast furnaces Amagasaki, No. 1 (a) and Hirohata, No. 1 (b) according to data [10, 11]: numbers next to curves – isotherms; K – coke mass; PZ – plastic zone

Reducing the intensity of the furnace operation leads to reverse processes.

To sum up, it should be noted that reduced melting intensity leads to the degeneration of the stable axial zone of low-mobility coke above the tuyere horizon, which worsens the conditions for its heating and hinders the formation of the lower parts of the MCM with sufficient temperature, gas permeability, and drainage capacity, as convincingly demonstrated by the structure of the coke mass of DP No. 1 Amagasaki (**Fig. 3, a**).

While intensive furnace operation with coal dust injection helped preserve the properties of coke in its low-mobility mass (**Fig. 2, a, b**), such operation in the tuyere zone intensified coke destruction and increased the yield of fines (**Table 2**), which is understandable, since it is known that high temperatures destroy the carbon texture through graphitization by the catalytic effect of fine iron fractions [6]. The destruction effect is enhanced by the high temperature in the combustion zone, which is achieved by enriching the blast with oxygen.

Table 2 - Output of coke fines depending on furnace productivity and theoretical combustion temperature recorded one day prior to coke sampling at CSC's DP No. 3 and 4 [7]

Indicators	High performance ⟶				⟵ Reduced productivity	
Furnace number / period	4/1	3/1	4/2	3/3	4/3	3/5
Productivity, $t/m^3 \cdot day$	2,44	2,38	2,45	2,26	1,93	1,94
Small change output, %	12,1	19,2	13,1	20,7	6,8	6,1
Theoretical combustion temperature, °C	2100	2283	2141	2197	2049	2055

The middle part of the MCM between the levels of the tuyeres and cast iron nozzles. This is the most critical area of the slow-moving coke mass, as it is here that the final cast iron and slag compositions are formed, and the melts are separated and accumulated. Hence its functional purpose is to create the necessary conditions for these processes to take place.

An idea of the state of coke after staying in the tuyere hearth compared to its initial state and coke that was in the coke nozzle at the core sampling horizon located 1.0-5.2 m below the level of the air tuyere (**Fig. 4, a**) can be obtained using the results of work [8].

The experimental coke samples were obtained in a 5,800 m^3 blast furnace manufactured by Shagang Group (China). The furnace, with a hearth diameter of 15 m, had 40 air blast pipes, 3 cast iron troughs, and hearth depths below the air blast pipe and sump horizons of 5.2 and 4.4 m, respectively. The quality coke had M40 90% and M10 5.7% indicators. Coke and pulverized coal fuel consumption was 380 kg/t and 152 kg/t of cast iron, respectively. The furnace's productivity (October 2009) was 12,500 t/day.

It was found that the largest pieces of coke suffered the most damage in the furnace hearth and in a 2 m long section. The underfurnace coke (**Fig. 5, a**) had a characteristic “cut” shape, significantly different from both the coke of the low-mobility mass (**Fig. 5, b**) and the initial coke.

Given the nature of coke piece destruction, the authors [8] proposed a mechanism for reducing the size of pieces under the tuyere hearth due to the downward movement of liquid metal (**Fig. 5, b**) and the process of its carbonization. In our opinion, this mechanism does not sufficiently explain the loss of coke mass under the tuyere zone, since, in addition to liquid metal, liquid slag formed on the tuyeres during the oxidation of Fe, Si, Mn, and P components of cast iron also passes through the coke under the tuyere. The carbonization of metal oxidized on the tuyeres and the reduction of the listed impurities require corresponding consumption of coke carbon.

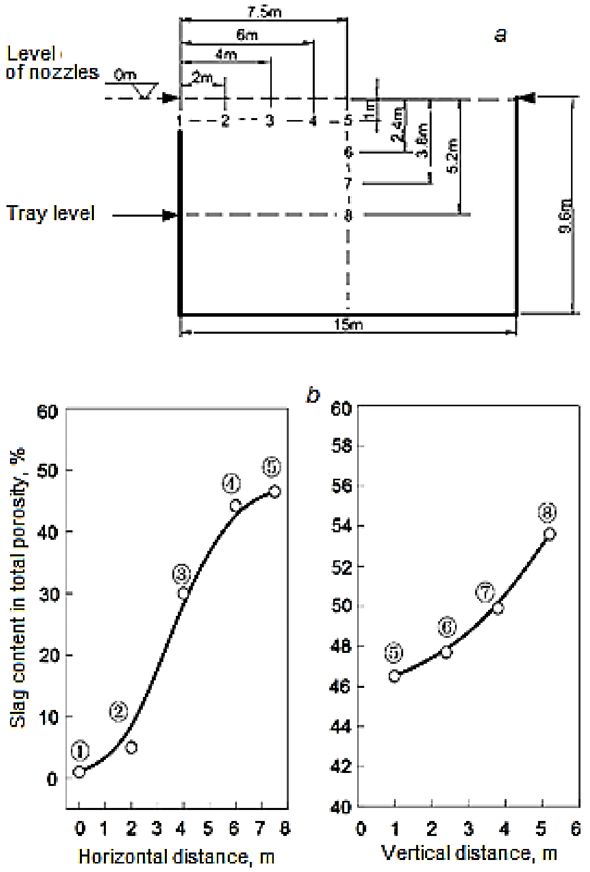

Fig. 4. Locations for sampling coke from a 5800 m3 blast furnace (a) and slagging of coke samples depending on location (b) according to data [8]: 1-8 – locations according to Fig. 4, a

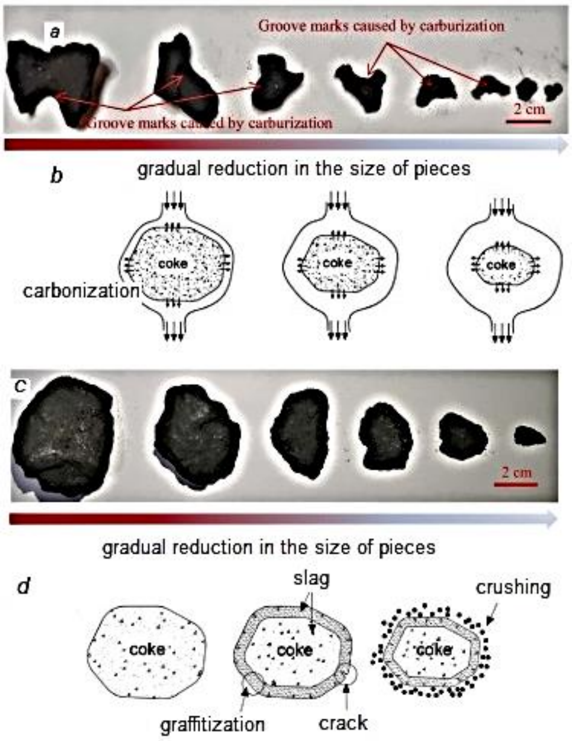

Fig. 5. Mechanisms for grinding peripheral (a, b) and central coke (c, d) below the air blast horizon proposed by the authors [8]

When studying the microstructure of coke samples, slag was found inside coke pieces taken at a distance of 2 meters from the center of the furnace. According to the data obtained, the amount of slag contained in the coke samples varied – it was minimal under the combustion zone and maximal in the center of the furnace (**Fig. 4, b**). The graph shows that the coke contained < 10% slag in the pores at a distance of 0 and 2 m from the edge of the furnace and more than 30% slag at distances of 4.6 and 7.5 m from the furnace walls.

The authors [8] explain the observed dependence by the time the coke remains in the furnace cross-section. At the periphery of the furnace in the charging zone, coke is consumed and moves down faster than coke in the coke bed. Therefore, a small part of the slag falls on the surface of the coke pieces. In addition, due to active gasification and carbonization, the coke surface saturated with slag is consumed more actively. The central coke moves down slowly, which gives enough time for the slag to penetrate deeper into it. Combined with the low amount of metal in the center of the furnace, the coke is almost not washed away and is not absorbed by the liquid metal.

There are no serious comments regarding the mechanism of “slag” crushing of coke pieces removed from the furnace hearths, but the somewhat simplified diagram (**Fig. 5, d**) does not quite correspond to the appearance of the coke samples (**Fig. 5, c**).

The lower part of the low-mobility coke mass. Functionally, this is the zone of gradual MCM depletion. The task of technologists is to maintain the buoyancy of the mass without losing its drainage capacity. The materials of the study of the state of coke in this part of a 4350 m^3 blast furnace in China deserve the attention of the professional community, but the author's interpretation [12] of the results obtained cannot be agreed with without critical comments.

The study was conducted in August 2020 [9]. The furnace had 38 air nozzles and 4 cast iron tuyeres. Before it was shut down for repairs in June 2020, the furnace had been operating since October 2006 with a productivity of 2.14 t/m^3·day and a slag yield of 242 kg/t of cast iron. Coke and pulverized coal consumption amounted to 330 and 180 kg/t of cast iron, respectively.

According to the authors [9], at the time of the shutdown for repairs, the diameter of the burning furnace was 15.17 m, and the diameter of the coke nozzle was 11.95 m, or 78.77% of the actual diameter of the furnace. The coke samples studied were obtained by drilling cores from the coke mass during major repairs. The sampling locations were located at a distance of 1.2, 1.8, 2.4, and 3.0 m from the horizon of the cast iron nozzles in the direction of the tongs (**Fig. 6**). The diameter of the cores was 100 mm. The researchers emphasize the buoyancy of the coke mass and the fact that the area below location S4 to the clamp was free of coke.

It is clear that diagrams always have some degree of conventionality, but the one shown in **Fig. 6, a** differs significantly from the actual state of the low-mobility mass in the blast furnace sump, for example, blast furnace No. 4 in Kurashiki (Japan, T. Nohashi et al., 2004). This is especially true for the upside-down conicity of the coke mass in the direction of the cast iron tuyere of the Chinese blast furnace.

Fig. 6, a-d shows the cross-section of samples at the sampling horizons, and **Fig. 6, e-h** shows images of samples after digital processing, which was used to calculate the average porosity and size of coke pieces in the coke mass (**Fig. 7**). Unlike the author's [9] interpretation of the research results, the abscissa axis in **Fig. 7** shows not the numbers of sampling locations S1-S4, but the actual distance from the axis of the cast iron trough. This allows us to see the gradients of change in coke properties as it descends toward the bottom without even performing calculations. As shown in the last figure from the location 1.2 m below the cast iron trough, the coke void increased with a slight decrease in location S4. In contrast to the porosity, the size of the pieces in locations S1-S4 continuously decreased over a distance of 1.8 m, with the rate of decrease in piece size gradually slowing down. At the same time, it is not difficult to see the contradiction in the opposite changes in the average size of coke pieces in the sump and its voids filled with cast iron. It would be worth explaining why the pieces are getting smaller and the voids between them are increasing.

The low porosity of the coke mass layer, located 1.2 m away from the cast iron tuyere in the direction of the clamp (**Fig. 6, c**), can be explained by the significant difference in the sizes of large and small fractions, as well as the action of Archimedes' buoyancy force, which together contributed to the significant packing of pieces in the molten cast iron. The unexpectedly high void volume in the layers of the nozzle at horizons S2-S4 within the range of 44-47% is noteworthy. If we assume the initial void content of skip coke to be 50%, then the void content of the coke charge in the sump at levels S2-S4 will be 88-94% relative.

The authors [9] considered the chemical composition of coke samples (**Table 3**) to be almost identical, with the exception of the CaS content in core S2, since all samples contained K, Na, and Zn. A more careful analysis of the data in the table does not allow us to agree with this conclusion of the researchers. First, there is a clear decrease in the concentration of alkalis in the coke samples from top to bottom, which can be explained by a decrease in the temperature of cast iron and MCM with distance from the heat generation horizon on the air nozzles and the consumption of alkalis for interaction with transitional slag in the pores of coke.

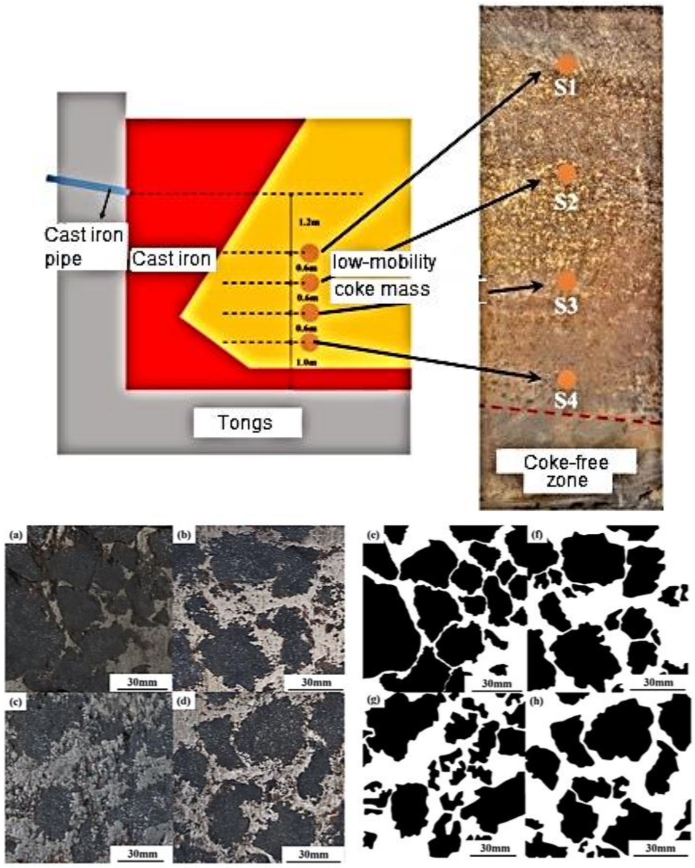

Fig. 6. Diagram of the structure of a low-mobility coke mass in the sump of a Chinese blast furnace with a volume of 4350 m^3 with an index of locations (S1–S4) for coke sampling (α) and binary images of coke samples (a–d) with the morphology of these samples corresponding to locations S1–S4 (e–h) according to [9]

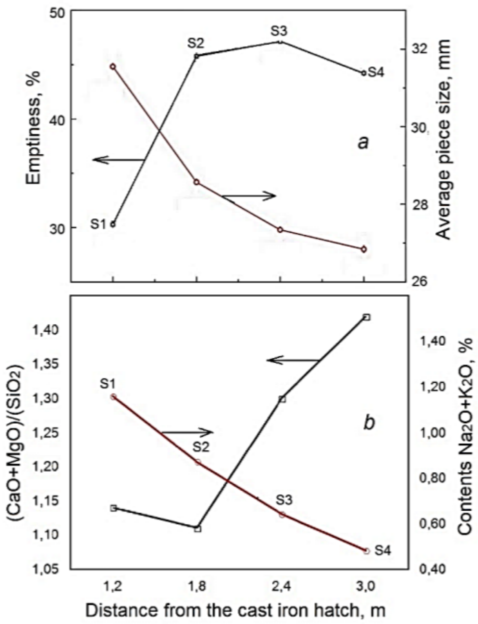

Fig. 7. Graphs showing changes in the average size of coke pieces and coke porosity (a), as well as the alkali content and basicity of the mineral mass of coke (b) in the sump of a Chinese blast furnace with a volume of 4350 m^3, constructed based on data from [9]

Table 3 - Chemical composition of coke samples taken from the nozzle below the level of cast iron taps according to [9]

Location of sample	Contents, %					
	C	Al_2O_3	SiO_2	MgO	CaO	CaS
S1	50.88	6.98	17.99	2.59	17.98	2.36
S2	37.22	9.53	18.79	2.81	18.12	12.61
S3	50.14	8.10	15.83	2.81	17.79	4.67
S4	36.05	10.60	19.71	3.76	24.26	5.11

Continuation of Table 3

Location of sample	Contents, %					
	K_2O	Na_2O	K_2O+Na_2O	ZnO	CaO/SiO_2	$\frac{CaO + MgO}{SiO_2}$
S1	0.82	0.34	1.16	0.06	1.00	1.14
S2	0.58	0.29	0.87	0.05	0.96	1.11
S3	0.44	0.20	0.64	0.02	1.12	1.30
S4	0.25	0.23	0.48	0.03	1.23	1.42

The first factor that slowed down the reduction in coke pieces was a gradual decrease in the alkali content in coke samples from 1.16% to 0.48%, i.e., by 2.4 times. The second factor was the active adhesion of CaS to the surface of coke due to the desulfurization reaction of CaO metal in blast furnace slag, which is captured by coke when it is above the cast iron tuyere. Due to the action of the above factors, the reduction in the average size of the coke piece and its porosity at a distance of 1.8-3.0 m below the coke nozzle was only 6.1% and 3.4% (relative), respectively.

Given the process of absorption of blast furnace slag by coke pores, it became possible to evaluate the composition of coke together with transition slag in pores using known basicity indices. This leads to the second difference in the chemical composition of coke samples, which is a significant increase in basicity at horizons S3 and S4 compared to S1 and S2. This indicates that, despite the relatively low temperatures in the sump at horizons S3 and S4, silicon was recovered from the transition slag, which reduced the silica content and increased the basicity. The possibility of silicon recovery in the sump of DP No. 1 of the Hirohata plant (Japan) with a volume of only 1407 m^3 was noted in [13].

As shown in **Fig. 8**, the mineral layer at the interface between cast iron and coke was in direct contact. Due to the presence of coke pores (**Fig. 8, b**), coke continuously adsorbed blast furnace slag, which interacted with coke ash. After contact with molten cast iron, calcium in the newly formed slag reacts with cast iron sulfur: $CaO + S_ч + C_к = CaS + CO$. Since the melting point of CaS is about 2673 K, the authors [9] claim that the slag phase adheres to the interface between coke and molten iron as a highly viscous mineral. This conclusion was made based on the fact that minerals were present both at the interface and in the iron.

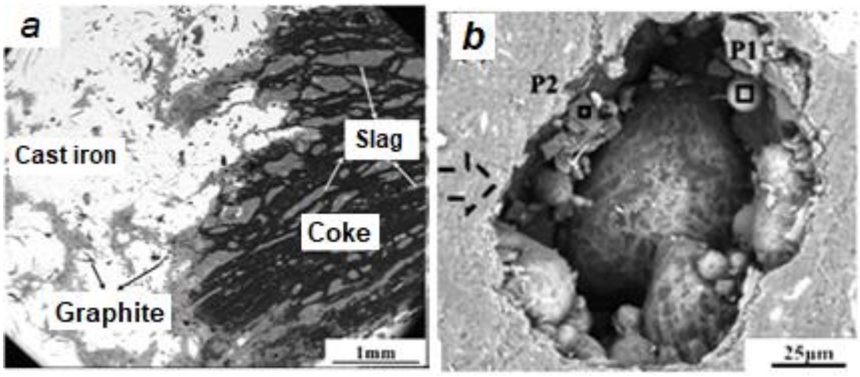

Fig. 8. Interface between coke and cast iron (a) and slag phase in coke pores (b) in micrographs of varying magnification, presented in [9]

Considering the use of coke carbon in the desulfurization and SiO_2 reduction reactions, it should be emphasized that the data presented here contradict the conclusions of [9], which states that coke consumption in the sump is only for metal carbonization. The pore content in the coke sample from location S1 is shown in **Fig. 8, b**. The pores contained perfectly spherical and massive phases containing potassium and represented by $Ca_2Al_2SiO_7$, and the massive phases were represented by the final slag of the blast furnace. Since the upper coke was closer to the cast iron tuyere and to the layer of blast furnace slag containing alkalis, the alkaline elements were deposited in the pores of the coke of horizons S1 and S2. Due to this, the catalytic effect of alkalis on the coke graphitization process was manifested precisely at these horizons (**Table 4**). As the coke gradually descended into the hearth, the alkali content and their effect decreased, and the catalytic effect of iron in the molten iron increased to a certain limit S3. The authors [9] suggest that at the S4 horizon, the heavily graphitized surface of the coke was washed away by the upper molten iron, and as a result of the temperature decrease near the hearth, the degree of coke graphitization decreased.

Table 4 - Structural parameters of coke samples from coke oven feedstock compared with coke from other furnace horizons according to [9]

Sample	Average carbon stacking height L_C, nm	Number of nefs, n_{ave}
S1	72.10	214
S2	79.96	238
S3	83.25	248
S4	53.13	158
skip coke	2.31	7
coke from the cohesive zone	4.59	13
coke from the furnace area	6.82	20

Based on the above, it is possible to present the processes occurring with the coke mass in the sump in the following sequence:

1) in locations S1 and S2, due to the preliminary capture of blast furnace slag and alkalis by coke pores at the horizon of cast iron troughs, the catalytic effect of alkalis on the formation of alkali-containing compounds and the formation of transitional slag with blast furnace dissolution of coke ash is enhanced.

2) in locations S2-S4, CaO of the transition slag at the coke-metal boundary desulfurizes the metal

$CaO + [S] + C_K = CaS + CO - 47.594$ MJ;

3) in locations S3 and S4, SiO_2 is reduced from transition slag

$SiO_2 + 2C_K = [Si] + 2CO - 635.096$ MJ;

4) in locations S3 and S4, the catalytic effect of Fe on coke graphitization is enhanced due to a decrease in coke piece size and an increase in MCM porosity, while the catalytic effect of alkalis is significantly weakened due to their consumption in locations S1 and S2;

5) washing away the graphite layer from coke pieces in location S4 enhances the catalytic effect of Fe on further coke graphitization on the one hand and cast iron carbonization on the other $3Fe + C_K = Fe_3C$.

The interaction of these processes ultimately leads to continuous graphitization and crushing of coke with complete depletion of the lower part of the low-mobility coke mass in the blast furnace sump. According to the presented sequence of processes, it is shown that there is not one process of coke consumption in the sump, as stated in [9], but three. To sum up, it should be noted that the factors determining the degree of coke graphitization below the horizon of cast iron troughs are the increased alkali content in the upper part of the sump, the catalytic effect of iron in the cast iron melt in its lower part, and the temperature distribution along the height of the under-trough space.

It should be noted separately that, despite all the positive aspects of labor-intensive and research methodology [9], the lack of data on the composition of cast iron of selected cores reduces the value of the data obtained.

Duration of operation of a low-mobility coke mass. During normal operation of a blast furnace, the process of feeding the MCM and consumption continues uninterrupted. However, thanks to the results of research [1], it is possible to roughly estimate the hidden impact of MCM changes on coke consumption and blast furnace productivity. According to [1], we assume that one “cycle” of MCM change (the time it takes for marked coke to get from loading to the clamp) is 11 days. There will be 32 such revolutions per year. We assume the volume of MCM for the blast furnace to be 5000 m^3, which is 27.8% of the useful volume, by analogy with blast furnace No. 1 in Hirohata, calculated by us (see **Table 4**). Then the volume of MCM DP 5000 m^3 will be 1390 m^3 with a mass of 695 t. With 32 MCM changes per year, the total coke consumption will be 22,240 tons, from which, with a specific coke consumption of 380 kg/ton with coal dust injection, 58,526 tons of pig iron can be obtained.

With a daily production of 9,500 tons of pig iron, the annual output will be 3,372,500 tons, which will require 1,281,550 tons of coke. With these figures, the percentage of coke consumption for the gradual replacement of the MCM will be 1.74%. Given the accepted scale of production, this does not seem like very much, but the consumption of 22,400 tons of coke per year is not insignificant, considering today's realities. Therefore, work on a possible extension of the service life of the MCM makes sense, but research in this area is only just beginning, given its labor intensity and complexity.

Conclusions

(1) The question was raised about the appropriateness of using the archaic term "tooterman" in relation to the low-mobility coke mass (LMC) in the working space of the lower part of blast furnaces, without which the blast furnace process is impossible. The functional purposes of characteristic zones of the LMA and the correspondence of the characteristics (properties) of coke to the implementation of these functions were formulated.

(2) The superheater part of the LMA performs a feeding function, the implementation of which forms the coke mass in a state that meets the requirements of the technology. An important function of this part is also the preliminary (above the air blast horizon) heating of coke to ensure the completion of blast furnace smelting processes. A comparison of the structure of the MCM of two Japanese blast furnaces cooled during operation shows that operation at reduced smelting intensity leads to the degeneration of the stable central zone of low-mobility materials above the air blast horizon, which changes the conditions for preliminary heating of coke and the uniformity of its supply to the lower parts of the MCM. It is emphasized that continuous normal operation of powerful blast furnaces without an active feeding part of the MCM is impossible.

(3) The functional purpose of the middle part of the MCM, located between the horizons of the tuyeres and the nozzles (conditionally the working area), is to provide conditions for the formation of final cast iron and slag compositions, as well as the separation and accumulation of melts. The preferred option is to operate the furnace using high-quality coke, which should preserve the strength, size, and porosity of the coke in the MCM as much as possible. At the same time, the carbon in the coke must be freely consumed in the necessary metallurgical reactions for the reduction of iron oxides and impurities, carbonization, and desulfurization of the metal. The example of a 5800 m3 blast furnace manufactured by SG (China) shows that the balance between the conflicting requirements for the physical and chemical properties of coke is maintained thanks to two processes that are beneficial for the working zone of the MCM. These are the positive effect of the "washing away" effect of melts on the strength of coke in the peripheral zone of the MCM and the slagging of coke pores in the chemically unloaded central zone of the MCM.

(4) The lower part of the low-mobility coke mass, which is located below the air blast horizon and immersed in molten cast iron, is functionally designated as the zone of gradual MCM depletion. Referring to the results of the study of the state of coke in this part and the known theoretical principles of the blast furnace process, the sequence of processes affecting the rate of MCM consumption has been formulated. In the order of these processes shifting downwards towards the clinker, these are: the capture of blast furnace slag and alkalis by the pores of the coke above and at the level of the cast iron trough; the desulfurization of the metal CaO of the transition slag and the restoration of SiO2 at the coke-metal boundary and the carburization of cast iron. The latter process can be useful when using carbonaceous clinker. All of the above processes are accompanied by active graphitization of coke, which can be partially slowed down by reducing the supply of alkalis to the furnace.

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