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PROSPECTS FOR THE USE OF HYDROGEN AND HYDROGEN-CONTAINING ADDITIVES TO REDUCE CO_2 EMISSIONS AND TO IMPROVE THE PERFORMANCE OF BLAST FURNACE SMELTING

Introduction. *Global warming is currently one of the most important problems of humanity, the dominant cause of which is the anthropogenic factor, particularly, a significant increase in greenhouse gases. Given the extremely negative consequences of this process in the future, in 2015, 195 countries, including Ukraine, ratified the Paris Climate Agreement that obliges them to reduce* CO_2 *emissions, in particular in the steel industry, where carbon pollution is extremely high: 6% globally and 26% in Ukraine, as of the beginning of 2022.*

Problem Statement. *According to the International Energy Agency, blast furnace production will be the dominant steelmaking process by 2050, with a thermal efficiency of over 90%. The introduction of new steelmaking technologies may lead to a 50% reduction in conventional steelmaking by 2050, but requires significant investments.*

Purpose. *To study the effect of using hydrogen-containing fuel in a blast furnace on carbon dioxide emissions and the technical and economic indicators of blast furnace smelting.*

Materials and Methods. *To assess the potential of using hydrogen and hydrogen-containing fuels in a blast furnace for reducing* CO_2 *emissions and the technical and economic indicators of blast furnace smelting, we have used the mathematical model of the complete energy balance of blast furnace smelting, as developed at the Institute of Ferrous Metallurgy of the National Academy of Sciences of Ukraine.*

Results. *We have analyzed and established the regularities of the effect of hydrogen and hydrogen-containing fuel additives on* CO_2 *emissions and the blast furnace performance indicators, such as iron production, coke con-*

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sumption, and secondary energy resources. The critical consumption of fuel additives, at which full iron recovery is expected to be achieved by an indirect method, has been determined. The coefficient of coke replacement by coke oven gas and hydrogen has been found.

Conclusions. *The efficiency of using hydrogen and hydrogen-containing fuels separately and in combination with pulverized coal has been proven. It is a promising way to select the rational blast furnace operating conditions in terms of environmental (CO_2 emissions reduction) and economic feasibility.*

Keywords: ecology, blast furnace, CO_2 emissions, hydrogen, coke gas, natural gas, coke.

The main greenhouse gases entering the atmosphere are water vapor and carbon dioxide. However, unlike carbon dioxide, water vapor is a natural greenhouse gas that maintains the planet's water cycle. Fossil fuels, deforestation, and certain industrial processes contribute significantly to increasing atmospheric carbon dioxide concentrations through chemical transformations. This substantial rise in atmospheric carbon dioxide levels leads to the greenhouse effect, resulting in global temperature increases that can negatively impact both human populations and the planet's ecosystems as a whole [1, 2].

In response to global warming and its anticipated adverse effects, 195 countries and the European Union ratified the Paris Climate Agreement in 2015. This agreement obliges signatories to reduce carbon dioxide emissions, including those from the metallurgy sector, where emission levels are notably high [3].

Ukraine was one of the first European countries to ratify the Paris Agreement. This decision was driven by significant climate changes within its territory, which pose increased risks to human health and life, natural ecosystems, and various economic sectors. Additionally, the ratification aims to ensure Ukraine's national, ecological, economic, and energy security. In January 2020, Ukraine introduced the Concept of Green Energy Transition, which aims to achieve carbon neutrality in its economy by 2070 [4]. The structure of emissions in Ukraine differs from the rest of the world, as globally, metallurgy produces 6% of CO_2 emissions, while in Ukraine, its share reaches 26% [5, 6]. Accordingly, the role of steelmaking in the decarbonization of the Ukrainian economy is significantly over the world average. However, there is no government program to reduce CO_2 emissions in Ukraine's metallurgy.

According to forecasts by the International Energy Agency (IEA), blast furnace production will remain the dominant method for steel production until 2050 due to its economic profitability, with thermal efficiency reaching up to 90% or more. Compared to other iron production technologies, blast furnaces offer more flexible and dynamic processing of ores of varying quality. In terms of productivity, blast furnaces significantly outperform other technologies. Consequently, blast furnace converter technologies account for the majority (60—70%) of global steel production.

The active implementation of new steel production technologies is expected to begin only after 2030, potentially reducing the reliance on conventional steel production methods by 50%, by 2050. However, achieving this shift requires significant investments, amounting to tens of billions of dollars, in the development and deployment of these new technologies.

One of the most effective methods for reducing carbon dioxide emissions from blast furnaces is the use of fuel additives where part or all of the carbon is replaced by hydrogen. These fuel additives include natural gas, coke gas, and hydrogen itself [7, 8].

Since natural gas has been the primary fuel additive in Ukraine for a long time, its influence on technical and economic indicators has been well studied [9]. However, these studies have paid little attention to its impact on environmental indicators, particularly carbon dioxide emissions from blast furnaces. It should be noted that the use of natural gas in cast iron production is limited by its cost.

Industrial research on the use of coke oven gas was conducted at many blast furnaces from the late 1950s to the late 1990s. These studies reported coke replacement coefficients with coke gas ranging from 0.36 to 0.62 kg/m^3 [9—16]. At that time, reducing coke consumption was prioritized over decarbonizing the metallurgical industry, resulting in a lack of studies on CO_2 emissions during coke gas injection. Currently, many foreign researchers have been focusing on coke gas, including its reforming and injection into the blast furnace shaft. However, the technology for using coke gas has not yet become widespread [7].

The use of coke gas that contains 55—60% hydrogen can be a transitional stage for the abandonment of carbon-containing fuel additives and the use of hydrogen in the blast furnace.

Recently, the priority direction of research aimed at reducing CO_2 emissions from blast furnaces is the use of hydrogen technologies, namely, hydrogen injection into the blast furnace hearth. Practical studies have been conducted only by ThysenKrupp at BF No. 9, in Duisburg, in November 2019, during which the technical possibility of hydrogen injection into the blast furnace has been demonstrated [17]. Also, an experimental blast furnace having a volume of 12 m^3 has been created in Japan for the study of hydrogen blowing. It has been established that with a hydrogen consumption of 277 m^3/t of cast iron, CO_2 emissions decrease by 12% [18]. However, most of the studies have been of analytical nature. At the same time, the results obtained by numerical methods are contradictory: according to some studies, the coefficient of replacement of coke by hydrogen is 0.06 kg/m^3 [19], while according to others, it amounts to 0.15 kg/m^3 [20], or 0.27—0.36 kg/m^3 [21].

Considering the above, studying the effect of the use of hydrogen-containing fuel in the blast furnace on the emission of carbon dioxide and the technical and economic indicators is a relevant task.

To assess the potential of using hydrogen and the influence of hydrogen-containing fuel additives in a blast furnace on carbon dioxide emissions and the technical and economic indicators of blast furnace smelting, we have made calculations using the method developed at the Institute of Ferrous Metallurgy named after Z. Nerasov of the NAS of Ukraine of the mathematical model of the complete energy balance of blast furnace melting [22—24].

The method of total energy balance is based on the three laws of thermodynamics and is applicable for analyzing any process. This technique is termed "total energy balance" because it accounts for all types of energy, including the chemical energy of fuel, raw materials, and materials in the input, as well as products and process waste in the output. The total energy balance method enables the assessment of energy efficiency and the identification of ways to reduce the energy intensity of products.

The total energy balance in relation to blast furnace production includes the general calculation and consideration of material, heat, and exergy balances. The material balance is calculated by V.P. Izhevsky's technique, the thermal one is determined by I.D. Semikin's thermal energy model, the exergy balance is based on researchers by A.V. Borodulin and V.S. Stepanov.

The influence of hydrogen and hydrogen-containing fuel additives (such as natural gas and coke gas) on CO_2 emissions and the technical and economic indicators of blast furnace operation has been analyzed in a wide range of flow rate variations:

- natural gas: from 0 to 200 m^3/t cast iron;
- coke gas: from 0 to 300 m^3/t cast iron;
- hydrogen: from 0 to 600 m^3/t cast iron.

The following chemical composition of fuel additives has been used for the calculations (Table 1).

All calculations for the use of fuel additives have been made at a constant theoretical temperature of combustion in the hearth (hereinafter referred to as the theoretical temperature), under variations of the theoretical temperature in the range of 1800—2200 °C, maintained by increasing the moisture (to reduce the temperature) and the oxygen (to increase it) content in the blast

Table 1. **The Properties of Hydrogen-Containing Fuel**

Fuel	Content, % wt.:							H_2S, g/m³	Combustion heat, MJ/m³	Density, g/m³
	H_2	CH_4	CO	CO_2	N_2	Heavy hydrocarbons	O_2			
Natural gas	0.0	92.6	0.0	0.1—0.2	1.4	5.8—5.9	0.0	0.0	37.7	0.78
Coke gas	55—60	20—30	5—7	2—3	4	2—3	0.4—0.8	0.12—0.5	15—19	0.4—0.5
Hydrogen	100	0.0	0.0	0.0	0.0	0.0	0.0	0.0	10.7	0.09

furnace (Figs. 1—2). The calculated influence of the change in the theoretical temperature on the consumption of various fuel additives is shown in Table 2.

Thus, it has been established that an increase in the hydrogen consumption per every 10 m³/t cast iron has the least effect on reducing the theoretical temperature (by 12 °C per 10 m³/t cast iron), while that in the natural gas consumption has the greatest effect (by 39 °C per 10 m³/t cast iron).

The basic period of the blast furnace operation for the analysis of the influence of various factors on carbon dioxide emissions and the technical, economic, and exergetic indicators, as well as the values of these parameters at the maximum consumption of fuel additives are given in Table 3.

1. The influence of hydrogen and hydrogen-containing fuel additives on the blast furnace productivity. Keeping the theoretical temperature at a constant level, it is possible to achieve the most significant increase in blast furnace productivity with the use of hydrogen, while coke gas gives the smallest effect. This is explained by more oxygen to be blown into the blast furnace for maintaining the theoretical temperature. An increase in the flow of hydrogen for blowing into the blast furnace from 0 to 585 m³/t cast iron leads to a growth in the productivity by 145% (from 4000 to ~9800 t cast iron/day). An increase in the natural gas flow from 0 to 200 m³/t cast iron allows raising the productivity by 117% (from ~4000 to ~8700 t cast iron/day). Increasing the consumption of coke gas from 0 to 300 m³/t cast iron results in a 89% growth in the productivity (from ~4000 to ~7550 t cast iron/day) (Fig. 3).

Table 2. **Theoretical Temperature Variations Depending on Varying Fuel Additives Consumption**

Fuel consumption variation	Change in the theoretical temperature depending on an increase in the fuel additive consumption, °C		
	Natural gas	Coke gas	Hydrogen
By 1 thousand m³/h	27	14	7
Per 10 m³/t cast iron	39	22	12

At the same time, at variable theoretical temperature, an increase in the consumption of hydrogen and hydrogen-containing additives has a much smaller effect on the blast furnace productivity. Increasing the flow rate of hydrogen for blowing into the blast furnace from 0 to 600 m³/t cast iron leads to an increase in the productivity by 48% (from ~4000 to ~5900 t cast iron/day). Increasing the consumption of natural gas from 0 to 200 m³/t cast iron enables raising the productivity by 30% (from ~4000 to ~5200 t cast iron/day). Increasing the consumption of coke gas from 0 to 300 m³/t cast iron leads to a 14% increase in the productivity (from ~4000 to ~4550 t cast iron/day).

Such a feature in increasing the productivity of the blast furnace is associated with a significant difference in the technical oxygen content in the blast furnace (to vary the total oxygen content in the blast furnace), which is necessary to keep the theoretical temperature at the required level.

Thus, increasing the fuel additive consumption per every 10 m³/t cast iron at a constant/variable

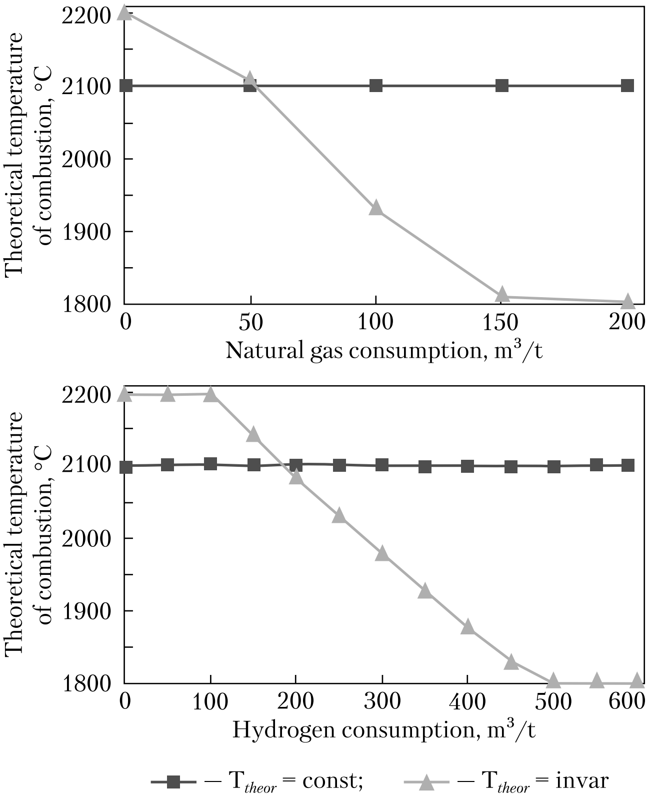


Fig. 1. Change in the theoretical temperature depending on the consumption of natural gas, coke gas, and hydrogen

Table 3. **Estimated CO_2 Emissions and the Technical and Economic Indicators of Blast Furnace Smelting Depending on Various Fuels**

Parameter	Fuel						
	Basic	Natural gas		Coke gas		Hydrogen	
Consumption of hydrogen-containing fuel additive, m³/t cast iron		200	200	300	300	585	600
Theoretical temperature of combustion in hearth, °C	2172	2100	1802	2100	1800	2100	1800
Productivity, cast iron t per 1 day	4694	8738	5213	7539	4551	9800	5919
Total consumption of coke and coke nut, kg/t cast iron	352	355	340	394	379	401	378
Pulverized coke fuel consumption in the base period, kg/t cast iron	153	—	—	—	—	—	—
Gas consumption in the base period, m³/t cast iron	25.6	—	—	—	—	—	—
Blow consumption, m³/min	4011	4011	4011	4011	4011	4011	4011
Blow temperature, °C	1112	1112	1112	1112	1112	1112	1112
Oxygen content in blow, %	25.7	53.2	30.0	41.5	23.6	49.2	27.1
Fe content in charge, %	56.70	56.70	56.70	56.70	56.70	56.70	56.70
Basicity of slag CaO/SiO_2	1.10	1.10	1.10	1.10	1.10	1.10	1.10
Basicity of slag $(CaO + MgO)/SiO_2$	1.27	1.27	1.27	1.27	1.27	1.27	1.27
SER output, kg conventional fuel/t cast iron	82	144	125	137	116	152	154
Estimated CO_2 emission given CO after burning outside blast furnace, kg/t cast iron	1439	1348	1313	1350	1318	1093	1033

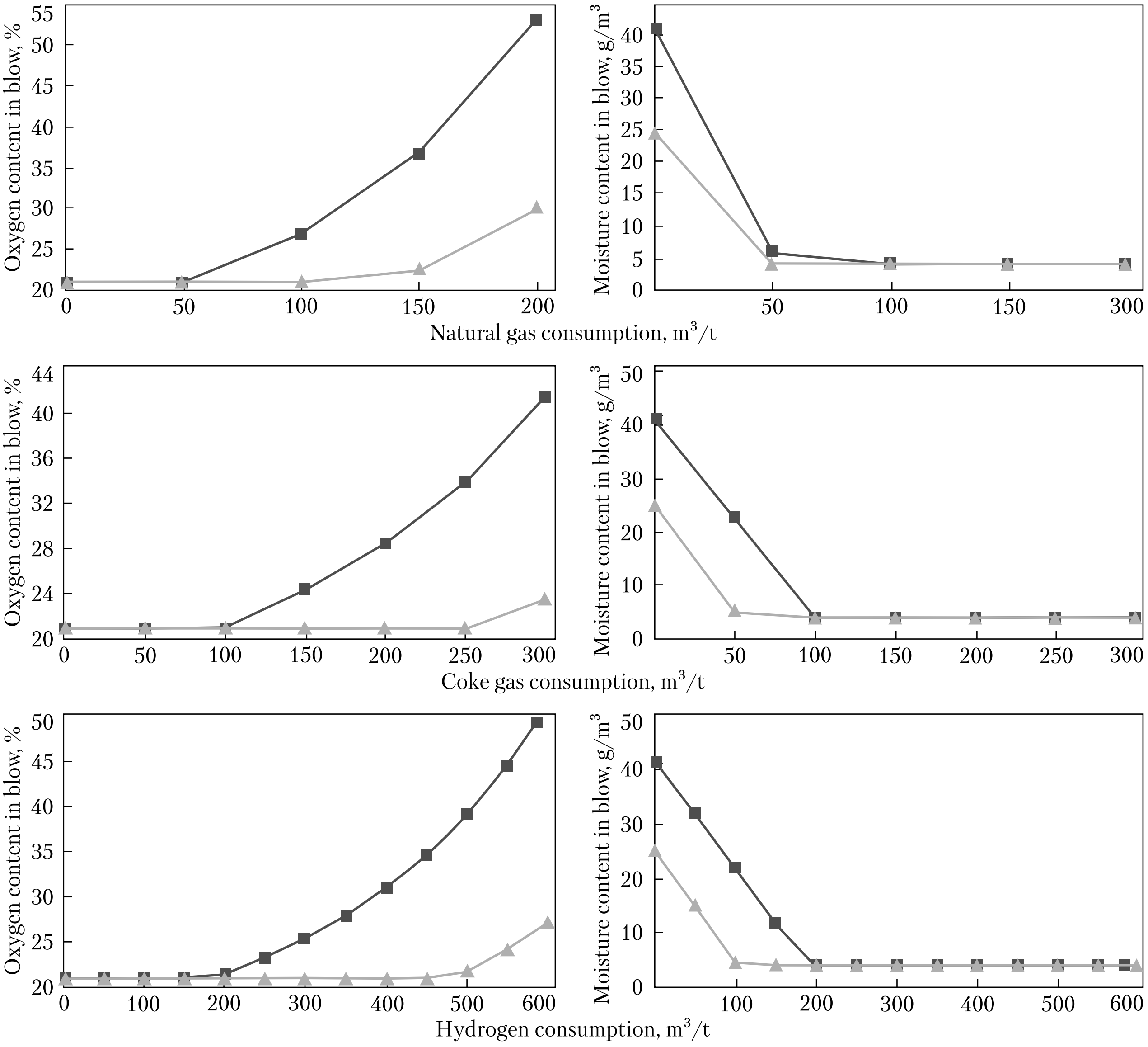


Fig. 2. Oxygen and moisture content in blow depending on the use of natural gas, coke gas, and hydrogen at constant (—■—, ~2100 °C) and at variable theoretical temperature of combustion (—▲—, 1800—2200 °C)

theoretical temperature makes it possible to increase the productivity of the blast furnace by 2.5%/0.8% (hydrogen), by 5.9%/1.5% (natural gas), and by 3.0%/0.5% (coke gas).

2. The influence of hydrogen and hydrogen-containing fuel additives on the coke consumption in blast furnace. The use of any fuel additive allows reducing coke consumption in blast furnace. According to the research results, it has been established that the use of hydrogen or hydrogen-containing fuel additives in the specified ranges enables reducing the coke consumption from 530 kg/t cast iron to 400 kg/t cast iron and more (Fig. 4).

The use of natural gas in the blast furnace allows reducing the consumption of coke by 1.7%/1.8%

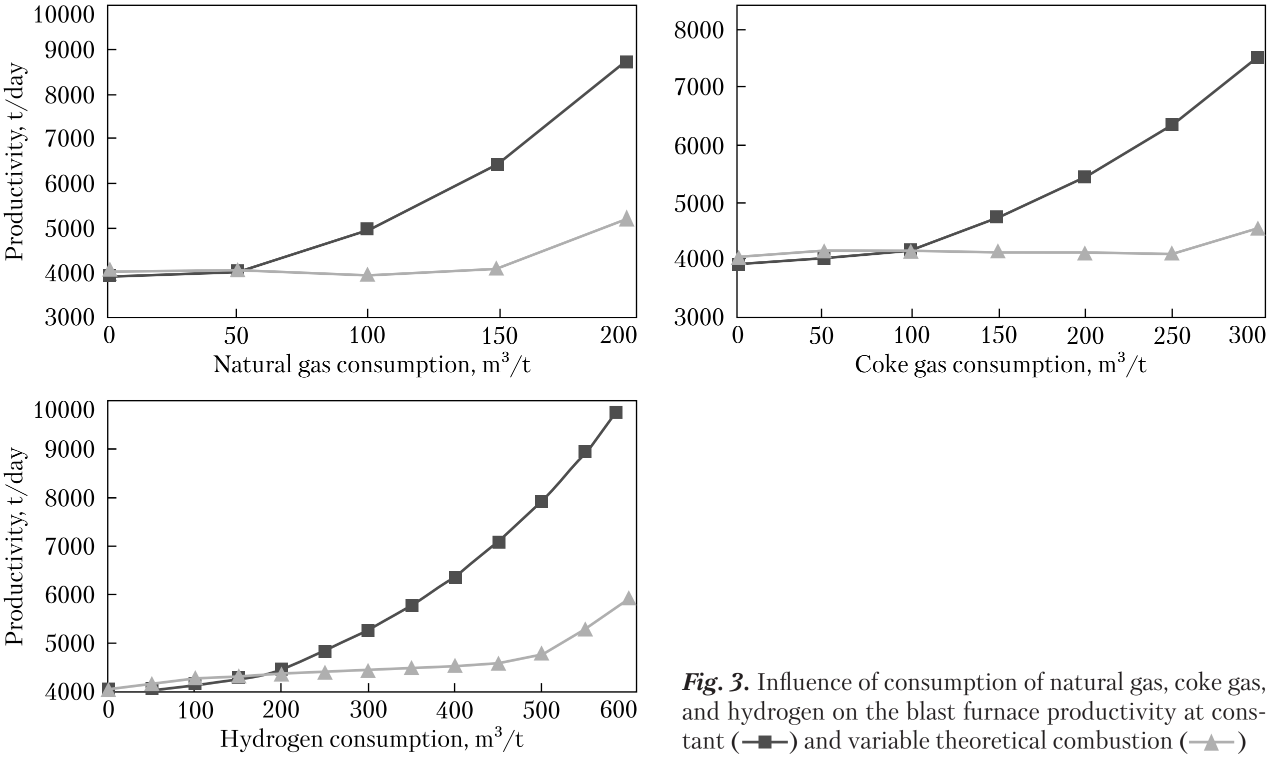


Fig. 3. Influence of consumption of natural gas, coke gas, and hydrogen on the blast furnace productivity at constant (—■—) and variable theoretical combustion (—▲—)

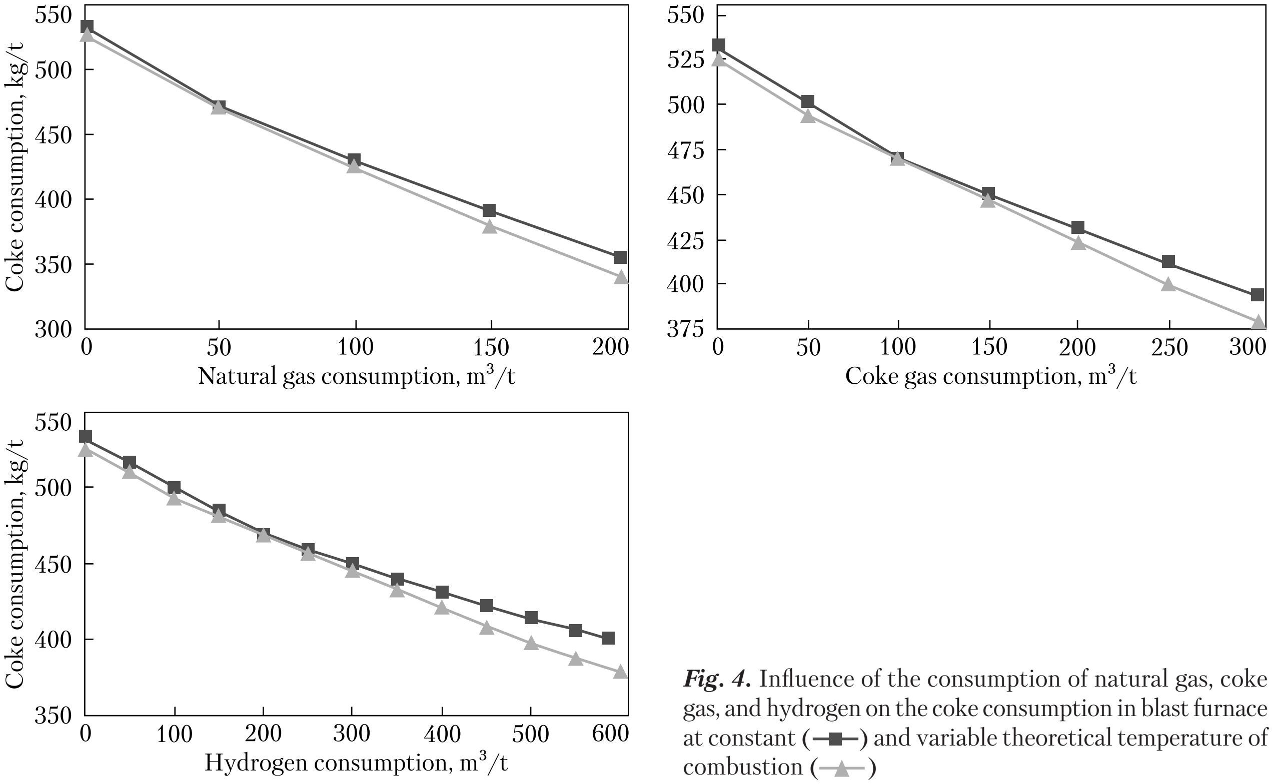


Fig. 4. Influence of the consumption of natural gas, coke gas, and hydrogen on the coke consumption in blast furnace at constant (—■—) and variable theoretical temperature of combustion (—▲—)

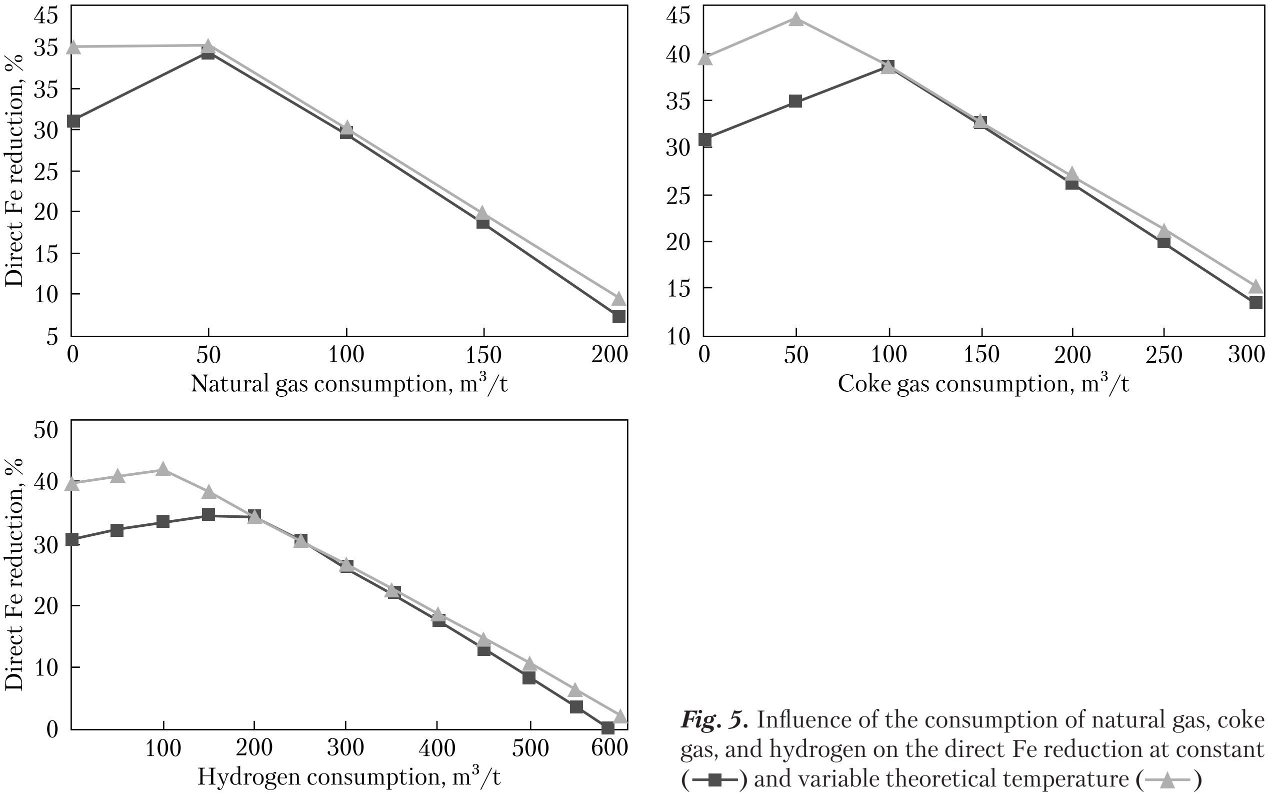


Fig. 5. Influence of the consumption of natural gas, coke gas, and hydrogen on the direct Fe reduction at constant (—■—) and variable theoretical temperature (—▲—)

per every 10 m^3/t cast iron, in the case of using natural gas at a constant/variable theoretical combustion temperature. This is equivalent to reducing the coke consumption by 0.88 kg/0, 93 kg for every 1 m^3 natural gas consumption. This ratio of coke replacement by natural gas is consistent with the known ones used in production [9].

The use of coke gas in blast furnace allows reducing the coke consumption by 0.87%/0.92% per every 10 m^3 coke gas/ton cast iron, which is equivalent to reducing coke consumption by 0.46 kg/m^3/0.49 kg/m^3 coke gas, at a constant/variable theoretical temperature. The coefficient of coke replacement by coke gas when injected into blast furnace has been analytically determined. It differs from the known ones and varies in the range of 0.46—0.49 kg/m^3.

The use of hydrogen in blast furnace allows reducing the coke consumption by 0.48%/0.46% per every 10 m^3 H_2/t cast iron, which is equivalent to reducing the coke consumption by 0.25 kg/m^3/0.22 kg/m^3 hydrogen, at constant /variable theoretical combustion temperature. The coefficient of coke replacement by hydrogen in blast furnace has been analytically determined to vary within 0.22—0.25 kg/m^3.

The obtained results allow us to conclude that increasing the use of fuel additives (hydrogen, natural and coke gases) per every 10 m^3/t cast iron at a constant/variable theoretical temperature creates conditions for reducing the coke consumption in blast furnace, respectively, by 0.48%/0.46%; by 1.7%/1.8%, and by 0.87%/0.92%.

3. The influence of hydrogen and hydrogen-containing fuel additives on the direct reduction of iron in blast furnace. The use of hydrogen and hydrogen-containing fuel additives makes it possible to increase the iron reduction in an indirect way, which leads to a decrease in the direct reduction of iron in furnace, as a result of the increasing share of mine gases in the composition [9].

At a small consumption of fuel additives (natural gas up to ~50 m^3/t cast iron, coke gas up to 100/50 m^3/t cast iron, and hydrogen up to 150/100 m^3/t cast iron), at a constant/variable theoretical temperature, the direct reduction of iron in furnace (r_d) remains unchanged or tends to increase, probably, because of a significant moisture content in the blow (Fig. 5).

After reaching the extremum, the direct reduction of iron in the furnace (r_d) decreases for all types of fuel both at constant and variable theoretical temperature.

Increasing the consumption of natural gas from 50 to 200 m^3/t cast iron leads to a decrease in the direct reduction of iron in furnace from 39.3/40.2% to 7.4/9.5% at a constant/variable theoretical temperature.

Increasing the consumption of coke gas from 100/50 m^3/t cast iron to 300 m^3/t cast iron leads to a decrease in the direct reduction of iron in furnace from 38.6%/43.7% to 13.5%/15.3%, at a constant/ variable theoretical temperature.

Increasing the hydrogen consumption from 150/100 m^3/t cast iron to 585/600 m^3/t cast iron leads to a decrease in the direct reduction of iron in furnace from 34.3%/42.0% to 0.1%/2.0%, at a constant/variable theoretical temperature. At a hydrogen consumption of 585/600 m^3/t cast iron, at a constant/variable theoretical temperature, the value of r_d is close to zero. This may indicate the achievement of conditions under which the share of indirect reduction of iron reaches about 100%. In 1872, L. Gruner first proposed what later became known as the Gruner principle. It posits that iron ore in blast furnaces should be reduced, as much as possible, by carbon monoxide converting to CO_2, without consuming solid carbon. Gruner referred to this principle as “the ideal course” of blast furnace operation. When this method is applied, the reactions are simplified: carbon monoxide formed near the lances reduces the ore, transforms into CO_2 that then exits the furnace without reacting with solid carbon. In this scenario, all the carbon introduced into the furnace, upon reaching the horizon of the lances, is converted into CO by the action of air. Therefore, according to the Gruner principle, with a given hydrogen consumption, full reduction of iron can be achieved indirectly, resulting in minimal fuel consumption [25].

That is, increasing the fuel additive content in the blow composition at a constant/variable theoretical temperature leads to a decrease in the direct reduction of iron in blast furnace by 0.79%/0.80% (hydrogen), by 2.12%/2.05% (natural gas) and by 1.26%/1.14% (coke gas) per every 10 m^3 additive/t cast iron.

4. The influence of hydrogen and hydrogen-containing fuel additives on the output of secondary energy resources from blast furnace. One of the important parameter, which characterizes the environmental friendliness of blast furnace smelting and the prospects of obtaining additional energy effect from heating is the output of secondary energy resources (SER). The output of SER is the difference between the specific indicators of the energy carried by the furnace gas and the energy consumption for blow heating, compression, and enrichment with oxygen in the equivalent of conventional fuel consumption.

It has been established that the output of secondary energy resources has an extremum at the following consumption rates: ~50 m^3/t cast iron (natural gas), ~100/50 m^3/t cast iron (coke gas), and ~150/100 m^3/t cast iron (hydrogen), at a constant/variable theoretical temperature. Until reaching the extremum, the SER output from the blast furnace increases or remains unchanged, which, similarly, as in the case of the iron reduction, is associated with a significant moisture content in the blow (Fig. 6).

As follows from the analysis of the curves in Fig. 6, as the consumption of natural gas increases from 50 m^3/t cast iron to 200 m^3/t cast iron, the output of secondary energy resources grows from 70 kg c. f./t cast iron up to 145/125 kg c. f./t cast iron. As the consumption of coke gas increases from 100/50 m^3/t cast iron to 300 m^3/t cast iron, the output of SER grows from 75/67 kg c.f./t cast iron up to 137/116 kg c. f./t cast iron. As the hyd-

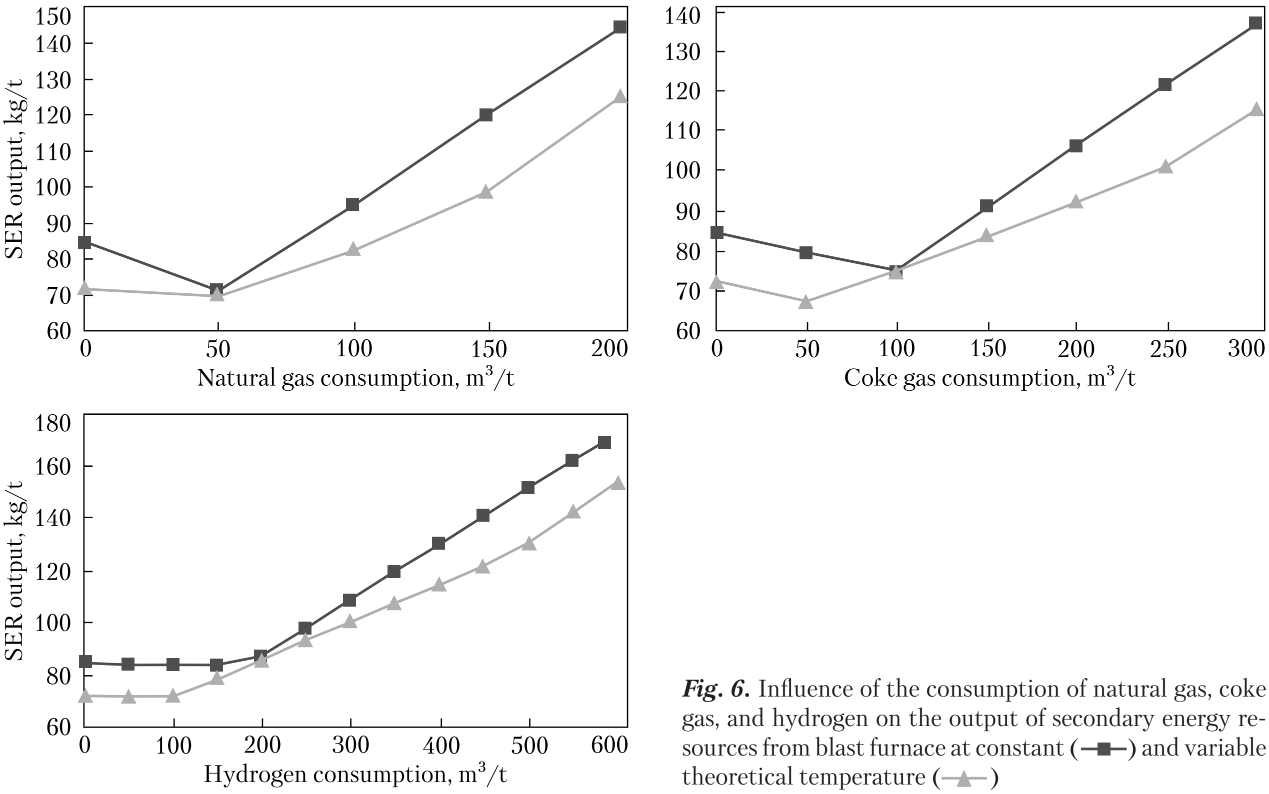


Fig. 6. Influence of the consumption of natural gas, coke gas, and hydrogen on the output of secondary energy resources from blast furnace at constant (—■—) and variable theoretical temperature (—▲—)

rogen consumption increases from 150/100 m^3/t cast iron to 585/600 m^3/t cast iron, the output of SER grows from 84/72 kg c.f./t cast iron up to 169/154 kg c. f./t cast iron at a constant/variable theoretical temperature.

The output of secondary energy resources at constant/variable theoretical temperature may increase by 2.33%/2.28% per every 10 m^3/t cast iron (in the case of hydrogen as fuel additive); that, in the case of using natural and coke gases as fuel additives, may grow by 7,1%/5.2% and 4.1%/4.9%, respectively.

Therefore, the use of hydrogen and hydrogen-containing fuel additives allows raising the output of secondary energy resources that be used in other plants of the metallurgical enterprise or at thermal power plants for electricity generation.

5. The influence of hydrogen and hydrogen-containing fuel additives on the estimated output of CO_2, given CO afterburning outside the blast furnace. The estimated output of CO_2, given CO afterburning outside the blast furnace, is the main parameter that characterizes the environmental friendliness of blast furnace smelting. This is because of the fact that the afterburning of CO to CO_2 takes place directly in the process units of the plant (for example, in the air heaters for heating the blast), at thermal power plant, or in torches. Ultimately, CO enters the atmosphere as CO_2.

When the fuel additive consumption ranges within 0—200 m^3/t cast iron (that is, in the range where the SER output and the direct iron reduction reach their extrema), there is reported a more intense decrease in the estimated output of CO_2. This is probably because of the use of additional moisture before blowing to keep the theoretical temperature. The analysis of the obtained results has shown that an increase in the moisture content in the blow per every 10 g/m^3 leads to a growth in the output of CO_2 by ~2.8—3.2%,

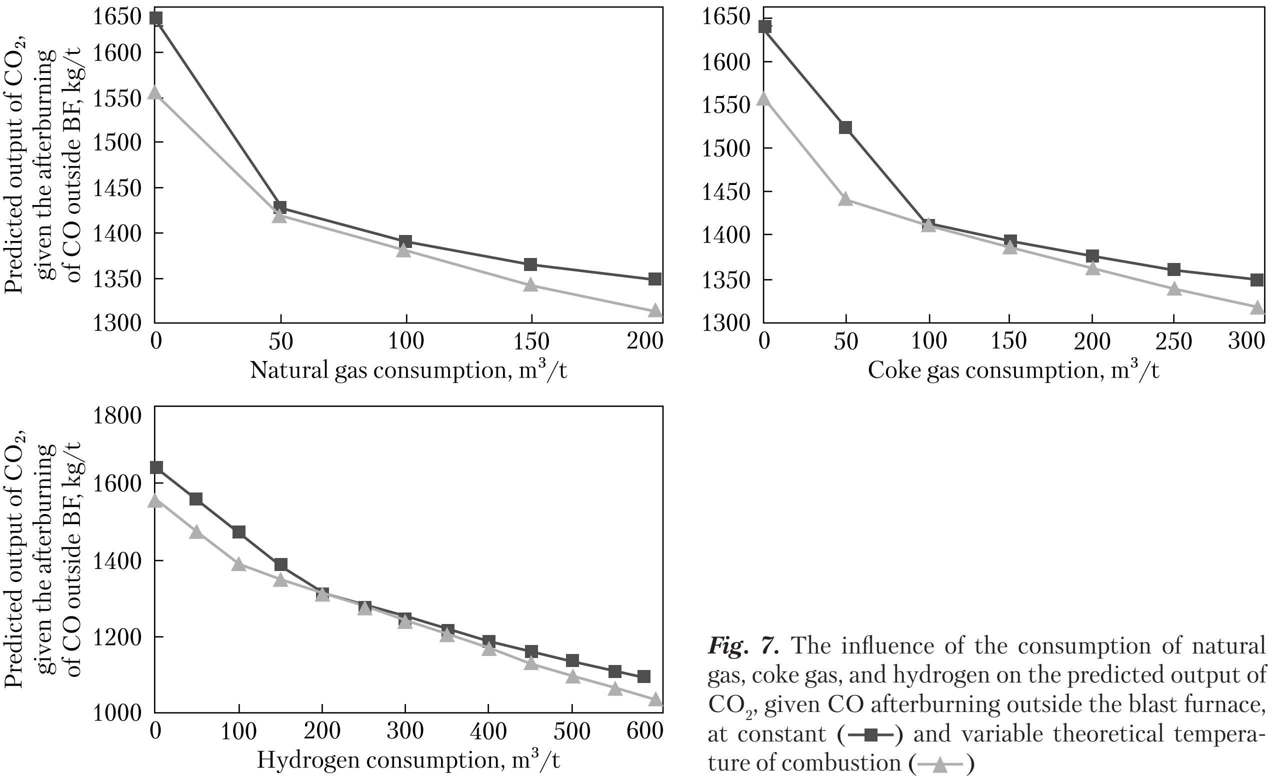


Fig. 7. The influence of the consumption of natural gas, coke gas, and hydrogen on the predicted output of CO_2, given CO afterburning outside the blast furnace, at constant (—■—) and variable theoretical temperature of combustion (—▲—)

given the afterburning of CO outside the blast furnace (Fig. 7).

Increasing the consumption of natural gas from 50 m^3/t cast iron to 200 m^3/t cast iron allows reducing carbon dioxide emissions by 5.6%/7.7% (from 1430/1420 kg/t cast iron to 1350/1310 kg/t cast iron). Increasing the consumption of coke gas from 100/50 m^3/t cast iron to 300 m^3/t cast iron results in a decrease in the emissions by 4.3%/8.6% (from 1410/1440 kg/t cast iron to 1350/1320 kg/t cast iron). Increasing the consumption of hydrogen from 150/100 m^3/t cast iron to 585/600 m^3/t cast iron leads to a drop in the emissions by 21.3%/25.9% (from 1385 kg/t cast iron to 1090/1030 kg/t cast iron), at a constant/variable theoretical temperature.

The estimate of the effect of increasing the amount of fuel additive in the blast furnace at constant/variable theoretical temperature on the reduction of carbon dioxide emissions from the blast furnace has shown that as the hydrogen consumption increases by 10 m^3/t cast iron, the CO_2 emissions are expected to decrease by 0.37%/0.51%; in the case of a similar increase in the consumption of natural and coke gases, the emissions drop by 0.22%/0.34% and by 0.49%/0.52%, respectively.

The obtained results have indicated the prospects for using hydrogen and hydrogen-containing fuel additives in the blast furnace to reduce carbon dioxide emissions.

6. The influence of hydrogen-containing additives on the degree of hydrogen use in the blast furnace. It should be noted that the use of hydrogen and hydrogen-containing fuel additives in blast furnace has been understudied in practice. In particular, the effect of increasing the hydrogen content in the hearth on the indirect iron reduction requires deeper and more thorough research [19—21].

The authors of most studies choose the degree of use of H_2 in blast furnace close to that of CO. The same assumption has been used in our study.

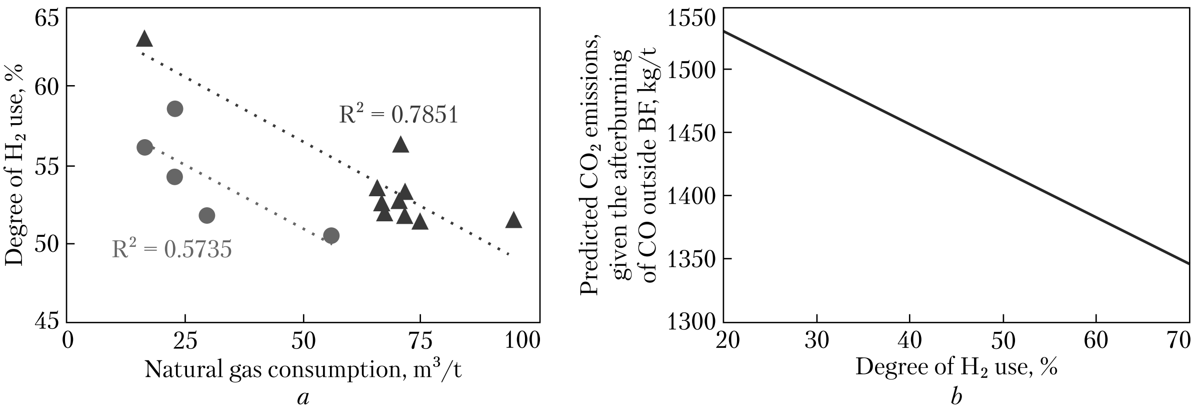


Fig. 8. The effect of natural gas consumption on the degree of hydrogen use in blast furnace gas (*a*) and the effect of the degree of hydrogen use on CO_2 emissions from blast furnace (*b*)

However, with this approach, one cannot be sure of obtaining reliable results, since the practice of blast furnaces with natural gas has shown that an increase in the consumption of natural gas leads to a decrease in the degree of use of H_2, namely, an increase in the consumption of natural gas by 25—30 m^3/t cast iron results in a decrease in the degree of use of H_2 by 5% (Fig. 8, *a*).

The obtained results allow us to conclude that the use of hydrogen-containing fuel additives leads to a decrease in the degree of hydrogen use in the blast furnace. Based on this, the influence of the degree of H_2 use on the estimated output of CO_2, given CO afterburning outside the blast furnace has been studied. It has been established that an increase in the degree of H_2 use by 1% leads to a decrease in CO_2 emissions by 0.13% (that is equivalent to a decrease in emissions by ~2 kg/t cast iron) (Fig. 8, *b*).

Thus, the use of hydrogen and hydrogen-containing fuel additives may have a less significant effect than the expected one because of a decrease in the degree of hydrogen reduction in the blast furnace as the fuel additive consumption increases. Therefore, the problem of studying the influence of hydrogen on the physical and chemical processes in the blast furnace is relevant and requires further research.

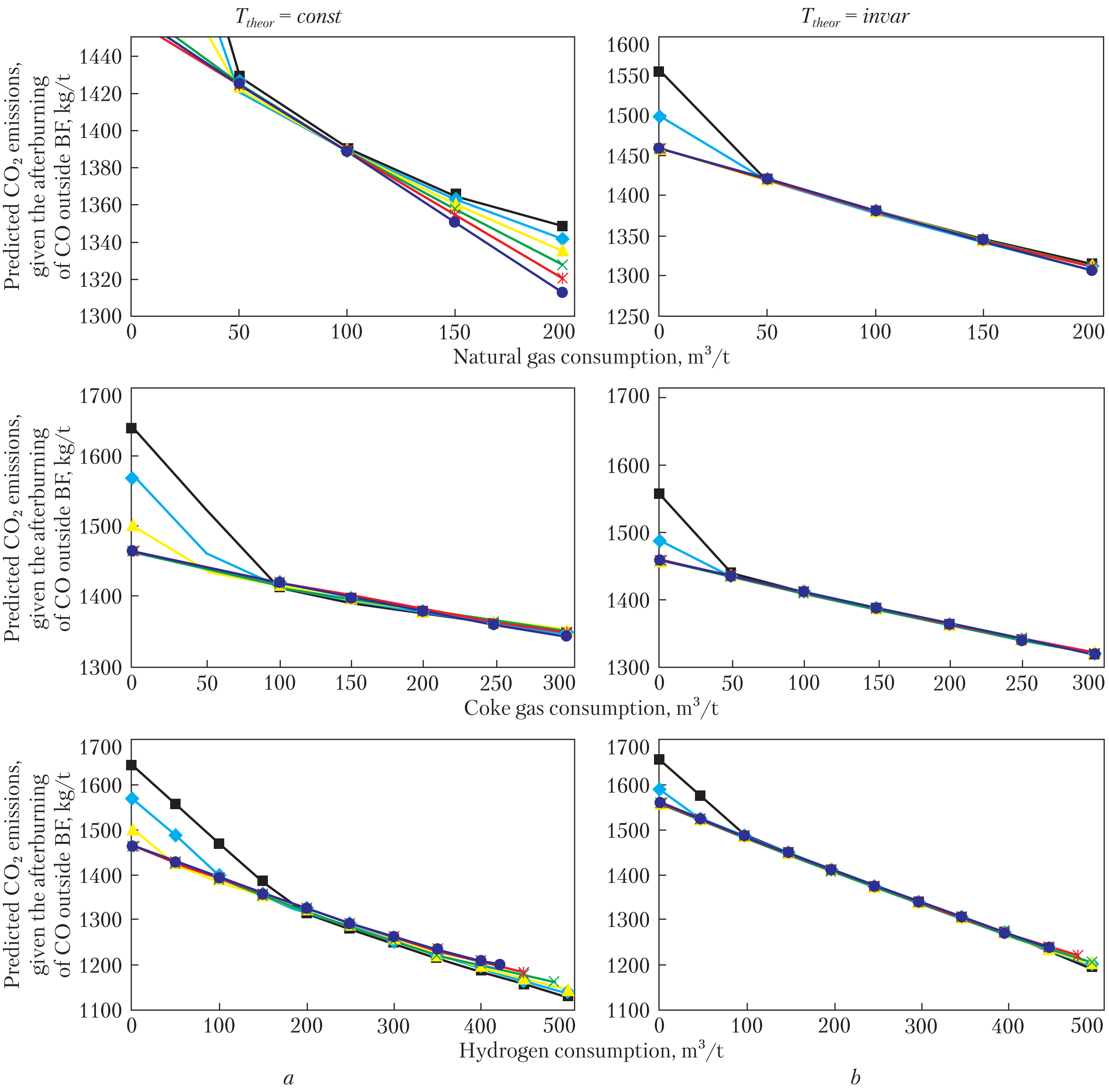
7. The effect of the use of hydrogen-containing additives in combination with pulverized coal fuel (PCF) on the decarbonization of blast furnace production.

Since recently in the blast furnace production of Ukraine, the PCF blowing technology has become widespread due to its cost-effectiveness, studying the technology of combined use of PCF and hydrogen-containing fuel additives is a relevant problem.

It has been established that the predicted CO_2 emissions, given CO afterburning outside the blast furnace, practically do not depend on the PCF consumption during the injection with hydrogen or hydrogen-containing fuel additives, with the dynamics of their change being the same as in the case of the use of hydrogen or a hydrogen-containing fuel additive (Fig. 9).

However, the use of PCF together with hydrogen-containing fuel additives leads to a decrease in the direct reduction of iron. Moreover, with high consumption of fuel additives that are blown into the hearth of the blast furnace, the direct reduction decreases to zero, which may indicate the achievement of conditions under which iron in the blast furnace is reduced exclusively in indirect way (Fig. 10).

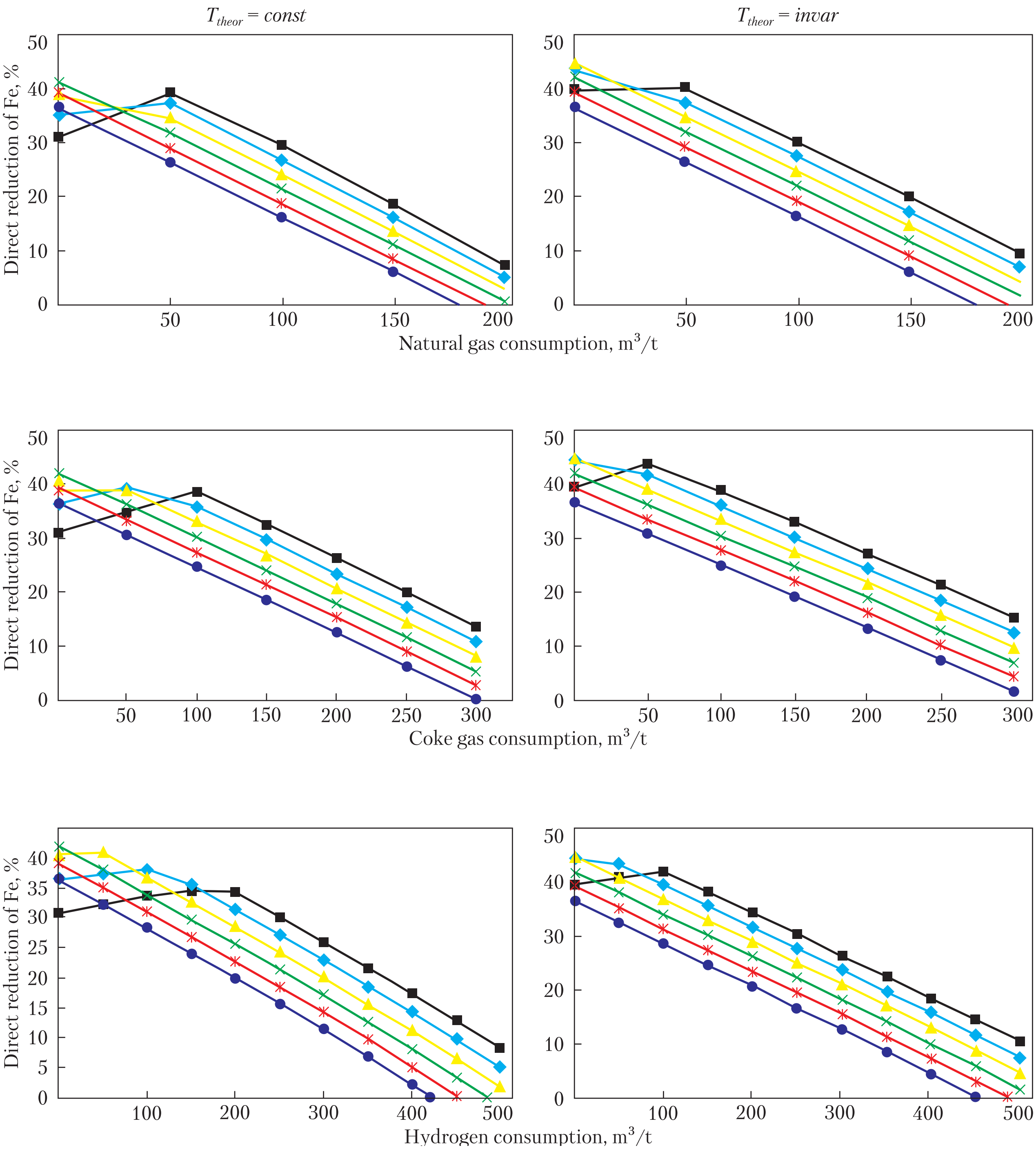
The given results also show the critical consumption of fuel additives, at which it is expected to achieve full indirect reduction of iron, and therefore, minimum consumption of fuel (Table 4).



Legend: ■ — PCF: 0 kg/t cast iron; ◆ —PCF: 50 kg/t cast iron; ▲ — PCF: 100 kg/t cast iron; × — PCF: 150 kg/t cast iron; ✳ — PCF: 200 kg/t cast iron; ● — PCF: 250 kg/t cast iron

Fig. 9. The influence of the consumption of hydrogen and hydrogen-containing fuel additives at different PCF consumption on the predicted CO_2 emissions, given CO afterburning outside the blast furnace, at constant (*a*) and variable theoretical temperature of combustion, within 1800—2200 °C (*b*)

8. Effectiveness of using hydrogen and hydrogen-containing fuel additives on CO_2 emissions and blast furnace productivity. The generalized results of the use of hydrogen and hydrogen-containing fuel additives on the predicted CO_2 emissions, the output of secondary energy resour-



Legend: —■— — PCF: 0 kg/t cast iron; —◆— —PCF: 50 kg/t cast iron; —▲— — PCF: 100 kg/t cast iron; —×— — PCF: 150 kg/t cast iron; —✳— — PCF: 200 kg/t cast iron; —●— — PCF: 250 kg/t cast iron

Fig. 10. The influence of the consumption of hydrogen and hydrogen-containing fuel additives on the direct reduction of Fe at constant (*a*) and variable theoretical temperature of combustion, within 1800—2200 °C (*b*)

Table 4. **Fuel Consumption at Which All Iron in the Furnace is Reduced Indirectly**

Parameter	Fuel additives combination					
	PCF + natural gas		PCF + coke gas		PCF + hydrogen	
Theoretical temperature	Constant	Variable	Constant	Variable	Constant	Variable
PCF consumption, kg/t cast iron	200—250	200—250	200—250	200—250	100—250	200—250
Hydrogen-containing additive consumption, m^3/t cast iron	191—179	193—180	300	300	500—421	485—450

Table 5. **Effectiveness of the Use of Hydrogen and Hydrogen-Containing Fuel Additives on Carbon Dioxide Emissions, the SER Output, and Coke Consumption at Their Maximum Content in the Blow Composition**

Parameter	Type of fuel additive and its maximum consumption					
	Natural gas, 200 m^3/t cast iron		Coke gas, 300 m^3/t cast iron		Hydrogen, 585/600 m^3/t cast iron	
Theoretical temperature	Constant	Variable	Constant	Variable	Constant	Variable
Decrease in CO_2 emissions	5.6% (0.22%)	7.7% (0.34%)	4.3% (0.49%)	8.6% (0.52%)	21.3 % (0.49%)	25.9% (0.51%)
Increase in SER output	107% (7.1%)	79% (5.2%)	83% (4.1%)	73% (4.9%)	101% (2.33%)	114% (2.28%)
Decrease in the specific consumption of coke	34.0% (1.7%)	36.0% (1.8%)	26%.0 (0.87%)	27.6% (0.92%)	28.0% (0.48%)	27.6% (0.46%)

* change in the parameter with an increase in the fuel additive consumption by 10 m^3/t cast iron is indicated in parentheses.

ces (SER), and the coke consumption are shown in Table 5.

CONCLUSIONS

1. With the use of thermal energy and the exergy models of blast furnace smelting, created at the Iron and Steel Institute of the NAS of Ukraine, the influence of using the hydrogen and hydrogen-containing fuel additives on CO_2 emissions and on the technical and economic indicators of blast furnace operation has been established and analyzed.

2. The effectiveness of using the hydrogen and hydrogen-containing fuel additives on CO_2 emissions has been established. The use of fuel additives allows reducing the emission of carbon dioxide by 0.22—0.34% (natural gas), by 0.49—0.52% (coke gas), and by 0.49—0.51% (hydrogen) per every 10 m^3/t in cast iron increase in the content of the appropriate fuel additive in the blast furnace.

3. Joint injection of hydrogen-containing fuel additives and PCF into blast furnace allows solving the two tasks at the same time: decreasing CO_2 emissions and ensuring the minimum cost of iron and steel. At the same time, an increase in the consumption of natural or coke gases leads to a decrease in CO_2 emissions, while an increase in the consumption of PCF results in a decrease in the cost of iron production.

4. The critical consumption of fuel additives, at which, according to Gruner's principle, it is expected to achieve full indirect reduction of iron, and therefore, minimum fuel consumption when the degree of direct reduction is close to zero, has been determined at the following conditions:

- a PCF consumption of 200—250 kg/t cast iron and a natural gas consumption of 193—179 m^3/t cast iron;
- a PCF consumption of 200—250 kg/t cast iron and a coke gas consumption of 300 m^3/t cast iron;
- a PCF consumption of 100—250 kg/t cast iron and a H_2 consumption of 500—420 m^3/t cast iron and 585—600 m^3/t cast iron.

5. The use of hydrogen and hydrogen-containing fuel additives makes it possible to increase the output of secondary energy resources that can be used in other plants of the metallurgical enterprise or at a thermal power plant for the electricity generation.

6. When using the hydrogen-containing fuel additives, the degree of hydrogen use in the blast furnace may decrease, which leads to a decrease in the expected effect on the emission of carbon dioxide, provided the fuel additive consumption increases. Therefore, studying the hydrogen influence on the physico-chemical processes in the blast furnace, as well as determining the rational ratios of blown reducing agents — hydrogen and carbon-containing fuel additives — are relevant tasks that require further research.

7. The coefficients of coke replacement by hydrogen and coke gas blown into the blast furnace have been established: 0.22—0.25 kg/m^3, for hydrogen, and 0.46—0.49 kg/m^3, for coke gas.

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ПЕРСПЕКТИВИ ВИКОРИСТАННЯ ВОДНЮ ТА ВОДНЕВМІСНИХ ДОБАВОК ДЛЯ ЗМЕНШЕННЯ ВИКИДІВ CO_2 І ПОКРАЩЕННЯ ПОКАЗНИКІВ ДОМЕННОЇ ПЛАВКИ

Вступ. Глобальне потепління наразі є однією з найважливіших проблем людства, домінуючою причиною якого є антропогенний фактор — суттєве збільшення кількості парникових газів. Зважаючи на вкрай негативні наслідки цього процесу в майбутньому 195 країн світу, серед яких і Україна, у 2015 р. ратифікували Паризьку угоду щодо клімату, яка зобов'язує зменшити викиди CO_2, зокрема, в металургії, де ці показники надвисокі — у світі — 6 %, в Україні на початок 2022 р. — 26 %.

Проблематика. За прогнозами Міжнародного Енергетичного Агентства до 2050 р. доменне виробництво буде домінуючою ланку у сталеварінні з тепловим коефіцієнтом корисної дії понад 90 %. Впровадження нових технологій одержання сталі може призвести до зменшення традиційного способу виробництва сталі на 50 % до 2050 року лише за умови значних інвестицій.

Мета. Дослідження впливу використання водневмісного палива в доменній печі на емісію діоксиду вуглецю та техніко-економічні показники доменної плавки.

Матеріали й методи. Для оцінки потенціалу використання водню та водневмісного палива в доменній печі на викиди CO_2 та техніко-економічні показники доменної плавки виконано розрахунки з використанням розробленої в Інституті чорної металургії НАН України математичної моделі повного енергетичного балансу доменної плавки.

Результати. Виконано аналіз та встановлено закономірності впливу водню та водневмісних паливних добавок на рівень викидів CO_2 та показники роботи доменної печі — виробництво чавуну, витрату коксу, вихід вторинних енергоресурсів. Визначено критичні витрати паливних добавок, за яких очікується досягнення повного відновлення заліза непрямим шляхом. Визначено коефіцієнт заміни коксу коксовим газом та воднем.

Висновки. Доведено ефективність використання водню та водневмісного палива окремо та спільно з пиловугільним паливом, що є перспективним шляхом, який дозволить раціонально підходити до вибору режиму роботи доменної печі з точки зору екологічності (зниження викидів CO_2) та економічної доцільності.

Ключові слова: екологія, доменна піч, емісія CO_2, водень, коксовий газ, природний газ, кокс.