PHYSICO-CHEMICAL BASICS OF METALLURGICAL PROCESSES / ФИЗИКО-ХИМИЧЕСКИЕ ОСНОВЫ МЕТАЛЛУРГИЧЕСКИХ ПРОЦЕССОВ

UDC 669.162.275.2
DOI 10.17073/0368-0797-2025-3-287-296

Original article
Оригинальная статья

EFFECT OF BORON OXIDE ADDITIVES ON VISCOSITY AND MELTING POINT OF THE $CaO – SiO_2 – Al_2O_3 – MgO$ SYSTEM

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Abstract. The share of local iron ore raw materials of metallurgical enterprises of the Ural region is 50 – 60 %. The rest is brought from Central Russia, the Kola Peninsula and Kazakhstan. The issue of replacing imported raw materials with local, cheaper ones, is very relevant. The extraction of siderite iron ore of the Bakalskoye deposit (Southern Urals), the reserves of which are about 1 billion tons, is many times less than the mining and geological conditions allow because of the insignificant demand for this raw material due to its low quality. The high content of magnesium oxide in the ore makes blast furnace smelting difficult or impossible using more than 20 % of siderites in the charge. The basis of any blast furnace slag is a four-component system $CaO – SiO_2 – Al_2O_3 – MgO$ with the following composition, wt. %: 30 – 40 SiO_2, 31 – 49 CaO, 3 – 18 MgO, 7 – 20 Al_2O_3. The melting point of such slags is 1280 – 1320 °C. At a temperature of 1450 °C, their viscosity is about 0.5 Pa·s. An increase in the magnesium oxide content (>20 %) leads to a sharp increase in melting point of the slags, reduces the crystallization interval and makes them unstable. In this regard, the materials made from siderite ore using various technologies for preparing them for blast furnace smelting (raw ore, roasting-magnetic separation, agglomeration) are introduced into the blast furnace charge only as additives. Their share does not exceed 20 %. The effect of boric anhydride on the viscosity of high-magnesia blast furnace slags containing 15 – 36 % MgO was studied using modern methods of statistical processing of experimental data. It was shown that addition of boric anhydride to the initial charge allows to reduce the melting point of the slag and to increase the crystallization interval. This makes it possible to conduct blast furnace smelting on slags containing about 40 % MgO, which corresponds to a siderite share of 40 – 50 % in the initial charge.

Keywords: blast furnace slag, viscosity, melting point, siderite ore, magnesium oxide, boron oxide, modeling, blast furnace smelting

Acknowledgements: The work was performed with the support of the Russian Science Foundation under project No. 25-29-00363 using the equipment of the Ural-M Common Use Center.

For citation: Vusikhis A.S., Mikheenkov M.A., Leont'ev L.I., Agafonov S.N. Effect of boron oxide additives on viscosity and melting point of the $CaO – SiO_2 – Al_2O_3 – MgO$ system. *Izvestiya. Ferrous Metallurgy*. 2025;68(3):287–296. https://doi.org/10.17073/0368-0797-2025-3-287-296

Влияние добавок оксида бора на вязкость и температуру плавления системы $CaO – SiO_2 – Al_2O_3 – MgO$

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Аннотация. Доля местного железорудного сырья металлургических предприятий Уральского региона составляет 50 – 60 %. Остальное завозится из Центральной России, Кольского полуострова и Казахстана. Вопрос замены привозного сырья на местное, более дешевое, является весьма актуальным. Добыча сидеритовой железной руды Бакальского месторождения (Южный Урал), запасы которой составляют около 1 млрд т, во много раз меньше, чем это позволяют горно-геологические условия, что связано с незначительным спросом на это сырье из-за низкого качества. Высокое содержание в руде оксида магния делает затруднительным или невозможным ведение доменной плавки с использованием более 20 % сидеритов в шихте. Основой любого доменного шлака является четырехкомпонентная система $CaO – SiO_2 – Al_2O_3 – MgO$ состава, мас. %: 30 – 40 SiO_2, 31 – 49 CaO, 3 – 18 MgO, 7 – 20 Al_2O_3. Температура плавления таких шлаков составляет 1280 – 1320 °C. При температуре 1450 °C их вязкость имеет значение ~0,5 Па·с. Увеличение содержания оксида магния (>20 %) приводит к резкому повышению температуры плавления шлаков, сокращает интервал кристаллизации и делает их нестабильными. В связи с этим материалы, изготовленные из сидеритовой руды с использованием различных технологий подготовки их к доменной плавке (сырая руда, обжиг-магнитное обогащение, агломерация), вводят в шихту только в качестве добавок. Их доля не превышает 20 %. С использованием современных методов статистической обработки экспериментальных данных изучено влияние борного ангидрида на вязкость высокомагнезиальных доменных шлаков, содержащих 15 – 36 % MgO. Показано, что добавление борного ангидрида в исходную шихту позволяет снизить температуру плавления шлака и увеличить интервал кристаллизации. Это дает возможность вести доменную плавку на шлаках, содержащих около 40 % MgO, что соответствует доле сидерита 40 – 50 % в исходной шихте.

Ключевые слова: доменный шлак, вязкость, температура плавления, сидеритовая руда, оксид магния, оксид бора, моделирование, доменная плавка

Благодарности: Работа выполнена при поддержке Российского научного фонда по проекту № 25-29-00363 с использованием оборудования ЦКП «Урал-М».

Для цитирования: Вусихис А.С., Михеенков М.А., Леонтьев Л.И., Агафонов С.Н. Влияние добавок оксида бора на вязкость и температуру плавления системы $CaO – SiO_2 – Al_2O_3 – MgO$. *Известия вузов. Черная металлургия*. 2025;68(3):287–296. https://doi.org/10.17073/0368-0797-2025-3-287-296

Introduction

For blast furnace smelting to proceed efficiently, the slag formed during the process must possess stable physicochemical properties that are only slightly affected by fluctuations in chemical composition and temperature.

Slag melt viscosity is one of the most important physicochemical parameters that determine the stability and productivity of blast furnace operation. The final blast furnace slag should have good flowability during tapping. At tapping temperatures corresponding to those of steelmaking pig iron (1450 – 1550 °C), slag viscosity should be approximately 0.5 Pa·s [1; 2].

In slags, the transition from solid to liquid occurs over a certain temperature range, so the melting point (T_m) is a conditional value. The theoretical indicator of melting point is the liquidus temperature (T_l) – the temperature at which the solid phase fully disappears upon heating. In practice, the melting point is considered the temperature at which slag begins to flow freely from the coke bed, which typically occurs when viscosity drops below 2.5 Pa·s. This temperature is usually 200 – 300 °C lower than the tapping temperature and falls within the range of 1250 – 1350 °C [3].

Slag viscosity is greatly influenced by chemical composition, which is determined by the chemical and mineralogical makeup of the iron ore gangue, fluxes, and coke ash. It also depends on the nature of the smelting process, the thermal state of the furnace, and the grade of pig iron being produced. The content of major components in final slags at ironmaking plants across Russia, Ukraine, Europe, and the USA typically includes (wt. %: 30 – 40 SiO_2, 31 – 49 CaO, 3 – 18 MgO, 7 – 20 Al_2O_3. Minor components include MnO (0.1 – 3.0 %), FeO (0.2 – 0.8 %), and S (0.8 – 2.2 %) [4; 5]. Excluding trace oxides (MnO, FeO, S), it is reliably established that the base of any blast furnace slag is the four-component system $CaO – SiO_2 – Al_2O_3 – MgO$.

The relationship between slag viscosity and temperature in terms of these major components (CaO, SiO_2, Al_2O_3, MgO) has been studied extensively, with findings presented in numerous works.

In melts containing less than 15 % alumina, an increase in basicity (*R*) from 0.6 to 1.5 and in MgO content from 0 to 20 % raises the melting point to 1350 – 1400 °C and narrows the solidification interval. The slags become "short" (i.e., less fluid). At temperatures below 1400 °C, slags with more than 25 % MgO exhibit poor flowability [6 – 9].

Changing MgO content from 0 to 25 % in slags with basicity within 0.6 – 1.5 leads to a decrease in viscosity to a minimum value that depends on alumina content and temperature. In acidic slags, viscosity decreases more significantly than in basic ones [10].

For slags containing 5 % aluminum oxide, the minimum viscosity of 0.15 Pa·s at 1500 °C is reached in the composition range of $R \approx 0.9 – 1.1$, with 17 – 20 % MgO and 36 – 38 % SiO_2. Reducing the temperature to 1400 °C raises the minimum viscosity to 0.35 Pa·s and expands the MgO range for achieving this minimum to 13 – 20 %, while shifting toward more acidic slags with 39 – 41 % SiO_2.

Raising the alumina content to 10 % increases the minimum viscosity. As the temperature decreases from 1500 to 1400 °C, viscosity rises from 0.2 to 0.3 Pa·s. The composition range for achieving this minimum narrows from $R \approx 0.8 – 1.2$, 13 – 24 % MgO, 35 – 40 % SiO_2 (at 1500 °C) to $R \approx 1.05 – 1.2$, 14 – 16 % MgO, and 39 – 41 % SiO_2 (at 1400 °C).

With 15 % Al_2O_3, the minimum viscosity increases further from 0.30 to 0.55 Pa·s. The corresponding composition range narrows from $R \approx 0.9 – 1.2$, 15 – 26 % MgO, and 30 – 33 % SiO_2 to $R \approx 0.8 – 1.05$, 18 – 22 % MgO, and 33 – 35 % SiO_2 as the temperature drops from 1500 to 1400 °C. Increasing MgO content leads to a particularly sharp decrease in viscosity in acidic slags containing 25 – 35 % CaO. In slags with $R \approx 0.5 – 0.8$, 13 – 18 % Al_2O_3, and 16 – 25 % MgO, sufficient flowability is maintained at 1350 – 1400 °C.

In slags containing 20 % Al_2O_3, the melting point exceeds 1500 °C for any MgO content in the $R \approx 1.2 – 1.5$ range. At $R \approx 1.1 – 1.2$, crystallization occurs when MgO exceeds 16 %. As *R* decreases to 0.6, the critical MgO content increases to 20 %. When the MgO/Al_2O_3 ratio is approximately 0.5, T_1 is close to 1450 °C at $R \approx 1.1 – 1.2$ and decreases to 1350 °C when *R* drops to 0.6. In such slags, the minimum viscosity varies from 0.4 Pa·s (at 1500 °C) to 1.0 Pa·s (at 1400 °C) at SiO_2 contents of 34 – 36 % [11 – 13].

Analysis of the data shows that in slags with basicity below 1.0, MgO content may reach 15 – 20 % without significantly complicating smelting, since the slags remain sufficient fluid and melt below 1350 °C. According to calculations [14], such slags form from blast furnace charges containing approximately 20 – 30 % siderite ore with 10 – 15 % MgO. A further increase in MgO content raises the slag melting point and leads to poor fluidity and process instability. Smelting with such charges becomes technically challenging or even unfeasible.

The gangue of siderite ores contains about 50 % MgO [15 – 17]. In this regard, in blast furnace smelting, siderite ore is used as an additive either directly in the initial charge or during sinter production. Smelting with a monocomponent charge of siderite ore from the Bakalskoye deposit is not feasible, since the resulting slags would have excessively high melting points. However, it is known [18 – 21] that the addition of boron oxide to blast furnace slags reduces their viscosity across the entire temperature range and makes them more fluid.

Materials and methods

Using a mathematical balance logical-statistical model, we assessed the feasibility of conducting blast furnace smelting with increased magnesium oxide content in the slag (from 15 to 30 %) due to the addition of 50 % roasting–magnetic separation concentrate (RMC). Within this framework, the effect of adding 1 – 3 % B_2O_3 on smelting parameters was evaluated [14].

According to the calculations, the changes in process performance parameters do not exceed 3 %. Productivity decreases, while coke consumption and total ore consumption increase. The addition of B_2O_3 reduces the content of all oxide components in the slag, including MgO, and introduces boron oxide into the system.

To evaluate the influence of boron oxide additions on the viscosity and melting point of the $CaO – SiO_2 – Al_2O_3 – MgO$ system, a simplex-lattice design of experiments was employed. This method provides a process model that closely reflects real-world behavior by accounting for the simultaneous influence of all varying factors.

Composition–property diagrams are geometric representations of multicomponent equilibrium systems. They include a compositional base, which reflects the chemical composition of the system, and a geometric property component (response surface) represented by a set of points, lines, or surfaces located above it. These diagrams provide quantitative information about specific properties corresponding to particular compositions within a multicomponent system.

However, constructing such diagrams requires a large number of experimental runs to determine how a property depends on the chemical composition of a multicomponent system.

The labor intensity of experimental studies necessitates optimizing the number of experiments. To achieve this, mathematical modeling is used in experimental design to analyze the influence of different components on the property under investigation and to obtain sufficiently complete information with minimal experimental effort. This approach significantly reduces the number of required experiments while ensuring that the results are obtained with an adequate level of reliability. One such method is the simplex-lattice approach, which analytically expresses the property–composition relationship as a continuous function [22].

In the simplex-lattice design of experiments, it is assumed that the properties of any mixture depend solely on the relative proportions of its components rather than on the total amount of the mixture. Examples of such properties include density, surface characteristics, viscosity, specific electrical conductivity of homogeneous metal and slag melts, gas solubility in solvent mixtures, and the hydrogen ion concentration (pH) of aqueous solutions, provided that their phase composition remains unchanged.

The preparation of the experimental design matrix was aimed at studying the methods of experimental planning, execution, and statistical processing of the results.

The matrix was developed based on the assumption that the target dependency could be approximated by a third-degree polynomial model, with the following initial conditions:

$$\frac{CaO}{SiO_2} = R = 0.9 \div 1.2;\ MgO = 15 - 36\ \%;$$
$$B_2O_3 = 0 - 15\ \%;\ Al_2O_3 = 5 - 20\ \%.$$

These starting conditions were based on the following: according to the calculations, increasing the share of siderite ore in the charge from 0 to 50 % results in SiO_2 and MgO contents rising from 35 to 38 % and from 9 to 36 %, respectively, while CaO and Al_2O_3 contents decrease from 40 to 17 % and from 14 to 8 %, respectively. The addition of up to 3 % boric anhydride to the charge leads to up to 15 % B_2O_3 in the final slag.

Table 1. **Experiment matrix**

Таблица 1. **Матрица эксперимента**

Mixture No.	Mixture composition				Pseudo-component ID	Mixture composition				Slag composition				
	*X*1	*X*2	*X*3	*X*4		*R*	MgO	B_2O_3	Al_2O_3	CaO	SiO_2	MgO	B_2O_3	Al_2O_3
1	1	0	0	0	*Y*1	1.2	15	0	5	43.6	36.4	15.0	0	5.0
2	0	1	0	0	*Y*2	0.9	36	0	5	27.9	31.1	36.0	0	5.0
3	0	0	1	0	*Y*3	0.9	15	15	5	30.8	34.2	15.0	15.0	5.0
4	0	0	0	1	*Y*4	0.9	15	0	20	30.8	34.2	15.0	0	20.0
5	0.333	0.667	0	0	*Y*122	1.0	29	0	5	33.0	33.0	29.0	0	5.0
6	0.333	0	0.667	0	*Y*133	1.0	15	10	5	35.0	35.0	15.0	10.0	5.0
7	0.333	0	0	0.667	*Y*144	1.0	15	0	15	35.0	35.0	15.0	0	15.0
8	0	0.333	0.667	0	*Y*233	0.9	22	10	5	29.8	33.2	22.0	10.0	5.0
9	0	0.333	0	0.667	*Y*244	0.9	22	0	15	29.8	33.2	22.0	0	15.0
10	0	0	0.333	0.667	*Y*344	0.9	15	5	15	30.8	34.2	15.0	5.0	15.0
11	0.667	0.333	0	0	*Y*112	1.1	22	0	5	38.2	34.8	22.0	0	5.0
12	0.667	0	0.333	0	*Y*113	1.1	15	5	5	39.3	35.7	15.0	5.0	5.0
13	0.667	0	0	0.333	*Y*114	1.1	15	0	10	39.3	35.7	15.0	0	10.0
14	0	0.667	0.333	0	*Y*223	0.9	29	5	5	28.9	32.1	29.0	5.0	5.0
15	0	0.667	0	0.333	*Y*224	0.9	29	0	10	28.9	32.1	29.0	0	10.0
16	0	0	0.667	0.333	*Y*334	0.9	15	10	10	30.8	34.2	15.0	10.0	10.0
17	0.333	0.333	0.333	0	*Y*123	1.0	22	5	5	34.0	34.0	22.0	5.0	5.0
18	0.333	0.333	0	0.333	*Y*124	1.0	22	0	10	34.0	34.0	22.0	0	10.0
19	0.333	0	0.333	0.333	*Y*134	1.0	15	5	10	35.0	35.0	15.0	5.0	10.0
20	0	0.333	0.333	0.333	*Y*234	0.9	22	5	10	29.8	33.2	22.0	5.0	10.0
21	0.625	0.125	0.125	0.125	*Y*1112	1.0875	17.625	1.875	6.875	38.4	35.3	17.6	1.9	6.9
22	0.125	0.625	0.125	0.125	*Y*2221	0.9375	28.125	1.875	6.875	30.5	32.6	28.1	1.9	6.9
23	0.125	0.125	0.625	0.125	*Y*3331	0.9375	17.625	9.375	6.875	32.0	34.1	17.6	9.4	6.9
24	0.125	0.125	0.125	0.625	*Y*4441	0.9375	17.625	1.875	14.375	32.0	34.1	17.6	1.9	14.4
25	0.250	0.250	0.250	0.250	*Y*1234	0.9750	20.250	3.750	8.750	33.2	34.1	20.3	3.8	8.8

Considering that MgO has significantly lower desulfurization capacity than CaO, the basicity of the slag was maintained in the range of 0.9 – 1.2. The MgO content in blast furnace slags was varied between 15 and 36 %, as concentrations below 15 % have little effect on the smelting process. In most final blast furnace slags produced during pig iron smelting in Russia and Western countries, the Al_2O_3 content varies from 5 to 20 %.

Thus, the studied composition field within the full five-component CaO – SiO_2 – Al_2O_3 – MgO – B_2O_3 system is represented by a tetrahedron, the vertices of which correspond to pseudocomponents $Y1$, $Y2$, $Y3$, and $Y4$. For each experimental slag composition in the design matrix, the precise content of each component was calculated (Table 1).

Synthetic slags were prepared for experimentation with CaO and SiO_2 in a ratio corresponding to $R = 0.9 – 1.2$. The calcium oxide used (analytical grade) was pre-calcined in a muffle furnace at 910 °C for 6 h. The base samples were produced by heating and melting a mixture of oxides (CaO–SiO_2) in a graphite crucible at 1500 – 1550 °C (30 min hold). The melt was poured into a mold and cooled.

The resulting slags were then blended in appropriate proportions with magnesium oxide (pre-calcined at 400 °C), aluminum oxide, and boric anhydride (pre-melted in a resistance furnace at 900 °C for 4 h). These mixtures were melted in a graphite crucible at 1500 – 1550 °C (30 min hold), poured into molds, cooled, and ground.

The powders were pressed into pellets, placed in a molybdenum crucible, heated to 1550 °C, and subjected to viscosity measurements. A vibrational viscometer operating in forced oscillation mode was used for this purpose [23; 24], with the melt temperature recorded using a tungsten–rhenium thermocouple. The measuring probe was made of molybdenum. Viscosity was measured during cooling at a rate of 5 – 7 °C/min.

Results and discussion

The results of the experiments are presented in Table 2 and Figs. 1 – 4.

Fig. 1 shows the isolines of the response function for the temperature at which the given viscosity is achieved, with increasing B_2O_3 content from 0 to 10 %. According to the data in Fig. 1, an increase in B_2O_3 content in the slag leads to a decrease in the temperature required to achieve the specified viscosity, particularly in the simplex region with high MgO content.

Fig. 2 presents the isolines of the response function for the temperature corresponding to the given viscosity, as the basicity of the slag increases from 0.9

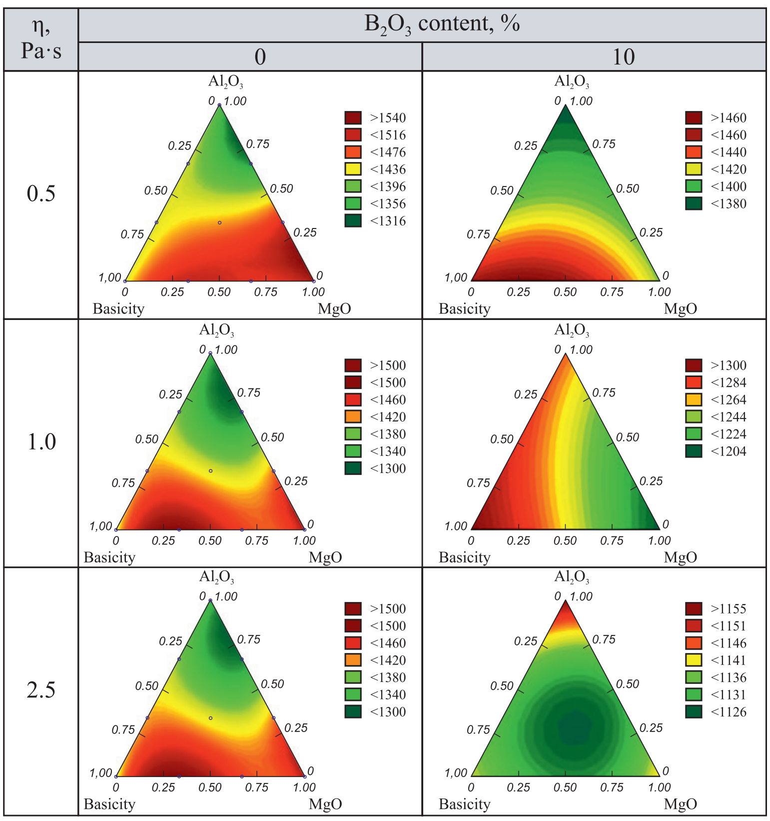

Fig. 1. Isolines of the temperature response function at which a given viscosity is achieved with an increase in B_2O_3 content from 0 to 10 %

Рис. 1. Изолинии функции отклика температуры, при которой достигается заданная вязкость, при увеличении содержания B_2O_3 от 0 до 10 %

Table 2. **Experimental results**

Таблица 2. **Результаты экспериментов**

Mixture No.	Slag temperature, °C at given viscosity, Pa·s					Slag viscosity, Pa·s at given temperature, °C				
	0.4	0.5	0.6	1.0	2.5 (T_m)	1550	1500	1450	1400	1350
1	1449	1434	1422	1398	1378	0.120	0.188	0.350	0.680	–
2	1554	1532	1510	1475	1462	0.432	0.651	5.102	–	–
3	1430	1380	1317	1200	1130	0.124	0.295	0.384	0.461	0.548
4	1422	1388	1372	1340	1290	0.162	0.215	0.264	0.461	0.900
5	1532	1513	1479	1448	1440	0.295	0.567	0.807	–	–
6	1545	1493	1430	1323	1140	0.384	0.478	0.548	0.629	0.750
7	1435	1418	1400	1378	1335	0.137	0.210	0.374	0.601	1.314
8	1426	1433	1386	1204	1137	0.124	0.232	0.369	0.461	0.495
9	1350	1330	1319	1314	1306	0.490	0.071	0.113	0.215	0.392
10	1399	1373	1354	1310	1210	0.600	0.103	0.198	0.384	0.629
11	1515	1493	1498	1485	1450	0.287	0.542	2.427	–	–
12	1350	1290	1275	1260	1248	0.110	0.124	0.174	0.315	0.404
13	1435	1409	1407	1398	1387	0.150	0.243	0.364	0.836	7.000
14	1358	1357	1356	1350	1340	0.082	0.096	0.096	0.110	0.994
15	1535	1510	1490	1420	1403	0.305	0.550	0.842	2.800	–
16	1545	1407	1360	1276	1150	0.384	0.461	0.461	0.530	0.608
17	1455	1430	1392	1333	1270	0.174	0.305	0.414	0.536	0.857
18	1510	1454	1420	1397	1388	0.370	0.403	0.524	0.730	1.200
19	1380	1348	1330	1291	1200	0.082	0.215	0.215	0.355	0.478
20	1490	1410	1380	1320	1225	0.248	0.355	0.478	0.548	0.868
21	1418	1416	1415	1409	1400	0.103	0.143	0.198	2.350	–
22	1440	1410	1397	1389	1378	0.105	0.162	0.399	0.495	–
23	1360	1322	1290	1243	1150	0.124	0.162	0.248	0.355	0.414
24	1378	1362	1337	1300	1240	0.103	0.162	0.215	0.325	0.530
25	1426	1377	1356	1282	1258	0.162	0.221	0.335	0.456	0.659

to 1.1. As shown in the figure, higher basicity results in higher temperatures needed to reach the given viscosity in simplex regions with elevated MgO and Al_2O_3 content. At the same time, in regions with high B_2O_3 content, the required viscosity is achieved at relatively low temperatures – between 1100 and 1300 °C – regardless of the slag basicity.

Fig. 3 shows isolines of the response function for the temperature at which the given viscosity is reached as MgO content increases from 15 to 29 %.

The results presented in Fig. 3 indicate that, despite nearly doubling the MgO content in the slag, in the simplex region with maximum B_2O_3 content, the increase in the temperature needed to reach the given viscosity is minor. The temperature remains below 1380 °C at minimum viscosity and below 1340 °C at maximum viscosity.

Fig. 4 presents isolines of the response function for the temperature at which the given viscosity is reached, as Al_2O_3 content increases from 5 to 15 %.

The results in Fig. 4 demonstrate that increasing the Al_2O_3 content in the slag lowers the temperature required to reach the desired viscosity in the region with high MgO content. This temperature is further reduced when B_2O_3 content is also increased.

Across the entire composition range of the $CaO-SiO_2-Al_2O_3-MgO-B_2O_3$ system, in the absence of boron oxide, the temperature corresponding to the slag melting point (defined as the temperature at which viscosity reaches 2.5 Pa·s) exceeds 1390 °C. At basicity below 1.1, MgO content below 20 %, and Al_2O_3 content above 10 %, the melting point lies in the range of 1300 – 1400 °C. The viscosity of 0.5 Pa·s, which corresponds to the tapping viscosity, is reached at 1300 – 1440 °C for any basicity level, provided that MgO content is below 20 % and the Al_2O_3/MgO ratio exceeds 0.5. Moreover, the higher this ratio, the lower the temperature required to reach that viscosity. This indicates that blast furnace smelting with slags of this composition can proceed without operational difficulties.

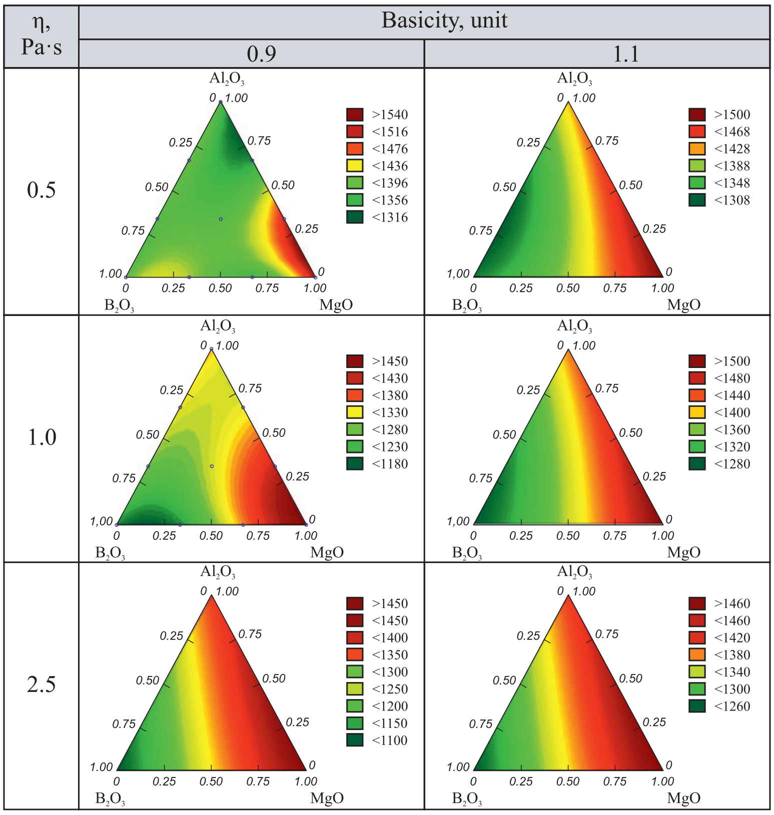

Fig. 2. Isolines of the temperature response function at which a given viscosity is achieved with an increase in basicity from 0.9 to 1.1 units

Рис. 2. Изолинии функции отклика температуры, при которой достигается заданная вязкость, при увеличении основности от 0,9 до 1,1 ед

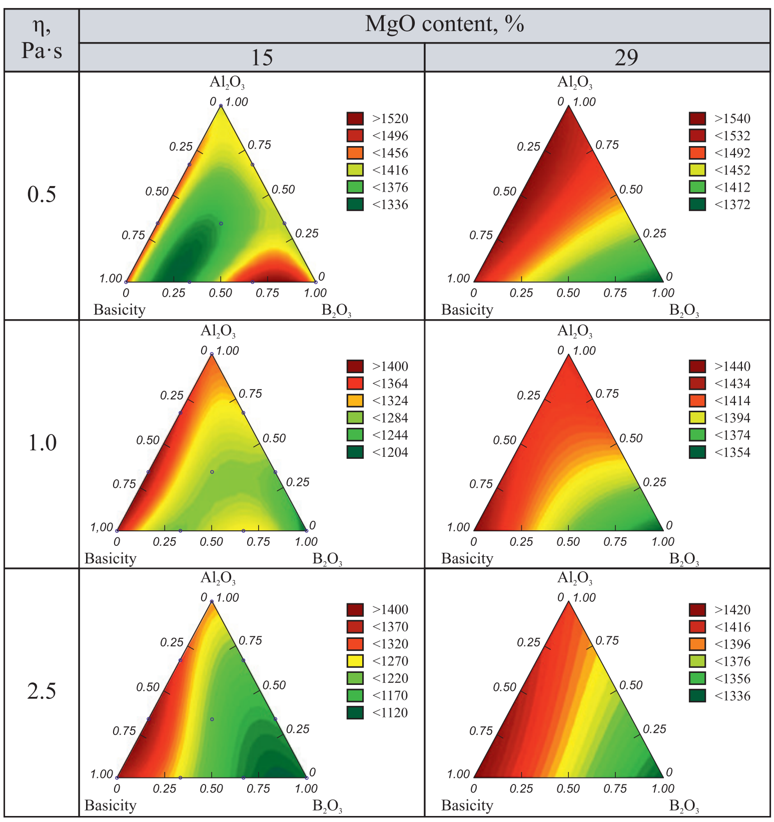

Fig. 3. Isolines of the temperature response function at which a given viscosity is achieved with an increase in MgO content from 15 to 29 %

Рис. 3. Изолинии функции отклика температуры, при которой достигается заданная вязкость, при увеличении содержания MgO от 15 до 29 %

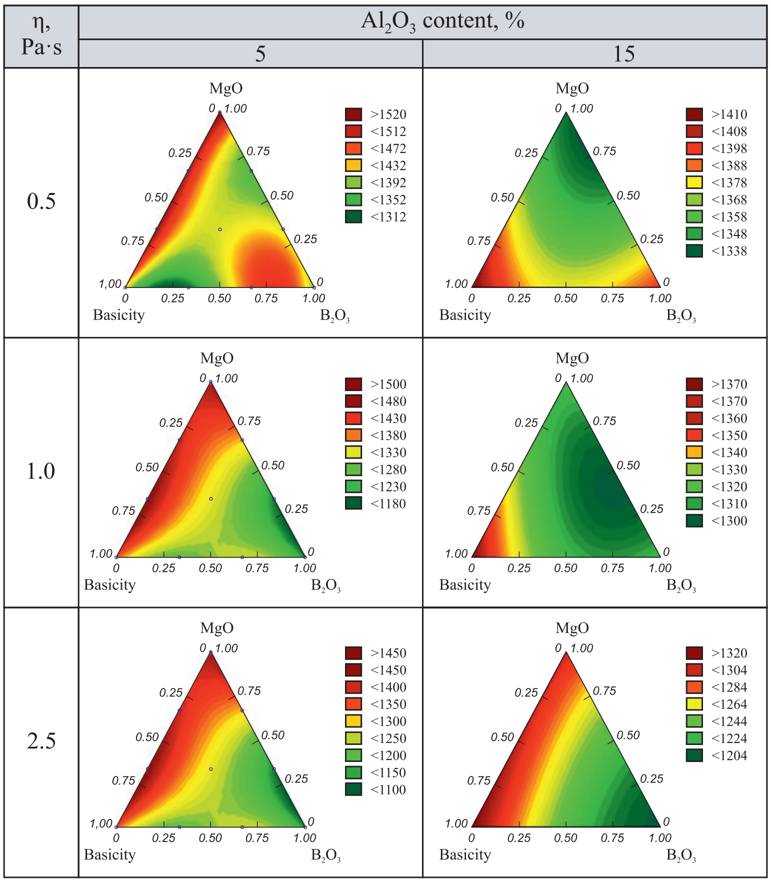

Fig. 4. Isolines of the temperature response function at which a given viscosity is achieved with an increase in Al_2O_3 content from 5 to 15 %

Рис. 4. Изолинии функции отклика температуры, при которой достигается заданная вязкость, при увеличении содержания Al_2O_3 от 5 до 15 %

A further increase in magnesium oxide content causes a sharp rise in slag melting point – up to 1500 °C – alongside a narrowing of the crystallization interval. The tapping viscosity temperature rises to 1540 °C when MgO content reaches 36 %, making smelting under such conditions difficult or even infeasible.

The addition of B_2O_3 lowers the temperature at which the viscosity of the melt reaches 2.5 Pa·s, and at 15 % B_2O_3, this temperature drops to below 1150 °C. the slags exhibit improved fluidity and greater thermal stability.

Conclusions

At present, the content of major components in most blast furnace slags is as follows (wt. %): 30 – 40 SiO_2, 31 – 49 CaO, 3 – 18 MgO, and 7 – 20 Al_2O_3. Minor components include MnO (0.1 – 3.0 %), FeO (0.2 – 0.8 %), and S (0.8 – 2.2 %). Such slags exhibit good fluidity (viscosity below 0.5 Pa·s) at temperatures above 1450 °C. An increase in magnesium oxide content above 25 % significantly reduces slag fluidity and raises the melting point, making the slags viscous and difficult to process, which complicates blast furnace operation. For this reason, materials produced from siderite ore using various preparation technologies (raw ore, roasting–magnetic separation, agglomeration) are added to the blast furnace charge only as supplementary components. Their share in the initial charge is kept below 20 % to ensure that the resulting slag does not contain more than 15 – 20 % MgO.

The addition of boron oxide–containing materials to the initial charge lowers the slag melting point. This enables blast furnace smelting with slags containing approximately 40 % MgO, which corresponds to a siderite ore share of 40 – 50 % in the initial charge.

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М. А. Михеенков – проведение расчетов, анализ результатов исследований.
Л. И. Леонтьев – научное руководство, анализ результатов исследований, редактирование статьи.
С. Н. Агафонов – проведение расчетов, проведение экспериментов.

A. S. Vusikhis – setting the research task, performing calculations, writing the text, formation of conclusions.
M. A. Mikheenkov – performing calculations, analysis of the research results.
L. I. Leont'ev – scientific guidance, analysis of the research results, editing the article.
S. N. Agafonov – performing calculations, conducting the experiments.

Поступила в редакцию 24.03.2025
После доработки 01.04.2025
Принята к публикации 23.04.2025

Received 24.03.2025
Revised 01.04.2025
Accepted 23.04.2025