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ASSESSMENT OF PROSPECTS FOR IMPROVING BLAST FURNACE TECHNOLOGY FOR CO_2 EMISSIONS

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ABSTRACT

The blast furnace route remains the dominant technology for primary ironmaking; therefore, improving its environmental performance is a key challenge for the steel industry. This study presents a comprehensive assessment of technological measures aimed at reducing carbon dioxide emissions from blast furnace operation using an original total energy and exergy balance model developed at the Iron and Steel Institute of the National Academy of Sciences of Ukraine. The influence of pulverized coal injection, hydrogen, natural gas, coke oven gas, metallic additives, hot blast temperature, heat losses and gas utilization efficiency on furnace performance and carbon footprint was investigated over a wide range of operating conditions. Attention was paid to the combined effects of hydrogen-containing fuels and pulverized coal, as well as to operational constraints associated with raceway adiabatic flame temperature, oxygen enrichment requirements, top-gas temperature and the degree of direct reduction. The calculations demonstrate that different decarbonization measures provide significantly different environmental and economic effects. Among the investigated options, hydrogen injection and metallic burden additives exhibit the highest potential for reducing specific CO_2 emissions, while improvements in gas utilization and thermal efficiency provide additional opportunities for lowering fuel consumption. The obtained results establish practical operating ranges for implementing low-carbon blast furnace technologies and may serve as a basis for evaluating decarbonization strategies in existing ironmaking plants.

Keywords: *blast furnace ironmaking, hydrogen injection, energy balance, CO_2 emissions, fuel efficiency.*

INTRODUCTION

Global decarbonization commitments place the iron and steel industry under unprecedented pressure to reduce CO_2 emissions. The blast furnace–basic oxygen furnace route, owing to its unmatched productivity and cost effectiveness, will remain the dominant primary ironmaking technology for many countries in the foreseeable future. Since the blast furnace is among the most CO_2-intensive stages of steelmaking, even incremental improvements in its operation and fuel management can yield substantial absolute emission savings [1 - 4].

A broad spectrum of low-carbon measures has been explored over the past decade. These include the injection of hydrogen and hydrogen-containing gases, co-injection with pulverized coal or natural gas, increased scrap charging, higher blast temperatures, reduced heat losses and improved top-gas utilization. Computational fluid dynamics studies have provided detailed insights into how tuyere-injected hydrogen alters raceway chemistry and heat distribution [5], while shaft-injection schemes have been modelled to assess their operational feasibility and constraints [6]. Co-injection analyses further mapped the trade-offs between direct reduction, flame temperature management and top-gas composition [7]. Parallel efforts employing whole-furnace process models demonstrated that properly designed hydrogen injection can indeed lower coke consumption and CO_2 emissions [8, 9].

The understanding of preheated hydrogen injection has been substantially refined by recent CFD studies employing validated three-dimensional process models [10]. Using a validated 3D CFD model of a 400 m^3 blast furnace, the authors systematically examined the effect of preheated hydrogen injection over a temperature range of 40°C - 1000°C and its interaction with pulverized coal injection. Their findings show that raising the hydrogen injection temperature reduces the total fuel rate and shifts the optimal hydrogen injection rate upward. The key advantage of preheating lies in mitigating the compensatory increase in coke combustion that otherwise limits cold hydrogen injection. Under pure hydrogen injection, fuel consumption can be reduced approximately threefold compared to the best mixed-fuel case, albeit at the cost of exceptionally high injection temperatures and with the recognition that coke cannot be eliminated because of the direct reduction requirement. These findings, together with comprehensive reviews summarizing the current state of pilot and industrial trials, underscore that while the potential of hydrogen-assisted blast furnace operation is firmly established, quantitative limits for hearth injection under combined measures remain incompletely characterized [11].

Gaseous fuels other than pure hydrogen have also received sustained attention. Life-cycle and techno-economic assessments indicate that natural gas, coke-oven gas or improved pulverized coal injection schemes can partially displace coke and lower direct CO_2 release, provided that upstream emissions and furnace-specific integration aspects are carefully managed [12, 13]. CFD and pilot-scale investigations confirm that co-injection of natural gas or coke-oven gas with pulverized coal can reduce the net coke rate, yet excessive gaseous shares depress raceway temperature and therefore necessitate oxygen enrichment or modified lance designs [14, 15]. Integrative assessments have attempted to quantify the trade-offs between coke replacement, hearth thermochemistry and downstream top-gas conditions, but these efforts typically remain confined to one or two technologies [16].

Taken together, the existing literature exhibits three interconnected gaps. First, studies are fragmented by methodology: CFD analyses focus on local raceway or shaft phenomena, while process-level models treat hydrogen substitution in a lumped manner. Second, parametric integration across multiple measures, simultaneous variation of hydrogen rate, hydrogen-containing additive composition, pulverized coal input, scrap charge, blast temperature and gas utilization, has not been performed over wide operating ranges. Third, although the existence of an optimal hydrogen injection rate and the beneficial role of preheating are now recognized, practical operating limits set by the degree of direct reduction, the permissible RAFT range, the availability of oxygen for enrichment and the allowable top-gas temperature have not been derived in a unified, energy-based framework [10].

The present study addresses these gaps by applying an original total energy and exergy blast furnace model developed at the Iron and Steel Institute of the National Academy of Sciences of Ukraine. Unlike earlier contributions, our work provides a comprehensive parametric assessment that:

- evaluates, among other things, the combined impact of hydrogen injection into the bottom, coke oven gas, natural gas, pulverized coal, scrap loading, blast temperature changes, heat losses, and improved gas utilization within a single thermodynamically consistent model;

- evaluates the quantitative variation of hydrogen and hydrogen-containing additive injection based on the degree of direct reduction, RAFT limitations, oxygen enrichment availability, and overhead gas temperature;

- expresses results both as CO_2 emission reduction potential and as technical and economic indicators (coke consumption, hot metal productivity) directly applicable to plant-level feasibility studies.

Calculations show that with realistically selected combinations of measures, blast furnace CO_2 emissions can be reduced by 25 - 30 % - a figure that complements and summarizes the detailed, but technology-specific results of recent CFD modelling [10] and experimental data [17]. By combining energy and exergy balances with extensive parametric studies, this work provides a decision support tool for steelmakers who need to reconcile continued blast furnace operation with increasingly stringent climate targets.

EXPERIMENTAL

To assess the impact of new and existing ironmaking technologies on the decrease of CO_2 emissions and the technical and economic indicators of BF smelting, calculations were made using the mathematical model of BF complete energy balance developed at the ISI NASU [18].

The method of compiling a complete energy balance is based on the three laws of thermodynamics and is suitable for the analysis of any processes. It is called a complete energy balance, because allows to consider all types of energy, including chemical energy of fuels and materials in the incoming part, as well as products and process waste in the consumable part. The model consists of three calculation modules, including material, thermal and exergy balance (Fig. 1). A complete energy balance allows us to assess the degree of energy efficiency and choose ways to cut the energy amount on unit of production [19 - 21].

The model of the complete energy balance of blast furnace smelting developed at ISI NASU provides comprehensive accounting of the inflow and outflow of material and heat flows in the blast furnace. The input data for calculating the energy balance are:

- consumption, chemical composition and temperature of the charging materials into the furnace, including metal additives, iron ore materials, fluxes, coke and alternative fuels;
- chemical composition, quantity and temperature of smelting products (hot metal, slag, blast furnace gas, as well as dust and sludge fractions);
- blast parameters (consumption, temperature, pressure, oxygen content), as well as the gas-dynamic characteristics of the process (pressure drop);
- the amount of heat loss through the furnace cooling system.

However, the model does not consider the influence of the distribution of charge materials across the blast furnace radius on the thermal regime and gas dynamics of blast furnace smelting. The degree of hydrogen utilisation in the furnace volume is set as a percentage of the degree of carbon monoxide utilisation, which is one of the key limitations of the mathematical scheme of the total energy balance.

Despite these limitations, the model has been successfully used to forecast blast furnace smelting indicators during the transition from natural gas to pulverised coal in blast furnaces at metallurgical enterprises in Ukraine (Zaporizhstal, Alchevsk Metallurgical Plant, Ilyich Iron and Steel Works, Azovstal) during the period 2009 - 2025. The model has proven to be an effective tool for developing recommendations for adjusting furnace operating modes in order to increase productivity and reduce coke consumption.

To verify the adequacy of the mathematical model, its results were analysed in comparison with data from the literature. Using the initial parameters of Japanese researchers, calculations were made of the change in carbon consumption when coke oven gas and hydrogen are supplied [17]. Table 1 contains a comparison of the results of modelling an experimental 12 m^3 blast furnace obtained using a three-dimensional unsteady model and the ISI NASU full energy balance model.

It is shown that the differences in carbon consumption are minimal: when hydrogen is supplied at a rate of 360 $m^3 t^{-1}$, the differences do not exceed 1.2 %, and at moderate consumption of hydrogen and coke oven gas, they are about 0.2 %. The differences are probably due to differences in the quality of the charge materials and the chemical composition of the coke oven gas used in different models.

RESULTS AND DISCUSSION

Analysis of the effect of pulverized coal fuel (PCI) and hydrogen-containing fuel additives such as natural gas (NG) and coke oven gas (COG) on CO_2 emissions and technical and economic indicators (KPI) of blast furnace (BF) operation was carried out in a wide range of flow rates: PCI = 0 - 250 kg t^{-1}; NG = 0 - 200 $m^3 t^{-1}$ (0 - 160 kg t^{-1}); COG - from 0 to 300 $m^3 t^{-1}$ (0 - 130 kg t^{-1}); hydrogen - from 0 to 500 $m^3 t^{-1}$ (0 - 45 kg t^{-1}). All calculations of fuel additives injection were performed for the RAFT range 1800 - 2200^{o}C. Maintaining RAFT in this range was carried out by increasing the steam in the hot blast (to reduce it) and oxygen (to increase it). The base period of BF operation for study of the

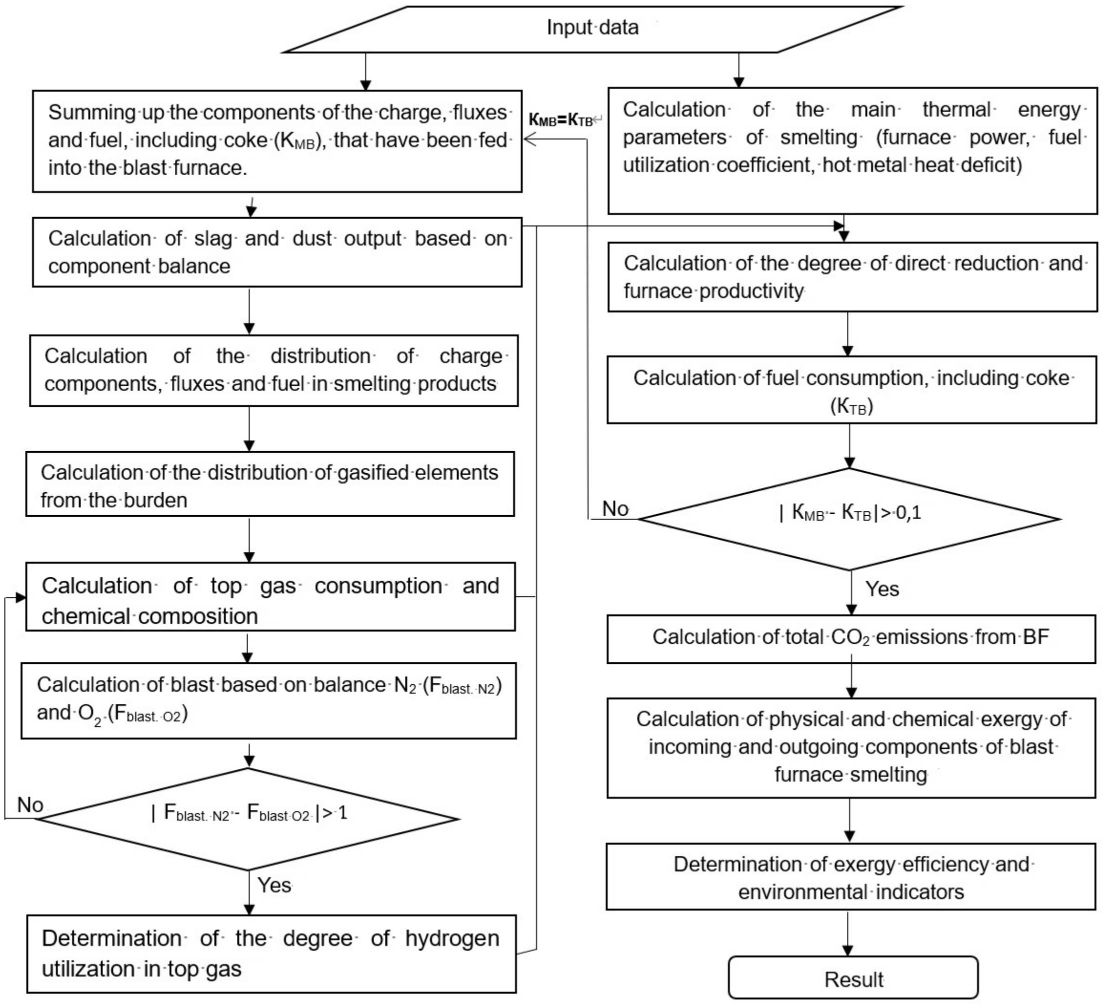

Fig. 1. Model technological diagram of the complete energy balance of blast furnace smelting (F_{blast}. N_2 and F_{blast}. O_2 - blast consumption, m^3 t^{-1} HM; K_{MB} and K_{TB} - coke consumption, kg t^{-1} HM according to material and heat balance).

Table 1 Results of modelling indicators using the ISI NASU blast furnace complete energy balance model compared with a three-dimensional non-stationary mathematical model validated by smelting indicators on an experimental 12 m^3 blast furnace [17].

Model	Base	ISI NASU	ISI NASU	ISI NASU
COG*, Nm^3 h^{-1}	0	119	0	0
H_2, Nm^3 h^{-1}	0	0	143	360
Blast volume, Nm^3 h^{-1}	1857	1188	1320	962
Blast temp., ^oC	1000	1000	1000	1000
O_2 enrichment, %	3.1	10.5	9	15
Productivity, t d^{-1}	34	34	34	34
Reduction rate of C consumption**, %	-	3.0 / 3.2	5.7 / 5.9	13.7 / 14.9

** Coke oven gas; **In the numerator, the value from the literature source [17]; in the denominator, calculated values based on the ISI NASU model.*

Table 2. Calculated CO_2 yield and KPI of blast furnace process when using different types of fuel.

Parameter	Base	PCI	NG	COG	H_2
Amount of additive, kg t^{-1}	0	250	160	130	45
Productivity, t d^{-1}	4694	4621	5213	4551	4787
Coke rate (with small coke), kg t^{-1}	352	293	340	379	397
PCI rate in the base period, kg t^{-1}	153	-	-	-	-
NG rate in the base period, kg t^{-1}	25.6	-	-	-	-
Hot Blast, m^3 min^{-1}	4011	4011	4011	4011	4011
Temperature of Hot Blast, °C	1112	1112	1112	1112	1112
Oxygen in the blast, %	25.7	25.7	30.0	23.6	21.8
Fe content in the burden, %	56.70	56.70	56.70	56.70	56.70
Slag Basicity, B2 = CaO/SiO_2	1.10	1.10	1.10	1.10	1.10
Slag Basicity, B3 = $(CaO + MgO)/SiO_2$	1.27	1.27	1.27	1.27	1.27
Calculated CO_2 yield including after burning of CO outside the BF, kg t^{-1}	1439	1463	1313	1318	1095

influence of various factors on the carbon dioxide yield and KPI, as well as the values of these parameters at the maximum consumption of fuel additives are given in Table 2.

Hydrogen injection able to decrease CO_2 emissions (including afterburning CO outside BF) by up to 30 % or by 6.7 % for every 10 kg t^{-1} of hydrogen.

Growth of hydrogen injection for every 10 kg t^{-1} has a significant impact on cut the RAFT (by 86°C per 1.0 t h^{-1}), however, since H_2 density is knowingly less than other fuels, then in terms of a ton of hot metal will have a smaller effect on reducing the RAFT in comparison with NG (34°C per 1,0 t h^{-1}) or COG (32°C per 1.0 t h^{-1}). PCI has the least effect on the decrease of RAFT (9°C per 1.0 t h^{-1}). Injection of NG and COG can drop CO_2 emissions up to 15 % (by 0.94 % for every 10 m^3 t^{-1} of NG and by 1.15 % for every 10 kg t^{-1} COG). Injection of PCI can drop CO_2 emissions up to 11 % (0.44 % for every 10 kg t^{-1} PCI), but such drop is achieved only at a PCI rate of less than 150 kg t^{-1}, where steam is used to maintain the RAFT. With PCI consumption above 150 kg t^{-1}, there is no decrease in CO_2 emissions (Fig. 2).

On the coke rate saving is significantly influenced by an increase in PCI up to 45 % (by 1.8 % for every 10 kg t^{-1} of PCI). The use of NG can decrease coke rate up to 35 % (by 2.2 % for every 10 kg t^{-1} of NG), use of COG can decrease coke rate up to 28 % (by 2.15 % for every 10 kg t^{-1} of COG), and hydrogen injection can decrease coke rate up to 25 % (by 5.6 % for every 10 kg t^{-1} of H_2).

The influence of discussed fuel additives on the hot metal production rise has been recognized: up to 18 % when using hydrogen up to 45 kg t^{-1} (4 % for every 10 kg t^{-1} of H_2); up to 29 % when using NG with a flow rate of more than 80 kg t^{-1} (3.63 % for every 10 kg t^{-1} of NG); up to 11 % when using COG with a flow rate of more than 65 kg t^{-1} (1.7 % for every 10 kg t^{-1} of COG); up to 13 % when using PCI rate more than 150 kg t^{-1} (1.3 % for every 10 kg t^{-1} of PCI).

The results on the reduction of coke consumption obtained with the use of pulverized coal injection, natural and coke gas are consistent with the data on the operation of blast furnaces with these fuel additives. However, most studies on hydrogen injection are analytical, and the results obtained by numerous methods are contradictory: according to some studies, the coefficient of coke replacement by hydrogen is 0.06 kg m^{-3} [22], according to others - 0.15 kg m^{-3} [23], or 0.27 - 0.36 kg m^{-3} [24]. Based on the results of the study, the coefficient of coke replacement by hydrogen when using hydrogen in blast furnace smelting was established in the range of 0.22 - 0.25 kg m^{-3}, which is consistent with the results obtained in an experimental blast furnace with a volume of 12 m^3 [17]. The reduction in coke consumption with an increase in PCI feed is primarily due to the replacement of coke carbon with coal dust carbon, as well as additional heat release due to the combustion of volatile PCI components in the blast furnace hearth. The use of hydrogen-containing fuel additives (natural and

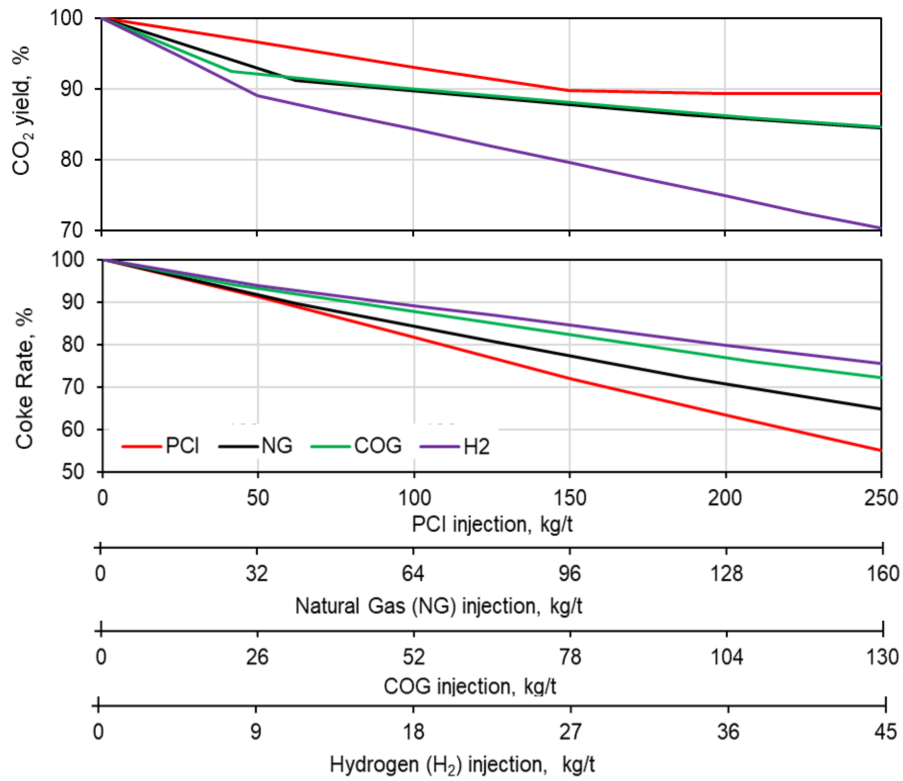

Fig. 2. Dependence of calculated carbon dioxide yield and coke rate on fuel additives injection.

coke oven gas), as well as pure hydrogen, significantly affects the thermal and reduction modes of blast furnace smelting. This is due to the intensive combustion of fuel in the tuyere zone and an increase in the proportion of indirect iron reduction due to reactions with CO and H_2. The use of hydrogen and gaseous fuels leads to a reduction in specific CO_2 emissions from the blast furnace, as it reduces the total carbon input into the system. Thus, hydrogen-containing fuel additives are an effective tool for decarbonising the blast furnace process and increasing its energy efficiency.

When PCI is using in the BF, high requirements are imposed on safety and reliability of the operation of the PCI preparation and injection plant. An important task is to assess how changes in the chemical content of coal injecting into BF influences on CO_2 emissions and technical and economic indicators. The results of these calculations are given in Table 3.

According to calculations, the drop in CO_2 emissions is facilitated by a carbon rise in the coal (by 0.11 % for every 1 % of C), hydrogen (by 0.57 % for every 1 % of H_2) and decrease in oxygen (by 0.44 % for every 1 % O_2) in PCI. Other PCI components practically do not affect the yield of CO_2.

Coke rate can be reduced by increasing carbon in PCI (by 0.43 % for every 1 % of C) and hydrogen (by 0.33 % for every 1 % of H_2), Influences of other elements does not affect coke rate.

Increasing of carbon in PCI (by 0.36 % for every 1 % of C), as well as hydrogen drop (by 0.24 % for every 1 % H_2) and oxygen drop (by 0.73 % for every 1 % of O_2) contributes to rise in productivity rate.

One of the ways to cut CO_2 emissions is to charge metal additives over a blast furnace throat. However, using of metallic additives into BF burden is limited by their availability and price, growth of the caloric value of top gas, etc.

It was found that metallic additives (scrap or DRI/HBI) use with rate up to 500 kg t^{-1} can reduce CO_2 emissions up to 47 % (0.93 % for every 10 kg t^{-1} of Fe) and decrease coke rate up to 18 % (by 0.35 % for every 10 kg t^{-1} of Fe). Production rate can be increased on 75 %

Table 3. Effect of PCI chemical composition on blast furnace performance and CO_2 emissions.

Parameters	Changes when the element content in PCI is rise by 1%					
	C	H_2	O_2	N_2	Ash	S
Productivity	+ 0.36	- 0.24	- 0.73	0.0	- 0.06	+ 0.01
Coke rate	- 0.43	- 0.33	+ 0.76	+ 0.40	+ 0.45	+ 0.41
Heat and power characteristics:						
Total heat output	+0.05	0.0	-0.26	0.0	0.0	0.0
Absorbed heat output	+ 0.90	- 1.63	- 0.91	+ 0.09	0.00	+ 0.11
Fuel utilisation ratio	+ 0.76	- 1.52	- 0.59	+ 0.09	0.00	+ 0.10
Heat deficit of hot metal	+ 0.50	- 1.40	- 0.18	+ 0.10	+ 0.07	+ 0.10
Degree of Fe direct reduction (r_d)	+ 2.32	- 3.36	- 1.02	+ 0.12	- 0.06	- 0.05
Calculated CO_2 output with afterburning CO outside BF	- 0.11	- 0.57	+ 0.43	+ 0.03	+ 0.09	+ 0.08

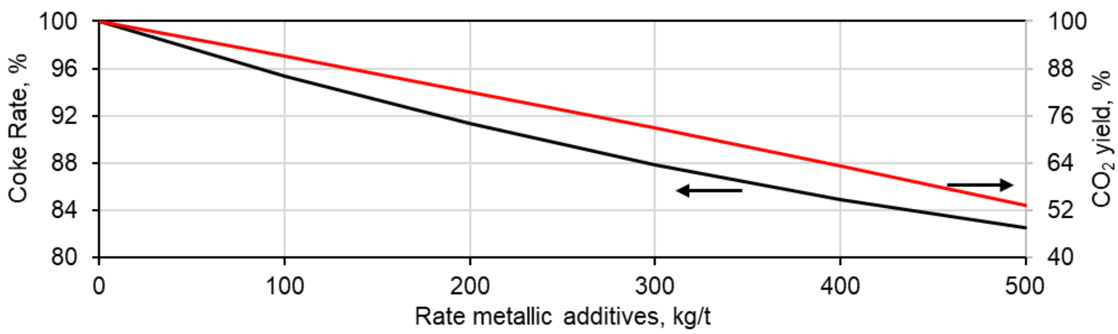

Fig. 3. Dependence of calculated carbon dioxide yield and coke rate on the metallic additives.

(by 1.5 % for every 10 kg t^{-1} of Fe). It is shown on Fig. 3.

The influence of hot blast temperature and heat losses in the cooling system on the carbon dioxide emissions changes and technical and economic indicators of blast furnace is considered. Results are presented on Fig. 4. It should be noted that heat losses depend on the conditions and property of the BF lining and design of cooling system.

Calculations have confirmed that an increase of hot blast temperature by every 100°C reduces CO_2 yield by 2.3 % and coke rate by 2.8 % and allows to increase production rate by 3.8 %. Thus, with an increase in hot blast temperature from 1100°C to 1450°C, it is possible to reduce CO_2 emissions by 8.1 %.

Reducing heat losses in the cooling system by every 1 MW leads to a drop in CO_2 emissions by 0.18 %, cur coke rate on 0.21 % and rise BF production rate on 0.3 %. Coke amount for compensation of heat losses can vary from 10 to 40 kg t^{-1}, depending on the design and technical condition of BF and operation. Decrease of heat losses can be achieved by design of cooling system and lining improvements and by technological measures. Technological measures include, first, optimization of the charging regime aimed at reducing the peripheral gas flow, as well as actions for working scull formation, and optimization of the tuyere's parameters.

The influence of changes in degrees of CO and H_2 utilization, which are depends on charging regime and gas-dynamic mode of operation of BF was studied.

It is found that degree of CO utilization has a stronger impact vs. degree of H_2 utilization on the change in the calculated CO_2 yield and technical and economic indicators of BF (Fig. 5).

Increasing degrees of CO and H_2 utilization for every 1 % over a wide range cuts CO_2 emissions by 2.9 % and 0.25 %, correspondingly, and increases BF output by 1.5 % and 0.2 %, also coke rate reduces by 3.5 % and 0.3 %, respectively.

Joint injection of hydrogen-containing fuel additives together with PCI was studied. It was found that total CO_2 yield (including afterburning of CO outside BF) is almost independent of the PCI rate, so tendency of CO_2 yield change is the same as when using only a hydrogen-containing additive. Injection of hydrogen-containing fuel additives with PCI into BF allows to solve two problems simultaneously: dropping CO_2 emissions (due to use hydrogen-containing fuel) and ensuring the minimum cost of hot metal (due to coke substitute by PCI). Reasonable limits of fuel additives injection rate have been determined, at which, according to Gruner's principle, it is expected to achieve complete indirect reduction of iron, and hence the minimum fuel rate when the degree of direct reduction (r_d) close to 0 % is reached Table 4 [25].

Limits for effective using of PCI technologies, injection of hydrogen-containing additives (NG and COG) and hydrogen for carbon dioxide emissions cut and coke rate drop have been calculated (Table 5 and 6). Calculations have been shown that hydrogen and hydrogen-containing additives providing greater drop

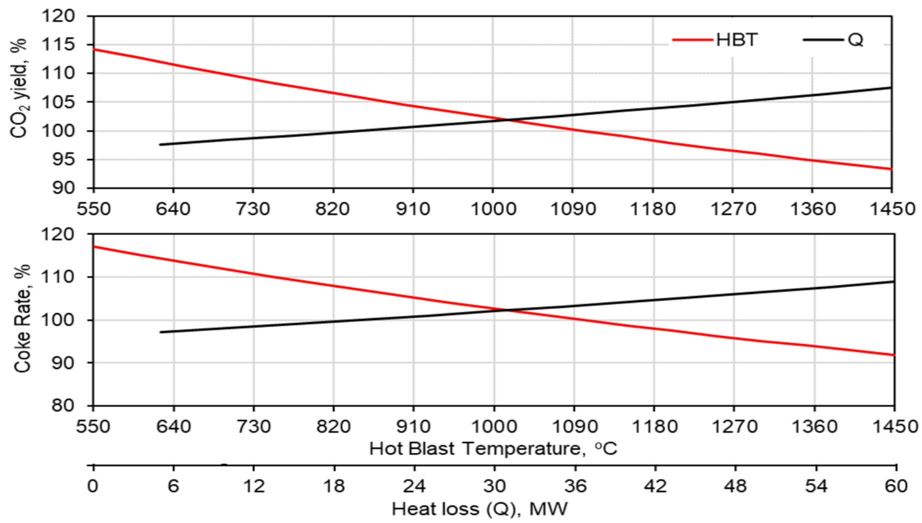

Fig. 4. Dependence of the calculated carbon dioxide yield and coke rate on the hot blast temperature (HBT) and heat loss in the cooling system (Q).

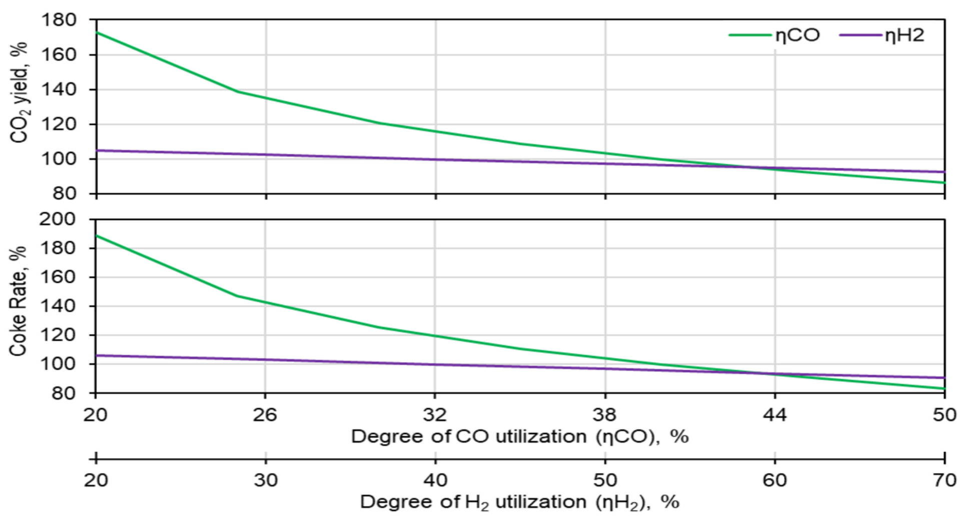

Fig. 5. Dependence of calculated CO_2 yield and coke rate on the degree of CO (η_{CO}) and (η_{H2}) H_2 utilization.

Table 4. Fuel rate, at which all iron in the furnace is reduced by indirect way.

Parameters	PCI + NG	PCI + COG	PCI + H_2
PCI rate, kg t^{-1}	200 - 250	200 - 250	200 - 250
Rate of Hydrogen-containing additive, kg t^{-1}	150 - 140	130	44 - 40

Table 5. Efficiency of application of various fuel additives with their maximum rate on CO_2 emissions and coke rate (in parentheses shown parameter change when fuel additive rate increases by 10 kg t^{-1}).

Parameters	PCI	NG	COG	H_2
	250 kg t^{-1}	160 kg t^{-1}	130 kg t^{-1}	45 kg t^{-1}
CO_2 emission, %	- 11 (- 0.44)*	- 15 (- 0.94)	- 15 (- 1.15)	- 30 (- 6.7)
Coke rate, %	- 45 (- 1.8)	- 35 (- 2.2)	- 28 (- 2.15)	- 25 (- 5.6)
Including fuel pre-heating:				
Temperature	400°C	800°C	800°C	1000°C
CO_2 emission, %	- 12 (- 0.48)*	- 21 (- 1.3)	- 20 (- 1.54)	- 40 (- 8.9)
Coke rate, %	- 44 (- 1.76)	- 40 (- 2.5)	- 32 (- 2.46)	- 31 (- 6.9)

**For PCI: drop of CO_2 emissions is reached by cutting steam rate to keep RAFT within the certain limits.*

Table 6. Impact of metal additives use and technical measures as: hot blast temperature (HBT) rise, heat loss (Q) cut, and degrees of CO and H_2 (η_{CO} and η_{H2}) utilization on CO_2 emissions and coke rate.

Parameters	Metal additive, kg t^{-1}	HBT, °C	Q, MW	η_{CO}, %	η_{H2}, %
Change range	0 - 500	1100 - 1450	20 - 5	40 - 50	40 - 70
CO_2 emission, %	- 47 (- 0.93)	- 8.1 (- 2.3)	- 2.7 (- 0.18)	- 13.4 (- 1.34)	- 7.5 (- 0.25)
Coke rate, %	- 18 (- 0.35)	- 6.7 (- 2.8)	- 3.2 (- 0.21)	- 16.4 (- 1.64)	- 9.3 (- 0.31)

of CO_2 emissions vs. PCI. At the same time, PCI can provide the greatest reduction in coke rate [25].

To save coke and reduce CO_2 emissions, there are proposals to heat PCI - up to 400°C C (before the start of pyrolysis). Heating of gaseous fuel additives (natural gas, coke oven gas, and hydrogen) can further reduce CO_2 emissions and decrease coke rate, since PG and KG can be confidently heated to 800°C and H_2 - up to 1000°C. Calculations are presented in Table. 5.

There were calculated limit values for effectiveness of metal additives use and technical actions (to increase hot blast temperature, reduce heat losses in the cooling system and increase degree of CO and H_2 utilization) on CO_2 emissions and coke rate (Table 6).

Table 6 indicates (in parentheses) the effect increasing of metal additive consumption on 10 kg t^{-1}, rise hot blast temperature on100°C, increase in CO and H_2 utilization on a 1 %, and a 1 MW reduction in heat loss on 1.0 MW.

The use of a metal additives will contribute to the most significant reduction in CO_2 emissions, but such technology is limited by its availability and price.

Improving the gas-dynamic conditions aimed at increasing the degree of CO and H_2 utilization by every 1 % reduces CO_2 emissions by 1.34 % and 0.25 % and cut coke rate by 1.64 % and 0.31 %, respectively.

Increasing the hot blast temperature by every 100°C can reduce CO_2 emissions (by 2.3 %) and reduce coke rate (by 2.8 %).

Reducing heat losses has an impact on drop of CO_2 emissions up to 2.7 % and decreasing coke rate up to 3.2 %, while decreasing heat losses by 15 MW.

As shown by the results of recent studies and the high level of interest among the global scientific community, hydrogen is considered one of the most promising areas for decarbonisation of blast furnace production and the metallurgical industry. However, the large-scale introduction of hydrogen is accompanied by several significant challenges, mainly related to its high cost and transportation difficulties. In our opinion, these limitations can be overcome by installing small-scale high-temperature nuclear reactors at metallurgical enterprises, capable of producing hydrogen and meeting the energy needs of steel companies.

The issue of the effectiveness of indirect iron reduction at increased hydrogen consumption also requires further study. A comprehensive approach is needed to address this issue, including not only analytical calculations but also experimental studies of the reducibility of iron ore materials with hydrogen.

CONCLUSIONS

- Calculations carried out using original mathematical model developed in the ISI NASU for blast furnace total energy balance.
- Limit values for several fuel injection effectiveness for CO_2 emissions cut is calculated: when using PCI, CO_2 emissions are reduced by 11 %, with natural gas or coke oven gas - by 15 %, with hydrogen by 30 %. At the same time, there is a potential to reduce CO_2 emissions deeper due to fuel pre-heating.
- Heating of gaseous additives (H_2, NG and COG) can give a greater effect - up to 10 %, 6 % and 5 % reduction of CO_2 emissions, respectively, and 4 - 6 % decrease in coke consumption due to possibility of pre-heating NG and COG up to 800^{o}C and H_2 - up to 1000^{o}C, compared to PCI (only up to 400^{o}C).
- Values of reducing CO_2 emissions when using a metal additive up to 500 kg t^{-1} and technological measures to increase the blast temperature to 1450^{o}C and reduce heat losses are calculated.
- The regularities of changes in the chemical composition of PCI on CO_2 emissions and blast furnace smelting indicators are presented, which will allow a rational approach to the choice of coal for PCI.
- Critical consumption of fuel additives has been determined at which, according to Gruner's principle, it is expected to achieve complete reduction of iron indirectly, and hence when reaching r_d index close to 0 %, - the minimum fuel rate will achieve. It happens with PCI rate = 200 - 250 kg t^{-1}, with NG = 140 - 150 kg t^{-1}, with COG rate = 130 kg t^{-1}, and with H_2 rate= 40 - 44 kg t^{-1}. This will reduce CO_2 emissions by 18 - 28 %.

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Authors' contributions

B.K.: Investigation, Methodology, Writing - review & editing. O.C.: Project administration, Conceptualization, Methodology, Investigation, Writing - original draft. O.M.: Writing - review & editing, Data curation, Formal analysis. A.M.: Methodology, Visualization. M.A.: Validation, Visualization. I.M.: Investigation, Methodology. A.C.: Data curation, Formal analysis.

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