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Improvement of pig iron production technology by using the useful properties of the potential of secondary resources of raw materials and fuels

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Удосконалення технології виробництва чавуну шляхом використання корисних властивостей потенціалу вторинних ресурсів сировини та палива

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Abstract. *The scientific and technical relevance of the study lies in determining the directions for improving the ways of using the useful properties of secondary resources in order to intensify the blast furnace process, increase its energy efficiency and reduce pollutant emissions. At the same time, economic efficiency is achieved by reducing the cost of purchasing primary raw materials and reducing waste generation, which corresponds to modern concepts of sustainable development on the way to "green" metallurgy.* ***Purpose of the study.*** *Scientific and practical substantiation of directions for improving the technology of pig iron production through the use of useful properties of secondary resources of raw materials and fuels that have a man-made origin. It is aimed at increasing the level of energy efficiency and improving the slag regime of the blast furnace process, reducing the man-made load on the environment of industrially developed regions of Ukraine. To achieve this goal, the following theoretical and practical tasks will be solved in the study: 1. The analysis of the current state of use of secondary resources of mineral raw materials and fuel in blast furnace production in the conditions of world and domestic metallurgical enterprises has been carried out; 2. The physicochemical properties of the most common types of secondary resources (man-made wastes of metallurgical origin: dust, sludge, scale, production of metallurgical lime: fractions from gas cleaning devices and heat treatment products of waste of plant origin, which are sources of pyrocarbon) have been investigated. Further - determination of the spectrum of their probable purpose, impact on the features and indicators of the blast furnace process, as well as justification of rational ways of their preparation and use; 3. Rational shares of substitution of traditional raw materials and fuels with secondary materials in the blast furnace process are substantiated, the use of which will not reduce the quality of pig iron and will not increase the specific consumption of coke. Their influence on physicochemical and heat-gas-dynamic processes, which is reflected in the characteristic zones of the blast furnace, has been studied; 4. The optimal technological schemes and recommendations for the methods of introduction and rational specific consumption of innovative materials based on man-made wastes have been determined, which will ensure the maximum level of use of their useful properties in the material and thermal balances of the blast furnace process; 5. The technological and environmental advantages of introducing into the blast furnace process a monomaterial, the composition, physicochemical features and spectrum of purpose of which are formed by heat treatment of a mixture of man-made industrial waste, are evaluat-*

ed and their prospects as a substitute for the corresponding part of pulverized coal fuel (PCF) and fluxes are determined. ***Research methods.*** *When conducting a comprehensive study, the following methods will be used: analysis and generalization of materials of scientific and technical literature and patent sources, coordination of their results in accordance with modern trends and the best results of the practice of using secondary resources in blast furnace production; physicochemical methods of analysis chemical, thermogravimetric, to determine the composition, structure, metallurgical value, probable spectrum of purpose and reactivity of secondary resources of materials - substitutes for iron ore raw materials, coke and pulverized coal fuel (PCF); thermodynamic forecasting and kinetic modeling of the behavior of experimental materials of secondary origin under the conditions of their heat treatment to assess the influence of their properties on the course of physical and chemical processes and transformations to the thermal and gas-dynamic regime of the blast furnace. The expected results of the study should also include: development of scientifically grounded recommendations for the effective use of useful properties of the initial potentials of secondary resources of raw materials and fuel in blast furnace production; establishment of quantitative ratios regarding rational levels of substitution of traditional fuel and raw materials with secondary ones, without reducing the productivity of the furnace and the quality of pig iron while reducing the specific consumption of lime and PCF; development of a method for the implementation of a complex technological scheme for the preparation, heat treatment of experimental mixtures based on components of mineral raw materials and fuel, followed by the use of an innovative product in the conditions of blast furnace production of pig iron.* ***Scientific novelty of the work.*** *For the first time, systematically, on the basis of the results of an analytical and practical study, the energy efficiency of production and use in the blast furnace process of a two-component monomaterial based on dispersed waste from the production of lime and materials – waste of plant origin, obtained by implementing the effect of their pyrolysis under conditions of joint heat treatment of the initial mixture layer, was substantiated, tested on high-temperature models, poured thermal, in an inclined rotary drum-type furnace. For the first time, a resource-efficient and results-efficient approach has been used to assess the efficiency of the use of materials based on secondary resources of metallurgical and plant origin, based on an integrated combination of the results of thermodynamic forecasting, physical modeling and taking into account the provisions of the exergical methodology for assessing the energy efficiency of the objects of study. Methodological bases have been developed for the selection of rational schemes for the introduction of complex materials based on secondary materials into the blast furnace charge and in the air blast flow to stabilize gas-dynamic conditions in the charge layer, intensify recovery processes with a decrease in the specific consumption of coke per ton of liquid pig iron. The regularities of the influence of the composition and dispersion of secondary resources on the gas-dynamic and thermal parameters of blast furnace smelting have been revealed, which makes it possible to increase the accuracy of predicting the furnace course. It has been proved that the use of materials based on secondary resources of mineral raw materials and fuels can provide the effects of increasing the energy efficiency of pig iron production and reducing the environmental burden, which meets the requirements of sustainable development and the concept of "green metallurgy".*
Keywords: *pig iron, secondary materials, rational schemes, metallurgical lime, fuel, injection, pulverized coal, natural gas.*

Анотація. *Науково-технічна актуальність дослідження полягає у визначенні напрямів удосконалення способів використання корисних властивостей вторинних ресурсів з метою інтенсифікації доменного процесу, підвищення його енергоефективності та зниження викидів забруднювальних речовин. Водночас економічна ефективність досягається за рахунок зменшення витрат на закупівлю первинної сировини та скорочення обсягів утворення відходів, що відповідає сучасним концепціям сталого розвитку на шляху до «зеленої» металургії.* ***Мета дослідження.*** *Науково - практичне обґрунтування напрямків удосконалення технології виробництва чавуну шляхом застосування корисних властивостей вторинних ресурсів сировини та палива, які мають техногенне походження. Спрямована на підвищення рівню енергоефективності та поліпшення шлакового режиму доменного процесу, зниження техногенного навантаження на довкілля промислово розвинутих регіонів України. Для досягнення поставленої мети в дослідженні будуть вирішені наступні теоретико-практичні завдання: 1. Провести аналіз сучасного стану використання вторинних ресурсів мінеральної сировини та палива в доменному виробництві в умовах світових та вітчизняних металургійних підприємств. 2. Дослідити фізико-хімічні властивості найбільш поширених видів вторинних ресурсів (техногенних відходів металургійного походження: пилу, шламів, окалини, виробництва металургійного вапна: дріб'язок з апаратів газоочищення та продуктів теплової обробки відходів рослинного походження, що є джерелами піровуглецю). В подальшому – визначення спектру їх вірогідного призначення, впливу на особливості та показники доменного процесу, а також, обґрунтування раціональних способів їх підготовки та використання. 3. Обґрунтовати раціональні частки заміщення в доменному процесі традиційної сировини та палива вторинними матеріалами, використання яких не знизить якість чавуну та не підвищить питому витрату коксу. Досліджено їх вплив на фізико-хімічні та тепло-газодинамічні процеси, що відбивається в характерних зонах доменної печі. 4. Визначено оптимальні технологічні схеми та рекомендації щодо способів введення та раціональних питомих витрат інноваційних матеріалів на основі техногенних відходів що забезпечать максимальний рівень використання їх корисних властивостей в матеріальному та тепловому балансах доменного процесу. 5. Оцінити технологічні та екологічні переваги від впровадження в доменний процес мономатеріалу, склад, фізико-хімічні особливості та спектр призначення якого формуються шляхом термічної обробки суміші техногенних промислових відходів та визначено їх перспективність як замінника відповідної частини пиловугільного палива (ПВП) та флюсів.* ***Методи дослідження.*** *При проведенні комплексного дослідження будуть застосовані наступні методи: аналіз та узагальнення матеріалів науково-технічної літератури та патентних джерел, узгодження їх результатів у відповідності до сучасних тенденцій та кращих результатів практики використання вторинних ресурсів у доменному виробництві; фізико-хімічні методи аналізу - хімічний, термогравіметричний для визначення складу, структури, металургійної цінності, вірогідного спектру призначення та реакційної здатності вторинних ресурсів матеріалів – замінників залізорудної сировини, коксу та пиловугільного палива (ПВП); термодинамічне прогнозування і кінетичне моделювання особливостей поведінки дослідних матеріалів вторинного походження в умовах їх термічної обробки для оцінювання впливу їх властивостей на перебіг фізико-хімічних процесів і перетворень на тепловий та газодинамічний режим доменної печі. До очікуваних результатів виконання дослідження доцільно віднести, також: розробку науково обґрунтованих рекомендацій щодо ефективного використання в доменному виробництві корисних властивостей вихідних потенціалів вторинних ресурсів сировини та палива; встановлення кількісних співвідношень щодо раціональних рівнів заміщення традиційних матеріалів палива та сировини вторинними, без зниження продуктивності печі та якості чавуну при зменшені питомих витрат вапна та ПВП; розроблення способу впровадження комплексної технологіч-*

ної схеми підготовки, термічної обробки дослідних сумішей на основі компонентів мінеральної сировини та палива з наступним використанням інноваційного продукту умовах доменного виробництва чавуну. ***Наукова новизна роботи.*** *Вперше, системно, на основі результатів аналітико – практичного дослідження обґрунтовано, апробовано на високотемпературних моделях, в умовах наближених до реальних та підтверджено енергетично-сировинна ефективність виробництва та використання в доменному процесі двокомпонентного мономатеріалу на основі дисперсних відходів виробництва вапна та матеріалів – відходів рослинного походження, що отримується шляхом реалізації ефекту їх піролізу в умовах сумісної термічної обробки шару вихідної суміші, що пересипається термічної, в похилій обертовій печі барабанного типу. Використано вперше раціональний за витратою ресурсів та ефективний за результатами підхід для оцінювання ефективності застосування матеріалів на основі вторинних ресурсів металургійного та рослинного походження, що базується на інтегрованому поєднанні результатів термодинамічного прогнозу, фізичного моделювання та з урахуванням положень ексергійної методології оцінки енергоефективності об'єктів дослідження. Розроблено методичні основи для вибору раціональних схем введення комплексних матеріалів на основі вторинних матеріалів у доменну шихту та в потоці повітряного дуття для стабілізації газодинамічних умов в шарі шихти, інтенсифікації процесів відновлення при зниженні питомої витрати коксу на тонну рідкого чавуну. Виявлено закономірності впливу складу та дисперсності вторинних ресурсів на газодинамічні та теплові параметри доменної плавки, що дозволяє підвищити точність прогнозування ходу печі. Доведено, що застосування матеріалів на основі вторинних ресурсів мінеральної сировини та палива здатне забезпечити ефекти підвищення енергоефективності виробництва чавуну та зниження екологічного навантаження на довкілля, що відповідає вимогам сталого розвитку та концепції «зеленої металургії».*

Ключові слова: *чавун, вторинні матеріали, раціональні схеми, чорне вапно, паливо, вдування, пиловугільне паливо, природний газ.*

Introduction. The modern development of the metallurgical industry is characterized by increased requirements for the efficiency of the use of raw materials and fuel and energy resources, as well as for the environmental safety of production. One of the most energy-intensive processes is the production of pig iron in blast furnaces, which requires the consumption of significant volumes of natural raw materials and coke. Reducing the negative impact on the environment leads to the search for new ways of development and innovative solutions to improve the technology of the domain process.

One of its promising directions is the complex and rational use of the properties of the potential of secondary resources of raw materials and fuels. Such resources include metallurgical waste (sinter and blast furnace dust, sludge, scale), carbon-containing waste from coke oven and coal production, dispersed waste from limestone preparation and lime production, as well as alternative reducing agents and energy materials. Their rational use allows not only to partially replace traditional types of raw materials and fuel, but also to increase the complexity of the use of mineral and fuel and energy resources on the scale of the enterprise.

Thus, improving the technology of pig iron production through the use of secondary resources of raw materials and fuel is an important task for both scientists and industrial enterprises, because it combines economic feasibility, environmental responsibility and technological progress.

Keywords: cast iron, secondary materials, rational schemes, black lime, fuel, injection, pulverized coal fuel, natural gas.

Analysis of the results of the influence of external factors on the physical and chemical features of processes in the characteristic zones of the furnace and the main indicators of the blast furnace process. Establishing the influence of component and chemical composition, granulometry and ratio of components of the initial charge on physical and chemical processes in the characteristic zones of the furnace; determination of the rational composition of blast, specific costs and rational ratio of PCF and natural gas (NG) in it, as factors affecting the stability of the blast furnace operation, are relevant areas of research aimed at improving the technology of iron smelting.

The energy efficiency of pig iron production, in the context of changes in the ratio of PCF and NG costs as components of the fuel and recovery potential of the process, is influenced by the consistency between the theoretical basis and the results of practical verification of its main provisions: the rationality of the costs of the components of the initial potential and the efficiency of the results of the actual use of their useful properties.

Changes in the conditions of heat and gas-dynamic processes, which is reflected in the increase in thermal loads on the air lances and the shaft, on their service life, the stability of the gas-dynamic melting mode, the evenness of the furnace and its technical and economic indicators, caused the need to adjust the physical properties of the charge. The latter affect the indicators of the slag regime, which requires, in turn, neutralization of the negative impact of PCF ash, namely, its chemical composition on the course of blast furnace smelting.

Therefore, in the conditions of blowing PCF into the blast furnace, ensuring cost-efficient production of mineral raw materials and energy is an urgent task. Its solution requires research aimed at determining the patterns and methods of controlling processes in the blast furnace furnace, which are characterized by a high level of uncertainty. Thus, according to the results of the study [1], when using the PCF injection technology, the volume of gases emitted during the combustion of its combustible components differs from similar conditions during the combustion of GHG by more than 150 times, and the density of PCF in the transport system before their introduction into the furnace in air blast jets can vary by 2 or more times. In the conditions of injection of pulverized coal fuel, it is obvious that it is becoming relevant to continue research aimed at:

1. To determine, for the conditions of variability of physical characteristics and chemical composition of the components of the blast furnace charge, the most rational ratios in the blast of PCF and NG. At the same time, it is necessary to take into account the change in gas-dynamic conditions in the blast furnace column and compare the contributions of thermal effects from their combustion to the energy balance of the smelting.

2. Study of the influence of dispersion, moisture and chemical composition of PCF on combustion processes and features of the formation of reducing gases (CO, H_2) in the mure zone.

3. Clarification of the gas dynamics of the blast furnace in case of changes in the volume of PCF injection, the ratio of PCF and NG, including the distribution of temperatures and concentrations of reducing gases in different areas of the mine.

4. Study of the conditions for the formation and ensuring the stability of the interaction of hot blast with PCF, NG, coke and their carbon-containing substitutes of plant origin with the prediction of the rational level of oxygen enrichment of the blast and the heating temperature.

5. Clarification of the influence of PCF on the formation, composition and properties of blast furnace slag and pig iron, especially on the results of its desulfurization.

6. Reduction of specific energy consumption and CO_2 emissions by replacing part of the coke with pulverized coal fuel without reducing the level of useful use of the properties of gases: their reducing capacity and physical heat of gaseous iron reduction products.

7. Development of complex physical and chemical models of the thermal and material balance of the blast furnace, taking into account the injection of PCF and its alternative substitutes, to predict changes in the quality, efficiency and cost of pig iron.

As a logical conclusion of the stages of research aimed at improving the domain process, a concise structured scheme has been developed in the format of a scientific and technical task, the use of the components of which determines the expected effects of the implementation of the main areas of research (Table 1).

Table 1 - Structured scheme in the format "main areas of research - expected technical and economic effects.

No.	Research areas	Expected effect
1	Optimization of the coke-PCF ratio in the domain process.	Reducing coke consumption, saving fuel, reducing the cost of pig iron.
2	Study of the thermal balance of the blast furnace during the introduction of PCF in the air blast flow.	Stabilization of the temperature regime, increasing the thermal efficiency of the process.
3	Determination of gas-dynamic conditions in the characteristic zones of the furnace (gas flow distribution, pressure, gas permeability of the charge, etc.).	Rational in terms of costs and efficient in terms of the results of using the components of the energy potential of gases (CO, H2): their chemical and physical heat as a condition for increasing the productivity of the process.
4	Analysis of the influence of chemical composition and granulometry of the components of the base charge (iron ore components and fuel).	Improving the gas permeability of the base charge layer, reducing energy costs for its purging, reducing the level of dust removal.
5	Improvement of the technology of preparation and supply of PCF (drying, grinding, dosing, introduction of oxygen into the blast.	Improving the gas permeability of the base charge layer, reducing energy costs for its purging, reducing the level of dust removal.
6	Comprehensive environmental assessment of the level of CO_2, SO_x, NO_x emissions with/without the use of PCF and its replacement with pyrolyzed biomass.	Reduction of harmful emissions, increase of environmental safety of production.

In our opinion, the consequences of the use of secondary iron-containing materials and pyrolyzed biomass (pyro-biocarbon – hereinafter referred to as PBC) in the blast furnace process should be considered to establish their impact on the process, by implementing the following step-by-step research algorithm: improving the technology using these materials → determining specific technical requirements for their granulometry, physical properties, chemical composition → establishing particles and their rational ratio. The introduction of which will not increase/decrease the specific consumption of coke, will not worsen the gas permeability of the charge, the quality of pig iron and will not reduce the productivity of the blast furnace.

According to the scheme of the previously developed algorithm, we will focus on the analysis of the probable consequences of the use of secondary iron-containing resources, pyrolyzed biomass and materials obtained by joint heat treatment of components of their mineral base and waste of plant origin containing carbon.

1. Impact on the consumption of reducing agent (coke). Partial replacement of a certain proportion of PCF and PBC coke injected into the furnace in the blast stream by implementing PCI-like technology can reduce coke consumption. In this case, the real replacement factor depends on the origin of the material containing carbon, its composition and, especially, on the method of production, during the implementation of which the physical and chemical properties and functional spectrum of the purpose of the substitute

material are formed. And a change in gas composition, which provides a change in the growth of the value of the H_2/CO indicator, can, in turn, cause a change in the intensity and features of the reduction of the components of iron ore components of the blast furnace charge.

Regarding the question of the essence and expediency of using the terms "biochar" and "pyrucarbon". It refers precisely to the terminological distinction in modern thermochemical technology of carbon materials.

Pyrolysis is the thermal decomposition of organic raw materials without access or with limited access to oxygen (αO2 < 1). That is, regardless of the temperature or type of furnace, this process is the basis of both biochar and pyrocarbon.

Biochar is a solid product formed by the pyrolysis of biomass, usually at low or medium temperatures (300÷700 °C) [2]. The main characteristics of its production process include the following:

- preserves the structure of the initial biomass (porosity, carbon matrix);
- has a high content of fixed carbon (60÷90%), but still contains volatile substances;
- it is used in metallurgical processes, in particular as a substitute for coke or anthracite, as well as energy as a fuel, ecology as a sorbent, CO_2 absorber;
- in the future, the beneficial properties of carbon can significantly expand the range of its functional purpose in combination with other elements.

As for pyrocarbon, according to [3], it is more temperature-forming, which is formed during deeper pyrolysis or carbonization, when volatile components are almost completely removed. Its important properties include: almost pure amorphous or graphite-like carbon; high electrical and thermal resistance; lower reactivity than biochar; used in composites, anodes, electrodes, metallurgical processes as a reactionally stable material. reducing agent. The temperature range for obtaining pyrucarbon according to the data [3] is 800 -1300°C, the coefficient of excess oxygen ensures the production of volatile content ≤5 % in it, and together these parameters provide a compact, graphite-like structure of carbon and complete carbonization.

Based on the analysis of the features of the relevant technologies, the temperature criterion and their other differences, Table 2 was created, the data of which allow determining the limit in this issue

Table 2 – Characteristic features and parameters of biochar and pyro-biocarbon production processes.

No.	Parameter	Biochar	Pyro-biocarbon
1	Pyrolysis temperature	300÷700°C	At 300 ÷ 450°C - low-, and in the range of 800÷1200°C - high-temperature biomass pyrolysis
2	Degree of carbonation	Partial	Partial/full
3	Volatile content, %	10÷40	min - ≤5, max ~40
4	Structure	Porous, organic	Compact, porous/graphite
5	Application	Sorbent, energy (fuel/reducing agent)	Reducing Agent/Fuel, Synthetic Materials for Metallurgy
7	Process atmosphere	α_{o2}= 0,7÷0,9 (insufficient oxygen supply)	α_{o2} = 0,3 ÷0,85- regulated by the type, conditions of the thermal unit and factors of external influence on them

In the studies, the results of which are given in [4], a two-level technological scheme for the production of metallurgical materials - slag-forming materials for the purpose of production has been developed: protection against secondary oxidation and cooling of steel, protective for the crystallizer of continuous caster and ladle, refining, deoxidation, as well as the production of an effective reducing agent. The use of experimental batches of materials, products of compatible pyrolysis of the initial mixture of components, in industrial conditions confirmed their effectiveness.

The characteristic features that determine the advantages of the technology of combined heat treatment of mixtures based on materials - waste of plant origin as a source of pyrocarbon, and their mineral part, the properties of the components of which form the composition, physical properties and spectrum of their purpose, include the following:

- technological flexibility and peculiarities of the behavior of the initial mixture in the conditions of an inclined rotary furnace ensure the production of pyrolyzed materials with a content of 5÷ 95% pyrocarbon in them by its heat treatment; up to 40% of pyrogases (CO, CH4, H2);
- parameters that are regulators of heat treatment conditions, namely the coefficient of excess oxygen (αO2), the temperature of the furnace working space, the speed of rotation of the furnace, the angle of its inclination, the specific consumption of charge, fuel and cooling conditions ensure the receipt of materials of the expected quality and the required purpose.
- the use of the secondary energy potential of pyrolysis products (their physical and chemical components) provided a reduction in the specific consumption of fuel (natural gas) by 50-75%, depending on the ratio in the initial charge of waste materials of plant origin (lignin) and components that form the mineral base of the product, usually from several oxides.

Therefore, in the future, in the study, pyrocarbon obtained under the conditions of a rotary inclined furnace, by implementing the technology created by DMetI scientists, will be defined as pyro-biocarbon.

Regarding the effect on the gas permeability of the charge layer [5].

In blast furnace production, gas permeability (permeability [5]) is often expressed in conventional units according to empirical dependencies of the type: $K=a(d_p)^2/f$, where: dp is the average diameter of the charge particles; f is the resistance factor (depends on the shape of the grains, humidity and their bulk density); a is the proportionality factor. The value of the permeability coefficient depends on the particle size distribution (small fractions reduce permeability; increased moisture reduces gas permeability;— particles that are heterogeneous in geometry cause "channel formation"; embankment pressure - when compacted, the pores are compressed; The position of the melting zone of the melting zone of small particles sharply impairs the permeability. As for the practical significance of the coefficient: high permeability contributes to the stable movement of gases (CO, CO_2, H2, H2O), uniform reduction of $Fe_2O_3 \rightarrow Fe$. Low - leads to the formation of "hanging" zones, an increase in pressure, overconsumption of coke and can cause disruption of the furnace. Therefore, ensuring optimal permeability is an important task in the formation of charge, granulation of agglomerate, preparation of pellets and coke and its substitutes (PCF, NG, PBC).

The introduction of a large number of finely dispersed PCF fractions (<5–10 mm) according to data from [5] leads to clogging of the pore space: the gas permeability of the layer decreases, the pressure drop increases, and local zones of "suffocation" of the gas flow appear. The identified negative effects will lead to an increase in specific fuel consumption and instability of recovery coefficients. Therefore, a prerequisite before feeding into the furnace is the operation of agglomeration / handling of substitute materials, which form a secondary reserve resource base of raw materials and fuel [6]. They, for the most part, are dispersed materials that have, for the most part, a man-made origin

3. To get a more complete picture of the likely consequences of the use of secondary resources, it is necessary to determine their impact on the behavior of the sintering zone. Their introduction into the charge will change its physical properties (temperature interval that determines the softening and melting temperatures, thickness of softening and melting zones in the characteristic zones of the blast furnace

4. Chemical risks. Secondary materials often contain an increased content of S, P, Cl, $R_{,2O}$, Zn, which, accordingly, increases the content of harmful impurities and their negative impact on the quality of the metal (S and P); leads to the accumulation of R2O in the slag/gas circuit, refractory furnace lining. and their substitutes. The total content of R2O (Na_2O+K_2O) should be, according to [7], limited to 2–3 kg/t of pig iron, depending on the characteristics of the blast furnace.

5. Effects of mechanical and physical origin. If secondary materials have low strength, they are able to form large amounts of fines and dust during the transportation of bulk materials, which makes it difficult to evenly distribute materials on the blast furnace when they are loaded. In the study [6], it was found that pelletized (pellets), pre-sintered (agglomerate) or cold-bonded briquettes, which have additionally passed the stage of stabilization of their properties, work much better under the conditions of the blast furnace process.

Thus, taking into account the consequences of the possible impact of the use of secondary materials in the form of the above effects and the occurrence of risks for the stability of the process, we can state the following. The creation and implementation of an algorithm for improved blast furnace smelting technology with their use is a step-by-step process, the successful implementation of which requires control of external risks, the source of which is the physical and chemical properties of substitute materials. It is advisable to define the scheme of its implementation using an integrated approach as: (A) preparation of secondary raw materials → (B) laboratory experiments/pilot tests → (C) phased introduction of experimental materials in a real furnace with constant monitoring and control of the main indicators of the process → (D) correction of technology parameters / specific consumption of coke, fluxes, etc., which will be determined by the test results as important.

Regarding specific technical requirements and recommendations regarding the "safety" of boundaries and quantitative ranges of parameters of secondary substitute materials. On the basis of the generalized and agreed upon the results of theoretical studies and the results of industrial practice adaptation of substitute materials to the conditions of blast furnace smelting (specific furnaces, technologies, coke consumption, agglomeration properties of iron ore components of secondary origin), the authors [7] define the following requirements-recommendations as important.

Granulometry of substitute materials for iron ore components:

- the target size of pellets/agglomerate is Ø 8÷16 mm with a probable optimum of 9÷13 mm) for pellets [8];

- the content of fractions <5÷10 mm should be ≤ 2–5 wt% of the total mass of iron ore materials. For "risky" stoves - aim for ≤2%. Fractions <1–3 mm should be minimized at the stages of control in the warehouse, when sorting materials) [9];

- the fraction of large pieces, depending on the characteristics of the furnace, can be 20–40 mm, but changes in the size in the direction of their increase negatively affect the gas permeability of the layer of charge materials. Therefore, it is necessary to control the ratio of fractions (large/medium/small) to avoid local "failures" in the course of the domain process.

Physical characteristics, according to [10], are determined by such indicators as:

- strength (pellets) - (+6.3 mm) ≥ 90–92%;

- abrasiveness - abrasiveness index ≤ 5–8% for typical classes;

- porosity/impact strength of the pellet: must ensure the preservation of shape during transportation before loading and in the furnace to a temperature of

1250–1350 °C.

Regarding the chemical composition of iron ore materials (pellets/agglomerate), the study [10] determines their rational chemical composition. For iron ore raw materials, it is desirable to have a Fe content of ≥ 60–65%. A lower iron content increases the amount of slag, which reduces iron yield [11].

Regarding (SiO_2), (S) and (P). For high-performance smelting modes, according to studies[10], it is necessary to strive to ensure the total content of + and raw materials in the fuel: SiO_2 ≤ 3–5%; sulfur (S) ≤ 0.02–0.06%, since most of it turns into liquid cast iron; phosphorus (P) ≤ 0.03–0.05%

For pyrolyzed biomass and biochar, the authors [12] requirements:

- total carbon: the higher and more stable its content, the better the replacement of coke;

- moisture - ≤ 5–10% (higher humidity worsens the quality of its introduction with blowing into the furnace, reducing the efficiency of coke replacement);

- ash, which may include harmful impurities (Cl, S, P, Zn) - their content must be minimized, because an increase in Zn, Cl provokes problems when they condense on furnace fires, corrosion, etc.

In addition to the requirements for the physical and chemical properties of ferroraw materials, an important issue is to determine its rational share, which should replace traditional agglomerate and pellets. Based on the analysis, it can be argued that their values depend on the specific furnace, specific consumption of coke, equipment, technology of their pelleting and other factors that have a theoretical basis and practical confirmation.

Thus, the total share of the introduction of iron ore substitutes that have not passed the agglomeration stage, which meet the basic requirements given above, can probably be ≤ 5% of the total mass of iron ore components. In the future, when implementing a step-by-step algorithm, it is advisable to increase it to 10–15%, which is confirmed by the results of the study [6].

It is advisable to increase the specific consumption of PBC (pyro-biocarbon) as a substitute for the coke fraction introduced into the furnace in blowing jets using PCI technology, replacing the corresponding share of PCF in it: initially from 10% of the coke equivalent; After successful tests, it is possible to increase up to ~15–20% of the equivalent, depending on the reactivity capacity, mechanical resistance, and other important properties of pyro-pyrucarbon. It can also be expected that the implementation of the combined method with the supply of PCF, PBC and NG in the air blast stream can become a factor that will contribute to reducing the specific consumption of coke, stabilizing the thermal balance of smelting and reducing the level of CO2 emissions, as indicated by the authors [12].

Generalized according to the results of the research and industrial practice, "safe" ranges of specific consumption of materials, substitutes for traditional components of blast furnace charge and blasting, it is necessary to adapt to the conditions of a particular furnace, which is noted in [13], only after pilot tests. In the future, based on the results obtained and after adjusting the main process parameters for new materials, the process is examined in real conditions on a blast furnace.

To create safe conditions for the introduction of the technology of introducing materials, which are defined as substitutes for the VFR part, which are introduced in the flow of air blast enriched with oxygen, the following practical measures have been defined. Achieving a significant level of energy efficiency of the combined heat treatment of the mixture of starting materials – waste in the conditions of pyrolysis of waste of plant origin is possible when monitoring the parameters of the current batches of raw materials and fuels: their chemical composition, humidity and granulometry, as well as compliance with the mass ratio of the components of the initial mixture.

When implementing biomass pyrolysis in the conditions of an inclined furnace [4], rotating, creates a spilling layer of charge, constantly updating the surface of interaction of volatile (CO, CH4, H2) with oxygen of the working atmosphere of a thermal reactor, - to control the temperature indicators, the duration of the initial mixture in the characteristic zones of change in its state: evaporation of moisture, drying, pyrolysis, and stabilization of the final product in terms of the content of pyrocarbon, C, volatile components, sulfur, phosphorus, SiO2. These indicators, together with its particle size distribution, determine the further spectrum of functional purpose of materials for heat treatment of the initial mixture.

A promising method of heat treatment of dispersed materials of substitutes based on waste materials of plant origin (biomass), based on the results of high-temperature experiments and practical use of the material [4], it is necessary to recognize the combined heat treatment of a number of materials of secondary mineral origin as its oxide part and waste of plant origin as a source of pyrocarbon. At the same time, the physical and chemical properties of the metallurgical product, which is based on secondary materials, were formed by transforming their initial properties under the influence of appropriate heat treatment conditions into an innovative material with the expected spectrum of functional purpose.

In the conditions of blast furnace production, when using innovative materials based on materials that form its secondary resource and fuel base, it is recommended to gradually increase them when introduced into the initial blast furnace charge or air-blasted feeding, starting, according to [14], with 5–10% of the coke equivalent, or the proportion of PCF, lime or iron ore component removed from the blast furnace before its sintering. The requirements, the fulfillment of which will ensure the effective use of materials of the secondary base of raw materials and fuel/reducing agent resources in the blast furnace process, are constant monitoring of the main parameters of the process: conditions of their loading and distribution, pressure drop, gas permeability of the charge material layer, coke consumption, changes in the composition of liquid pig iron and its productivity when introducing substitute materials into the charge (iron ore components) or into blasting.

The transition of blast furnaces from blowing natural gas (BNG) to the use of pulverized coal fuel (PCF) changes the conditions for the flow of heat and gas dynamic processes (physical chemistry of the furnace as a whole). The implementation of this technological solution can have a number of consequences that will affect the following parameters that are important for the stability of the process in the blast furnace.

1. Thermal balance of the process: decrease in the calorific value of the gaseous medium: PCF has a lower specific calorific value compared to BNG, which requires compensation due to increased oxygen consumption when the blast parameters change; increased thermal load on the tuture zone: PCF combustion is more localized, which creates high temperature gradients.

2. Gas-dynamic state in the furnace: increase in the volume of gases from combustion: PCF gives more CO and N_2, which changes the distribution of gas flow in the mine; deterioration of the gas permeability of the charge: small particles of coal and ash can accumulate in the intergranular space, increasing the hydraulic resistance of the layer; change in the nature of iron reduction: the ratio of CO/CO_2 and H_2/H_2O in gases on the furnace changes, which affects the kinetics of iron, manganese, silicon reduction reactions.

3. Chemical composition of products of chemical reactions and physicochemical transformations: an increase in the proportion of solid carbon in the reducing medium of the initial charge layer → enhances the carbonization of iron, affecting the composition of cast iron (an increase in carbon, sulfur is possible); increase in ash removal, PCF impurities (SiO_2, Al_2O_3, Fe_2O_3, S) pass into slag, changing its composition, basicity and viscosity.

4. Stability of the furnace running and controllability of the iron smelting process: ensuring an increase in sensitivity to fluctuations in blow parameters requires a more precise regulation of oxygen consumption, pressure, temperature and humidity; minimization of the likelihood of local "clogging" of the charge due to insufficient gas distribution; increased requirements for automated systems for control and regulation of the main process parameters, including loading and distribution of charge components.

5. Economic and environmental aspects: reduction of the cost of pig iron due to cheaper fuel (PCF) compared to coke and GHG; increase in specific emissions of CO_2 and dust compared to the use of natural gas; substantiation of the feasibility of combined injection (PCF + NG + H_2) for further optimization of the blast furnace process in terms of its energy and environmental indicators.

Thus, the transition of blast furnaces from natural gas injection to the use of pulverized coal fuel (PCF) leads to changes in heat-gas-dynamic (physicochemical) conditions in the furnace working space. This leads to certain consequences for the course of processes, the stability of pig iron smelting and the efficiency of its results. Table. 3 for the system "change - consequence - expected result" shows possible consequences and physicochemical effects, the source of which can be the replacement of natural gas with PCF (Pulverized coal fuel).

On the basis of analytical-theoretical analysis and scientific forecasting of the expected, when replacing the main components of the material and thermal balances of the blast furnace process (iron ore components of the blast furnace charge and natural gas), the results summarized in (Table 1-2), it is advisable to make a scientifically - practically grounded and generalized conclusion on the expediency of using combined blasting (PCF + NG + H_2) in the form of recommendations on their rational ratios, conditions, features mechanism and analysis of restrictions on the use of hydrogen in blast.

Regarding the mechanism of action and factors affecting the level of application in the production of hydrogen pig iron:

1. According to the data given in [15], which are consistent with the thermodynamic forecast, hydrogen (H_2) contributes to the shift in the development of iron reduction reactions to the upper part of the furnace, increasing the proportion of indirect reduction. This reduces the specific consumption of coke and CO_2 yield, but becomes a source of the cooling effect of the charge. The thermal level of the process decreases: RAFT (raceway adiabatic flame temperature) falls, which requires compensation for heat losses by increasing the temperature and enriching the blast with oxygen and preheating the gases - components of the blast) [16].

RAFT (Raceway Adiabatic Flame Temperature) is the adiabatic flame temperature in the combustion zone near the blast furnace lances, i.e. the maximum temperature that is theoretically reached during the combustion of fuel (coke, PCI, gases) without taking into account heat loss. RAFT determines:

heat dissipation intensity in the lance zone;

FeO → Fe reduction conditions;

combustion stability and thermal balance of the blast furnace process.

The unit of measurement is degrees Celsius (°C) or Kelvin (K).

Typical values: 2000–2300 °C (for coke), 1900–2200 °C (at PCI).

2. The use of NG (methane) gives a high reducing capacity and, according to data [17], has a significant potential for coke substitution, but its dissociation is an endothermic physicochemical transformation that requires heating of NG before its introduction into the blast or additional oxygen, which will ensure the leveling of the effect of "cooling" the endothermic reaction of methane decay and retains RAFT [16].

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Table 3 – Generalized table of the impact of the use of PCF as a substitute for natural gas on the results of the blast furnace process.

No.	Changing smelting conditions	Consequence	Expected result
1	Replacing natural gas with PCF	Increase in specific oxygen consumption, change in the composition of the gas flow	Accelerating iron recovery, reducing natural gas consumption
2	Change in the ratio of gas volumes in the furnace	Increase in the proportion of CO, decrease in the content of H_2 in the gas phase	Increasing the regenerative capacity of the gas flow
3	Increase in the temperature of the torch in the combustion zone	Growth of temperature gradients in the lance zone	Intensification of heat exchange, improvement of charge melting
4	Increase in slag mass from PVP	Change in the composition and viscosity of slag	Improvement of cast iron desulfurization conditions in slag optimization
5	Reducing the gas permeability of the blast furnace with an excess of PCF	Complication of the course of gases, increase in hydraulic resistance	The need to optimize the granulometry of the charge and the flow rate of PCF
6	Increasing the proportion of carbon potential in the furnace	Intensification of FeO Reduction in Slag and Iron Ore Material	Reduction of specific consumption of coke, fuel economy
7	Increasing the amount of solid carbon in the combustion zone	Intensification of CO generation, increase in combustion temperature	Increasing the recovery capacity of the gas flow, improving the reduction of FeO
8	Reducing the volume of gases entering the furnace	Change in gas dynamics, decrease in N_2 volumes in blast furnace gas	Reduction of heat loss, increase in the concentration of reducing gases
9	Increase in the proportion of oxygen in the tuar's blow	Improving the combustion conditions of PCF, stabilizing the temperature regime	Increasing process stability and blast furnace performance
10	Change in the structure of the slag (introduction of additional sulfur and ash from coal)	Complications of the cast iron desulfurization regime	The need to optimize the chemical composition of slag and the slag mode of smelting
11	Increased heat load on the combustion zone	Risk of overheating of the lances, uneven heat distribution in the charge layer	Implementation of measures for cooling and control of the distribution of PCF

Pulverized coal fuel (PCF) contributes to the provision of carbon "support" due to the positive effects of slag formation from PCF ash components and the preservation of the structure of the coke bed; high PCF consumption is possible only at RAFT ≈ 2150 – 2300 °C when enriching blast O_2. ≈1200 °C and enrichment O_2. Marginal modes of use of H_2 were determined by the authors by the minimum permissible RAFT and the temperature of the furnace gases. The rational specific consumption of hydrogen injected into the furnace in the stream of carrier gas together with PCF, theoretically justified, modeled and experimentally confirmed by the authors in the study [19] in the absence of radical reconstructions of the furnace, is approximately 7÷20 kg of H_2/t of pig iron (~ 80 ÷ 220 nm³/t of pig iron). The equivalent of coke substitution is approximately 1.9 kg of PCF per 1 kg of H_2. From an industrial perspective, the injection of heated H_2 in the test blast furnaces demonstrated a 33–43% reduction in CO_2 when carefully balanced with the thermal balance of the smelting. This indicator, obviously, corresponds to the level of development of science, technology and equipment, the technical limit of which in the conditions of pig iron production is not typical for modern process modes.

As a summary based on the analysis of the results of the studies discussed above, it is necessary to give the following recommendations for the use of secondary materials - substitutes for iron ore components and coke in the blast furnace process:

As for the introduction of secondary components, it should be noted that the exact values of rational particles will depend on a specific blast furnace, technological features of the process, physical and chemical characteristics of coke, when operating them - from technologies and equipment for agglomeration and its other methods. Therefore, the recommendations below relate to the rational in terms of "starting" particles of substitute components, their chemistry and granulometry, the conditions of preparation for use at the stage of practical tests:

- keep the content of <5–10 mm fraction in the initial charge of ferroraw materials ≤ 2–5%;
- Fe content in pellets/agglomerate/pellets - ≥60–65%; the content of S, P – minimize (S ≤0.02–0.06%);
- $\Sigma(Na_2O+K_2O)$ – to control their total content at the level of 2–3 kg/t of liquid pig iron;
- biomass/materials of plant origin - must be pre-pyrolyzed and mechanically stable;
- pellets from secondary concentrates - 10-30% with optimization of the content of fluxes, coke, or other carbon source material.

We believe that for the appropriate level of development of blast furnace production technology, it is important to search for substitutes for traditional materials of its resource base, which will improve the process in the direction of increasing its energy efficiency in accordance with the social and environmental requirements of our time. And the rational use of the components of their physical and chemical potential should become a benchmark of efficiency for researchers when improving the process in the blast furnace.

Scientific and technological forecasting of the practical application of materials of the secondary base of resources of raw materials, fuels in the conditions of blast furnace production. The main requirements that will contribute to their effective use include the following parameters and characteristics: granulometry, physical characteristics, chemical composition of iron ore materials and pyro-biocarbon, as well as determination of approximate shares of substitute materials and practicalmeasures to ensure their safe implementation in blast furnace production.

In the conditions of blast furnace production, when using innovative materials based on production waste, which form its secondary resource and fuel base, it is advisable to gradually introduce them into the initial blast furnace charge or air-blasted feed, starting according to [12], with 5–10% of the coke equivalent, or lime as a particle removed from the blast furnace before its sintering. The requirements, the fulfillment of which will ensure the effective use in the blast furnace process of materials of secondary, with signs of man-made origin, the base of raw materials and reducing fuel, are constant monitoring of the main parameters of the process: conditions of their loading and distribution, pressure drop, gas permeability of the charge materials layer, coke consumption, changes in the composition of liquid cast iron and its productivity when introducing substitutes into the charge (iron ore components) or feeding into a blast furnace (PBV, dispersed CaO, etc.).

The operation of PCI blast furnaces can cause changes in the conditions of physicochemical and heat-gas-dynamic processes occurring in the reaction zone, which affect similar processes in other characteristic zones of the furnace [1] during the transition to PCI technology. Therefore, in order to determine the peculiarities of pulverized coal injection and its impact on the processes implemented in the blast furnace, we will consider the essence, goals and probable results of the impact on the main indicators of the blast furnace process. The process of modern technology is based on replacing part of the coke with a cheaper and more energy-efficient type of fuel.

Regarding the technological essence, goals and outcome of PCI. Dispersed coal dust (0÷75 μm) is supplied through the lances along with air directly to the coke carbon combustion zone of the blast furnace. As a result, part of the coke in the charge is replaced by PVP, which is supplied by jets of gas to the carrier gas into the zone of interaction of air oxygen with coke carbon of the blast furnace charge. The main goals of the introduction of PCI technology are: reducing the consumption of coke, which is a source of economic effect, because coke is the most expensive element of the charge - in the cost of pig iron it is ~ 40%; providing flexibility in the choice of fuel through the use of anthracite and other types of coal) and, as a result, reducing total CO_2 emissions

It is more expedient under the condition of heat treatment/preparation of dispersed materials - waste, which is proven by the results of high-temperature experiments and practice [4], is the implementation of combined heat treatment of a number of materials of secondary origin - mineral origin (oxide part) and waste of plant origin (sources of pyrolysis carbon). At the same time, the properties of materials based on secondary materials, the common feature of which is man-made origin, and their physical and chemical properties of the initial properties and composition of components, which, during combined heat treatment under the conditions of biomass pyrolysis, are transformed into the properties of an innovative material. The latter determine the spectrum of functional purpose of the material. The two-level closed circuit of regeneration of initial and secondary energy resources of the process developed by the authors allowed: to use the fuel and chemical energy of pyrogases in the thermal unit of the first level as much as possible; physical heat of gases generated during the combustion of pyrogas for pyrolysis of biomass in the second-level unit; chemical energy of pyrogas generated in the unit of the second level – as an additional source of fuel and chemical energy in the unit of the first level. A promising direction for improving the RSI technology is the replacement of a fraction of coke or PVP with materials based on pyro-biocarbon, which have undergone joint heat treatment [20].

A modern method of replacing part of the coke with a cheaper and more energy-efficient type of fuel, which is currently PVP, is implemented by implementing PCI technology) - injection of pulverized coal fuel into a blast furnace. The main goals of the implementation of the RSI are defined: reducing the consumption of coke, the most expensive element of the charge, by using fine coal dust (0–75 microns), which is supplied through the lances along with air directly to the combustion zone; achieving a higher level of energy efficiency of the blast furnace process; the possibility of using less scarce types of coal.

Regarding the reduction of CO_2 emissions, since less coke is burned (1 kg of PCI ≈ 0.85 kg of coke), according to [21], the coke replacement factor is not a direct indicator of the change in CO_2 emissions. The reduction in emissions is achieved by reducing the production of coke. In total, this gives a noticeable reduction in CO_2/t of pig iron [22]. The results of the study [23] also state that the coke replacement rate is not a direct indicator of changes in total CO_2 emissions.

The authors [21] refer to the optimal parameters of PCI technology that ensure the effectiveness of the use of VFR:

- consumption of pulverized coal fuel 120÷200 kg/t of pig iron (the optimal value according to their definition is 150÷180 kg/t);
- particle size: 0÷75 μm (average diameter 30-40 μm);
- humidity: ≤ 1.0 %;
- ash content: ≤ 10 %;

- volatile substance content: 18–25%;
- blast temperature: ≥ 1100 °C.

The study also determined that when inflating 150 kg/t, the coke savings are about 130 kg/t of pig iron.

In our opinion, the determination of the coefficient of replacement of coke with pulverized coal fuel, which is introduced into the zone of interaction of oxygen of air blast with the components of the charge, with the involvement of coke production and taking into account its CO2 emissions, is not scientifically, technologically and economically justified. This approach neutralizes the individual contributions of coke production and its use in the blast furnace process, generalizing them, which calms and distracts from the search for more advanced schemes and innovative materials, the introduction of which will meet the challenges of our time and are aimed at improving blast furnace production.

It is advisable to determine the following as components of the overall integral effect of partial replacement of coke with materials such as PCF, NG, H_2, pyro-biocarbon by using PCI technology (Pulverized Coal Injection):

1. Reduction of coke oven consumption in kg of coke/t of pig iron as a direct positive effect created by the partial replacement of coke, PCFNG, H_2 / pyro-biocarbon. It is determined by the substitution coefficient of each material introduced into the furnace [21].

2. Reduction of specific CO_2 emissions (kg CO_2 / t pig iron % of baseline values) as the total result of the reduction of carbon burned due to its replacement with H_2 or pyro-biocarbon [24]. At the same time, part of the hydrogen → H_2O, which reduces specific CO_2 emissions.

3. The introduction of H_2 into the blast changes the kinetics of the reduction reactions and the temperature regime, which contributes to a moderate increase in the productivity of the furnace, but in order to obtain the effect, according to [25], thermal compensation of the thermal balance of the process is necessary.

4. To guarantee the positive effects of the introduction of H_2, it is necessary to reduce technological and operational risks due to the preliminary heating of H_2/NG before the introduction of H_2/NG into the blast, modernization of lances, control systems, ensuring stable properties of PVP, pyro-biocarbon, as well as ensuring appropriate levels of logistics and their cost, especially H_2 [26].

Based on the generalization, systematization and coordination of the results of these works in a similar direction, an analysis of indicators for the system "Coke – PCI → PCF" for the conditions of the domain process was carried out (Table 4). Its use allows you to determine the difference in the use of materials (coke, PCF) according to the main energy, technological, environmental and economic criteria, which, based on the achieved process indicators, will make it possible to predict the prospects of their application. In Table. Figure 4 presents the results of the influence of PCI technology on the indicators of the domain process, systematized according to the data from [21-23, 27].

Table 4 – Impact of VFR use on coke consumption and main parameters of the blast furnace process.

No.	Parameter	Impact PCI
1	Coke consumption	It decreases (for every 1 kg of pulverized coal injected with the blast, approximately 0.8–0.9 kg of coke is saved).
2	Combustion zone temperature	It decreases, by about 80-100°C, so you need to increase the oxygen supply
3	Reducing capacity of gases (CO, H_2)	Increases, which has a positive effect on the level and time of metallization
4	Gas permeability of the charge	It does not change, it deteriorates slightly if you increase the consumption of PVP >200 kg/t of pig iron
5	Cast iron quality	Does not change at optimal melting mode
6	Blow consumption	Increases due to additional oxygen supply
7	Total heat of the process	It can decrease — partially compensated by an increase in the O_2 content in the blast

Based on the coordination of the research data analyzed in the work, the following are established as the most probable, rational parameters of the PSI technology:

- PCF consumption: 150–180 kg/t;
- particle size: the average diameter is 20–80 microns;
- humidity: ≤ 1.0 %;
- ash content: ≤ 10% using PCF, for pyro-biocarbon (PBC) - ≤ 5%;
- volatile substance content: 18–25%; for PBC – regulated by pyrolysis conditions (time, temperature, ɑO2);
- blast temperature: ≥ 1100 °C.

The interchange of coke with PCF, according to data [21], is approximately:1 kg of pulverized coal fuel can replace ≈ 0.75 - 0.90 kg of coke. With an injection of 150 kg/t PCI, the coke savings are about 130 kg/t of pig iron.

Coordination of the results obtained in the study, their systematization and generalization according to the main features, made it possible to coordinate them with the data of the analyzed works and on their basis to develop a comparative table. 5 the data of which, in our opinion, give an objective characterization of the reducing agents of the blast furnace process: coke, PCF and pyro-biochar of plant origin. The choice of indicators in it is focused on the energy, environmental and technological aspects of the blast furnace process, which makes it possible to predict the prospects for their use in the conditions of modern pig iron production.

Table 5 – Comparative data of indicators of carbon-containing materials and their impact on the parameters of the domain process.

Indicator	Coke	PCI - pulverized coal fuel	Pyro-biochar of plant origin
Origin	Primary product of coal coking	Crushed coal (anthracite or other types of thermal coal	Secondary resource with fuel and reducing agent properties obtained by biomass pyrolysis (wood, agricultural waste, lignin)
Filing form	Solid lumpy particles of 25÷80 mm, introduced into the furnace from above as a component of the charge, according to the algorithm of the current technology of its loading	Dusty, blown through the lance of the device in the flow of carrier gas (air blast)	The device is blown through the lance by analogy with the introduction of PCF into the blast furnace
Upper calorific value (HHV), MJ/kg	28÷30	25÷28	20–25 MJ/kg (depending on biomass origin and pyrolysis conditions)
Fixed carbon content, %	85÷90	60÷75	60 ÷ 70; 90÷96 (depending on the conditions of pyrolysis, the type of biomass, and the purpose of the pyrolyzed material
Ash content, %	10÷12	8÷10	1–5
Volatile content, %	1÷2	15÷25	20÷35 (at a humidity of ≤ 1.0, which is obtained in the process of drying biomass without the implementation of the pyrolysis stage, ~ 60)
Humidity, %	1÷3	≤1	initial for waste of plant origin 5÷10; lignin, which is a product of hydrolysis treatment of waste of plant origin 48÷60
Reactivity to CO_2 (CRI) / reactivity as a reducing agent	Low (slow combustion) / significant, implemented in the blast furnace process in the form of C and CO	High – burns quickly in the reaction zone when it is injected with heated air blast	Very high due to the porous structure of pyro-biocarbon/ higher than coke and PCF
Mechanical strength	High, which is necessary to maintain gas permeability to the blast furnace charge layer)	No requirements - it is introduced into the furnace with a heated air blast through lances, used mainly as fuel	There are no requirements for using PVP or GHG as a substitute. Medium – low strength requires agglomeration of pyrocarbon with iron ore material
CO_2 emissions from combustion, kg/GJ	94÷96	92÷94	15–20 (neutral balance, because CO_2 is of biogenic origin)
Coke substitution effect, kg/t of pig iron	—	0,8÷0,9 kg of coke per 1kg PCI	0,6–0,8 kg of coke per 1 kg of pyro-biocarbon
Optimal consumption, kg/t of pig iron	350÷450	120÷200	According to some data, 40÷120; clarified by further research
Effect on the temperature of the combustion zone	Basic level (2200÷2300 °C)	Decrease (by 50÷100 °C)	Decrease (by 50 - 100°C) - requires an increase in O_2
Gas permeability of the charge	High	Virtually unchanged	May decrease with excess specific flow rate
Impact on the quality of cast iron	Stable	Stable or slightly higher due to purity	Improves due to less sulfur and ash
Ash content	10÷12 %	8÷10 %	1÷5 % (depending on the type and raw material)
Sulfur content, %	0,5÷0,7	0,3÷0,6	≤0,1
Phosphorus content (P)	0,05÷0.1 %	0,03÷0,08 %	< 0.02 %
Impact on the quality of cast iron (S, P, Si)	Basic level	Slight decrease S i P	Significant decrease S i P
Equivalent of replacing coke	-	1 кг PCI ≈ 0,85 kg of coke (as fuel)	1 kg of pyro-biocarbon: as fuel ≈ 0.60÷0.85 kg of coke (depending on the carbon content); as a reducing agent - 0,90÷1, 1 кг

Table 5 (continued)

Indicator	Coke	PCI - pulverized coal fuel	Pyro-biochar of plant origin
Cost, % of coke	100	50÷70	40÷50 - due to the use of the heat of combustion of volatile and the use of physical heat of gaseous combustion products of volatile biomass under the conditions of its pyrolysis (CO2, H2O, NO2) and higher reactivity as a reducing agent
Environmental assessment	High values of CO_2 emissions and environmentally harmful gases	Less CO_2. With partial substitution with biocarbon, a decrease in CO_2 by 10÷20%	Minimal CO_2 emissions, renewable resource. Reduction of CO_2 by 40÷60%; SO_x < 0, 07.
Основна перевага	Стабільність властивостей і міцність	Reduced coke consumption, cost-effective	Environmental friendliness, higher reactivity as a reducing agent, renewability, low S and P content
Main disadvantage	High price, CO_2 emissions, exhaustive source	Requires blowing system, combustion control	Lower heat of combustion, dependence of chemical composition on the type of biomass
The best application	Base blast furnace charge (also agglomerated)	120÷180 kg/t of pig iron through lances	5–15% equivalent to coke; 20–30% replacement of PCF when implementing PCI.
Overall score	Traditional and reliable reducing agent	Cost-effective and flexible, requires further research and adaptation to the process conditions in the blast furnace	A promising substitute for the useful properties of PCF and NG (fuel, reducing agent), and in the future coke Requires further research on adaptation to existing technologies

Based on the generalization of the data obtained in the work, it is necessary to determine the following:

1. Coke is a basic, structural component of the charge, provides sufficient, regulated by external factors gas permeability and thermomechanical stability of the layer of components of the blast furnace charge.

2. PCI as a technological solution is an optimal, under the conditions of the development of science and technology, an intermediate option that reduces coke consumption without losing process stability.

3. Pyro-biocarbon is environmentally friendly, requires minor thermal correction of blowing (increase in oxygen, temperature increase and their control). An effective substitute for the share of coke can be effective when it is administered in an amount of up to 20–30% of the mass of coke.

Thus, with a high probability, it can be stated that the integrated-integrated direction of blast furnace production improvement, which combines the technologies of pulverized coal injection with the introduction of pyro-biocarbon, the use of hydrogen reduction agents, as well as the involvement of secondary iron-containing materials and fuel and energy resources of man-made origin, is a promising and strategically justified way of development of modern blast furnace metallurgy.

Regarding the requirements for metallurgical quality indicators of components and basic blast furnace charge, as well as for the optimality of combined blast parameters, based on the coordination of the research results analyzed above, the following was determined. The components of the expected and most real integral effect from the use of hydrogen technologies on operating furnaces should be the following:

- reduction of specific CO_2 emissions: approximately **−10 – 15%** in mode B, **−20 – 30%** in mode C (subject to careful thermal compensation of certain heat losses; 33–43% is currently confirmed in test furnaces with **heated** H_2 and special heat balance measures)..

- **coke oven consumption**: up to **≤ 280–310 kg/t** in modes B–C (actually recorded range of values) with high PCF/NG; H_2 injection allows you to reduce the carbon fraction, but requires optimization of O_2/Tsuv for RAFT).

- performance: +2÷8% depending on gas permeability limits and maintaining a rational thermal level - O_2 blast enrichment stabilizes the flame and the reaction zone of combustion of fuel components.

Theoretical analysis of the relevant sources and scientifically grounded forecasting of the physical and chemical features of the process in the blast furnace indicates the following.

Combined injection of **PVP + GHG + H_2** is **an effective** way to increase energy efficiency and "greening" of the blast furnace process, **provided that the heat balance is controlled** (RAFT, TCG) through **the enrichment of O_2, a sufficiently high TDV. and heating of gases injected into the blast furnace** . . with a consistent, phased increase in the flow rate H_2 and a corresponding correction of PVP/O÷$_2$ **coke ≤ 280 ÷ 310 kg/t**. With such indicators, the stability of the blast furnace process is also maintained.

Determining the prospects of technological solutions for the efficiency of the use of VFR and GHG as substitutes for coke, increasing the level of use of useful properties of the initial potential of traditional raw materials and fuels is a reserve for improving the blast furnace process.

The reserves of the blast furnace process as a set of hidden or not fully realized technical and technological capabilities of blast furnace smelting, allow, when they are involved in the process of iron smelting, to determine specific technical directions for its improvement by:

- reduction of specific fuel consumption (coke, VFR, PCI, pyro-biofuel energy);
- increasing the productivity and duration of the furnace campaign;
- improving the quality of cast iron;
- reduction of CO_2, CO, NO_x, SO_x and dust emissions;
- rational use of the properties of secondary and alternative resources of raw materials and fuel, which contributes to ensuring the stable operation of the furnace.

Regarding the forecast for the development of blast furnace production in Ukraine, taking into account the resource base, the level of technology development, the state of the environment and economy during the war.

After a sharp decline in 2022 (due to the destruction of factories, changes in the quality of mineral raw materials, fuel, their sources and logistics supply routes), the recovery in 2024-2025 was partial, but the metallurgy sector as a component of the state's economic potential is still well below the pre-war level, and the total capacity remains reduced due to the failure of a significant part of the plants.

Raw material and energy constraints (especially coking coal, ultra-high electricity prices) are a key bottleneck for the sustainable recovery and further development of carbon metallurgy. To compensate for them, manufacturers increase coke imports, which can cause risks in logistics and pricing. And the growing level of exports of iron ore intermediate products (enriched concentrate, pellets) significantly reduces the possible added value - the profit of the enterprise, industry, state.

The resumption of exports remains dependent on the operation of ports and railways; Logistics tariffs and safety of transportation of metallurgical products affect their competitiveness.

Environmental commitments and the global decarbonization trend are driving the transition from large blast furnaces to a steel production scheme using EAF/DRI solutions (direct reduced chipboard/iron) and the use of hydrogen technologies in the medium term.

The combination of the technology of injection of pulverized coal fuel with the introduction of pyro-biocarbon, the use of hydrogen, as well as with the involvement of secondary iron-containing materials and fuel and energy resources of man-made origin will make it possible to:

- reduce specific coke consumption and CO_2 emissions due to partial substitution, artificially created from fossil coal, coke for renewable bio-pyrocarbon materials of plant origin;
- to increase the resource and energy efficiency of the process through the utilization of by-products and secondary products of the metallurgical cycle;
- provide flexibility in managing the material, thermal and recovery balance of the furnace due to the combination of iron, carbon and hydrogen sources;
- to bring the blast furnace process technology closer to the requirements of low-carbon ironmaking.

Thus, the direction of further development indicated in the study is of high scientific and practical importance, corresponds to modern trends in circular metallurgy, energy efficiency and decarbonization, and also creates the basis for a gradual transition to hydrogen-oriented processes of direct and partially restored pig iron production.

The analysis of unused reserves of blast furnace production, and the development of innovative materials, including those based on man-made materials of metallurgical origin, made it possible to develop a method for the production and use of "black lime" as a monomaterial, which is advisable to introduce into the blast furnace in combination with other air blast components (PVP, NG), as a substitute for part of their specific costs.

Fig. 1 shows the form of "black lime -CHV", which was obtained under the conditions of a pilot installation - a laboratory inclined drum-type furnace with a rotating drum at α_{O2} = 0.85; Tmax = 1150°C. Material composition in % wt.: CaO = 88.2; C = 10.7.

The results of the research, which were obtained when determining the features of the combined pyrolysis of dispersed lime and lignin - the waste of agricultural waste processing, indicate that the degree of fixation of pyrocarbon on the particles of the mineral base (CaO) is 20 times higher than the similar indicator of mechanical mixing of two dispersed materials.

Fig. 1 – The appearance of "black lime" after carrying out compatible pyrolysis of components in the conditions of the spilled layer at temperature T_{max} =1150°C, α_{O2} = 0,85.

Pyrucarbon is firmly fixed on the surface of lime particles, significantly increasing the size of monomaterial particles (2.5 ÷ 4.5 mm).

Regarding the fractional and chemical composition of dispersed lime accumulated in gas cleaning cyclones during the production of metallurgical metastable lime, it is necessary to determine the following. The typical fractional structure of pulverized lime is very variable and depends on the type of dust collector (cyclone/bag filter), combustion / calcination and grinding conditions. In the practice of metallurgical lime production, lime dust has the following fractional composition <10 μm-5–30 %; 10–63 μm - 30–60 %; 63–125 μm-10–30 %; 125–250 μm-5–15 %; >250 μm - 0–5%. The given ranges of lime dust are often fixed in practice.

Under the conditions of high-temperature pyrolysis of the initial charge based on a mixture of CaO and a material of plant origin containing carbon, at its initial moisture content ~ 17.8% and temperature of ~ 1200°C, the following physicochemical processes and transformations are carried out:

- at the stage of preparation - mixing of components - primary enlargement of dispersed particles of the original mixture, which led to the hydration of lime (CaO → CaCO3);

- under the conditions of heat treatment with the implementation of compatible pyrolysis of the mixture - final enlargement with the formation of a product - monomaterial CaO-C_{pyro}; dehydration of lime (CaCO3 → CaO); stabilization of fractional, chemical composition and properties of monomaterial;

- cooling of "black lime", its accumulation, transportation, quality control, functional purpose.

In addition to pulverized lime, it is advisable to use a fraction of CaCO3, which is formed in sufficient for industrial use (recycling) as a component in the CaO-C mixture.

As for the methods of production of Ch. For the first time, on the basis of theoretical justification after experimental testing in laboratory conditions, the method of black lime production was implemented under the conditions of an inclined rotary kiln using the initial mixture of lignin (humidity ≈ 48%) + fineness CaO (dry). The result of the next stage of the study was the development of a method for obtaining HF without the use of external sources of thermal energy [28].

The implementation of the process in the temperature range, which is 1150 ÷ 1200°C, made it possible to dehydrate lime using the thermal effect of the reaction to heat the initial mixture before loading it into the furnace, as well as to exclude the development of the FexOy reduction reaction with pyrocarbon. The content of iron oxide in an innovative material - a product of heat treatment of the components of the initial mixture, determining the level of its oxidation potential, expanded the range of functional purpose and physicochemical capabilities of the pyrolyzed monomaterial (CaO + C + FeO) as a slag-forming material [4].

The calculation method established the optimum replacement of PVP in the composition of PVP blasting with black lime, which is 10÷13 % of the specific consumption or energy contribution of PVP. At the same time, there is an objective possibility of reducing the modulus of the basicity of the agglomerate (and, accordingly, the basicity of blast furnace slag), which in the modern blast furnace process is the main iron ore component of the charge, to B ≈ 1.15, which reduces the melting point and viscosity of the blast furnace slag. At the same time, we should expect an acceleration of the dissolution of CaO in the furnace slag, which intensifies the desulfurization of cast iron.

Thus, an additional advantage of the use of monomaterial (FR) is the improvement of the agglomeration process, the properties of the sintered material, the reduction of the specific consumption of limestone and fuel for sintering of the initial charge, and in the future, in the blast furnace process: increasing the stability of tuyere devices (coating CaO with pyrocarbon reduces abrasiveness/corrosion), reducing the specific consumption of PCF, coke and CO2 emissions.

The calculations determined that for the initial conditions (current PCF supply = 120 kg/t of pig iron; carbon content 85%; black lime: C content ≈ 25%, free CaO ≈ 75%) when replacing 10% of PCF with black lime by mass of PCF, approximately 30.6 kg of CaO/t of pig iron will be introduced into the reaction zone of interaction with the components of the charge. With the optimum replacement of PCF with black lime, which is 10–13%, the introduction of such an amount of CaO into the furnace is sufficient to significantly affect the local balance of slag basicity in the lance zone. However, it is necessary to adjust the amount of fluxes to obtain the recommended limits of the basicity of furnace slag by reducing the corresponding indicator of iron ore agglomerate to ≈ 1.15. That is why, when implementing this technological solution, the optimal combination of adding CaO, which contains pyrolyzed monomaterial "from below" and reducing part of the fluxes included in the agglomerate fed from above, is achieved.

Let us turn to the analysis of physicochemical mechanisms explaining the above data.

1. Microcontact (CaO–C): Carbon is on the surface of CaO. The result of the reaction of carbon with CO_2 is a local intense formation of CO near the surface of CaO. This increases the partial pressure of CO, which contributes to rapid gasification, reduction of iron, that is, increases the efficiency of the fuel fraction, which reduces the specific losses of coke.

2. Faster dissolution of CaO in slag: dispersed CaO particles with a large reaction surface dissolve in the furnace slag faster, compared to the flux of agglomerate fed from above. Therefore, at an early stage of the formation of furnace slag, a rapid local correction of its basicity occurs, which increases the effect of refining liquid drops of iron-carbon melt from sulfur.

3. Lowering the melting point of agglomerate at B ≈ 1.15: reducing the viscosity and melting point of the slag phase improves the conditions for its formation, removal and facilitates the contact of metal with slag as a condition favorable for creating kinetic advantages of desulfurization.

4. Protective coating of CaO - dust with pyrovchar: the layer of carbon on the surface of CaO reduces the abrasiveness and aggressiveness of materials supplied through the lances, helps to prolong the operation of blowing lances.

5. Improving the agglomeration conditions and strength of the agglomerate by reducing its modulus of basicity, which has a positive effect on the thermal balance of the process, reducing fuel consumption.

It is advisable to implement the practical use of innovative material based on man-made materials – waste from relevant industries that have passed a joint stage of high-temperature or low-temperature pyrolysis, according to two technological schemes. According to the first, the main goal is to improve the slag mode of smelting with a certain reduction of the modulus of the basicity of the agglomerate to B ≈ 1.15÷1.10, with obtaining an additional effect due to the use of the fuel component of the potential of pyro-biocarbon as a substitute of the corresponding share of PCF. For such a scheme, the rational range of the composition, which will provide the necessary properties and purpose of the CF, is defined: C = 10 ÷12%; CaO = 88 ÷90%. The second scheme is implemented in order to replace the maximum possible proportion of PVP with pyro-biocarbon (C_{pyro} → CO2 + Skox → CO), the reactivity of which as a fuel and reducing agent exceeds similar characteristics of graphite, coke and is on a par with charcoal. For this version of the technological solution, the content of PBC in the monomaterial is ≥ 85, and the effect of the presence of CaO in it is minimized. The possibility of its increase has been experimentally determined due to the introduction of 5÷7 % of dispersed waste of fine iron ore or metallurgical waste containing iron oxides into the initial mixture of components that are sources of C and CaO. In this case, in the tuyere zone of the furnace, the formation of the slag phase with the participation of CaO, which is part of the monomaterial, proceeds along the ferritic path, which accelerates the creation of furnace slag with increased reactivity.

Conclusions & recommendations

The integrated-integrated direction of blast furnace production improvement, which combines the technologies of pulverized coal injection with the introduction of pyro-biocarbon, the use of hydrogen reduction agents, as well as the involvement of secondary iron-containing materials and fuel and energy resources of man-made origin, is a promising and strategically justified way of development of modern blast furnace metallurgy.

Replacement of PVPCF (full or its parts) with a monomaterial - "black lime", in comparison with the supply of a mechanical mixture (PCF+CaO), subject to segregation during transportation, should provide a technological advantage - a better microcontact combination (CaO↔C) and less segregation in the supply path. The use of waste materials in the production of "black lime" also provides an economic advantage - a reduction in the cost of material and has an environmental orientation - the disposal of man-made waste. When using it as a blast component, it is necessary to exclude the possibility of bringing the basicity of furnace slag beyond the values recommended according to the current technological instructions.

The components of the direction of improvement of the blast furnace process, having a scientific justification, correspond to modern trends in circular metallurgy, energy efficiency and decarbonization, and their implementation contributes to the creation of a basis and conditions for a gradual transition to hydrogen-oriented processes of direct reduction of iron and, partially, carbon, recovered through the use of innovative solutions for the production of pig iron.

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