ECONOMIC AND TECHNICAL ENGINEERING

Scientific and practical journal "Economics and technical engineering"

Founders: State University of Economics and Technology
ISSN: 3041-1246
E-mail: ete@duet.edu.ua Journal homepage: https://ete.org.ua

JEL: L6

DOI: -10.62911/ete.2025.03.01.08

Approaches to determining the theoretical combustion temperature of fuel in a blast furnace furnace when varying the parameters of the blowing mode

Citation: Kassim, D., Chuprynov, Ye., Shmeltser, K, Liakhova, I. & Korenko, M. (2025). Approaches to determining the theoretical combustion temperature of fuel in a blast furnace furnace when varying the parameters of the blowing mode. Scientific and practical journal "Economics and technical engineering". Vol.3 No.1 (2025), 85-94. https://doi.org/10.62911/ete.2025.03.01.08

Daria Kassim
Prof. DSc, State University of Economics and Technology, Kryvyi Rih, Ukraine
e-mail: kassim@duet.edu.ua
ORCID ID: 0000-0002-1750-1237

Yevhen Chuprynov
Assoc. Prof. PhD, State University of Economics and Technology, Kryvyi Rih, Ukraine
e-mail: chuprynov_yv@duet.edu.ua
ORCID ID: 0000-0001-8605-3434

Kateryna Shmeltser
Assoc. Prof. PhD, State University of Economics and Technology, Kryvyi Rih, Ukraine
e-mail: shmeltser@duet.edu.ua
ORCID ID: 0000-0001-6830-8747

Iryna Liakhova
Assoc. Prof. PhD, State University of Economics and Technology, Kryvyi Rih, Ukraine
e-mail: liakhova_ia@duet.edu.ua
ORCID ID: 0000-0001-7589-8351

Maryna Korenko
Assoc. Prof. PhD, State University of Economics and Technology, Kryvyi Rih, Ukraine
e-mail: marinak20162010@gmail.com
ORCID ID: 0000-0002-4582-1756

Received: 10/06/2025
Accepted: 17/06/2025

CC BY

Abstract: The study of blast furnace melting practice in a 5000 m³ furnace using pulverized coal fuel allowed us to establish the key factors that cause deformation and burnout of lances and coolers. The reasons are the asymmetry of the combustion zone in front of the lances and the violation of gas dynamics associated with the uneven supply of blast and fuel, which directly affects the temperature distribution and gas composition. The above processes, in turn, are caused by the uneven supply of blast and pulverized coal fuel to the lances, which causes variations in the theoretical combustion temperature and changes in the volume of furnace gas along the circumference and radius of the furnace. Accordingly, when determining the optimal consumption of blast additives, focusing only on the theoretical combustion temperature, as a universal indicator of the state of temperature-oxidative conditions in the lance zone, is methodologically limited. This is especially true in cases of significant changes in the initial melting parameters, when the use of standard methods does not allow to ensure the required accuracy of calculations. This work aims to create methodological principles for calculating the theoretical fuel combustion temperature, taking into account stoichiometric ratios and fuel characteristics based on the results of technical analysis, as well as actual blowing parameters in conditions of replacing part of the coke with natural gas and pulverized coal fuel. The developed method allows to determine the theoretical fuel combustion temperature in tuyeres of combustion zones when supplying natural gas and/or pulverized coal fuel, using operational information on the blowing parameters and fuel component consumption, which are recorded by automation systems and control and measuring devices on the blast furnace control panel. The introduction of this method provides the possibility of accurate calculation of the furnace gas output and theoretical combustion temperature, which is the basis for effective optimization of the blowing mode, with special emphasis on modes using pulverized coal fuel.

Keywords: blowing, blowing mode, theoretical combustion temperature, combustion zone natural gas, pulverized coal fuel, furnace gas.

JEL: L6

Approaches to determining the theoretical combustion temperature of fuel in a blast furnace furnace when varying the parameters of the blowing mode

Daria Kassim
Prof. DSc, State University of Economics and Technology, Kryvyi Rih, Ukraine
e-mail: kassim@duet.edu.ua
ORCID ID: 0000-0002-1750-1237

Yevhen Chuprynov
Assoc. Prof. PhD, State University of Economics and Technology, Kryvyi Rih, Ukraine
e-mail: chuprynov_yv@duet.edu.ua
ORCID ID: 0000-0001-8605-3434

Kateryna Shmeltser
Assoc. Prof. PhD, State University of Economics and Technology, Kryvyi Rih, Ukraine
e-mail: shmeltser@duet.edu.ua
ORCID ID: 0000-0001-6830-8747

Iryna Liakhova
Assoc. Prof. PhD, State University of Economics and Technology, Kryvyi Rih, Ukraine
e-mail: liakhova_ia@duet.edu.ua
ORCID ID: 0000-0001-7589-8351

Maryna Korenko
Assoc. Prof. PhD, State University of Economics and Technology, Kryvyi Rih, Ukraine
e-mail: marinak20162010@gmail.com
ORCID ID: 0000-0002-4582-1756

Abstract: The study of blast furnace melting practice in a 5000 m³ furnace using pulverized coal fuel allowed us to establish the key factors that cause deformation and burnout of lances and coolers. The reasons are the asymmetry of the combustion zone in front of the lances and the violation of gas dynamics associated with the uneven supply of blast and fuel, which directly affects the temperature distribution and gas composition. The above processes, in turn, are caused by the uneven supply of blast and pulverized coal fuel to the lances, which causes variations in the theoretical combustion temperature and changes in the volume of furnace gas along the circumference and radius of the furnace. Accordingly, when determining the optimal consumption of blast additives, focusing only on the theoretical combustion temperature, as a universal indicator of the state of temperature-oxidative conditions in the lance zone, is methodologically limited. This is especially true in cases of significant changes in the initial melting parameters, when the use of standard methods does not allow to ensure the required accuracy of calculations. This work aims to create methodological principles for calculating the theoretical fuel combustion temperature, taking into account stoichiometric ratios and fuel characteristics based on the results of technical analysis, as well as actual blowing parameters in conditions of replacing part of the coke with natural gas and pulverized coal fuel. The developed method allows to determine the theoretical fuel combustion temperature in tuyeres of combustion zones when supplying natural gas and/or pulverized coal fuel, using operational information on the blowing parameters and fuel component consumption, which are recorded by automation systems and control and measuring devices on the blast furnace control panel. The introduction of this method provides the possibility of accurate calculation of the furnace gas output and theoretical combustion temperature, which is the basis for effective optimization of the blowing mode, with special emphasis on modes using pulverized coal fuel.

Keywords: blowing, blowing mode, theoretical combustion temperature, combustion zone natural gas, pulverized coal fuel, furnace gas.

Introduction

Despite the development of alternative metallurgical technologies for direct iron production, the blast furnace still remains the main technological unit for the production of liquid iron. Given the growing shortage of coal suitable for the coking process and the improvement of environmental protection measures, the strategic task of the ferrous metallurgy of Ukraine is to reduce the level of coke consumption in the production of iron. The main role in solving this problem, as before, belongs to blast furnace production, as the main consumer of coke.

Thanks to the efforts of scientists and blast furnace technologists, blast furnace smelting technology has undergone significant improvements over the past 50 years. Thus, the specific coke consumption has decreased from 0.9 to 0.3 t/t of pig iron, and the specific blast furnace productivity has increased from 1.3 to 3.2 t/(m3·day). It is important to note that such a significant reduction in the specific coke consumption was achieved through the introduction and improvement of blast furnace smelting technology using pulverized coal fuel to replace part of the coke.

Pulverized coal fuel was first used in Eastern European plants in the 1970s. Significant results from the use of this technology have been achieved at plants in Japan, the USA, Germany, China and other countries.

In Ukraine, the operation of blast furnaces with the injection of pulverized coal fuel was started back in 1963 at the Donetsk Metallurgical Plant (DMZ). This technology went through the stages of experimental and pilot-industrial operation (1968-1978), and since 1980, on the basis of the first industrial installation in Europe, the technology of joint injection of natural gas and pulverized coal fuel into the furnace using oxygen-enriched blast was mastered, which allowed replacing up to 35% of blast furnace coke.

However, some negative aspects of this technology have already become clear today. Replacing coke with pulverized coal fuel significantly increases the requirements for the quality of iron ore charge materials (strength, fines content, iron content), coke (post-reaction strength, reactivity, ash and sulfur content, narrow fractional composition), pulverized coal fuel (ash and sulfur content, reactivity), parameters of blast and slag melting modes (oxygen content in the blast, blast temperature), devices and automation systems that provide operational technological control.

The fuel combustion temperature in the tuyeres of a blast furnace is one of the most important technological parameters of smelting. It is the initial temperature of the gas flow, on which the efficiency of using its thermal and chemical energy in the working space of the furnace depends. Given the technical complexity of continuous and direct measurement of the fuel combustion temperature in the furnace, it is currently most often calculated, thus determining the so-called theoretical (adiabatic) combustion temperature.

A number of studies *(Novokhatskii, 2018)*, (*Bol'shakov, 2009)*, *(Rostovskii, 1998), (Wu, 2011)* have shown that the theoretical fuel combustion temperature in the tuyeres of a blast furnace is one of the main generalizing indicators, based on the calculation control of which rational values of the blowing mode parameters are determined.

The process of calculating and controlling generalizing theoretical indicators that characterize the operation of the gas flow in the furnace hearth, and therefore the gas-dynamic processes along the height of the furnace, becomes particularly relevant in modern blast furnace smelting with pulverized coal fuel injection into the furnace hearth. This is explained by the fact that the technology of blast furnace smelting with pulverized coal fuel injection, despite its high efficiency, is in many cases quite complex. To eliminate the problems and technological risks of implementing the technology of blast furnace smelting with pulverized coal fuel injection, it is necessary to implement measures for full and comprehensive compensation of the negative impact on blast furnace smelting of removing a large amount of coke from the charge and feeding coal dust into the furnace, which are given in the scientific and practical literature (*Chaika 2019)*.

In blast furnaces, the theoretical combustion temperature of fuel in tuyeres is calculated using approximate formulas, for example, using the empirical formula developed with the participation of specialists from the Z.I. Nekrasov Institute of Ferrous Metallurgy, which is given in the reference literature:

$$T_T = 2000 + 0{,}75(t_d - 1100) + 40(2{,}0 - \varphi +50(\omega - 25{,}0) + 53(9{,}0 - D) - 26\ KG - 4{,}0M,\ °C, \quad (1)$$

where ω – oxygen concentration in the blast, %; φ – humidity of the blast, %; D – natural gas consumption, % in the blast; t_d – blast temperature, °C; KG – coke oven gas consumption, % in the blast; M – fuel oil consumption, g/m^3 of the blast.

However, according to Professor Tarakanov A.K. and co-authors (Tarakanov (2015)), this equation often gives inflated results in modern conditions, which in turn prevents blast furnace technologists from rationally increasing the theoretical temperature.

Also, approaches are proposed for calculating the theoretical combustion temperature, taking into account the elementary analysis of the injected fuel, changes in the blowing parameters and the amount of additional fuels. Thus, the theoretical combustion temperature of coke and additional fuel in a blast furnace, in the most common cases, is proposed to be determined by the formula:

$$t_T = \frac{0{,}9341 t_b + 8208\omega - \varphi(2402 - 1{,}2177 t_b) - \left(1{,}9322 + 2{,}235 W^w\right) S_p - }{1 + \omega + 2\varphi + \left(0{,}0012 + 0{,}0013 W^w\right) S_p} \cdots$$

$$\cdots \frac{-(0{,}39 + 2{,}2175 C_s^W) Ss - 2673 S_g + 94{,}76}{+0{,}0005 Ss + 2{,}026 Sg},\ °C, \quad (2)$$

where t_b – blast temperature, °C; ω – oxygen content in the blast, m^3/m^3; φ – moisture content in the blast, m^3/m^3; S_p, S_s, S_g – consumption of liquid, solid and gaseous fuel, m^3/m^3; W^w – humidity of the working fuel, units; C^p_s – carbon content in solid fuel, units.

However, it should be noted that the elemental analysis of fuel, unlike the technical one, is quite complicated, so it is carried out relatively rarely and is most often limited to conducting a technical analysis. Therefore, the coefficients of equation (2) are most often calculated on the basis of averaged data of the elemental analysis of solid and liquid fuel. Therefore, we believe that with an unstable raw material base of modern metallurgical enterprises, the use of this equation may reduce the correctness of the results obtained.

Taking into account the elemental compositions of pulverized fuel for blast furnace smelting, it is necessary to recalculate the coefficients in the calculation formulas that depend on the compositions. In particular, the carbon content in the working fuel varies from 0.5287 to 0.7979 kg/kg, ash content from 0.0634 to 0.3555 kg/kg, etc., which, naturally, requires recalculation of the coefficients included in expression (2), and therefore complicates the calculation control of the furnace operation parameters.

The theoretical combustion temperature can be determined from the well-known equation given in the textbook (Efimenko (1981)), in which all the values included in it are related to 1 kg of carbon burning in the lances:

$$T_T = 273 + \frac{9797 + m_g \cdot q_g + V_d \cdot \left[\left(C_b + \varphi \cdot C_{H_2O}\right) \cdot t_b - 10806 \cdot \varphi\right]}{V_g \cdot C_g},\ K, \quad (3)$$

where 9797 – heat of combustion of coke carbon to CO, kJ/kg; m_g – natural gas consumption per 1 kg of carbon burned in the tuyeres, m^3; q_g – total thermal effect of transformations of gaseous fuel components in the combustion zone, kJ/m^3; V_d – dry blast consumption per 1 kg of carbon burned in the tuyeres, m^3; t_b – blast temperature, °C; φ – blast humidity, d.u.; C_b, C_{H_2O}, C_g – heat capacity of the blast, moisture and gas, kJ/(m^3·grad); 10806 – thermal effect of the endothermic decomposition process of 1 m^3 of moisture, kJ; V_g – total amount of gases formed in the tuyeres, per 1 kg of carbon burned in the tuyeres, m^3.

This expression is quite widely used in theoretical calculations. However, according to Professor Lyaluk V.P. *(Lyalyuk (2019)*, in this case, the enthalpy of coke carbon entering the combustion zone and the heat transfer from combustion products to liquid smelting products are not taken into account. In addition, calculating the estimated values related to 1 kg of carbon burned in the lances is not difficult if there is a material balance, but is quite problematic in cases where it is necessary to control the value of the theoretical combustion temperature under production conditions or conduct an analysis based on production data.

According to Professor Tovarovskii I.G. *(Tovarovskii (2016)*, when determining the possible consumption of any blowing additive, it is convenient to proceed from changes in the theoretical combustion temperature, which, as a complex parameter of the blowing mode, characterizes the temperature-oxidative conditions of the transformations of fuel additives in tuyeres. In this sense, the orientation towards preserving the values of the theoretical combustion temperature tested in practice, in the event of an increase in the consumption of the additive, should be considered justified.

Therefore, as the analysis showed, modern methods for determining the theoretical combustion temperature of fuel in the blast furnace hearth are not reliable enough with significant fluctuations in the input melting conditions (additive consumption, temperature and blast flow, oxygen concentration in it).

The purpose of this work is to develop methodological approaches to determining the theoretical combustion temperature of fuel using actually controlled blowing parameters when blowing natural gas and PCI into the blast furnace furnace based on stoichiometric ratios and data from technical analysis of fuel. Deriving complex formulas for calculating the theoretical temperature and furnace gas yield when using pulverized coal fuel and natural gas together will allow determining their values when using them separately.

Materials and Methods

During the study, an analysis of data from special literary sources was conducted regarding modern ideas about the features of blast furnace smelting when pulverized coal fuel is injected into the furnace, as well as methods for calculating the theoretical combustion temperature as one of the complex indicators of the thermal state of the furnace. When developing methodological approaches to determining the theoretical combustion temperature of fuel using actually controlled blowing parameters when natural gas and PCI are injected into the furnace, stoichiometric ratios and data from technical analysis of fuel were used.

Results

The conducted studies *(Lyalyuk (2017)* of the results of the implementation and development of the technology of blast furnace smelting with the injection of pulverized coal fuel in a blast furnace with a useful volume of 5000 m^3 of PJSC "ArcelorMittal Kryvyi Rih" allowed us to determine the causes of frequent cases of deformation and burning of air lances and coolers, which include significant unevenness of the length of the combustion zones in front of the lances along the circumference of the furnace and irrational changes in the distribution of the gas flow along the radius of the blast furnace.

In April 2016, measurements of the pulverized coal fuel consumption by tuyeres were performed at blast furnace No. 9 with a volume of 5,000 m^3 of PJSC "ArcelorMittal Kryvyi Rih", which revealed significant unevenness in its distribution (fuel consumption between several tuyeres differed by 63%). Taking into account the above, the presence of a large unevenness in the distribution of blast flow rates by tuyeres, theoretical temperature and furnace gas output along the circumference and radius of the blast furnace hearth was also recorded.

The uneven distribution of the blast on the lances around the circumference of the blast furnace significantly affects the distribution and formation of combustion centers near the air lances in the furnace, the depth of gas flow penetration into the center of the furnace, the change in the temperature field along the radius of the furnace, the configuration and location of the cohesion zone, the chemical composition of the gas flow and the physical state of condensed materials, the unevenness of the charge convergence, the furnace profile, etc., which, in turn, affects the smoothness of the blast furnace run, its productivity, specific coke consumption and the quality of pig iron.

Thus, the implementation of the technology of pulverized coal fuel injection in a blast furnace with a volume of 5000 m^3 of the enterprise “ArcelorMittal Kryvyi Rih” showed significant uncertainty in the change in the size of the combustion zones in front of the furnace lances and the distribution of the gas flow along the radius of its furnace when implementing the technology of pulverized coal fuel. This became the prerequisite for the development of a method for determining and controlling the theoretical combustion temperature and other complex indicators of air, combined blast and furnace gas for the technology of pulverized coal fuel injection into the blast furnace.

As is known, the theoretical combustion temperature of fuel is calculated as the ratio of the heat input (the sum of the enthalpy of the blast, the heat of fuel combustion, and the enthalpy of coke entering the lances) to the volume of lance gas formed and its specific heat capacity.

In general, the theoretical combustion temperature can be calculated using the equation:

$$T_m = \frac{Q_\Sigma}{V_g \cdot C_g}, \quad (4)$$

where Q_Σ – total heat input from fuel combustion (coke carbon, natural gas and pulverized coal fuel), kJ/s; V_g – furnace gas output, m^3/s; C_g – heat capacity of furnace gas, kJ/m^3·deg.

Heat generation through combustion of natural gas:

$$Q_g \cdot 1700, \text{ kJ//s},$$

where Q_g – natural gas flow rate, m^3/s; 1700 – thermal effect of the combustion reaction of 1 m^3 of natural gas, kJ/m^3.

Considering the stoichiometric ratios, when natural gas is burned according to the reaction:

$$CH_4 + 0{,}5O_2 + \frac{\beta}{2} N_2 = CO + 2H_2 + \frac{\beta}{2} N_2$$

oxygen consumption of the blow:

$$O_2 \cdot \left[Q_g \cdot \left(0{,}5 + \frac{1 - O_2}{2O_2} \right) \right], \text{ m}^3\text{/s},$$

where β – nitrogen content in dry blast, m^3/m^3, O_2 – oxygen content in dry blast, m^3/m^3.

Accordingly, the remaining oxygen is consumed for the combustion of coke carbon and pulverized coal fuel:

$$O_2 \cdot \left[Q_b - Q_g \cdot \left(0{,}5 + \frac{1 - O_2}{2O_2} \right) \right], \text{ m}^3\text{/s},$$

where Q_b is the normalized blast flow rate, m³/s.

In this case, heat is released:

$$10521{,}9 \cdot O_2 \cdot \left[Q_b - Q_g \cdot \left(0{,}5 + \frac{1 - O_2}{2O_2} \right) \right], \text{ kJ/s},$$

where 10521.9 is the thermal effect of burning carbon per 1 m³ of oxygen.

The remaining oxygen burns carbon:

$$O_2 \cdot \left[Q_b - Q_g \cdot \left(0{,}5 + \frac{1 - O_2}{2O_2} \right) \right] \cdot \frac{12}{11{,}2}, \text{ kg/s}.$$

Heat content of burnt carbon of coke heated to 1400 °C:

$$1400 \cdot 1{,}6 \cdot \left(O_2 \cdot \left[Q_b - Q_g \left(0{,}5 + \frac{1 - O_2}{2 \cdot O_2} \right) \cdot \frac{12}{11{,}2} \right] - Y \cdot C_y \right), \text{ kJ/s},$$

where 1.6 is the average heat capacity of carbon at 1400 °C, kJ/kg·grad; Y is the coal consumption, kg/s; Cy is the average carbon content in coal, units.

Assuming the average carbon content for gas coal to be 67.0%, we obtain:

$$2240 \cdot O_2 \cdot \left[Q_b - Q_g \cdot \left(0{,}5 + \frac{1 - O_2}{2 \cdot O_2} \right) \cdot \frac{12}{11{,}2} - 0{,}67 \cdot Y \right], \text{ kJ/s},$$

where the term 0.67·Y – takes into account that the coal enters the combustion zone cold.

Heat arrival with heated blast:

$$1{,}4 \cdot Q_d \cdot t_b, \text{ kJ/s},$$

where 1.4 is the average heat capacity of the blast in the temperature range of 1000-1200 °C, kJ/m³·degrees; t_b is the blast temperature, °C.

Heat is consumed for the dissociation of moisture in the blow:

Q_b·10806·φ, кДж,

where 10806 – thermal effect of moisture dissociation, kJ/m³; φ – humidity of the blast, m³/m³.

The following heat is consumed for the melting and slag formation of pulverized coal ash:

$$C_{shl} \cdot A_{PCI} \cdot m_{PCI}, \text{ kJ},$$

where C_{shl} – heat capacity of slag formed during the melting of pulverized coal ash, kJ/(kg·deg) (in the subsequent calculation C_{shl} is assumed to be = 1700 kJ/(kg·deg)), A_{PCI} – ash content in pulverized coal fuel, units.

The output of furnace gas during gas combustion according to the reaction:

$CH_4 + 0{,}5O_2 = CO + 2H_2$:

$$Q_g \cdot \left(3 + \frac{1-O_2}{2O_2}\right).$$

Furnace gas output from the combustion of coke carbon and coal:

$$\left(2 + \frac{1-O_2}{O_2}\right) \cdot \left[Q_b - Q_g \cdot \left(0{,}5 + \frac{1-O_2}{2O_2}\right)\right] \cdot O_2,\ \text{m}^3/\text{s}$$

Furnace gas output due to dissociation of blast moisture:

$1{,}5 \cdot Q_b \cdot \varphi$, m^3/s.

Therefore, the general equation for calculating the output of furnace gas (V_f) during fuel combustion has the form:

$$V_f = Q_g \cdot \left(3 + \frac{1-O_2}{2 \cdot O_2}\right) + \left(2 + \frac{1-O_2}{O_2}\right) \cdot \left[Q_b - Q_g \cdot \left(0{,}5 + \frac{1-O_2}{O_2}\right)\right] \cdot O_2 + 1{,}5 Q_b \cdot \varphi.$$

Along with the blast furnace gas formed in the blast furnace during the combustion of carbon and hydrocarbons of the fuel and the dissociation of the moisture of the blast, volatile substances of pulverized coal fuel and nitrogen, which performs the function of a carrier gas for pulverized coal fuel, are added to the total volume of the blast furnace gas. If we assume that the composition of volatile substances released in the blast furnace furnace corresponds to the composition of coke oven gas, then the heat capacity of volatile substances can be calculated according to the data given in the reference books for calculating equipment for capturing chemical coking products. That is, the average isobaric heat capacity of the mixture of gaseous compounds released in the furnace from pulverized coal fuel in the temperature range of 800-1227 ºC is 2.252 kJ/m^3·degree.

Taking into account the heat capacity of gases released from volatile substances of coal, the carrier gas of pulverized coal fuel (nitrogen) and the heat consumed for slag formation from pulverized coal fuel ash, the general equation for calculating the theoretical combustion temperature when natural gas and pulverized coal fuel are injected into the furnace furnace can be presented in the following form:

$$T_T = 273 + \frac{1700 \cdot Q_{og} + 10521{,}9 \cdot O_2 \left[Q_{ob} - Q_{og}\left(0{,}5 + \frac{1-O_2}{2O_2}\right)\right] + 1{,}4 \cdot Q_{ob} \cdot t_b + }{1{,}5 \cdot \left\{\left(3 + \frac{1-O_2}{2O_2}\right) Q_{og} + \left(2 + \frac{1-O_2}{O_2}\right) \cdot \left[Q_{ob} - Q_{og}\left(0{,}5 + \frac{1-O_2}{2O_2}\right)\right] O_2 + 1{,}5 \cdot Q_{ob} \cdot \varphi\right\} + } \cdots$$

$$\cdots \frac{+ 2340 \cdot O_2 \left[Q_{ob} - Q_{og}\left(0{,}5 + \frac{1-O_2}{2O_2}\right) - 0{,}67 \cdot Y\right] - 10806 Q_{ob} \cdot \varphi - C_{shl} \cdot A_{PCI} \cdot m_{PCI}}{+ (1{,}42 \cdot Q_{N_2} + 2{,}252 \cdot V^c) \cdot m_{PCI}}, \quad (5)$$

where 1.5 – heat capacity of furnace gas, kJ/m^3·deg; 1.42 – average heat capacity of nitrogen in the temperature range 100-1227 °C, kJ/nm^3·deg; Q_{N2} – specific flow rate of nitrogen carrier, m^3/kg of pulverized coal fuel; 2.252 – average heat capacity of dry coke oven gas in the temperature range 800-1227 °C, kJ/nm^3·deg, which is determined by the gas composition and average heat capacities of the components; V^c – yield of volatile substances of coal, d.u.

In order to assess the impact of changing the GCA flow rate on the value of the theoretical combustion temperature, we performed calculations of this theoretical indicator using the equation for the operating conditions of a blast furnace with a useful volume of 1033 m^3 using the proposed equation (5).

The following actual performance indicators of blast furnace No. 1 were selected as initial parameters for the calculation: Q_b – 2021 m^3/minute; t_b – 1067 °C; O_2 – 22.5%; φ – 0.01 m^3/m^3; Q_g – 75.2 m_3/t of pig iron. The following were taken as quality indicators of pulverized coal fuel: ash content (A) – 9%; volatile matter yield (V^d) – 24%; Q_{N2} – 0.75 m^3/kg of pulverized coal fuel.

Calculations of the theoretical combustion temperature were performed when changing the pulverized coal fuel consumption from 0 to 300 kg/t of cast iron with a step of 50 kg/t of cast iron for two options for natural gas consumption: 75.2 and 0 m^3/t of cast iron. As a result of the calculations, it was found that with an increase in the consumption of pulverized coal fuel from gas coal from 0 to 300 kg/t of cast iron, the theoretical combustion temperature without natural gas injection decreases by 357 °C, at a natural gas consumption of 75.2 m^3/t – by 301 °C, which, other things being equal, corresponds to a decrease of 1.2 °C/m^3 of natural gas and 1.0 °C/kg of pulverized coal fuel from gas coal.

Conclusions

1. Based on stoichiometric ratios and data from technical fuel analysis, methodological approaches have been developed to determine the theoretical combustion temperature of fuel based on the actually controlled blowing parameters when blowing natural gas and PCI into the blast furnace.

2. It was found that with an increase in the consumption of pulverized coal fuel from gas coal from 0 to 300 kg/t of cast iron, the theoretical combustion temperature without natural gas injection decreases by 357 °C, with a natural gas consumption of 75.2 m^3/t – by 301 °C, which, other things being equal, corresponds to a decrease of 1.2 °C/m^3 of natural gas and 1.0 °C/kg of pulverized coal fuel from gas coal.

3. Based on the developed methodology for determining the furnace gas yield and theoretical fuel combustion temperature using actually controlled blowing parameters, it is possible to solve practical problems related to optimizing the blowing parameters of blast furnace smelting, especially when injecting pulverized coal fuel.

Conflicts of interest

The authors declare no conflict of interest

Funding

This study did not receive external funding.

Authors contribution

Conceptualization, K. D., C. Ye. and S. K.; formal analysis, S. K..; Methodology, L. I. and C. Ye.; visualization, C. Ye. and K. M.; original draft, K. D. and C. Ye.; review and editing, L. I. and K. M. All authors have read and agreed with the published version of the manuscript

References

Bol'shakov, V.I., Murav'eva, I.G., Semenov, Y.S. et al. (2009) Predicting the thermal state of the blast-furnace hearth. *Steel Transl*., 39, 402–405. https://doi.org/10.3103/S096709120905009X

Chaika, A.L., Sokhatskii, A.A., Vasil'ev, L.E. et al. (2019) Investigation of the Influence of the Technology of Blast-Furnace Smelting with the Use of Pulverized Coal Fuel and Natural Gas on the Performance Indicators of Blast Furnaces. *Metallurgist*, 62, 1201–1212. https://doi.org/10.1007/s11015-019-00775-1

Efimenko, G.G., Gimmel'farb, A.A., and Levchenko, V.E. (1981) *Metalurgiya chuguna* (Metallurgy of the Cast Iron), 496.

Lyalyuk, V.P., Tarakanov, A.K., Kassim, D.A. et al. (2017) Pulverized-coal injection in a 5000-m^3 blast furnace. *Steel Transl*., 47, 675–681. https://doi.org/10.3103/S0967091217100060

Lyalyuk, V.P., Tarakanov, A.K. (2019) Gas-Dynamic Assessment of Blast-Furnace Smelting. *Steel Transl*., 49, 535–542. https://doi.org/10.3103/S0967091219080096

Novokhatskii, A.M., Diment'ev, A.O. & Padalka, A.V. (2018) Theoretical Combustion Temperature in Blast Furnaces. *Steel Transl.,* 48, 593–596. https://doi.org/10.3103/S0967091218090115

Rostovskii, A.V., Paren'kov, A.E. & Chernousov, P.I. (1998) Refining theoretical combustion temperature during the blow-in of a blast furnace. *Metallurgist*, 42, 474–476. https://doi.org/10.1007/BF02511767

Tarakanov, A.K., Bochka, V.V., Kostomarov, A.S. (2015) Optymyzatsyia parametrov dutevoho rezhyma domennoi plavky. *Metallurhycheskaia y hornorudnaia promushlennost*, 2, 11-15. http://nbuv.gov.ua/UJRN/MGRP_2015_2_6

Tovarovskii, I.G., Merkulov, A.E. (2016) Features of Temperature and Concentration Fields During Pig and Cast Iron Smelting in a Blast Furnace Workspace. *Metallurgist,* 60, 589–593. https://doi.org/10.1007/s11015-016-0336-1

Wu, Sl., Liu, Cs., Fu, Cl. et al. (2011) Improvements on Calculation Model of Theoretical Combustion Temperature in a Blast Furnace. J. *Iron Steel Res. Int.,* 18, 1–5. https://doi.org/10.1016/S1006-706X(12)60001-6