

SELECTION OF PULVERIZED COAL FUEL COMPONENTS FOR BLAST FURNACES BASED ON THE STUDY OF PHYSICO-CHEMICAL PROCESSES DURING THEIR HEATING

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Abstract

There is a global tendency to use technologies to save energy costs per unit of production in blast furnace production. This is due to the use of pulverized coal fuel (PCF) instead of part of the coke. Selecting the components of the PCF charge from a wide range of carbon-containing materials to expand the raw material base and minimize costs is an important task. One of these materials is peat. The aim of this work is to develop a methodology for the selection of pulverized coal fuel components based on a comprehensive study using peat milling as an example. Industrial experiments were carried out in an operating metallurgical plant. The particle size of PCF is no more than 70-100 μm . Thermal destruction of peat in an inert atmosphere is responsible for 59% of the mass loss. The maximum destruction rate is 2.69%/min compared to 2.0%/min for long-burning coal. The release of volatiles starts at 425 °C for lean coal, 300 °C for brown coal and 220 °C for peat. The destruction of the coal also leads to an increase in the specific surface area. It increases from 2.04 to 161.3 m^2/g for brown coal. Combustion accounts for about 27% of the total loss of peat mass; this value is twice as high for long-burning coal. The total thermal effect for coal ranges from 15510 to 17751 kJ/kg, for peat from 12816 to 14148 kJ/kg. The pulverized coal fuel produced during the pilot phase was blown into an industrial blast furnace. The equipment of the PCF feed path, the poppet mill, worked stably without changing the operating parameters. There were no deviations in the operation of the blast furnace. The introduction of peat reduced the consumption of lean coal. The consumption of PCF and natural gas has practically not changed.

Keywords: Blast furnace; Pulverized coal fuel; Dispersed state; Calorific value; Peat; Volatile fuel components

1. Introduction

Since the emergence of metallurgy, the main method of obtaining metals from ores has been to blow air through pieces of fuel and ore components. It was only in the second half of the 19th century that examples gradually began to emerge that it was more practical to burn not lumps of coal, but coal dust in blast torches or liquid fuel sprayed through nozzles. In other words, the switch was made to dispersed systems. It took another 100 years before dispersed systems were used in pyrometallurgical processes: pulverized coal fuel (PCF), sponge iron for steel smelting and others. The dispersed state of the substance thus became the basis for the development of pyrometallurgical technologies.

There is a global tendency to use technologies related to saving energy costs per unit of production in

blast furnace production. This is due to the use of pulverized coal fuel (PCF) instead of part of the coke. The trend is due to the cost of coke, which accounts for at least 30-50% of the cost of cast iron, as well as the shortage of coking coal and its low quality [1-2]. In addition to economic aspects, it is necessary to consider that coke production is one of the most harmful in metallurgy. The use of PCF allows the use of automated process control systems. The productivity of blast furnaces is significantly increased [2-3]. PCF is considered as a source of energy due to the burning of carbon. Coke in a blast furnace is not completely burned to CO_2 , but it mainly only burned to CO. Incomplete burning of carbon produces only 110 kJ/mol of heat instead of 350 kJ/mol when oxidized to CO_2 . It is known that of the mineral fuel reserves available in the earth's crust, over 93% are solid fuels (coal), and only 7% are liquid

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and gaseous (oil and natural gas) [4]. Over the past 20 years, pulverized coal injection has been mastered in blast furnace shops in more than 25 developed countries of the world. More than half of the annual production of cast iron is smelted with its use [5]. The consumption of pulverized coal fuel per 1 ton of cast iron has reached 170-290 kg, the share of its replacement of coke is 35-50% [5-6]. In several countries, work is underway to qualitatively improve this technology in order to increase the share of replacement of coke with PCF to 60-70% [6]. In the last 20 years, new or reconstructed blast furnaces have been built in conjunction with modern pulverized coal plants [7]: Russia, Spain, Brazil, South Korea, Turkey and other countries. More than 600 million tons of coal of almost all known brands are used for PCF annually around the world: anthracite, gas, long-flame, lean coals and others with a wide range of changes in the content of volatile and ash.

The selection of pulverized coal fuel charge components from a wide range of carbon-containing materials. This is done to expand the raw material base and minimize the cost is an important task. One of these materials is peat.

The purpose of the work is development a methodology for selecting the components of the PCF based on their comprehensive study on the example of milling peat.

2. Experimental

The processes occurring during heating of peat and coals were analyzed on a synchronous thermal analysis device (next, the thermal analyzer) STA 449 F5 Jupiter, combined with a mass spectrometer QMS 403 Aeolos Quadro. The thermal analyzer is a measuring complex in which the functions of a differential scanning calorimeter and highly sensitive analytical scales are combined. The control of the measurement and processing of the output information in the thermal analyzer is carried out on a computer using the software package "Proteus". The experiments were carried out in an argon atmosphere with different oxygen content in the measuring chamber of the device. The heating speed of the furnace is 10 °C/min, the total gas consumption is 30 ml/min.

A Tescan Vega 4 scanning electron microscope was used to study the structure of the material. It is equipped with an Oxford Instruments 30 Xplore energy dispersion console. This console allows determining the chemical composition. The diameter of the spectrum removal area is 2-3 microns. The content of the elements was determined with an accuracy of 0.1 wt.% [8].

The specific surface area was found by the Brunauer-Emmett-Teller method on the SORBI MS device. The highest calorific value was determined experimentally by increasing the temperature of water in a calorimetric vessel. A metal container is placed in this vessel for burning solid fuel in an atmosphere of compressed oxygen.

Industrial experiments were carried out at an operating metallurgical plant.

3. Results and discussion

The principal feature of the PCF is that, as already indicated, it is in a dispersed state unlike the other components of the blast furnace charge. The size of individual particles does not exceed 70-100 μm. The large specific surface area of the PCF (to our data 3.2 – 3.5 m²/g) determines the physicochemical properties and behavior of the material. In addition, dispersion dramatically increases the rate of burning. Reactions of reduction and burning on the surface of solid particles at temperatures above 900 – 1000 °C are in the diffusion mode. If we reduce the size of particles R, then the average distances L between neighboring particles in suspension will decrease proportionally to R, L = kR. Reaction rate V, which is the rate of particle size reduction:

$$V = -\frac{dR}{dt} \quad (1)$$

inversely proportional to the diffusion distance L:

$$V = -\frac{dR}{dt} = \frac{k_1}{L} = \frac{k_1}{kR} \quad (2)$$

We get for the response time:

$$t = \frac{R}{V} = \frac{R^2 k}{k_1} = k_3 R^2 \quad (3)$$

where k, k₁, k₂ are coefficients.

Thus, the response time t is proportional to R². If a suspension with grains of 7.4 mm reacts for 600 s, then a suspension with a particle size of 74 μm will react 104 times faster (0.06 s). Coal grinding is the most energy-consuming operation in the preparation of PCF. Therefore, the choice of the final product fraction should be based on a comparison of the costs of grinding and coal losses due to incomplete burning in the tuyere zone.

The heating time of individual peat and coal particles was estimated using the example of long-flame coal with a diameter of 80-100 microns to the temperature of 250 °C and 1000 °C without



considering possible reactions. The PCF is dried and crushed at a temperature of 250 °C, and PCF blowing is carried out in the tuyere zone at a temperature of 1000 °C. The problem of heating particles was solved by numerical methods in the Matlab package. The parabolic differential equation of thermal conductivity (nonstationary case) was solved under Dirichlet boundary conditions.

Peat on average has a higher thermal conductivity, heat capacity and lower density compared to coal. The heating time of peat particles is of the order of $4 - 6 \times 10^{-2}$ s, for coal it is more (10^{-1} s). It is likely that at such heating rates in industrial conditions, the processes of destruction and burning will overlap each other.

Calculations show [9] that when coal particles with a size of 100 µm are blown into the tuyere zone (at a blast temperature of 1000 °C), the particle's residence time in the tuyere zone is 0.01 – 0.04 s. It is comparable to or less than the heating time of individual coal particles to the blast temperature. Probably, for this reason, only about 80% of coal burns [9]. The rest will reach the borders of the tuyere zone in the form of degassed particles that are carried out through the grate. To reduce the loss of PCF, the blowing temperature is increased to 1100 – 1300 °C and its oxygen content is up to 25 – 33%, which requires additional costs. The completeness of the burning of peat particles due to greater thermal conductivity, shorter heating time and high dispersion of carbon will be higher than that of coal.

Coal is crushed, dried and classified in the poppet mill. To select the operating mode of this mill and the parameters of the tuyere zone of the blast furnace, data on the rates of reactions occurring in the PCF during heating are required. To date, scientists have studied the following problems:

- thermal destruction and burning of coal at different heating rates; activation energies have been determined [10-12];
- the effect of particle size, gas purge rate and oxygen amount on the destruction and burning of coal, on the composition of the gases released; reaction kinetics [12-15];
- thermal decomposition of peat at different oxygen content in the atmosphere, stages of mass loss and kinetics of reactions [16-19];
- composition of volatile compounds released during heating and burning of peat; activation energy and rate constants of the burning reaction and calorific value of coke residue [20];
- influence of the rate of heating of peat on its destruction and burning [17].

The data of different authors differ significantly, since many factors affect the properties and processes

in natural materials. There is no information in the literature about the use of peat as a part of pulverized coal fuel for blast furnaces. In addition, long-flame coals used as components of PCF are poorly studied.

The following results were obtained with the help of precision equipment (a thermal analyzer) [21]. Thermal destruction of peat in an inert atmosphere accounts for 59% of the mass loss. It is slightly higher than several literature data [17, 20]. It was found that the maximum destruction rate for peat is 35% higher than for coal (Fig. 1). It was found that the rate of thermal destruction decreases with increasing degree of metamorphism. For peat it is 2.69%/min, for brown coal it is 1.48%/min, for lean coal it is 0.55%/min, for anthracite it is 0.30 %/min. The release of volatile components begins later (at 425 °C for lean coal, against 300 °C for brown coal and 220 °C for peat). The loss of mass during burning does not depend on the oxygen content in the gas and it is about 86%. The heating of coal and peat was carried out in an atmosphere of synthetic air and in oxygen/argon mixtures. The peak rate of thermal destruction of long-flame coal was recorded at close temperatures: 6.7% O₂ – 439.5 °C, 10% O₂ – 438.4 °C, 13.3% O₂ – 434.2 °C, 20.9% O₂ – 439 °C. The rate of destruction practically does not depend on the oxygen content in the gas phase. The temperature of the beginning of the destruction of coal is 370-390 °C. The destruction products are H₂O, CO₂, CO, CH₄, H₂, SO₂, NO₂, NO (Fig. 2). The destruction of coal also leads to an increase in porosity, specific surface area and a corresponding increase in reactivity. Measurements on the device showed that the specific surface area of coal increases sharply during the removal of volatile components. For coals with a low degree of metamorphism, it increases by about 80 times. An increase in porosity leads to a decrease in thermal conductivity by orders of magnitude [22], which will slow down the rate of further heating of individual particles to the environment temperature.

The rate of burning coal and peat increases with an increase in the oxygen content in the sample washing gas (in the thermal analyzer) from 1.75%/min at 6.7% O₂ to 3.5%/min at 20.9% O₂ (Fig. 3). The rate of burning peat is higher than coal and it is equal to 4.5%/min in the atmosphere of synthetic air (Fig. 3). This corresponds to the law of acting masses, according to which the rate of reaction:



proportional to the partial pressure of oxygen P_{O₂}. The experimental temperatures of the beginning and end of burning, the maximum speed and the corresponding peak of carbon dioxide release fall with



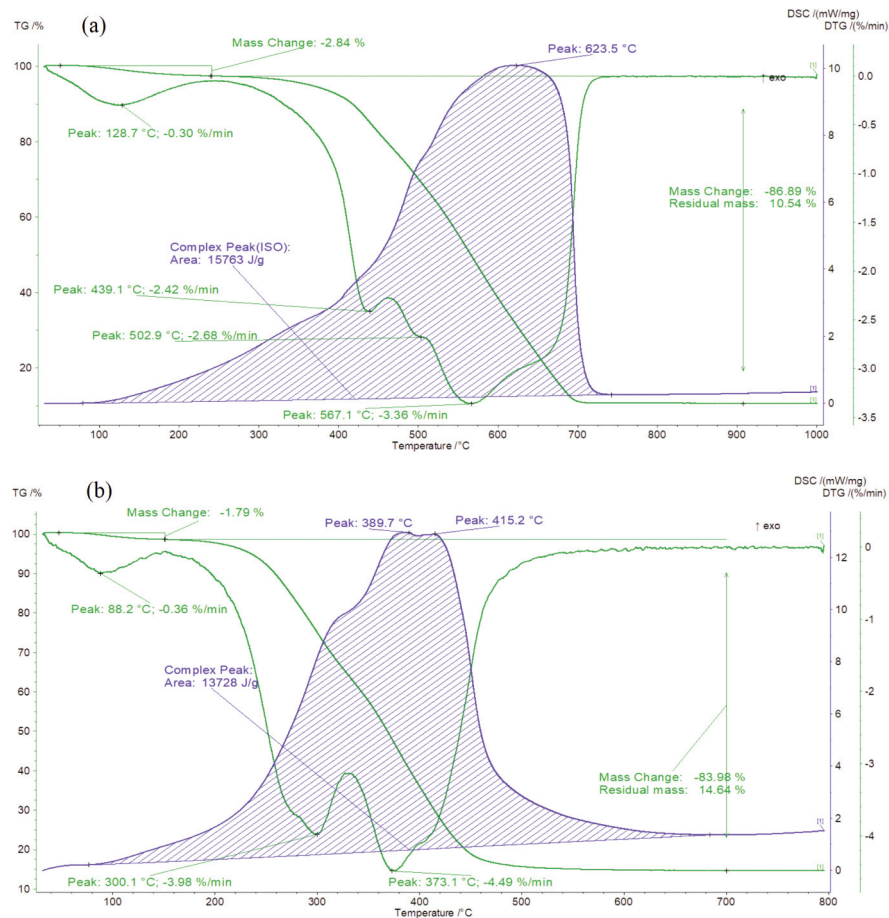


Figure 1. Curves of weight change (TG), rate of weight change (dTG) and thermal effects (DSC) when heating long-flame coal (a) and peat (b) in a synthetic air atmosphere (gas consumption 30 ml/min)

an increase in the oxygen content in the gas phase. For peat, all the listed temperatures are noticeably lower than for coal.

Burning proper refers to about 27% of the total loss of peat mass, whereas for long-flame coal this value is 57%. This is due to the low mass fraction of non-volatile carbon in the analytical sample of peat, $C_a^f \approx 26.3\%$.

Thus, it has been experimentally established that the power released during burning of peat is significantly higher than during burning of coal. This compensates for its lower calorific value.

A quantitative description of the relationship between the degree of transformation α during thermal destruction, time and temperature under non-isothermal conditions was carried out based on the assumption. This assumption is that a non-isothermal reaction in an infinitesimal period of time can be considered as isothermal.

Based on regression analysis, it was found that most of the experimental data are described by the Yander diffusion kinetics equation [21]:

$$f(\alpha) = \left[1 - (1 - \alpha)^{\frac{1}{3}} \right]^2 = K_{\text{Я}} \cdot \tau \quad (5)$$

and the destruction of brown oal are described by the anti-Yander equation:

$$f(\alpha) = \left[(1 + \alpha)^{\frac{1}{3}} - 1 \right]^2 = K_{\text{А-Я}} \cdot \tau \quad (6)$$

where $K_{\text{Я}}$, $K_{\text{А-Я}}$ are speed constants.

The thermal effects were determined by the DSC curves on the synchronous thermal analysis device, which are equal to the enthalpy change. The enthalpy change corresponds to the area under the DSC curve. It is calculated according to the Proteus program. Destruction and burning overlap each other. Both processes are exothermic. Therefore, the total thermal effect was determined, which for coal lies in the range from 15510 to 17751 kJ/kg. For peat it is lower (12816 – 14148 kJ/kg) due to the lower carbon



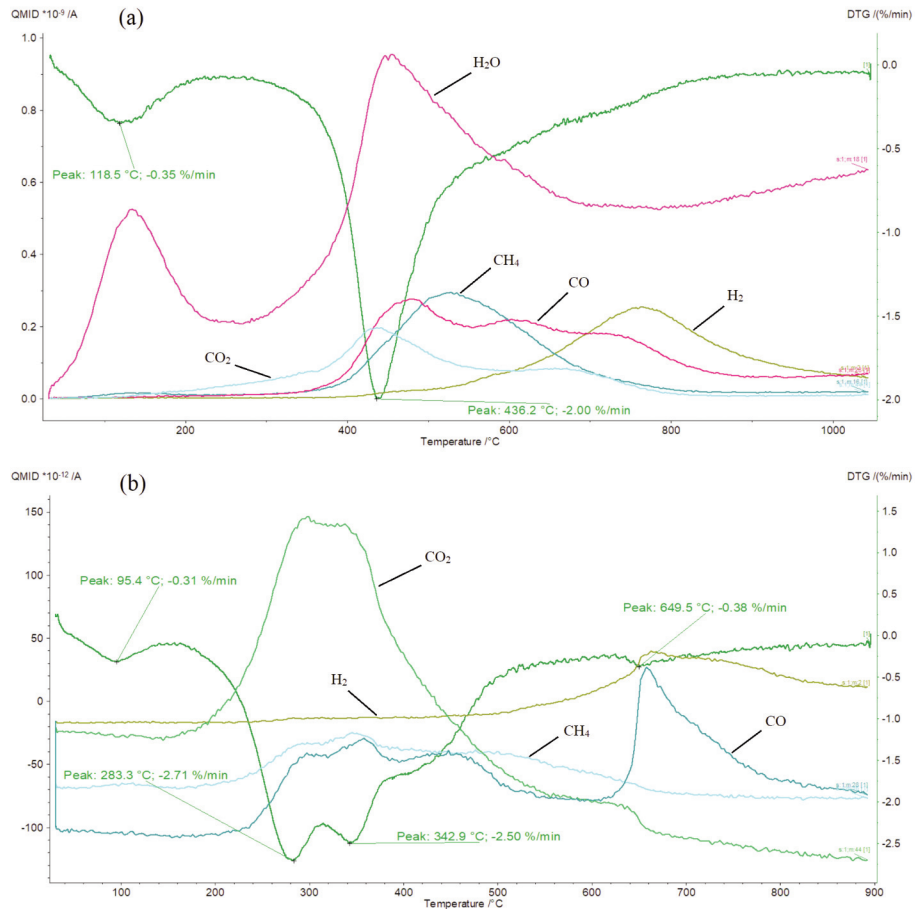


Figure 2. The rates of weight change (DTG) and the intensity of the release (QMID) of H₂O, CO, CO₂, CH₄ and H₂ from long-flame coal (a) and peat (b) when they are heated. The medium in the furnace is argon (gas consumption 30 ml/min)

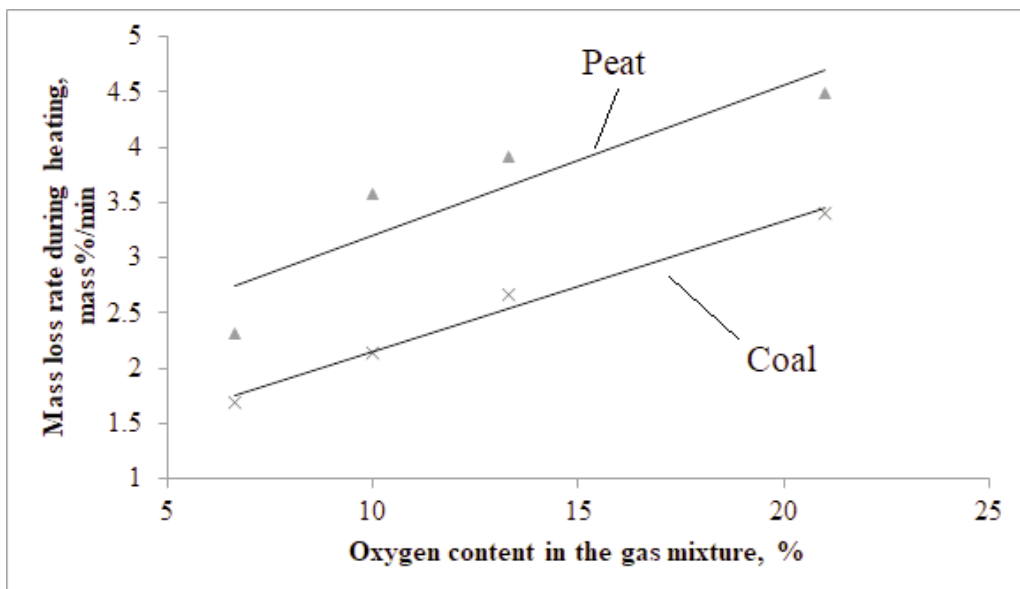


Figure 3. Dependence of the maximum rate of mass loss (peak of speed) of long-flame coal and peat when they heated to 900-1050 °C on the oxygen content in the gas mixture (total gas consumption 30 ml/min, heating rate 10 °C/min)



content. The highest calorific value of peat (in terms of the dry ashless state of the fuel) is also less for peat (23329 kJ/kg) than for long-flame coal (30961 kJ/kg). This highest calorific value determined by increasing the temperature of the water in the calorimetric vessel. The thermal effect of destruction was established alone in experiments with coal and peat in an argon atmosphere. It is 35-40% of the total amount of heat generated. The magnitude of thermal effects does not depend on the amount of oxygen in the atmosphere, since they are determined only by the initial and final states of the system.

A method was developed for replacing the components of the PCF charge with other types of fuel. The possibility of using milling peat instead of a part of lean coal was established. The second component of the PCF was long-flame coal. All this is done based on experimental laboratory and industrial experiments.

The composition of the PCF is selected experimentally, based on the technological conditions of the blast furnace process, considering the cost of the materials included in it. When choosing components, it is necessary to focus on the following parameters: carbon content and, accordingly, heat of combustion; low ash content (no more than 10%), its composition; minimum amount of alkali metal oxides; composition and amount of volatile substances. The calculation of the mass of the injected component should be based on the fact that the total carbon content in the basic version for a particular blast furnace should remain unchanged. The choice of parameters for drying the PCF is set based on the temperature intervals of destruction and burning components. Drying should be carried out at temperatures below the release of volatile and burning.

Peat differs from the coals used by a lower higher calorific value; a high yield of volatile $V^{\text{daf}} = 70\%$; high humidity (about 50%) and low carbon content $C^{\text{daf}} = 57.28\%$. Peat particles have an elongated shape of "fibers" ranging in size from 50 to 400 μm . The predominant particle structure is cellular (Fig. 4), less often fibrous and layered [23-26]. The average cell size is 10-30 μm . A comparison of peat studies with data on traditional PCF by ash composition shows that they differ in the content of the main components: CaO and MgO are elevated, Al_2O_3 is lower, SiO_2 is at a close level. The amount of alkali metal oxides (Na_2O , K_2O) and sulfur in peat ash is lower, phosphorus is slightly higher. The mass fraction of total sulfur in terms of the dry state of the fuel in peat is significantly lower than in PCF. Peat carbon is a part of cellulose, humic acids and other compounds [27]. As studies have shown, they are in a dispersed

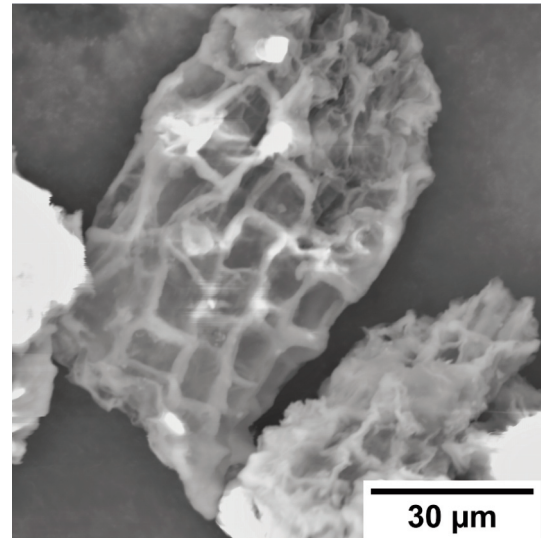


Figure 4. Peat particles with a cellular structure. The thickness of the walls of cells containing carbon does not exceed 1-2 microns. The picture was taken in BSE mode

state and they are distributed throughout the volume of peat fibers. The size of individual particles containing carbon is several μm . This explains the high rate of peat burning and the possibility of spontaneous combustion. In the process of thermal destruction, C passes into a separate presumably amorphous phase. It is established that the highest calorific value, the yield of volatile, the amount of non-volatile carbon in the PCF linearly depend on the peat content. The spread of values according to the key indicators for the PCF for coal charge (higher calorific value, volatile yield, carbon and sulfur content) does not exceed the values obtained even with the amount of peat instead of lean coal equal to 25% (Fig. 5).

Pulverized coal fuel produced during the pilot period was blown into an industrial blast furnace. The equipment of the PCF feed path and the poppet mill worked stably without changing the operating parameters. There were no deviations in the operation of the blast furnace. Due to the introduction of peat, the consumption of lean coal was reduced. Considering the carbon content in them, the substitution was 1 kg of lean coal on 1.59 kg of peat. The consumption of PCF and natural gas has practically not changed. The performance of the blast furnace, the basicity of the slag and the composition of the cast iron correspond to the work in the base period. The maximum peat content in the PCF mixture should be determined by the parameters of the blast furnace process (the temperature of cast iron, the composition of cast iron and slag).

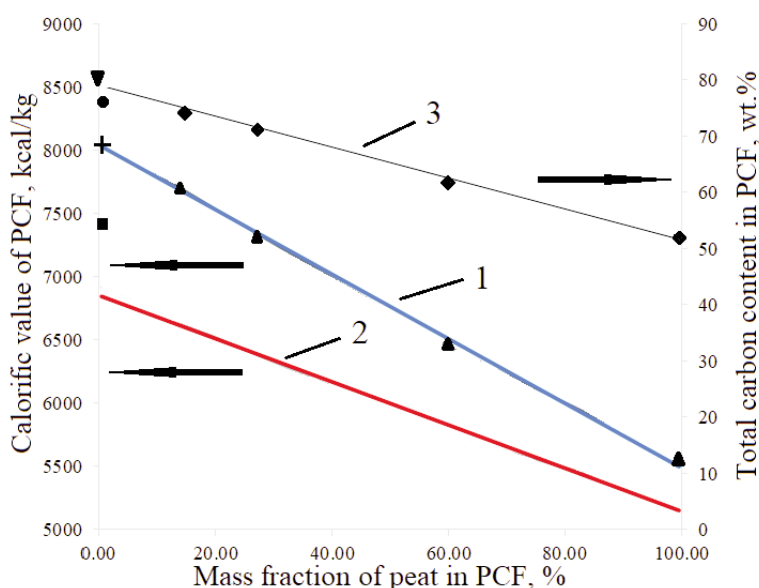


Figure 5. The dependence of the calorific value of the PCF on the content of dry ashless peat in it: 1 is the highest calorific value (calculated by additivity); 2 is the lowest calorific value (calculated by additivity); 3 is the total carbon content in the PCF; ▲ is experimental data on the highest calorific value; ● is the highest calorific value of lean coal; ■ is the highest calorific value of long-flame coal; ▼ is the content of non-volatile carbon in lean coal; + is the highest heat of combustion of PCF (calculation by additivity based on experimental data for lean and long-flame coal); the base PCF is 70% lean and 30% long-flame coal

4. Conclusion

The kinetics of thermal destruction and burning of PCF and its components, including peat, were studied with precision instruments. This was done during heating in an inert and oxidizing atmosphere.

The time of burning of PCF is inversely proportional to the square of the linear size. Grinding the coal is the most energy-consuming process in the production of PCF. Therefore, the choice of the final product fraction should be based on a comparison of the cost of grinding and coal losses due to incomplete burning in the tuyere zone of the blast furnace.

When selecting the components, it is necessary to focus on the following parameters: carbon content and, accordingly, calorific value; low ash content, its composition; minimum amount of alkali metal oxides; composition and amount of volatile substances. When calculating the mass of the injected component, it should be assumed that the total carbon content in the basic version for a given blast furnace should remain unchanged. The choice of parameters for drying the PCF is determined on the basis of the temperature intervals of destruction and burning components. Drying should be carried out at temperatures below the release of volatile and burning components.

The pulverized coal fuel produced during the pilot phase, containing peat instead of part of the lean coal, was blown into an industrial blast furnace. The

equipment of the PCF feed path and the poppet mill functioned stably without changing the operating parameters. No deviations occurred during operation of the blast furnace.

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Author contributions

Alexey M. Amdur: Supervision, Writing – review and editing, Investigation, Writing – original draft
Sergei A. Fedorov: Data curation, Writing – original draft, Conducting analyses and laboratory experiments

Data availability

Data availability will be provided on request.

Conflict of interest

The authors declare that they have no conflict of interest.



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IZBOR KOMPONENATA UGLJENE PRAŠINE KAO GORIVA ZA VISOKE PEĆI NA OSNOVU PROUČAVANJA FIZIČKO-HEMIJSKIH PROCESA TOKOM NJIHOVOG ZAGREVANJA

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Apstrakt

Postoji globalna tendencija primene tehnologija koje smanjuju energetske troškove po jedinici proizvodnje tokom rada visoke peći. To se postiže korišćenjem ugljene prašine kao goriva (PCF) umesto dela koksa. Izbor komponenata PCF smeše iz širokog spektra materijala koji sadrže ugljenik, kako bi se proširila sirovinska baza i smanjili troškovi, predstavlja važan zadatak. Jedan od takvih materijala je treset. Cilj ovog rada je razvoj metodologije za izbor komponenata ugljene prašine kao goriva na osnovu sveobuhvatnog istraživanja, koristeći mlevenje treseta kao primer. Industrijski eksperimenti su sprovedeni u metalurškom postrojenju. Veličina čestica PCF nije veća od 70–100 μm . Termička destrukcija treseta u inertnoj atmosferi odgovorna je za 59% gubitka mase. Maksimalna stopa destrukcije iznosi 2,69%/min u poređenju sa 2,0%/min za dugogorući ugalj. Izdvajanje isparljivih materija počinje na 425 °C za mrki ugalj, 300 °C za lignit i 220 °C za treset. Destrukcija uglja takođe dovodi do povećanja specifične površine, koja raste sa 2,04 na 161,3 m^2/g za lignit. Sagorevanje čini oko 27% ukupnog gubitka mase treseta, dok je ta vrednost dvostruko veća za dugogorući ugalj. Ukupan termički efekat za ugalj kreće se od 15510 do 17751 kJ/kg, dok za treset iznosi od 12816 do 14148 kJ/kg. Usitnjeno ugljeno gorivo proizvedeno tokom pilot faze ubrizgavano je u industrijsku visoku peć. Oprema za dovod PCF, kao i ventil sa čepom, radili su stabilno bez promene operativnih parametara. Nisu zabeležena odstupanja u radu visoke peći. Uvođenje treseta smanjilo je potrošnju mrkog uglja. Potrošnja PCF i prirodnog gasa praktično se nije promenila.

Ključne reči: Visoka peć; Ugljena prašina kao gorivo; Disperzno stanje; Kalorijska vrednost; Treset; Isparljive komponente goriva

