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# INFLUENCE OF THE PROPERTIES OF BLAST FURNACE SLAG ON CAST IRON HEATING AT PULVERIZED COAL INJECTION


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***На двох промислових доменних печах досліджені шлаковий режим і нагрів чавуну при переході на вдування пиловугільного палива. Негативним наслідком зміненого шлакового режиму було зниження фізичного нагріву чавуну. Досліджено вплив змін у складі шлаків на в’язкість розплавів. Вивчено вплив характеристик шлакового режиму – в’язкості, основності і стехіометрії на нагрів чавуну. Суттєвий вплив шлаку на нагрів металу свідчить про необхідність врахування цього впливу при управлінні доменною плавкою і наступній переробці чавуну в сталь***



***Ключові слова: доменна піч, шлаковий режим, в’язкість, основність, шлак, нагрів чавуну***



***На двух промышленных доменных печах исследованы шлаковый режим и нагрев чугуна при переходе на вдувание пылеугольного топлива. Отрицательным следствием измененного шлакового режима явилось снижение физического нагрева чугуна. Исследовано влияние изменений в составе шлаков на вязкость расплавов. Изучено влияние характеристик шлакового режима – вязкости, основности и стехиометрии на нагрев чугуна. Существенное влияние шлака на нагрев металла свидетельствует о необходимости учета этого влияния при управлении доменной плавкой и последующем переделе чугуна в сталь***



***Ключевые слова: доменная печь, шлаковый режим, вязкость, основность, шлак, нагрев чугуна***


## 1. Introduction

The transition of blast furnaces in Ukraine to the injection of pulverized coal fuel (PCF) was, as a rule, accompanied by a change in slug mode. Such a change was often characterized by a decrease in slag basicity both in relation to $CaO/SiO_2$ (C/S) and to $(CaO+MgO)/SiO_2$ (C+M)/S. A decrease in slag basicity was supposed to compensate for the negative influence of PCF on permeability of the coke head in the zone of melts flow. As a result, as shown in paper [1], there was a shift in the slag mode in the direction of formation of semi-slags, with a decrease in temperature of the produced cast iron. This decrease is known to create certain problems at subsequent converter processing of liquid cast iron. Semi-slags C/S=1.1–1.2 received their name from the specifics of hardening a sample, consisting of two parts in the fracture: glassy (C/S<1.1), characteristic of acidic, and stone-like (C/S>1.2), characteristic of the basic ones. Prior to the transition to PCF injection, operation on highly-sulfuric Donetsk coke required the formation of base slag. That is why the properties of semi-slags with less sulfur absorbing capacity were not sufficiently studied.

If the transition to PCF injection necessitated operation on basic slags, the physical heating of cast iron at the outlet did not decrease. However, in order to ensure normal operation of the hearth and to maintain the smooth run of a furnace, it was required to increase the number of washes and consumption of washing materials up to 32 kg/t of cast iron [3].

In the course of analysis of changes in slag mode of the blast furnace with a volume of 1,386 $m^3$ at Dneprovsky Metallurgical Plant (DMP, Ukraine), it was shown that the transition to semi-slags was accompanied, due to the injection of PCF, by a decrease in melting temperatures of slag melts [1]. Results of the studies did not contradict known provisions on the influence of basicity on the above characteristic of slag. At the same time, using a diagram of viscosity of the triple system $CaO–SiO_2–Al_2O_3$ (C–S–A), slag viscosity was found to decrease at a decrease in slag basicity. This, to some extent, contradicted common views on the dependence of slag fluidity on its basicity. Taking into account a significant influence of slag melts on cast iron smelting, it was necessary to study the causes of this phenomenon. It should be recognized that the problem on enabling a rational slag mode at transition of furnaces to PCF injection still exists, thereby the search for the ways to solve it is important.

## 2. Literature review and problem statement

Over the last decade, a lot of attention has been paid to alumina and magnesia, ranking, as a rule, third and fourth by mass in the blast furnace slag composition [3–8]. Although $Al_2O_3$ and MgO are not slag «heavyweights», such as CaO and $SiO_2$, the impact of the former on viscosity of melts and thermal level of blast furnace process is unquestionable.

Paper [3] shows that regardless of the content of FeO at one and the same basicity (C+M)/S, slag viscosity depends on alumina content in it. A significant decrease in viscosity of melts at a decrease in concentration of $Al_2O_3$ from 15 to 5 % in a wide range of basicity changes was established, in addition, minimum of viscosity decreased towards a smaller value of (C+M)/S. It is possible to judge about the temperature level of the process at the average alumina-magnesia module of 1.5 by the average slag temperature of 1,590 °C. Such a slag, formally belonging to semi-slags by the averaged index C/S=1.11, will provide high physical heating of cast iron. Formally, this is because lime-silicate semi-slags in Ukraine have a different mineralogical composition of primary crystalline phases.

Specialists from research unit of the company China Steel Corporation (CSC, Taiwan) established that the lower liquidus temperature and better viscosity stability lie in the region of MgO=5.4 %, $Al_2O_3$=10÷15 %, $TiO_2$=0.5 %, and C/S=1.2. It was shown that liquidus temperature decreased with a decrease in MgO concentrations, and slag viscosity did not depend on MgO content in the range of 5–9 % at C/S=1.2 and $Al_2O_3$=15 %. It was therefore decided to decrease magnesia concentration in CSC blast furnace slags from 6.5 % to 5.4 %. This made it possible to decrease the volume of slag. The module of $Al_2O_3$/MgO in this case increased from 2.2–2.3 to 2.7. A high thermal level of the process was ensured by the elevated level of basicity C/S within 1.18–1.20, and the temperature of cast iron at the outlet was 1,495–1,504 °C. Taking into account results of study [3], it may be assumed that the viscous aluminous slag contributed to high heating of cast iron. CSC slag is formally relaterd to the upper limit of semi-slags.

Authors of paper [5], based on the study of industrial and synthetic properties of aluminous slag, proposed a statistical model for the estimation of slag viscosity by the content of its four major components:

$$V=0.005+0.0262[SiO_2]+0.0184[Al_2O_3]-$$
$$-0.0172[CaO]-0.0244[MgO].$$

Judging by coefficients at slag constituents, $SiO_2$ must have the highest value and CaO must have the lowest value for determining viscosity of the melt. MgO and $Al_2O_3$ occupy intermediate places in this ranking. Construction of the model is in line with the established views that an increase in the content of oxides of complex forming components ($SiO_2$, $Al_2O_3$) in the slag increases slag viscosity. An increase in content of CaO and MgO, producing oxygen anions, in slag, destroys silica-oxygen complexes and decreases slag viscosity. However, the model above, like all statistical models has an «attachment» to the specific conditions of smelting and disregards the value of alumina-magnesia module, with a change in which the diluting influence of MgO may not manifest itself [4].

At the same time, construction of models is a promising direction, since experimental determining of slag viscosity requires high-temperature equipment and is very time-consuming [6].

A group of Japanese researchers, by using a radiation pyrometer, obtained not quite usual data on temperatures of cast iron and slag at the outlet of melting products [7]. According to measurement by the pyrometer, temperature of cast iron at some outlets reached and even exceeded 1,550 °C, while slag temperature in this case was lower by 20–30 °C. At lowered heating at 1,400–1,470 °C, temperature of melts was the same. It should be noted that in this study there are no data about the chemical composition of slag. It is considered that a slag layer above a cast iron layer and closer to the jet zone is more heated than cast iron. It should be found out which factors cause the unusual difference in temperature of melts: a greater depth of the hearth, development of direct liquid phase reduction or other factors.

Indian experts [8] consider operation of furnaces with «short» slag to be appropriate with a small difference between the temperature of the beginning of plastic deformation of iron ore lumps (ST) and the temperature of mobile liquid of the melt (FT). Under particular raw material conditions, when alumina concentration of in slag ranges from 18–21 %, and the ratio of $Al_2O_3$/MgO is 1.9–2.8, minimal difference of FT-ST is observed when MgO content in slag is 4.6–8.6 % and basicity of C/S=1.12. This difference at the rate of 93–98 °C increases almost by two times at a decrease in basicity or at an increase in MgO content in slag of up to 10 %. It is noteworthy that despite a significant difference in composition of raw materials and chemical composition of slag virtually on all continents, index C/S is maintained in the narrow range of 1.10–1.20.

In article [9], it is argued that at an increase in MgO content in the agglomerate, the intervals of softening and melting increase. It shifts and thickens the plastic zone of a blast furnace.

Thus, an analysis of current information on the examined problem revealed the following:

1. There are no data on the impact of significant changes in slag practice on viscosity of slag. It is clear that at high

quality of burden materials, transition of furnaces to pulverized coal fuel injection did not cause any significant changes in slag composition.

2. There is no information about how and in what way properties of slag affect physical and chemical heating of cast iron.

3. The authors of papers, discussed above, are uncertain of the role of magnesia in determining the properties of working, intermediate and finishing slag. This may have been caused by significant differences of melted raw material and a wide range of variability in alumina and magnesia in slag.

## 3. The aim and objectives of the study

The aim of present study was to determine a change in slag viscosity at transition from natural gas injection to pulverized coal fuel injection and to determine an impact of changes in slag practice on heating of cast iron. This will make it possible to establish a rational slag practice, providing for specified parameters of chemical and physical heating of cast iron.

To accomplish the set goal, the following tasks must be solved:

– to determine the extent to which the transition to semi-slags affected viscosity of melts;

– to estimate the impact of changes in slag viscosity on the heating of cast iron;

– to establish a relation between basicity and stoichiometry of slag and physical heating of metal;

– to estimate the effects of magnesia in slag on the temperature of cast iron.

## 4. Procedure of research into the influence of slag mode on viscosity of blast furnace slag and temperature of cast iron

Selection of production data arrays on slag practice and other indicators of the process was carried out during the transition of two blast furnaces at DMP from the injection of natural gas to the use of PCF. The duration of a single period was one calendar day. The days when the furnace did not operate were excluded from consideration. The duration of the periods of comparison is specified below.

Blast furnace «A» in comparison with the standard one (effective volume is 1,513 $m^3$) was distinguished by the height of the hearth of 4 m and of the dead layer of 1.4 m against 3.2 and 0.765 m, respectively. 20 air jets were mounted on the furnace. Dimensions of the blast furnace «B» also differed from the standard design (effective volume is 1,386 $m^3$) by the height of the hearth of 3.4 m versus 3.2 and the height of the sprue base of 1.1 m versus 0.45 m. During the latest overhaul, the number of air jets was increased from 16 to 18.

During the studied periods, furnace «A» operated on coke with hot strength of CSR within 59–64 %, furnace «B» operated on coke with CSR indicator of up to 57 %. Local agglomerate (100 %) with iron content of 54–57 % was used at furnace «A», local agglomerate (~70 %) and Kryvyi Rih iron ore pellets (~30 %) were used at furnace «B».

Estimation of slag viscosity of the studied periods was carried out using triaxal diagram of $CaO–SiO_2–Al_2O_3$ (C–S–A), known as the McCaffrey diagram. The influence of the fourth, by mass and by value, MgO slag component was considered by a reference book [10].

Estimation of properties of actual blast furnace slags with the use of the C–S–A–M system also has shortcomings because it does not take into consideration the entire composition of slag. Therefore, as a criterion of chemical properties of slag, one used stoichiometry indicator ρ, one of calculation parameters of the model of the ordered structure of oxide melts, developed at the Institute of Ferrous Metallurgy at NAS of Ukraine by E. V. Prikhodko. The stoichiometry indicator was calculated by the ratio of the number of cations ($K$) to the number of anions ($A$) [11]:

$$\rho = \frac{\sum_{i=1}^{m} M_{K_i}}{\sum_{i=1}^{m} M_{A_i}}, \qquad (1)$$

where

$$M_{K_i} = \frac{C_i X_i}{X_i m_{K_i} + Y_i m_{K_i}}; \quad M_{A_i} = \frac{C_i Y_i}{X_i m_{A_i} + Y_i m_{A_i}},$$

where $M_{K_i}$, $M_{A_i}$ are the mole shares of cations and anions in their cationic and anionic sub-lattices; $C_i$ is the weight percentage of oxide or sulfide content in slag; $m_A$, $m_K$ is the atomic mass of an anion or a cation; $X_i$, $Y_i$ is the number of cations and anions in the chemical formula of an oxide with number $i$; $m$ is the number of oxides in the system.

## 5. Results of the study of the influence of transient parameters of slag practice on slag viscosity and cast iron temperature

The periods of operation of furnaces either with minimal average consumption of PCF (BF A) or without coal injection (BF B) were taken as basic periods (Table 1). In addition to consumption of reducers for melting, slag characteristics of cast iron temperature are given.

The points of calculation compositions of actual slags of the studied periods I and II for BF A and I and III for BF B (Fig. 1–4) were mapped on the fragments of triaxial diagrams of slag viscosity of the C–S–A system.

In Fig. 1, 2, the groups of figurative points, responsible for compositions of slags of BF A in January and August, 2015, different in basicity of C/S, are compared. Line of equal viscosities on the sections of diagrams correspond to fixed temperatures of 1,400 °C (Fig. 1) and 1,500 °C (Fig. 2).

Graphical information, shown in Fig. 3, 4, refers to the periods of BF B operation in June, 2004 (with natural gas injection), and in May, 2015 (with PCF injection).

The temperature of the beginning of active drainage of melts is considered to be 1,400 °C. Using the data of the diagrams of C–S–A for the specified temperature (Fig. 1, 3), there was an attempt to assess the influence of slag viscosity for cast iron heating. Analysis showed that despite certain assumptions, it was possible to establish quite a close relationship between slag viscosity and silica content in it ($R^2 = 0.20 \div 0.82$). According to the obtained data, an increase in slag viscosity by 0.1 Pa·s was accompanied by an increase in silica concentration in cast iron by 0.08–0.1 %. Tightness of relationship between cast iron temperature and slag viscosity temperature proved to be low ($R^2 = 0.07 \div 0.21$), however, the tendency of temperature increase at an increase in viscosity was observed.

Table 1

Performance indicators of blast furnaces of Dneprovsky Metallurgical Plant with injection of natural gas and pulverized coal fuel

| Furnaces | A | | | B | | |
|---|---|---|---|---|---|---|
| Periods | I basic 01.01–31.01.2015 | II experimental 08.08–31.08.2015 | III experimental 01.12–20.12.2015 | I basic 06.06–30.06.2004 | II experimental 01.01–31.01.2014 | III experimental 01.05–31.05.2015 |
| Performance, % | 100.0 | 108.3 | 110.8 | 100.0 | 108.9 | 124.9 |
| Comsumption of reducers kg($m^3$)/t of cast iron: | | | | | | |
| coke | 475 | 389 | 436 | 501 | 559 | 400 |
| resistor coke | 0 | 16 | 32 | 0 | 0 | 0 |
| anthracite | 0 | 0 | 0 | 0 | 17 | 0 |
| natural gas | 6 | 4 | 0 | 73 | 12 | 0.8 |
| PCF | 112 | 135 | 140 | 0 | 0 | 156 |
| Content in slag, %: | | | | | | |
| CaO | 45.48 | 45.20 | 45.15 | 48.3 | 47.6 | 45.5 |
| $SiO_2$ | 39.16 | 40.92 | 41.15 | 40.22 | 39.4 | 40.5 |
| $Al_2O_3$ | 7.59 | 6.22 | 6.25 | 5.1 | 6.49 | 6.31 |
| MgO | 5.71 | 6.18 | 5.18 | 5.3 | 5.0 | 6.1 |
| $MgO/(CaO+SiO_2)$ | 0.067 | 0.071 | 0.060 | 0.060 | 0.057 | 0.071 |
| $Al_2O_3/MgO$ | 1.33 | 1.01 | 1.21 | 0.96 | 1.30 | 1.03 |
| $CaO/SiO_2$ | 1.16 | 1.10 | 1.10 | 1.20 | 1.21 | 1.12 |
| $(CaO+MgO)/SiO_2$ | 1.31 | 1.26 | 1.22 | 1.33 | 1.34 | 1.27 |
| Cast iron temperature, °C | 1,462 | 1,451 | 1,439 | Andmeid pole | 1,479 | 1.450 |

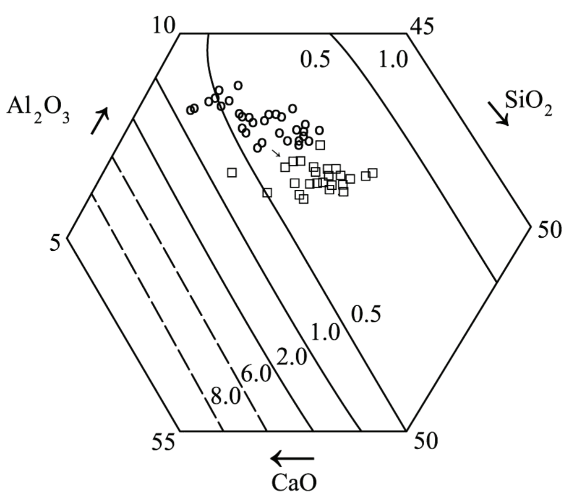


Fig. 1. Section of diagram of slag viscosity of system C–A–S at temperature of 1,400 °C with mapping of figurative points, corresponding to slag compositions of BF A: o – slag of basicity 1.16; □ – slag of basicity 1.10; figures at line of equal viscosities –viscosity, Pa·s: slag displacement is shown by the arrow

The merit of stoichiometry indicator ρ is the lack of the need to transit from the composition of actual slag to few-component simplified systems. Since slag basicity indicators are in their essence simplified stoichiometry indicators, between those and the other there should exist close relationship. This is proved by the data of Fig. 5, where the data, referring to operation periods of blast furnace «B» with injection of natural gas and ground coal are compared.

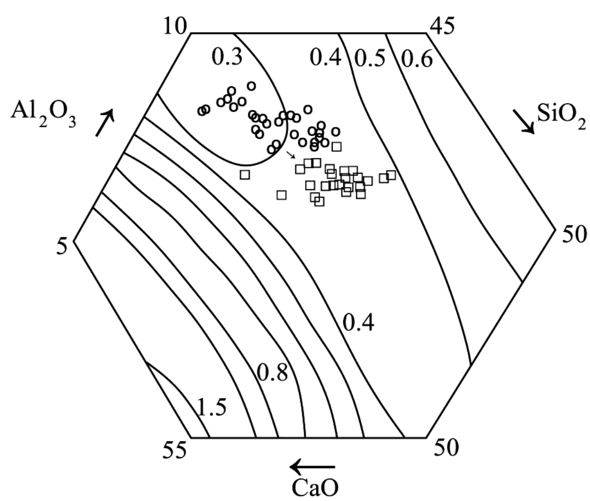


Fig. 2. Section of the diagram of slag viscosity of C–A–S system at temperature of 1,500 °C with mapping of figurative points, corresponding to slag compositions of BF A: designations are the same as in Fig. 1

Taking into account that one of the important functions of slag is the maintenance of the required temperature of cast iron in the furnace and at the outlet, there was a relationship between physical heating of metal and the indicators, reflecting its properties for specific conditions of smelting (Fig. 6, 7).

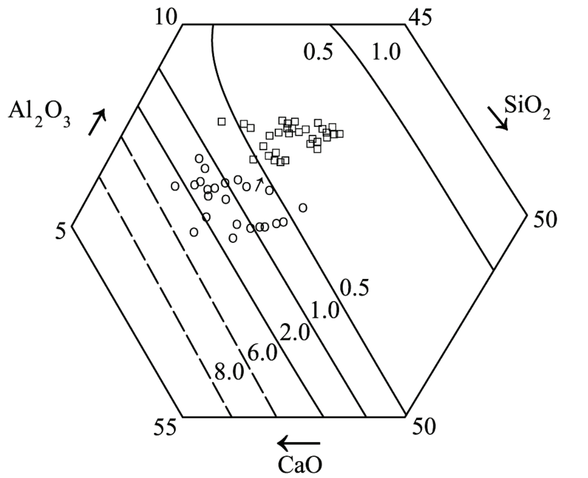


Fig. 3. Section of diagram of slag viscosity of system C—A—S at temperature of 1,400 °C with mapping of figurative points, corresponding to slag compositions of BF A: o — slag of basicity 1.20; □ — slag of basicity 1.12; other designations are the same as in Fig. 1

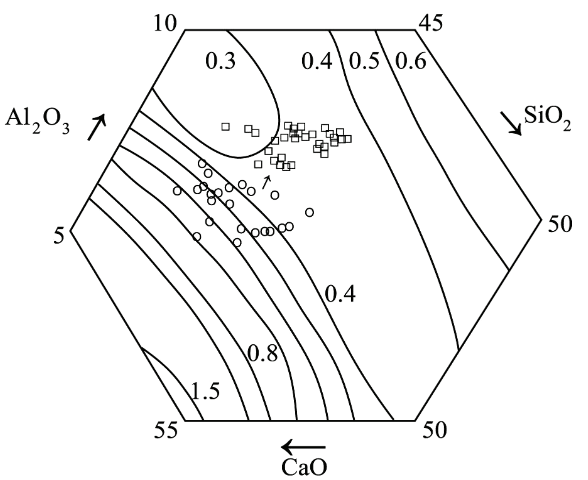


Fig. 4. Section of diagram of slag viscosity of system C—A—S at temperature of 1,500 °C with mapping of figurative points, corresponding to slag compositions of BF B: designations are the same as in Fig. 3

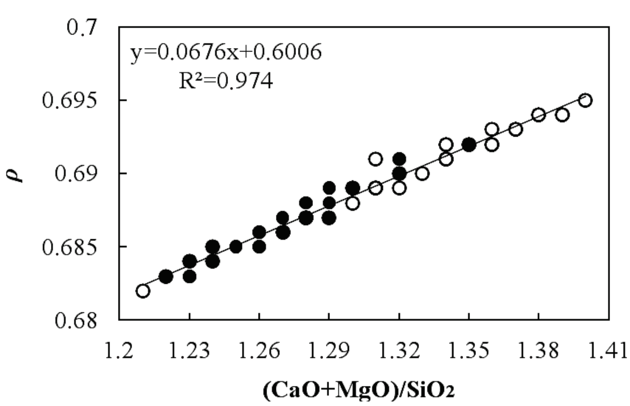


Fig. 5. Dependence between stoichiometry indicators and slag basicity in periods with injection of natural gas (○), pulverized coal fuel (●) for blast furnace B (periods I and III, Table 1)

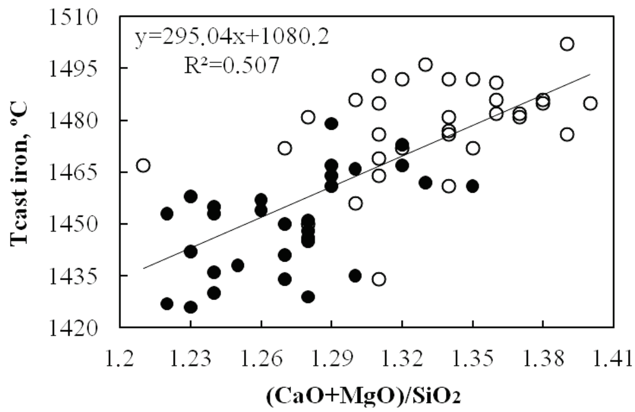


Fig. 6. Relationship between cast iron temperature and slag basicity in periods with injection of natural gas (○) and pulverized coal fuel (●) for blast furnace B (periods I and III of Table 1)

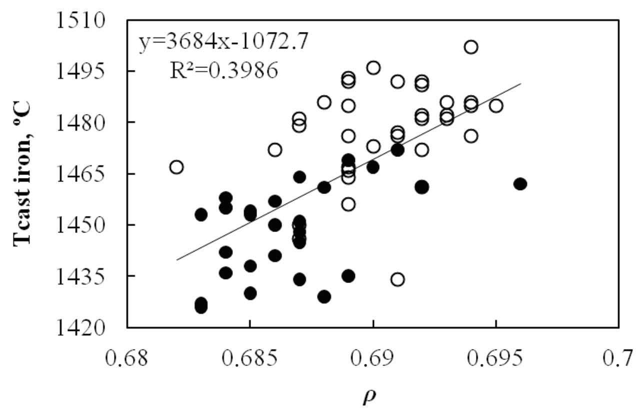


Fig. 7. Dependence of cast iron temperature on slag stoichiometry indicator ρ: the rest of the values are the same as in Fig. 6

It is interesting to note that dependence of cast iron temperature on the module of basicity (Fig. 6) was closer than stoichiometry indicator ρ (Fig. 7).

It is obvious that for a full evaluation of the properties of melt along with indicator ρ, it is also necessary to consider other average parameters that characterize slag individuality.

These parameters include the chemical equivalent of system $\Delta e$, inter-nucleus cation-anion distance d and a peculiarity of the cation sub-lattice $tg\alpha_c$ [11].

To determine the influence of magnesia on the temperature of produced cast iron, the following dependences of metal heating were considered (Table 2).

In Table 2, parameters of slag practice, reflecting magnesia proportion in the composition of slag and its ratio to major components, as well as to alumina, are used as *X* arguments.

These parameters are absolute (MgO) and relative $MgO/(CaO+SiO_2)$ content of magnesia in slag, as well as alumina-magnesia module $Al_2O_3/MgO$. Physical heating of iron, more specifically, its temperature at the outlet was used as depending variable *Y*.

Table 2

Data on the influence of slag mode parameters on temperature of produced cast iron (°C)

| Furnace | Period | Parameter of slag practice | Regression equation | Correlation ratio $R^2$ | Average for the period value of A/M |
|---|---|---|---|---|---|
| A | I | MgO, % | $y=-2.3487x+1{,}475.5$ | 0.0268 | 1.33 |
| | | $MgO/(CaO+SiO_2)$ | $y=-203.77x+1{,}475.9$ | 0.0310 | |
| | | $Al_2O_3/MgO$ | $y=11.42x+1{,}446.5$ | 0.0611 | |
| | II | MgO, % | $y=7.595x+1{,}404.1$ | 0.0945 | 1.01 |
| | | $MgO/(CaO+SiO_2)$ | $y=581.44x+1{,}409.3$ | 0.0855 | |
| | | $Al_2O_3/MgO$ | $y=-38.225x+1{,}490$ | 0.0668 | |
| B | II | MgO, % | $y=1.491x+1{,}471.6$ | 0.0026 | 1.30 |
| | | $MgO/(CaO+SiO_2)$ | $y=115.89x+1{,}472.4$ | 0.0023 | |
| | | $Al_2O_3/MgO$ | $y=-44.014x+1{,}496.1$ | 0.0762 | |
| | III | MgO, % | $y=8.9354x+1{,}395.8$ | 0.1033 | 1.03 |
| | | $MgO/(CaO+SiO_2)$ | $y=714.24x+1{,}399.5$ | 0.1056 | |
| | | $Al_2O_3/MgO$ | $y=4.332x+1{,}473.4$ | 0.0012 | |

## 6. Discussion of results of studying influence of slag practice parameters on slag viscosity and cast iron temperature

The graphic dependence, shown in Fig. 1, indicates that at 1,400 °C, a decrease in slag basicity from 1.16 to 1.10 on BF A practically did not change viscosity of melts. Both groups were mainly located in the region, limited by line of equal viscosities 0.5 Pa·s. Fig. 2 reflects the state of the same slags, but at fixed temperature of 1,500 °C, displacement of less basic slags (C/S = 1.10) from the region, limited by line of equal viscosities 0.3 Pa·s to the region of viscosity Pa·s can be clearly seen.

On the contrary, in BF B, a decrease in module C/S from 1.20 to 1.12 was accompanied by a significant decrease in viscosity both at temperature of 1,400 °C (Fig. 3) and at temperature of 1,500 °C (Fig. 4). It is possible to explain this difference by addressing calculation characteristics of slag that take into account a change in content of $Al_2O_3$ (an element of triple system C–S–A) and of MgO – the fourth component of the melt (Table 1). So, a decrease in average module of $Al_2O_3/MgO$(A/M) from 1.33 to 1.01 and an insignificant increase in the ratio of $MgO/(CaO+SiO_2)$ (M/(C+S)) from 0.067 to 0.071 corresponded to an increase in slag viscosity at BF A. There was a slight increase in alumina-magnesia module A/M at BF B in period III from 0.96 to 1.03 compared to period I, but a significant increase in parameter M/(C+S) from 0.060 to 0.071 led to a decrease in slag viscosity.

Dependence of chemical heating of cast iron on slag viscosity, established with the use of the diagrams of C–S–A system, can be explained as follows. Viscous slag of intermediate composition, on the one hand, brings more heat to the high-temperature zone. On the other hand, due to low fluidity of viscous slag, the time of contact of slag with reducing medium increases. Both circumstances contribute to strengthening of silicon reduction. Statistical evaluation of the relationship between slag viscosity and silica content in it showed a direct dependence of the latter on melt viscosity.

To identify the influence of basicity on viscosity of synthetic slag of the four-component system $CaO-SiO_2-Al_2O_3-MgO$ (C–S–A–M), based on the result of research [10], a family of curves of dependence of viscosity ŋ on a module of change in $CaO/SiO_2$ at constant content of alumina in the amount of 7 % and of magnesium in the amount of 5 % of the weight of the sample were plotted (Fig. 8).

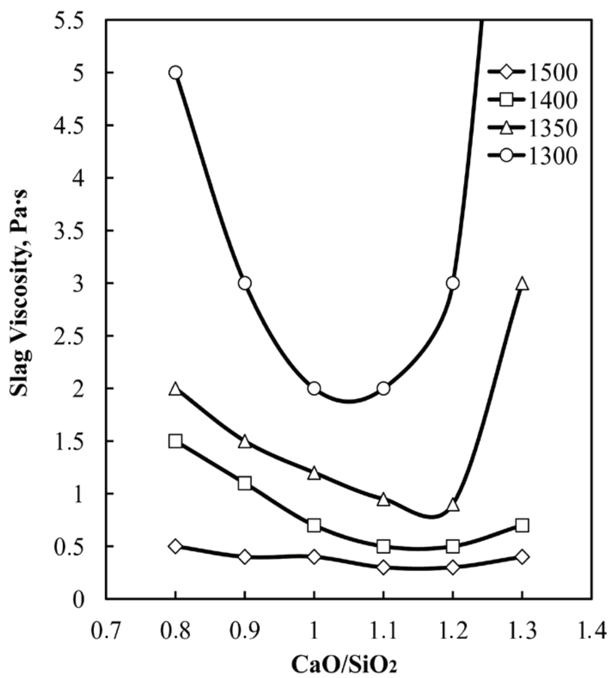


Fig. 8. Influence of basicity and temperature of synthetic blast-furnace slags on their viscosity according to data from ref. [10]

The obtained data indicate the existence of extrema on curves $ŋ=f(CaO/SiO_2)$, belonging to the range of changing in basicity of 1.0–1.2 units. It is possible to see that at a decrease in temperature, extremum appeared more sharply and at temperature of 1,300 °C shifted toward lower basicity. Distancing of basicity from extremum, both at a decrease in basicity and at its increase, was accompanied by an increase in slag viscosity. Viscosity increased more significantly at an increase in basicity, which is in accordance with the views on the nature of short and long slags.

In the range of basicity changes of 1.1–1.2 at temperatures of 1,400 °C and 1,500 °C, viscosity of melts of C–S–A–M system was virtually identical. It can be assumed that the influence of the fifth or the sixth component in actual slag of the specified basicity range can change slag fluidity in one direction or another.

Since the density of slag depends on basicity, the influence of the latter on cast iron heating manifests itself with sufficient strength of the bond (Fig. 6). It is caused by several factors. Firstly, viscosity of all varieties of slag in the operation space of the furnace, such as working, intermediate or finishing, depends on basicity. Secondly, the number of non-melted slag residues in inter-lump coke cavities is related to viscosity. Thirdly, the rate of lowering and warming-up of metal drops depends on viscosity of a slag layer in the hearth.

According to the obtained data, a decrease in stoichiometry criterion ρ by 0.01 units is accompanied by a decrease in temperature of cast iron on average by 36 °C. A decrease in indicator $(CaO+MgO)/SiO_2$ by 0.1 units leads to a decrease in cast iron temperature by 30 °C. It goes without saying, the drop in cast iron heating will affect thermal balance of the converter process.

Table 1 shows that at both furnaces, transition to the slags of lower basicity even in narrow limits of semi-slug formation was accompanied by a decrease in cast iron temperature. The data, shown in Table 2, indicate that neither magnesia nor alumina determine heating of cast iron, however, some influence of the latter is traced depending on their ratio. In the periods without injection at the A/M ratio within 1.35–1.30, value of $R^2$ for dependence $t_{\text{cast iron}}=f(\text{A/M})$ is significantly higher than the correspondent criterion for dependences $t_{\text{cast iron}}=f(\text{M})$; $f(\text{M}/(\text{C+S}))$. This indicates that under these conditions, alumina has more influence on heating than MgO. If the A/M ratio is close to unity, magnesia has a more significant impact on the temperature of metal, which can be clearly seen from comparison of correlation ratios for relationships between variables in periods (II) (furnace A) and III (furnace B).

Thus, in present research, the attempts to estimate the influence of changes in slag practice on slag viscosity and of slag viscosity on heating of cast iron were made. In addition, relationships between basicity and slag stoichiometry and physical heating of cast iron were established. The influence of magnesia in slag on temperature of cast iron was assessed. It is necessary to take into account slag influence on heating of produced cast iron not only to control and manage blast furnace process, but also to predict changes in the thermal balance of the converter process.

Incompleteness of evaluation of the impact of slag viscosity on physical heating of cast iron using the C–A–S system can be referred to the shortcomings of this research. This is due to both limitations in the use of this system and to obtaining of reliable data on cast iron temperature, averaged within tapping

Results of the above research are appropriate for application in blast furnace production, the raw conditions of which determine formation of lime-silicate slags. It is implied that assessment of physical and chemical heating of cast iron is required for integrated enterprises, where the route «blast furnace – cast iron finishing converter – oxygen converter» is used. In conclusion, it should be noted that the approach to solution of the problem of power interaction of aggregates of this route should be universal, regardless of the slag composition.

Materials of the present study are the continuation of research, started earlier [1], the studies will be subsequently continued and extended. It should be recognized that there exists the problem of providing a rational slag practice at transition of blast furnaces of Ukraine to injection of pulverized coal fuel and there is a need to find the ways to solve it.

## 7. Conclusions

1. We established a change in characteristics of slag practice and cast iron heating, resulting from the transition to injection of pulverized coal fuel with a decrease in slag basicity from 1.16 to 1.10 and from 1.12 to 1.20 units. It was shown that depending on the particular influence of alumina and magnesia in the composition of slag, as well as on their ratio, a decrease in basicity can be accompanied by both an increase and a decrease in viscosity.

2. Dependence between slag viscosity at the temperature of 1,400 °C and chemical heating of cast iron at the outlet was established. An increase in slag viscosity by 0.1 Pa·s was accompanied by an increase in silica concentration in cast iron by 0.08–0.1 %.

3. The relation of physical heating of metal to slag basicity and stoichiometry was established. A decrease in basicity of $(CaO+MgO)/SiO_2$ by 0.1 units led to a decrease in cast iron temperature by 30 °C. A decrease in slag stoichiometry criterion ρ by 0.01 units was accompanied by a decrease in cast iron temperature on average by 36 °C.

4. It was shown that in the studied range of slag compositions $(CaO+MgO)/SiO_2$ within 1.22–1.31 (BF A) and 1.27–1.34 (BF B), the influence of magnesia on heating of cast iron is limited. A slight influence of MgO on physical heating of metal manifests itself at the magnitude of alumina-magnesia module that is close to unity.

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