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ON SOME ASPECTS OF THE STUDY OF PULVERIZED COAL AND FUEL MIXTURES COMBUSTION IN A DROP TUBE FURNACE

The article considers some aspects of the pulverized fuel combustion modelling in the laboratory on installations called vertical tube furnaces (referred to as drop tube furnaces in scientific periodicals). We have considered the scheme of the installation to study the process of pulverized coal (PC) combustion in conditions similar to the conditions of heating and ignition of coal particles in the blast flow of the blast furnace and their subsequent gasification in the raceway. We have formulated the basic requirements for ensuring the reliability of modelling results. We have examined the methods of combustion completeness (burnout) estimation used in similar studies. We have proposed a convenient method for the estimation of the burnout of two-component fuel mixtures. According to this method, the estimation can be performed for any ratio of components in a two-component fuel mixture with the use of data on the initial ash content in each of them and the relevant burnout. We have obtained the estimated data on the dependence of the burnout of PC (anthracite, lean coal) with fuel additives. It has been shown that the proposed approach can be used to evaluate experimental data regarding the study of the combustion completeness of fuel mixtures. It has been established that for the initial stages of PC combustion (heating, emission and ignition of volatile matters), which occur before the fuel particles enter the blast furnace raceway, the fuel mixtures burnout values recorded in the experiments do not differ significantly from the estimated ones. For the final stages of PC combustion (heating and burnout of char), which occur mainly in the raceway and outside, the combustion completeness determined in laboratory studies was significantly higher than the estimated one. The obtained results confirmed the efficiency in the use of drop tube furnace to model the PC combustion process during the fuel injection with the heated blast flow in the blast furnace raceways and study of the influence of various factors on the combustion process. The results of such studies can be used to improve the design of PC injection units in the blast furnace and to study the possibilities for improving the coal particles combustion completeness and the specific consumption of PC.

Keywords: blast furnace, tuyere, raceway, pulverized coal (PC), drop tube furnace, fuel mixtures, additives, volatile matter, combustion completeness, burnout.

1. Problem statement

In the technology of pig iron smelting with the use of pulverized coal (PC), which is widely used in modern metallurgy, the use of fuel mixtures is promising, which is confirmed in practice, due to the growing shortage of quality coal. But the effective use of mixtures containing low-quality fuel or its substitutes such as waste from agricultural and other industries requires further research. One of the ways of such research consists in modelling of the PC combustion using the drop tube furnaces. This method is widely used by researchers and allows us to obtain results of practical value for the development of the processes of pyrolysis and gasification of various fuels, including those in power plants. But the methodology of laboratory studies with the simulation of combustion conditions which are similar to the conditions of PC combustion when injected into a blast furnace requires further development and refinement based on the gathered experience. The methodology for determining combustion completeness of mixtures in such studies also needs to be clarified.

2. Analysis of recent studies and publications

Coal usually has been and remains a raw material used for the production of PC for injection into blast furnaces. As a rule, it is unsuitable for coking, but it has high carbon content (anthracite, lean, etc.) and the lowest possible amount of ash and harmful impurities. At the end of the last century, the European plants of Tissen AG (now called ThyssenKrupp AG) and some others successfully tested and implemented the coal mixtures injection, with adding to the PC's main component a certain amount of coal with a high yield of volatile matters [1].

The A. Carpenter's monograph gives examples of injection of mixtures of PC with coal with a high yield of volatile matters, as well as with plastic waste, into a blast furnace. Concerning plastic waste, it is suggested that the interaction between coal and plastic waste can be used to increase PC combustion efficiency. Also, it can help to maximize furnace productivity while reducing costs and minimizing environmental impact. Among the problems with plastics, the author indicates the difficulty of their preparation to ensure a stable fractional and chemical

composition. Regarding coal mixtures, there are examples in which the flammability of PC from low-reaction coal is enhanced by mixing with coal with a high yield of volatile matters. However, the author raises the question of the need to further refine the relevant laboratory techniques and to verify the conformity of experimental data on the combustion of the mixtures with the conditions in the blast furnace. It is also emphasized the need to develop standard tests for evaluation of coal and plastic waste, standard tests for determining the reactivity of coal or plastic waste, and so forth. The main requirement is the compatibility of the test conditions with the conditions of the blast furnace [2].

Since the early 2000s, there have been more and more publications of studies on the combustion of new fuels, such as biomass of various origins and their derivatives, household waste such as rubber or plastics. For example, promising innovations in Japan involve combined injection scenarios in which crushed ore or renewable materials, such as biomass or plastic waste, are injected into blast furnaces through blow tuyeres. It is expected that such technologies can help to solve today's problems related to carbon emissions, energy production and resource availability [3]. However, the use of biomass in the metallurgical industry is still limited, and it is in strong competition with fossil fuels. As noted in publications [4, 5], the problems of biomass use in the metallurgical industry include technical and economic aspects that require synergies between the steel and bioenergy sectors.

Based on the above, it was advisable to compare the method developed and improved with the involvement of the author [6, 7], with those used in similar studies. The results of the analysis are shown in Table 1.

These examples became the motive for the refinement of the laboratory experiments method for modelling the combustion of PC and fuel mixtures using a drop tube furnace, as well as the methods for the evaluation of combustion process completeness and the influence of various factors on it.

Table 1

Comparison of methods for calculating pulverized fuel
combustion completeness used in some laboratory studies

Name*	Unit	Formula for calculation	Comments	Source
Combustion completeness	%	$$\left[1-\frac{A_{\text{PCl}}\left(100-A_{\text{res}}\right)}{A_{\text{res}}\left(100-A_{\text{PC}}\right)}\right]\times 100$$	A_{PC} – ash content in the original PC; A_{res} – ash content in the residue after combustion	[7]
Burnout	%	$$\left[1-\left(\frac{Ash_{\text{coal}}}{100-Ash_{\text{coal}}}\right)\left(\frac{100-Ash_{\text{char}}}{Ash_{\text{char}}}\right)\right]\times 100$$	Ash_{coal} – ash content in the original coal; Ash_{rc} – ash content in the residue after combustion	[8]
Burnout	%	$$\frac{Ash_{\text{uc}}-Ash_{\text{rc}}}{Ash_{\text{uc}}\left(1-\dfrac{Ash_{\text{rc}}}{100}\right)}\times 100$$	Ash_{uc} – ash content in the residue after combustion; Ash_{rc} – ash content in the original coal	[9]
Fixed carbon burnout	Unit fr.	$$1-\left(\frac{\%C_{\text{final}}\times\%Ash_{\text{initial}}}{\%C_{\text{initial}}\times\%Ash_{\text{final}}}\right)$$	$\%C_{\text{initial}}$ and $\%Ash_{\text{initial}}$ – content of carbon and ash in the original fuel, respectively; $\%C_{\text{final}}$ and $\%Ash_{\text{final}}$ – the same in the residue after combustion	[10]

* – reproduced according to the source materials

Name*	Unit	Formula for calculation	Comments	Source
Combustion ratio	%	$100 - \left(\dfrac{X_a \times A_b}{X_b \times A_a} \right) \times 100$	X_a and X_b – carbon content in the semi-coke particles and the raw coal, respectively; A_a and A_b – ash content in the semi-coke particles and the raw coal, respectively	[11]
Burnout	%	$\dfrac{10^4 \left(A_1 - A_0 \right)}{A_1 \left(100 - A_0 \right)}$	A_0 – ash content in the original coal; A_1 – ash content in the residue after combustion	[12]
Char burnout	Mass fr.	$\dfrac{f_a - f_{a,0}}{f_a \left(1 - f_{a,0} \right)}$	f_a and $f_{a,0}$ – mass fractions of ash in the residue after combustion and the original fuel, respectively	[13]

* – reproduced according to the source materials

3. The purpose of the study

The purpose of the study is to clarify the method of studying the combustion of PC, which is a mixture of coal with different degrees of metamorphism or contains several other types of pulverized flammable fuels. More accurate information on the processes that occur during the combustion and gasification of fuel particles in the hot blast and the blast furnace raceway is extremely important for the improvement of the PC injection technology, which is widely used in many enterprises.

4. The substantive material of the study

4.1. Method

The study of the pulverized fuel flow combustion was carried out in the drop tube furnace, the concept of which was developed under the guidance of P. Bondarenko and V. Kotov [6]. Later, this installation was improved in order to eliminate some shortcomings and expand the possibilities for modelling the final stages of PC combustion [7]. You can see a simplified principle diagram in Figure 1.
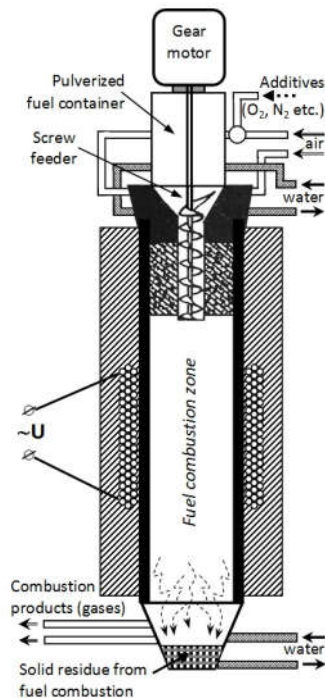

Figure 1 - Drop tube furnace scheme

In the upper part of the furnace the most critical unit of the installation is set: it is a screw feeder which provides the pulverized fuel to the combustion zone. In addition to the injection of fuel, this unit must provide oxidant delivery and uniform distribution of the oxidant, as well as cooling of the feeder structure elements to prevent premature heating of the fuel and other negative consequences. The combustion products and accumulation of the fuel residues after combustion are removed in the lower part.

Taking into account our own experience, as well as the results of experiments with the use of similar equipment of other researchers [8-13, etc.], the following basic requirements were met in the manufacture of the installation (Figure 1):

- the combustion zone of the furnace, where combustion takes place, had a clearly defined and unchanged over time isothermal zone of the required (under the conditions of modelling the combustion process) length;

- the design (technical characteristics) of the feeder provided acceptable dosing accuracy, stability and consistency of fuel consumption and its ratio to the oxidant (air, oxygen, etc.) throughout the experiment (series of experiments);

- the design of the cooler, mounted in the lower part of the furnace, provided a rapid stop of the combustion process (without smouldering) of fuel residues that have reached the lower part of the furnace;

- technical analysis of the raw fuel, as well as the residue after its combustion, was performed according to the requirements of the relevant standards [14, 15].

To evaluate the results of the fuel combustion process modelling, we used an advanced method [7], which was used to calculate the so-called combustion completeness (burnout) for a particular fuel. The main advantage of the method is the relative simplicity: only the data on the ash content in the raw fuel and in the residue after its combustion are used in the calculations. Comparison of this method with others (Table 1), which was given at the beginning, showed its acceptability in relation to the purposes of the study and the absence of fundamental differences with the approaches used in similar studies.

Several types of coal with different degrees of metamorphism, as well as peat and lignin were used in pulverized fuel fabrication. The raw coal and other fuels after drying were ground to a powdery state in a ball drum mill. The particles were ground to the size that meets the requirements for the PC fractional composition for injection into the blast furnace. The control of the fractional composition of pulverized fuel after grinding was carried out on vibromechanical sieves Fritsh Analysette. Technical analysis and fractional composition of fuels used in the studies are shown in Table 2.

Table 2

Proximate analysis and fractional composition of coal, peat and lignin

Type of fuel	Proximate analysis, %				Distribution by size, % (by weight)		
	W_t^r	A^d	S_t^d	V^{daf}	250-100 μm	100-71 μm	< 70 μm
COAL: Anthracite	6.7	17.2	1.26	4.8	39.9	31.6	28.5
Lean coal	10.0	9.5	1.82	10.6	29.8	40.8	29.4
Coal G	11.6	11.4	1.66	35.6	13.7	45.7	40.6
Coal D	12.6	26.3	1.38	40.0	17.8	33.0	49.2
Coal B	58.0	17.9	3.22	68.7	42.2	26.3	31.5
Peat	55.0	30.6	0.28	62.8	10.2	22.6	67.2
Lignin*	60.0	15.9	0.69	63.8	27.6	24.9	47.5

* – product of processing (acid process) of agricultural waste and wood chips

The isothermal zone of the furnace combustion zone (Figure 1) was constructed in such a way as to equal the residence time of the fuel to the residence time of PC particles entering the hot blast flow of the blast furnace at a point away from the tuyere cut by 0.3...0.6 m. This time was 0.01... 0.02 s, which corresponds to the estimates given in [16, 17], as well as to more recent ones, according to which the

residence time of coal particles in the PC plume before reaching the end of the raceway is about 0.01... 0.05 s [18]. Ensuring a stable and time-constant ratio between C_f and O_b (C_f – carbon content in the fuel, O_b – oxygen content in the atmosphere into which the fuel is released) was an important condition for modelling. Based on this ratio, the feeder productivity was calculated and the air flow was controlled (with or without oxygen).

4.2. Results and their discussion

Studies of previous years, the results of which were highlighted at the beginning of the article, showed the possibility to significantly intensify the PC combustion by adding coal with a high yield of volatile matters, as well as other fuel additives with low ignition temperature. But the next question remained unresolved, namely whether the higher completeness of fuel mixtures combustion is a consequence of mechanical mixing of individual results of combustion of two types of fuel, one of which has significantly higher flammability (combustion completeness in identical conditions).

To find the answer to this question, we composed and solved a system of six equations at the first stage:

$$\phi_1 = \left[1 - \frac{A_1^d \left(100 - A_{res1}^d\right)}{A_{res1}^d \left(100 - A_1^d\right)} \right] \times 100; \quad A_{\text{mix}}^d = A_1^d d_1 + A_2^d d_2;$$

$$\phi_2 = \left[1 - \frac{A_2^d \left(100 - A_{res2}^d\right)}{A_{res2}^d \left(100 - A_2^d\right)} \right] \times 100; \quad A_{res_{\text{mix}}}^d = A_{res1}^d d_1 + A_{res2}^d d_2;$$

$$\phi_{\text{mix}} = \left[1 - \frac{A_{\text{mix}}^d \left(100 - A_{res_{\text{mix}}}^d\right)}{A_{res_{\text{mix}}}^d \left(100 - A_{\text{mix}}^d\right)} \right] \times 100; \quad d_1 + d_2 = 1,$$

where φ_1, φ_2 and φ_{mix} are the combustion completeness (burnout) of the first and the second fuel of the mixture, as well as the mixture itself, calculated according to the method [6]; $A_1^d, A_2^d, A_{\text{mix}}^d$ and $A_{res_{\text{mix}}}^d$ are the ash content in the first and the second fuel, in the initial mixture and in the residue from its combustion (% by dry mass) respectively; d_1 and d_2 respectively are the share of basic fuel and fuel additive in the mixture.

As a result, we obtained an equation describing the dependence of the combustion completeness (burnout) of any two-component fuel mixture (φ_{mix}) on the amount of fuel additive (d) contained in it:

$$\phi_{\text{mix}} = \left[1 - \frac{\left(A_1^d - A_1^d d + A_2^d d\right)\left(100 - \dfrac{100(1-d)}{\dfrac{100-\phi_1}{A_1^d}+\dfrac{\phi_1}{100}} - \dfrac{100d}{\dfrac{100-\phi_2}{A_2^d}+\dfrac{\phi_2}{100}}\right)}{\left(\dfrac{100(1-d)}{\dfrac{100-\phi_1}{A_1^d}+\dfrac{\phi_1}{100}} + \dfrac{100d}{\dfrac{100-\phi_2}{A_2^d}+\dfrac{\phi_2}{100}}\right)\left(100 - A_1^d + A_1^d d - A_2^d d\right)} \right] \times 100, \%. \quad (1)$$

As can be seen from equation (1), the calculation of the fuel mixtures combustion completeness (burnout) requires data on the burnout of each fuel (φ) under conditions identical to the conditions of mixture combustion. For the fuels shown in Table 2, such data were obtained experimentally (Table 3). Experiments on the modelling of combustion in the initial stages (before the PC enters the raceway) were performed in the furnace shown in Figure 1. Modelling of the final stages was performed on the same equipment, but with some design differences which are considered in [6]. All studies of the PC and fuel mixtures combustion were carried out in normal ambient air without oxygen enrichment.

Table 3

Data on the combustion completeness of pure fuels (φ, %)
obtained experimentally in the furnace during PC combustion modelling (Figure 1)

Stages of PC combustion	Coal					Peat	Lignin
	Anthracite	Lean	Coal G	Coal D	Coal B		
Initial	12.2	17.4	41.4	44.1	51.4	59.6	56.5
Final	43.1	45.8	65.4	67.2	69.8	76.9	73.9

Using the obtained data (Table 3) with the equation (1) in the Excel spreadsheet environment, we obtained the dependences $\varphi_{\text{mix}} = f(d)$ for two-component mixtures of anthracite and lean coal with fuel additives. The proportion of additives (d) was varied from 0 to 50%. The results of the calculations are shown in Figure 2 and Figure 3.
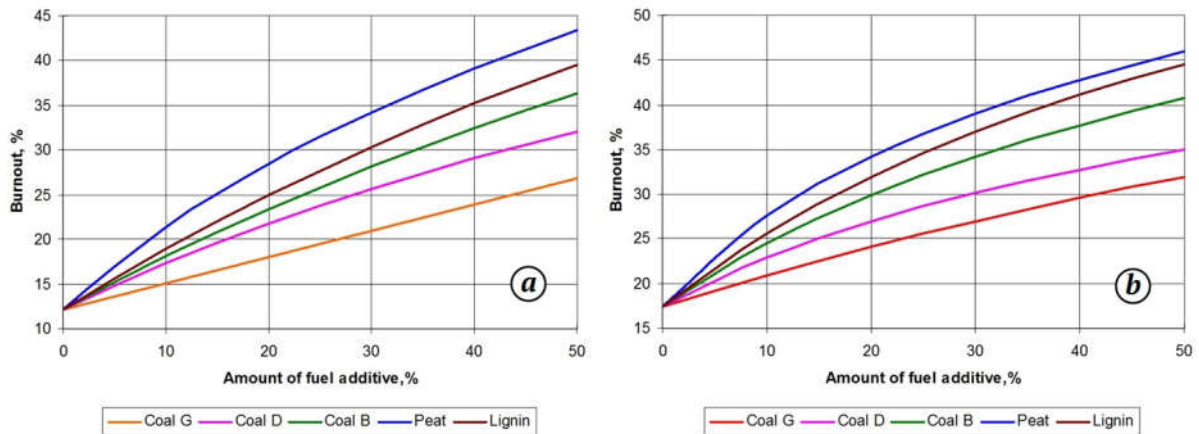
Figure 2 – Fuel mixture burnout (initial stages of combustion) depending
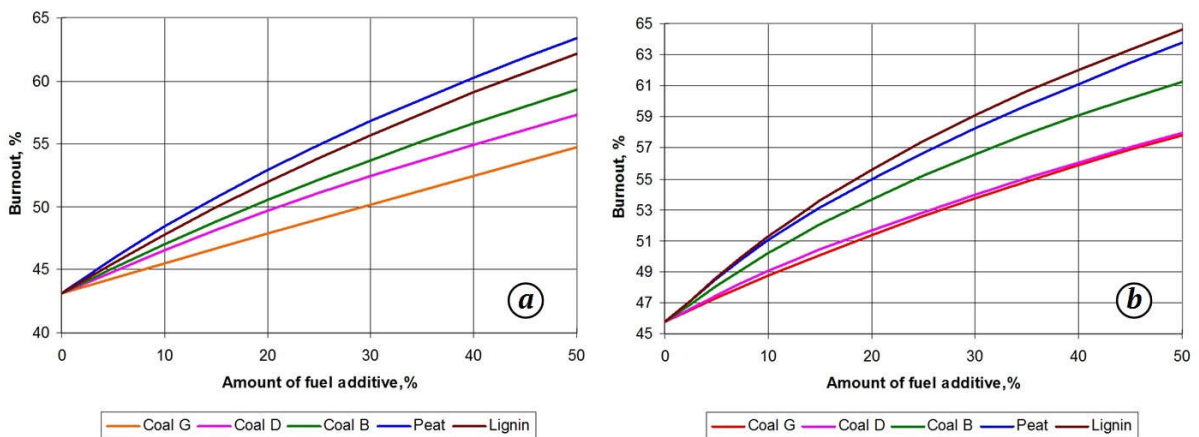on fuel additive amount: a – mixtures with anthracite; b – mixtures with lean coal

Figure 3 – Fuel mixture burnout (final stages of combustion) depending
on fuel additive amount: a – mixtures with anthracite; b – mixtures with lean coal

The results of the calculations shown in Figure 2 and Figure 3 were compared with experimental data regarding the fuel mixtures combustion completeness (burnout) in the initial and final stages of the combustion process. This comparison revealed that in the initial stages of the PC combustion process the experimentally determined combustion completeness of mixtures with the addition of fuels with a high yield of volatile matters does not exceed the calculated one. This is due to the short residence time of the fuel particles in the furnace's isothermal zone (in practice, in the hot blast flow in the area from the point of entry to the tuyere cut) and the rapid release of volatile matters from the relevant fuel additive. The latter is a significant barrier to the contact of oxygen molecules with the carbon skeleton of fuel particles. In the final stages, in contrast to the initial stages, the completeness of fuel mixtures combustion in the experiments was higher than the calculated one. With an increase in the share of additives in the fuel mixture over 15-20% (depending on the type of additive), the difference between the theoretical and the experimental combustion completeness increased markedly. It should be noted that

due to the small amount of experimental data, the obtained results need further clarification and are the subject of further research.

5. Conclusions and prospects for further studies

The analysis of recent publications has shown that the use of coal mixtures in energy and metallurgy, as well as fuel additives to PC such as biomass, wastes such as rubber or plastics, is very promising. We have considered the structure of experimental installation and the method for modelling the process of combustion of fuel mixtures during their injection into the blast furnace. We have offered the formula for the calculation of combustion completeness of PC mixtures with fuel additives. The obtained results allow us to summarize the following:

- in the initial stages of the PC combustion process, occurring in the inner space of the tuyere and partially in the raceway, the experimentally determined combustion completeness of mixtures with the addition of fuels with a high yield of volatile matters does not exceed the calculated one;

- in the final stages, the fuel mixtures combustion completeness in the experiments was higher. With an increase in the share of additives in the fuel mixture over 15-20% (depending on the type of additive), the difference between the theoretical and the experimental combustion completeness increased markedly;

- the proposed formula can be used to estimate the combustion completeness of coal mixtures of different quality, as well as PC with the addition of peat and other fuels containing carbon. The possibility to use the proposed formula in studies of PC combustion with the addition of wastes such as rubber or plastics needs to be clarified.

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ПРО ДЕЯКІ АСПЕКТИ ДОСЛІДЖЕННЯ ГОРІННЯ ПИЛОВУГІЛЬНОГО ПАЛИВА ТА ПАЛИВНИХ СУМІШЕЙ У ВЕРТИКАЛЬНІЙ ТРУБЧАСТІЙ ПЕЧІ

У статті розглянуті окремі аспекти моделювання горіння пилоподібного палива в лабораторних умовах на установках типу «вертикальна трубчаста піч» (в науковій періодиці - drop tube furnace). Розглянуто схему установки для дослідження процесу горіння пиловугільного палива (ПВП) в умовах, що подібні до умов нагріву та займання часток вугілля в потоці дуття доменної печі та їх подальшої газифікації у фурменому осередку. Сформульовані основні вимоги щодо забезпечення надійності результатів моделювання. Досліджені способи оцінки повноти згорання, що застосовуються в подібних дослідженнях. Запропонований зручний спосіб розрахункової оцінки повноти згорання двокомпонентних паливних сумішей. За цим способом розрахунок може здійснюватися для будь-яких співвідношень компонентів у двокомпонентній суміші палив з використанням даних щодо вихідного вмісту золи в кожному та відповідної повноти згорання. Отримані розрахункові дані щодо залежності повноти згорання ПВП з антрациту та пісного вугілля з паливними добавками. Показано, що запропонований підхід може застосовуватися для оцінки

експериментальних даних з вивчення повноти згорання паливних сумішей. Встановлено, що для початкових стадій горіння ПВП (нагрів, виділення та займання летких речовин), які відбуваються ще до потрапляння часток палива до фурменого осередку доменної печі, значення повноти згорання паливних сумішей, що фіксувалися в експериментах, суттєво не відрізняються від розрахункових. Для заключних стадій горіння ПВП (нагрів та вигорання вуглецевого залишку), що відбуваються переважно у фурменому осередку та за його межами, повнота згорання, визначена в лабораторних дослідженнях, виявилася помітно вищою за розрахункову. Отримані результати підтвердили ефективність використання установки типу «вертикальна трубчаста піч» для моделювання процесу горіння ПВП при введенні палива з потоком нагрітого дуття у фурмені осередки доменної печі та дослідження впливу на процес горіння різних факторів. Результати подібних досліджень можуть використовуватися для вдосконалення конструкцій вузлів введення ПВП в доменну піч і вивчення можливостей щодо підвищення повноти згорання часток вугілля та питомої витрати ПВП.

Ключові слова: доменна піч, фурма, фурмене вогнище, пиловугільне паливо (ПВП), вертикальна трубчаста піч, суміші палива, добавки, летючі речовини, повнота згорання, вигорання.

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