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Reducing emissions from hot blast stoves by configuring an automated control system

Abstract: This research focuses on reducing harmful emissions during hot blast stove (HBS) operation by enhancing the automated control system for checkerwork heating. The primary sources of emissions, including nitrogen oxides (NO_x), sulfur oxides (SO_x), and carbon oxides (CO, CO_2), generated during the combustion of blast furnace gas, are analyzed. The authors propose improving the automated control system by implementing feedback on fuel combustion quality, continuous monitoring of exhaust gas composition, and real-time assessment of the fuel's calorific value. The

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system's structure includes regulating combustion airflow, continuous monitoring of blast furnace gas calorific value, evaluating combustion efficiency through O_2, CO, and CO_2 content analysis in exhaust gases, and adjusting the combustion process according to the mode map, maintaining the dome temperature within 1,350–1,420°C to minimize NO_x formation. These measures contribute to reducing NO_x emissions, enhancing energy efficiency, and stabilizing the temperature regime. The proposed solutions offer a cost-effective approach to emission reduction and can be seamlessly integrated into existing metallurgical enterprise systems.

Keywords: hot blast stove (HBS), emission reduction, automated control system, combustion efficiency, blast furnace gas

Introduction

Hot blast stoves play a crucial role in the iron and steel industry by supplying preheated air to blast furnaces. However, their operation generates significant emissions, including CO, CO_2, NO_x, SO_x, and particulate matter, contributing to environmental pollution and regulatory challenges (Zhu et al. 2024). In response to increasing global and regional policies on emissions reduction, the implementation of advanced environmental management strategies has become essential (Woźniak et al. 2024). One of the most promising approaches is the integration of automated control systems, leveraging AI-driven optimization to enhance combustion efficiency, minimizing fuel consumption, and reducing greenhouse gas emissions (Woźniak et al. 2024; Psyuk and Polyanska 2024). By applying real-time monitoring, predictive analytics, and adaptive control mechanisms, these systems can dynamically adjust operational parameters, ensuring sustainable performance while maintaining production efficiency.

The use of artificial intelligence in environmental management is transforming industrial processes by enabling data-driven decision-making and predictive maintenance. In the context of hot blast stoves, AI-powered control systems can analyze both historical and real-time data to detect inefficiencies, predict emission trends, and suggest corrective actions (Psyuk and Polyanska 2024; Lewicka et al. 2023). This proactive approach not only helps industries comply with stringent environmental regulations but also reduces operational costs by optimizing energy consumption (Zhu et al. 2024; Seheda et al. 2024). AI enhances the integration of renewable energy sources and alternative fuels, further lowering the carbon footprint of metallurgical operations (Psyuk and Polyanska 2024; Dychkovskyi et al. 2024). By configuring an advanced automated control system, this research aims to demonstrate the feasibility and benefits of AI-driven emission reduction strategies, supporting the global transition toward cleaner and more sustainable industrial practices.

Hot blast stoves (HBSs) play a crucial role in blast furnace production by providing hot blast (oxygen-enriched air) that is essential for efficient furnace operation (Zhu et al. 2024; Polyanska et al. 2024). The composition and calorific value of the fuel used to heat HBSs are critical factors influencing both their thermal efficiency and emission levels. Variability in fuel quality can lead to fluctuations in combustion performance, affecting temperature stability and increasing the release of greenhouse gases and other pollutants (Zhu et al. 2024; Polyanska et al. 2024; Fedoreiko et al. 2014). Inefficient fuel utilization contributes to higher operational costs and greater environmental impact, making emission control a priority for sustainable industrial practices (Zhu et al. 2024; Taran et al. 2023). Advances in automated control systems, particularly those leveraging artificial intelligence and machine learning, offer promising solutions to optimize combustion efficiency and minimize emissions (Golovchenko et al. 2018). By continuously monitoring fuel properties, air-to-fuel ratios, and combustion dynamics, these systems can dynamically adjust parameters to maintain optimal performance while reducing harmful byproducts.

1. Literature review on reducing emissions from hot blast stoves through automated control systems

Blast furnace gas (BFG) is the most used fuel for heating the checkerwork of hot blast stoves (HBSs) due to its availability as a byproduct of ironmaking (Zhu et al. 2024; Richert et al. 2024). However, to enhance its calorific value and stabilize combustion, a mixture of gases can be used, typically including up to 5–10% of natural gas and/or coke oven gas in the total fuel volume (Golovchenko et al. 2018; Golovchenko et al. 2020). The composition of combustion products in such cases includes harmful substances such as nitrogen oxides (NO_x), sulfur oxides (SO_x), and carbon oxides (CO and CO_2), which contribute to air pollution and climate change (Table 1). The presence of sulfur compounds leads to acid rain formation and equipment corrosion, while nitrogen oxides play a significant role in smog formation and respiratory diseases (Zhu et al. 2024; Golovchenko et al. 2018; Sobolev et al. 2020). Incomplete combustion of these gases can result in increased emissions of particulate matter and unburned hydrocarbons, further worsening the environmental impact.

During combustion, carbon-based substances in blast furnace gas, coke oven gas, or natural gas undergo oxidation, producing carbon monoxide (CO) and carbon dioxide (CO_2) while releasing significant thermal energy (Zhu et al. 2024; Golovchenko et al. 2018; Kosenko et al. 2024). The high temperatures within the checkerwork facilitate not only heat transfer but also secondary reactions, such as CO oxidation and the breakdown of sulfur and nitrogen compounds into harmful emissions like SO_x and NO_x (Golovchenko et al. 2018; Dychkovskyi 2015). Incomplete combustion or fluctuating fuel compositions can lead to the formation of unburned hydrocarbons and particulate matter, further increasing environmental concerns (Golovchenko et al. 2018; Fedoreiko et al. 2020). To optimize fuel efficiency and minimize emissions, modern HBSs are integrating AI-driven control systems that dynamically adjust combustion parameters,

TABLE 1. Average values of concentrations of harmful substances in the HBS's exhaust gases at a dome temperature of 1,400°C

TABELA 1. Średnie wartości stężeń substancji szkodliwych w gazach wylotowych pieca nagrzewającego powietrze (HBS) przy temperaturze kopuły wynoszącej 1400°C

HBS No	Flue gas consumption from one HBS [m^3/h]	Concentration [mg/m^3]		
		CO (standard according to 2,890)*	SO_x (standard according to 200)*	NO_x (standard according to 120)*
1	52,800	1,800–3,200	27	65–135
2	63,800	1,980–3,880	31.6	71–148
3	79,500	2,200–3,450	29.6	75–141
4	83,200	2,000–3,500	31	71–141

* Technological standards... 2023.

enhancing heat distribution and ensuring complete oxidation of carbon compounds (Zhu et al. 2024; Sobolev et al. 2020). The development of cleaner fuel alternatives, such as hydrogen-enriched gases and carbon capture technologies, presents a promising direction for reducing the environmental footprint of HBS operations while maintaining energy efficiency in metallurgical processes (Zhu et al. 2024; Golovchenko et al. 2018; Fedoreiko et al. 2013).

Depending on the presence of sulfur and hydrogen sulfide in blast furnace gas, the concentration of sulfur oxides SO_x in flue gases is formed. A low concentration of CO determines the quality of fuel combustion (Polyanska et al. 2022). The NO_x concentration depends on factors such as the temperature under the dome, air flow rate, blast furnace gas humidity, and the presence of nitrogen-containing components (Wang and Dai 2014). Even though the NO_x concentration in the exhaust gases is relatively low, their gross emissions are significant – 100–300 tons per year. This is due to the total flue gas consumption of 180–250 thousand m^3/h per HBS block. A comparative analysis of standard values for permissible emissions (Technological standards... 2023) and average values for specific production (Table 1) shows the need to reduce them, although actual SO_x emissions are significantly lower than regulatory limits. The above information is generalized, so when calculating harmful emissions, it is necessary to take into account the specifics of a particular blast furnace production.

Studies show that failure to consider the fuel composition can lead to inefficient combustion, a decrease in the thermal efficiency of the system, and, as a result, an increase in pollutant emissions, including SO_x and NO_x. One approach to reducing emissions is the introduction of modern flue gas cleaning technologies, such as wet desulphurization methods, which are already used at metallurgical and other plants to reduce emissions (Zhu et al. 2024; Fedoreiko 2024). To reduce sulfur dioxide emissions and other harmful substances, it is recommended to install modern gas cleaning systems using vacuum carbonate, arsenic-alkali, and monoethanolamine cleaning methods (Levytska et al. 2021).

Currently, research is focused on improving the HBS's thermal efficiency by optimizing combustion cycles and using modern stimulation methods for more precise process control (Zhang et al. 2024; Wei et al. 2021). High combustion temperature and low NO_x emissions from the HBS can be achieved by proper configuration of the burner and regenerator checkerwork and the implementation of technologies such as flue gas flow field optimization.

The study (Graaff et al. 2022) examines the impact on nitrogen oxides (NO_x) emissions from an HBS system, as well as the ways in which they are formed and the possibilities for reducing their concentration. The study includes simulations using different compositions of flue gases to model the combustion process. A comparison of old and new burner designs, analyzing temperature profiles, NO and CO concentrations for each design were conducted.

Research of Voestalpine's blast furnace in Linz confirmed the well-known trend of increasing NO_x emissions with increasing dome temperature (Cavaliere 2019). Optimized scheduling of the HBS's operating periods, combined with control of the dome temperature and gas supply, ensures that the NO_x and CO emission load remains below the permissible limits. To reduce emissions of harmful substances, it is proposed to focus future improvements on modeling heat transfer in the HBS's checkerwork depending on its geometric parameters.

There are also problems with leaks of unburned gas due to the HBS design features in the form of a short circuit – the formation of a gap in the partition between the combustion chamber and the checkerwork (Cavaliere 2019). This can lead to a 50-fold increase in carbon monoxide (CO) emissions in flue gases, which has a negative impact on the environment (Nikolsky et al. 2022; Koyfman et al. 2025).

To reduce harmful emissions during the combustion of blast furnace gas, it is proposed to use gas preheating due to the heat of the exhaust gases, which allows the required combustion temperatures to be achieved without adding natural gas, reducing NO_x emission (Cuervo-Piñera et al. 2017; Freund et al. 2021; Zhang et al. 2020). The use of new types of burners that ensure uniform heat distribution minimizes the formation of NO_x. Emphasis is placed on the use of modern heat transfer models (SLWSGG) for more accurate combustion modeling and efficiency improvement, while CFD modeling allows optimizing burner designs and ensuring flame stability.

The study (Rieger et al. 2015) notes that the main causes of harmful emissions in HBSs include high dome temperatures, flow turbulence, transient periods when HBSs switch from one mode to another, unstable fuel composition, and excess air. The formation of nitrogen oxides (NO) increases significantly at dome temperatures above 1,300°C. Controlling factors such as maintaining the optimum dome temperature, regulating excess air, and optimizing transients can help reduce the production of harmful emissions in blast furnaces.

Studies (Sobolev et al. 2025; Zhang et al. 2014) address the problem of NO_x formation during combustion in HBSs with dome heating and propose a new type of dome burner based on high-temperature air combustion technology. It has been found that at temperatures above 1,400–1,420°C, the NO_x formation rate increases dramatically. The results show that at the same dome temperature, the amount of NO_x is 76% less compared to a traditional Kauper-type HBS. This study demonstrates that by providing a high combustion temperature, energy consumption and CO_2 emissions are reduced.

Improvement of the HBS's environmental performance is achieved through flue gas recirculation (Koyfman et al. 2025; Lewicka 2010; Gardner 2020; Hres et al. 2022). Mixing air with flue gases improves the combustion process, which leads to more complete fuel combustion and reduced formation of harmful substances. By optimizing the combustion process and recycling gases, the amount of nitrogen oxides (NO_x) and other harmful components is reduced.

Two-stage fuel combustion is an effective method of reducing harmful emissions, in particular NO_x (Hres et al. 2022). At the first stage, the fuel is burned with an excess air ratio α less than the stoichiometric one ($\alpha < 1$). This means that the amount of air is insufficient for complete combustion of the fuel, which leads to the formation of incomplete combustion products such as carbon monoxide (CO) and hydrogen (H_2). The temperature at this stage is lower, which reduces the formation of nitrogen oxides, as their formation is highly dependent on high temperatures. In the second stage, the products of incomplete combustion from the first stage are burned with additional air or oxygen ($\alpha > 1$). This ensures complete combustion of the remaining fuel, reducing CO and other harmful emissions. The temperature at this stage is also controlled to avoid excessive NO_x formation.

A well-known method of flue gas denitrification is the use of selective catalytic reduction (SCR) to reduce the concentration of nitrogen oxides (Meng et al. 2023; Wu et al. 2021; Liptak et al. 2018). Comprehensive flue gas cleaning from HBS blocks of two blast furnaces was implemented by Shanghai Prime Metallurgy Technology Co., Ltd, at the Tangshan Wenfeng plant in 2022, with a reduction of NO_x levels in the exhaust gases below 50 mg/m^3. The estimated cost of such a system is US$1M–6M (Polyanska et al. 2022).

Article (Chen et al. 2014) proposes several methods to reduce harmful NO_x emissions during the operation of a hot blast stove. It is noted that the dome temperature during checkerwork heating should be below 1,420°C to reduce the NO_x formation rate. Increasing the excess air ratio α reduces the dome temperature, which helps to reduce NO_x emissions. Oxygen enrichment of the combustion air can be used to optimize the combustion process. Reducing the duration of the period of maintaining the dome temperature in the checkerwork heating mode will reduce the NO_x concentration, especially at a high excess air ratio α.

Article (Yang et al. 2023) investigates combustion optimization in blast furnaces and proposes an intelligent combustion control system based on reinforcement learning methods. The authors also present a model that can learn hidden dependencies between the combustion state and the position of control valves without the use of flow meters. In the article, the authors do not focus directly on reducing emissions as a separate goal. However, their approach to optimizing the combustion process in HBSs can contribute to emissions reduction indirectly.

An analytical review of references has shown several ways to reduce emissions from hot blast stoves: implementation of modern flue gas cleaning technologies, such as wet desulphurization, vacuum carbonate, arsenic-alkali, and monoethanolamine methods; improvement of the HBS thermal efficiency by optimizing combustion cycles to more accurately control the checkerwork heating; use of new types of burners; flue gas recirculation; two-stage fuel combustion, etc. These approaches mostly require significant financial investments. Traditionally, at Ukrainian metallurgical enterprises, modernization and overhauls of a blast furnace do not involve the HBSs block and its automated control system. At the same time, the authors' experience confirms that the service life of some blocks exceeds the specified service life by several times.

2. Methods and methodology of the hot blast stoves operation

The approach chosen by the authors to reduce harmful emissions by configuring the existing automated control system for HBS's checkerwork heating is due to the current production conditions in Ukraine: limited use of natural gas for heating blast furnace air, lack of funding for the installation of flue gas analyzers on each hot blast stove, not to mention the replacement of old HBSs with modern ones, for example, with new types of burners.

This study employs a combination of experimental analysis and computational modeling to evaluate the impact of automated control systems on reducing emissions from hot blast stoves. Real-time operational data from industrial HBSs, including fuel composition, combustion temperature, and emission levels, are collected and analyzed to identify inefficiencies and pollutant sources. Computational fluid dynamics (CFD) modeling is used to simulate combustion processes and optimize air-to-fuel ratios, while the algorithm of the research is implemented to develop predictive models for dynamic control adjustments. The methodology also includes a comparative assessment of conventional control systems by measuring NO_x, SO_x, and CO_2 emissions under different operating conditions. Additionally, case studies from industrial applications are examined to validate the effectiveness of automated control strategies in enhancing combustion efficiency and reducing environmental impact. The findings contribute to the development of intelligent emission management frameworks, supporting the transition toward more sustainable and energy-efficient metallurgical operations.

Figure 1 shows the gas facilities of a blast furnace shop, which includes three blast furnaces, each with a block of 4 HBS to provide the furnace with hot blast. In addition to pig iron and slag, each blast furnace produces top gas, which, after purification, becomes blast furnace gas and is fed into a common collector, which delivers the gas to consumers. The main consumers of blast furnace gas are hot blast stoves. In some cases, a gas mixture is used to heat the HBS – high-calorie additives such as natural and/or coke oven gas are added to blast furnace gas in small quantities. This is done, for example, to compensate for the moisture content of blast furnace gas and increase its caloric value. Figure 1 shows the natural and coke oven gas collectors in a schematic way. Gas mixtures, such as natural-blast furnace, coke-blast furnace, and natural-coke-blast furnace gas, are produced at a gas mixing station.

It is possible to implement automatic control of the chemical composition of top gas separately for blast furnaces to analyze the quality of blast furnace smelting. However, the gas is supplied to the HBSs from a common collector. Too often, the chemical composition of the gas is not automatically monitored but is determined several times a day in a chemical laboratory.

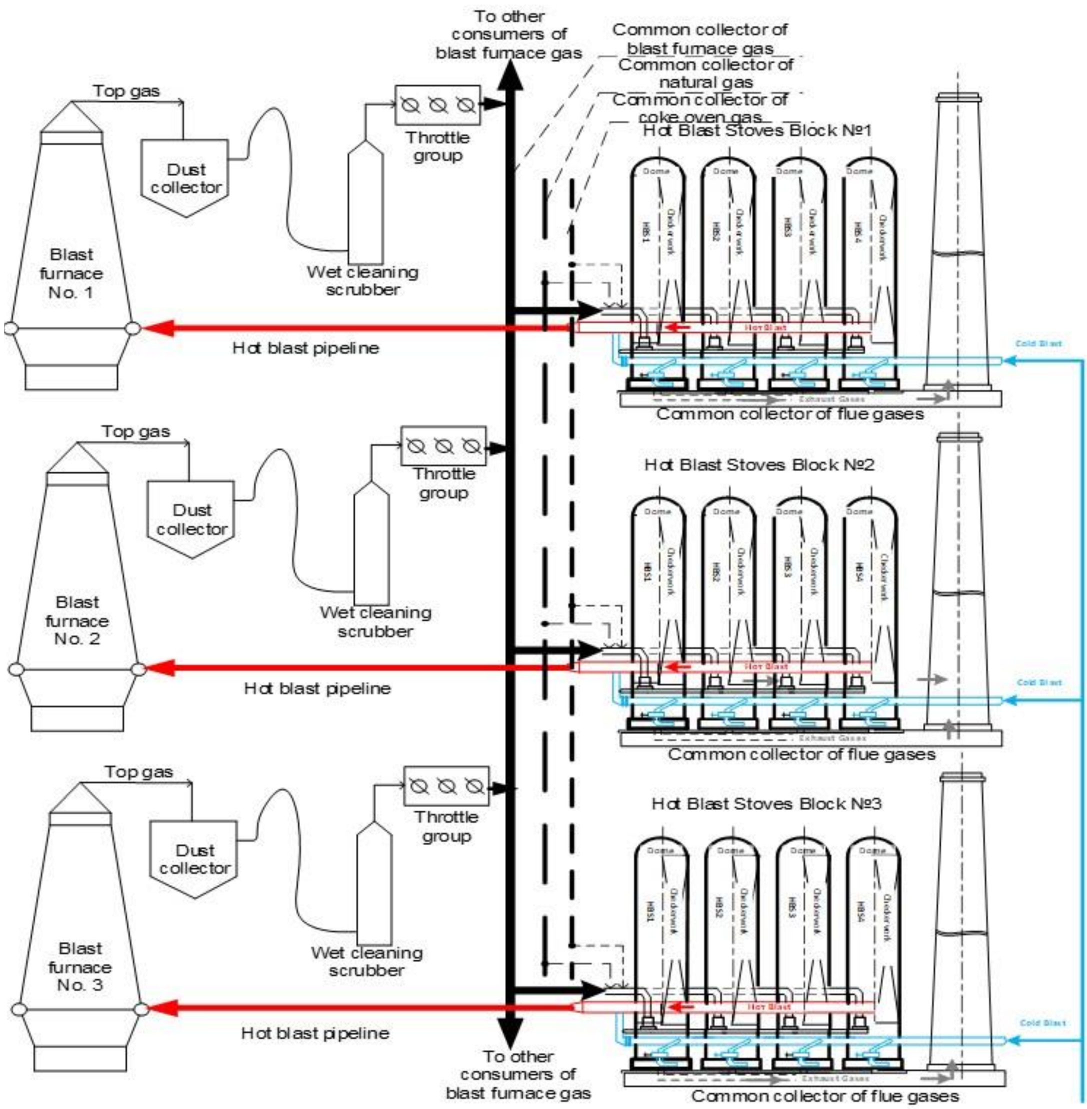

Fig. 1. Gas facilities of blast furnace shop

Rys. 1. Instalacje gazowe wielkiego pieca

An analysis of periodic measurements of blast furnace gas calorific value during several years in a blast furnace shop at the Ukrainian metallurgical plant showed quite frequent fluctuations of up to 30% of the calorific value of blast furnace gas per day (Table 2). The situation with determining the calorific value of coke oven gas is similar – there is no automatic control. In cases where HBSs is heated only with blast furnace gas, the lack of consideration of sharp fluctuations in its chemical composition makes it impossible to optimally adjust the control systems for the dome temperature and air-to-fuel ratio. As a result, the dome temperature decreases and emissions increase due to the lack of optimal combustion.

Table 2. Laboratory analysis of blast furnace gas composition and its lower heating value during the day

Tabela 2. Analiza laboratoryjna składu gazu wielkopiecowego oraz jego dolnej wartości opałowej (LHV) w ciągu doby

No. of measurement	Time of measurement [h]	CO_2	O_2	CO	CH_4	H_2	N_2	LHV [kcal/Nm^3]	LHV [MJ/Nm^3]
1	0:00	17.7	0	24.4	0	8.9	49	900	3.7681
2	4:00	18.3	0	23.7	0	8.7	49.3	875	3.6634
3	8:00	14.3	0	18	0	5.1	62.6	628	2.6293
4	12:00	14	0	18.1	0	5.1	62.8	631	2.6419
5	16:00	18.6	0	23.2	0	8.8	49.4	863	3.6132
6	20:00	19	0	23.7	0	8.5	48.8	870	3.6425

There can be from 3 to 5 units in an HBS block, but always two or more stoves will be operating simultaneously to heat the checkerwork. Flue gases from HBS are discharged through a common collector to the chimney. Due to this design feature, to control the quality of blast furnace gas combustion in HBS, it is necessary to install a separate gas analyzer for each stove. In the above case (Fig. 1), 12 gas analyzers must be installed, which requires a significant investment in the installation of devices and their subsequent maintenance.

In the best-case scenario, combustion quality control for each HBS is conducted in a laboratory only once a year during thermal studies of its operational condition. However, such infrequent assessments may not be sufficient to detect efficiency losses or rising emission levels, leading to potential environmental and operational risks. Continuous monitoring and automated control systems are therefore essential to ensure optimal combustion performance, minimize energy waste, and maintain compliance with emission regulations.

Figure 2 presents a standard system for automatic heating control of the HBS's checkerwork (dome), which regulates fuel flow, air distribution, and temperature settings to optimize heat transfer. Traditional control methods often rely on pre-set operational parameters, which may not account for real-time fluctuations in fuel composition or external conditions. Advanced automation, including machine learning algorithms, can dynamically adjust these parameters to enhance combustion efficiency while reducing pollutant formation. Implementing such intelligent control strategies allows for more consistent performance, prolongs equipment lifespan, and supports the industry's transition toward sustainable and energy-efficient metallurgical practices (Shibata et al. 2001; Nikolsky et al. 2020).

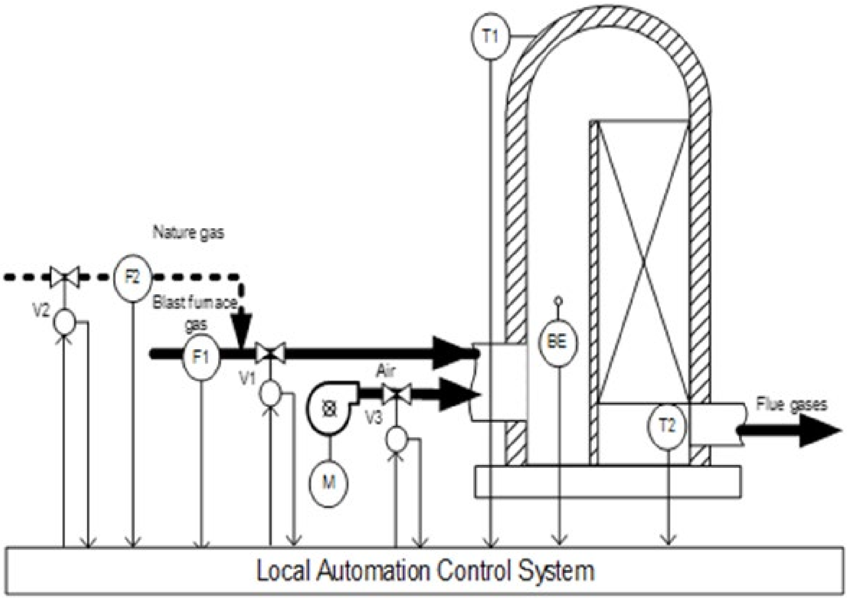

Fig. 2. Standard structure of the automated control system of the HBS heating mode:
T1 – dome temperature; T2 – exhaust gas temperature; F1 – blast furnace gas flow control; F2 – natural gas flow control; BE – flare presence control; M – fan motor; V1 – dome temperature control; V2 – fuel mixture ratio control; V3 – air-to-fuel ratio control.

Rys. 2. Standardowa struktura zautomatyzowanego systemu sterowania trybem nagrzewania pieca HBS

The heating process of the HBS's checkerwork consists of several periods. The first stage involves supplying the maximum amount of fuel to achieve the permissible heating temperature of the dome lining. During the second period, the checkerwork is heated by changing the air-to-fuel ratio to prevent overheating of the stove dome, either by increasing the airflow or reducing the fuel flow. The temperature of the under-checkerwork space determines further heating of the checkerwork; traditionally, the temperature of the exhaust gases should not exceed 400°C. The air-to-fuel ratio control subsystem is set to a constant fuel calorific value, and the excess air ratio varies in the range of 1.15–1.30. The checkerwork heating process is controlled manually by a technologist, based on their own experience and dome temperature limitations in accordance with the technological instructions for HBS controlling, the technologist manually changes the fuel and air consumption for combustion without considering changes in fuel calorific value and combustion quality. In this case, the main indicator is the dome temperature. If the technologist sees that the dome temperature does not reach the set value within a specified time, which may indicate, for example, a decrease in fuel calorific value, he begins to manually increase fuel consumption.

As a result of analyzing the operation features of the several HBS blocks at different metallurgical enterprises, the authors have identified the following problems:

1. Lack of automatic control of the chemical composition and calorific value of blast furnace gas in the common collector. Blast furnace gas composition is measured by a chemical laboratory several times a day. Changes in calorific value per day can reach 30%, which is not considered when adjusting the air-to-fuel ratio.

2. In the case when the combustion air is supplied not through a common collector, but by means of a blower fan, due to design features, there is no possibility of direct control of air flow. If the frequency method is used to control the fan speed, the air flow rate is indirectly calculated. If the control is carried out by throttling the flow, the air flow rate remains unknown, the air-to-fuel ratio does not change, and its regulation is realized using a system of rods between the actuators.

3. The local system of automatic control of the air-to-fuel ratio during the HBS's checkerwork heating is set to a conditionally average calorific value of blast furnace gas and does not take into account its change at all.

4. Combustion air losses are not considered.

5. A "short circuit" between the burner and the checkerwork leads to a significant increase in the CO concentration in the flue gases. In the presence of such a problem, the stove needs to be overhauled.

6. There is no automatic control of fuel combustion quality. The smoke ducts of each HBS of the block are combined into one smokestack, which requires the installation of gas analyzers for each unit, which is economically unreasonable. This parameter can be determined during a thermal engineering study of the stove, which is carried out at best once a year. In the absence of automatic fuel caloric control, these results are not very indicative due to the lack of consideration of the above factors.

Considering these problems, it can be argued that the harmful emissions generated by the HBS block operation may significantly exceed the calculated values. This is especially true given that a blast furnace shop usually includes several furnaces.

3. Results and discussion

The authors propose the structure of an automated control system for HBS's checkerwork heating with a backlink on the quality of fuel combustion (Fig. 3). This structure will make it possible to control the checkerwork heating, taking into account the requirements for harmful emission standards due to the following features:

- the availability of current air flow control and the use of frequency regulation of fan speed allows adjusting the air-to-fuel ratio in wide ranges, with the possibility of implementing an extreme control system that makes it possible to maintain an excess air ratio of about 1.0 (Béla and Lipták 2005);
- the availability of current calorific value control of the natural and blast furnace gases and regulation of the proportion of gas mixture components allows maintaining the dome

temperature at a given level to ensure optimal HBS's checkerwork heating within the regime map, considering the limitation on the maximum combustion temperature, the value of which should not exceed 1,350–1,420°C (Rieger et al. 2015; Sobolev et al. 2025; Zhang et al. 2014; Chen et al. 2014);

- the availability of current chemical composition control (O_2, CO, CO_2) of the exhaust gases (Liptak et al. 2018) allows real-time assessment of the combustion quality and provides a possibility to adjust the air-to-fuel ratio (Liptak et al. 2018; Béla and Lipták 2005) in real time;
- the availability of current emission control allows the automated combustion control system to adjust on the verge of a sharp acceleration of NO_x formation, for example, by reducing the temperature under the dome or reducing the excess combustion air.

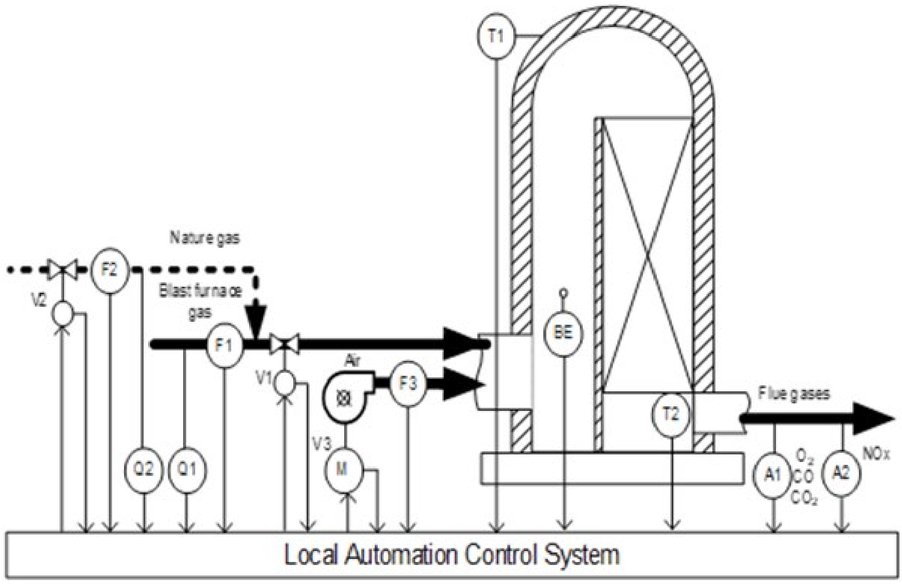

Fig. 3. Structure of the automated control system for the HBS heating mode with backlink on the fuel combustion quality:
Q1 – chemical composition and calorific value of blast furnace gas; Q2 – chemical composition and calorific value of natural gas; F3 – control of combustion air flow; A1 – gas analysis of exhaust gases for O_2, CO, CO_2; A2 – control of composition and harmful emissions.

Rys. 3. Struktura zautomatyzowanego systemu sterowania trybem nagrzewania pieca HBS ze sprzężeniem zwrotnym dotyczącym jakości spalania paliwa

The proposed system structure (Fig. 3) allows for automatic control of the checkerwork heating and combustion quality without the intervention of a technologist, whose task will be reduced to monitoring the technological process. Continuous monitoring of the current values of blast furnace gas calorific value Q1 and harmful emissions A1 and A2 allows, for example, the implementation at the controller level of: an algorithm for compensating for the decrease in blast furnace gas calorific value by adding natural gas; an algorithm for optimizing fuel combustion in order to reduce fuel consumption; an algorithm for controlling combustion quality by feedback on the chemical composition of flue gases in order to reduce the portion of CO in emissions; an algorithm for reducing NO_x emissions by maintaining the maximum fuel combustion temperature, taking into account the optimal checkerwork heating.

The system structure shown in Fig. 3 is an ideal desired option that will allow:

- have complete information about the quality of combustion;
- control the formation of harmful emissions in real time;
- adjust in a timely manner the combustion of fuel gas, considering the heating limitations of HBS's checkerwork.

When installing a new HBS unit, one of the environmental requirements is mandatory combustion quality control using automatic monitoring of O_2 and CO content in exhaust gases. According to the authors, the implementation of the proposed system structure (Fig. 3) during the construction of a new HBS unit will ensure that harmful emissions do not exceed the standard values (Technological standards... 2023), and the additional use of combustion optimization algorithms will significantly reduce emissions with proper ongoing maintenance of gas analyzers. Experience shows that this sensor operates for no more than one to two years due to its design features and installation conditions in the flue gas duct. Further readings from these sensors are not reliable, and their maintenance requires additional funding.

However, for specific reasons, the implementation of such a system in the structure of the considered blast furnace shop (Fig. 1) will be almost impossible due to its extremely high cost. Therefore, solving the problem of reducing harmful emissions from the HBSs block requires a different approach.

The authors propose the following modernization of the automated dome temperature control system (checkerwork heating) as an alternative way to reduce harmful emissions without significant financial investments, provided that the frequency control of the blower fan speed is available (Fig. 4).

It should be emphasized that this control method of combustion air flow rate will provide flexibility in controlling the dome temperature and improving the combustion quality with a significant reduction in harmful emissions and electricity consumption. This requirement is one of the integral components of the control system.

An existing automated control system for the blast furnace melting process, in particular, hot blast heating, in addition to local automatic control systems, necessarily requires the availability of current and archived databases containing a significant number of technological parameters over a long period of time. The use of current and archived technological information provides wide possibilities for analyzing the quality of the blast furnace process and blow heating (Koyfman et al. 2020, 2021). At present, the control of the HBS's checkerwork heating does not consider its thermal state at different switching durations, in particular, heat loss to the environment during switching between modes, when the dome temperature decreases by 15–25°C. Optimization

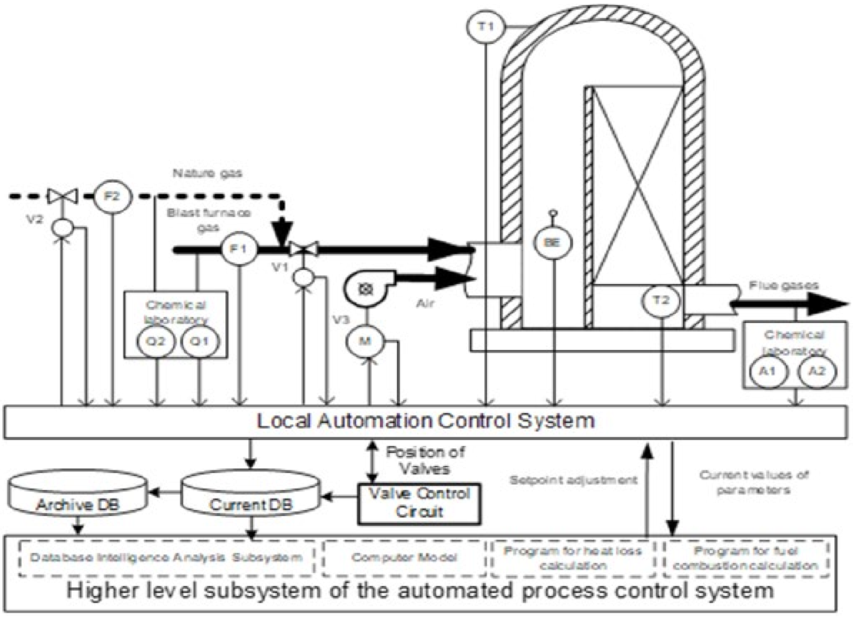

Fig. 4. Structure of the proposed automated control system for heating the HBS's checkerwork

Rys. 4. Struktura proponowanego zautomatyzowanego systemu sterowania nagrzewaniem rusztu cieplnego pieca HBS

of switching will reduce the switching time and, accordingly, reduce heat losses and the total amount of fuel consumed for checkerwork heating. The availability of a program for calculating heat losses when switching HBSs between modes (Koifman et al. 2020a) will make it possible to regulate the checkerwork heating process, taking into account the initial thermal state of the stove after switching from the blower heating mode to the checkerwork heating mode.

When modernizing the control system, it is necessary to additionally consider the caloric value of blast furnace gas, which periodically comes from the chemical laboratory (Fig. 4). The chemical composition of natural gas is mostly stable and rarely changes. In the current conditions, the use of natural gas in stove heating systems is limited, but, for example, it is added to compensate for high humidity and to ensure the required dome temperature during heating. Adjusting the air-to-fuel ratio, considering the air flow rate, calorific value of blast furnace gas, and the current fuel combustion calculation (Koifman et al. 2020b), will improve the quality of fuel combustion. To increase the accuracy of the combustion calculation, the algorithm uses the values of the thermal parameters of the gas components depending on their pressure and temperature (Hilsenrath et al. 1955).

Periodic monitoring of the composition of exhaust gases O_2, CO, CO_2 (6 times a day) and harmful emissions NO_x (monthly), carried out by the chemical laboratory, will make it possible to analyze the quality of the checkerwork heating system and adjust the calculations of fuel combustion and the set values for the control system.

The use of a mathematical model (Koifman and Simkin 2019) makes it possible to predict the duration of heating and blowing periods, considering current changes in the composition of blast furnace gas, a given limitation on the dome temperature, and to calculate fuel combustion with an optimal excess air ratio.

The complex of computer programs, which includes a subsystem for intelligent analysis of technological data, a program for calculating heat losses, refined calculation of fuel combustion and a mathematical model, is combined into a top-level subsystem (Fig. 4) with the following capabilities to reduce harmful emissions: adjustment of tasks to the subsystem for controlling the dome temperature and air-to-fuel ratio; optimization of the duration of HBS switching from mode to mode; calculation of heat losses during switching periods and in the process of checkerwork heating and hot blast; calculation of fuel combustion with the possibility of periodic adjustment for the composition of blast furnace gas and flue gases.

The proposed modernized automated control system of checkerwork heating (Fig. 4) operates according to the following algorithm:

- current values of technological parameters (dome and flue gas temperature, blast furnace and natural gas consumption, air blower motor speed, valve positions) from sensors are recorded in real time in the database and transmitted to the higher-level subsystem;
- the chemical composition of blast furnace gas is periodically (6 times a day) transmitted to the higher-level subsystem;
- the chemical composition of flue gases (O_2, CO, CO_2, NO_x) is transmitted monthly to the higher-level subsystem;
- the higher-level subsystem's set of computer programs, taking into account the current and periodic values of technological parameters, using parameter values from the archive database, simulates the HBS operation in the current production state, calculates the parameters of optimal fuel combustion to reduce harmful emissions, and transmits the setpoint values of fuel and air consumption to the local HBS heating control system;
- the calculated setpoint values can be used for the operation of the local control subsystem in automatic mode or when the checkerwork heating process is manually controlled by a technologist.

The proposed system structure (Fig. 4) can be implemented on an existing HBS unit and is an additional extension of the functionality of local control systems.

The authors modeled two operating modes of the HBSs block consisting of four units using the chemical composition of blast furnace gas (Table 2) for one day:

- when the checkerwork heating control system is set to the average value of the blast furnace gas composition;
- when the operation of the checkerwork heating control system is adjusted in accordance with fluctuations in the blast furnace gas composition.

Modeling is performed using software developed in the C++ programming language using MS Visual Studio 2019, according to the following algorithm:

1. The fuel combustion process is calculated based on software (Koifman et al. 2020b) with input data in the form of gas compositions (according to Table 2) and fuel and combustion

air consumption. The calculation results, such as combustion temperature, composition and consumption of combustion products, are transferred to a mathematical model (CFD) of each HBS operation.

2. The modeling of the each HBS operation in the checkerwork heating, blast heating, and switching between modes is performed using a mathematical model (Koyfman et al. 2020, 2021; Koifman and Simkin 2019) with the following input parameters: checkerwork dimensions, type of refractory blocks from which the checkerwork and HBS dome are made, combustion product flow rate and temperature, hot blast flow rate, initial temperature distribution across the checkerwork after HBS switching between modes.

3. The modeling of the HBS switching between modes is implemented using the developed software (Koifman et al. 2020a), and the obtained current thermal state of the checkerwork is transferred to the mathematical model of the HBS operation.

The results of modeling the HBSs block operation for one day showed that taking into account fluctuations in the composition of blast furnace gas with the current calculation of fuel combustion, heat losses of the checkerwork after switching, increasing the value of the excess air ratio from 1.15 to 1.30, optimizing the HBS switching between modes, showed that CO emissions can be reduced by 7% (from 23,1 to 21,4 tons) and NO_x emissions by 15% (from 1,77 to 1,5 tons).

The proposed solution for reducing emissions from HBSs considers the impossibility of making structural changes to the existing configuration of the HBS's technological equipment, while making it possible to optimize the fuel combustion process under conditions of changing blast furnace gas calorific value and in the absence of constant control over the quality of its combustion.

In further studies, it should be considered that frequency control of the blower fan speed, which allows adjusting the air-to-fuel ratio in wide ranges with the possibility of implementing an extreme control system, usually creates negative consequences for the power supply system of all electrical equipment. Possible ways to overcome such consequences are considered in (Pivnyak et al. 2013, 2017).

Conclusions

The proposed automated control system for heating hot blast stoves (HBSs) introduces an innovative approach to reducing harmful emissions by integrating real-time monitoring of fuel combustion quality. By implementing feedback mechanisms that regulate the air-to-fuel ratio, dome temperature, and exhaust gas composition, the system ensures stable and efficient combustion while minimizing nitrogen oxides (NO_x) and carbon monoxide (CO) emissions. The ability to dynamically adjust combustion parameters based on real-time calorific value and chemical composition of blast furnace gas significantly enhances process efficiency while maintaining compliance with environmental regulations. However, despite the technical advantages of this system, the high cost of full-scale implementation presents a major challenge, necessitating alternative solutions for emission reduction.

The proposed modernization of the automated control system for HBS checkerwork heating aims to optimize the combustion of blast furnace (mixed) gas, ensuring a reduction in harmful emissions within the HBS block's operational framework. This improvement is achieved through careful consideration of the chemical composition and calorific value of blast furnace gas, more accurate combustion calculations, and the ability to adjust the air-to-fuel ratio. Additionally, stabilizing the dome temperature at an optimal level (below 1,400°C) significantly mitigates NO_x formation. Nevertheless, further detailed studies and additional research are required to comprehensively address the issue of harmful emissions from the HBS block.

As a cost-effective alternative, the modernization of the automated dome temperature control system is proposed, utilizing frequency control of the blower fan speed to optimize combustion. This approach enables more flexible regulation of heat transfer within the checkerwork, enhancing fuel utilization efficiency while reducing both electricity consumption and emissions. By refining control strategies – such as real-time airflow rate adjustments and targeted fuel mixture optimization – the system can maintain optimal combustion conditions without excessive capital investment. The feasibility of this method makes it a practical step toward minimizing the environmental footprint of blast furnace operations while improving overall energy efficiency.

Further refinement of the control system requires a comprehensive approach that accounts for fluctuations in blast furnace gas calorific value, heat loss during switching periods, and real-time adjustments to combustion calculations. The integration of intelligent data analysis, heat loss modeling, and predictive algorithms enables precise control over heating and blowing periods, resulting in a more sustainable and efficient process. Simulation results demonstrate that adapting the checkerwork heating system to real-time fluctuations in blast furnace gas composition can reduce CO emissions by 7% and NO_x emissions by 15%, underscoring the effectiveness of data-driven combustion optimization.

Logical continuation of the current research is the implementation of proposed modernization of the automated control system for HBS's checkerwork heating in real production using periodic measurements of the chemical composition of blast furnace gas and flue gases from each HBS; improvement of the fuel combustion calculation program, considering the formation of SO_x when it is present in the blast furnace gas.

Moving forward, future research should focus on mitigating the potential negative impact of frequency-controlled blower fan operations on the power supply system. Developing advanced power regulation technologies or energy storage solutions could enhance system reliability and scalability. Furthermore, additional experimental validation and industrial testing of the proposed control strategies will be essential to refine the methodology and ensure seamless integration into existing metallurgical processes. By continuously improving these automation systems, the metallurgical industry can advance toward cleaner, more efficient, and environmentally responsible production practices.

The Authors have no conflicts of interest to declare.

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Redukcja emisji z pieców nagrzewających powietrze poprzez konfigurację zautomatyzowanego systemu sterowania

Streszczenie

Przedmiotem niniejszych badań jest ograniczenie emisji szkodliwych substancji podczas eksploatacji pieców nagrzewających powietrze (HBS) poprzez udoskonalenie zautomatyzowanego systemu sterowania procesem nagrzewania konstrukcji rusztowej. Przeanalizowano główne źródła emisji powstające podczas spalania gazu wielkopiecowego, w tym tlenki azotu (NO_x), tlenki siarki (SO_x) oraz tlenki węgla (CO, CO_2). Autorzy proponują modernizację systemu automatycznego sterowania poprzez wdrożenie sprzężenia zwrotnego dotyczącego jakości spalania paliwa, ciągły monitoring składu gazów spalinowych oraz bieżącą ocenę wartości opałowej paliwa. Struktura systemu obejmuje regulację przepływu powietrza do spalania, ciągły pomiar wartości opałowej gazu wielkopiecowego, ocenę sprawności spalania na podstawie analizy zawartości O_2, CO i CO_2 w spalinach oraz dostosowanie procesu spalania do mapy trybów pracy w celu utrzymania temperatury kopuły w zakresie 1350–1420°C, co sprzyja minimalizacji emisji NO_x. Zastosowane rozwiązania przyczyniają się do redukcji emisji NO_x, poprawy efektywności energetycznej oraz stabilizacji reżimu temperaturowego. Proponowane podejście stanowi opłacalną metodę ograniczania emisji i może zostać bezproblemowo zintegrowane z istniejącymi systemami przedsiębiorstw hutniczych.

Słowa kluczowe: piec nagrzewający powietrze (HBS), redukcja emisji, zautomatyzowany system sterowania, sprawność spalania, gaz wielkopiecowy