UDC 669.162

Determination of the theoretical temperature of combustion at the injection of the natural gas and pulverised coal into the blast furnace hearth

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Abstract

The average design temperature of the gaseous fuel combustion products in the combustion zones of the blast furnace (the theoretical combustion temperature of the fuel) is an important technological parameter of blast furnace smelting. It largely determines the temperature-thermal level of the blast-furnace process, the gas-dynamic intensity in the lower zone of the furnace, and, the technical and economic performance of the blast furnace in general. The theoretical temperature of combustion of fuel in combustion zones is the main generalizing indicator of the blast furnace mode of blast furnace melting using which, the blast parameters are optimized.

Metallurgical enterprises use different methods of calculating the theoretical combustion temperature. Often under present conditions, the most popular empirical technique gives overestimated values of this indicator, which psychologically keeps technologists from rationally raising the real theoretical temperature. In addition, it is problematic to take into account correctly the influence on the theoretical combustion temperature of the injection of additional fuels into the hearth of the blast furnace.

A method for determining the theoretical combustion temperature of tuyeres when injecting natural gas and / or pulverized coal into the hearth is proposed and justified using operational information on parameters of blast, natural gas and pulverized coal fuel discharged from test and measurement devices, as well as control and management systems of the blast furnace.

Key words: THEORETICAL COMBUSTION TEMPERATURE, BLAST, NATURAL GAS, PULVERIZED COAL

The combustion temperature in the tuyere zone is one of the most important parameters of the blast furnace. The heat and mass exchange with the charge materials depends on the initial temperature of the gas flow. At present, there are no reliable means of continuous measurement of the combustion temperature, and therefore, it is determined by calculation in the same manner as the theoretical (adiabatic) combustion temperature.

A number of studies have shown [1] that the theoretical temperature of fuel combustion in combustion zones is one of the indicators of the blast mode of blast-furnace for the optimization of blast parameters. In many factories, the theoretical temperature of fuel combustion in combustion zones is calculated by approximate formulas, for example, according to an empirical formula developed with the participation of specialists from the Nekrasov Ferrous Metallurgical Institute [2, p. 212]:

$$T_t = 2000 + 0.75(t_b - 1100) + 40(2.0 - \varphi) + 50(\omega - 25.0) + 53(9.0 - D) - 26CG - 4.0FO, °C \quad (1)$$

Where w - oxygen concentration in the blast, %; j - blast humidity, %; D – natural gas consumption, % to blast; t_b – blast temperature, °C; CG – coke gas consumption, % to blast; FO – consumption of fuel oil, g/m^3 of blast.

However, according to the authors of [3], this formula often gives overestimated values in modern conditions and psychologically keeps technologists from rational increase of T_t. In [4], formulas for calculating the theoretical combustion temperature taking into account the elementary analysis of the injected fuel, changing the blast parameters and the number of injected additional fuels with different combinations thereof were proposed, which the authors of [5] also propose to use suggesting that the theoretical combustion temperature of coke and blown fuel in a blast furnace in the most common cases can be determined by the formula:

$$t_t = \frac{0.9341t_b + 8208\omega - \varphi(2402 - 1.2177t_b) - (1.9322 + 2.235W^w)S_1 - \ldots}{1 + \omega + 2\varphi + (0.0012 + 0.0013W^w)S_1 \ldots}$$

$$\ldots \frac{-(0.39 + 2.2175C_s^p)S_s - 2673S_g + 94.76}{+0.0005S_s + 2{,}026S_g}, °C, \quad (2)$$

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_s, S_s, S_g – consumption of liquid, solid or gaseous fuel, m^3/m^3; W^w – humidity of the working fuel, unit fraction; C_s^p – Carbon content in solid fuel, unit fraction.

This formula, in the submitted or somewhat amended form, is applied at some metallurgical plants in Ukraine such as PJSC "ArcelorMittal Kryviy Rih", PJSC "Alchevsk Metallurgical Plant". However, the coefficients of this equation that determine the level of the theoretical combustion temperature with a change in the consumption of coke substitutes are calculated taking into account the averaged data of the elementary analysis of solid and liquid fuels, which reduces the correctness of the results obtained with the unstable raw materials base of modern metallurgical enterprises.

Thus, in [4] elementary compositions of pulverized fuel for blast furnace melting are given taking into account which, it is necessary to recalculate the coefficients in the calculation formulas depending on the compositions.

In particular, the carbon content in the working fuel varies from 0.5287 to 0.7979 kg/kg, ash – from 0.0634 to 0.3555 kg/kg etc., which, naturally, requires consideration when determining the coefficients entering into the expression for the theoretical combustion temperature (2).

The authors also state that the value of the theoretical fuel combustion temperature is unambiguously a function of the composition and flow rate of additives introduced into the blast, the blast temperature, the oxygen content and water vapor in it. Therefore, it is desirable to have computational equations in which these quantities would be included in an explicit form and not through additional variables.

The theoretical combustion temperature can be determined from the equation given in the textbook [6], in which all the quantities included in it are related to 1 kg of carbon burning on tuyeres:

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

where 9797 – combustion heat of carbon coke up to CO, KJ / kg m_g – consumption of natural gas per 1 kg of carbon burning at tuyeres , m^3; q_g – the total thermal effect of the transformations occurring in the combustion zone with the components of the injected gas, kJ /m^3; V_b – rate of dry blast referred to 1 kg of carbon, burning at the tuyeres, m^3; t_b – blast temperature, °C; φ – moisture content in the unit fractions; C_b,C_{H2O}, C_g – heat capacity of blast, moisture and gas, kJ /(m^3· deg); 10806 – heat consumption by decomposition of 1 m^3 moisture, kJ; V_g – total amount of gases produced by the tuyeres based on 1 kg of carbon burning at the tuyeres, m^3.

The authors of [6, 7] note that this formula does not take into account the enthalpy of carbon of coke entering the combustion zone and heat transfer from combustion products to liquid melting products. In addition, the computation of the calculated values assigned to 1 kg of carbon burned on tuyeres does not show difficulties in the presence of material balance, but it is very difficult in cases where it is necessary to monitor the value of the theoretical combustion temperature under production conditions or to carry out analysis on the basis of production data [4].

According to I.G. Tovarovsky [8], in determining the possible consumption of any blown additive, it is convenient to start from changes in the theoretical combustion temperature, which, as a complex parameter of the blowing regime, characterizes the temperature-oxidizing conditions for the transformation of additives in combustion zones. In this sense, the orientation toward preserving the valid values of the theoretical combustion temperature with increasing the consumption of the additive should be considered justified. However, this criterion is not sufficiently reliable for a significant change under the conditions (the consumption of the additive, the temperature of the blast and the concentration of oxygen in it) and is completely unsuitable when replacing one additive with another.

The objective of this work is the development of methodological approaches to determine the theoretical combustion temperature of fuel by controlled parameters of blasting when blowing natural gas and PC in the hearth of the blast furnace on the basis of stoichiometric ratios and data on technical analysis of fuel.

The theoretical temperature of fuel combustion (the average calculated temperature of the gaseous fuel combustion products in combustion zone) is calculated as the ratio of the heat input (the sum of the blast heat content, the heat of fuel burning and the heat content of the coke coming to the tuyeres) to the production of the volume of the tuyere gas and its specific heat capacity.

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

$$T_t = \frac{Q_\Sigma}{V_g \cdot c_g} \quad (4)$$

where Q_Σ – the total input of the heat of combustion of fuel (carbon coke, natural gas and pulverized coal), kJ / s ; V_g – output of tuyere gas, m³/s; c_g – heat capacity tuyere gas, kJ/m³· deg.

The input of heat through the combustion of natural gas:

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

where Q_g – combustion of natural gas, m³/s; 1700 – average thermal effect of the combustion reaction of 1 m³ of natural gas, kJ/m³.

When burning natural gas by reaction:

$$CH_4 + 0.5O_2 + \frac{\beta}{2}N_2 = CO + 2H_2 + \frac{\beta}{2}N_2$$

oxygen blast is expended:

$$O_2 \cdot \left[Q_g \cdot \left(0.5 + \frac{1 - O_2}{2O_2} \right) \right] \text{, m}^3\text{/s,}$$

where β – nitrogen content in dry blast, m³/m³, O_2 – oxygen content in dry blast, m³/m³.

The rest of the oxygen is consumed to burn coke carbon and coal dust:

$$O_2 \cdot \left[Q_b - Q_g \cdot \left(0.5 + \frac{1 - O_2}{2O_2} \right) \right] \text{, m}^3\text{/s}$$

where Q_b – reduced to normal blast flow rate, m³/s.

In this case, the following 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 – the thermal effect of carbon burning at1 m³ of oxygen.

The residual oxygen burns carbon:

$$O_2 \cdot \left[Q_{rb} - Q_{rg} \cdot \left(0.5 + \frac{1 - O_2}{2O_2} \right) \right] \cdot \frac{12}{11.2} \text{, kg/s.}$$

The heat content of the burned carbon of coke heated to 1400 °C:

$$1400 \cdot 1.6 \cdot \left(O_2 \cdot \left[Q_b - Q_g \left(0.5 + \frac{1 - O_2}{2 \cdot O_2} \right) \cdot \frac{12}{11.2} \right] - C \cdot A_c \right) \text{, kJ/c,}$$

where 1.6 – average heat capacity of carbon at 1400 °C, kJ/kg· deg ; C – coal consumption, kg/s; A_c – average content of carbon in coal, unit fractions.

Assuming an average carbon content of 67.0% for gas coals, we obtain:

$$2240 \cdot O_2 \cdot \left[Q_b - Q_g \cdot \left(0.5 + \frac{1 - O_2}{2 \cdot O_2} \right) \cdot \frac{12}{11.2} - 0.67 \cdot C \right] \text{, kJ/s,}$$

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

The input of heat with heated blasting:

$$1.4 \cdot Q_b \cdot t_b \text{, kJ/s,}$$

Where 1.4 – average heat capacity of the blast in the temperature range 1000-1200 °C , kJ/m³· deg ; t_b – blast temperature, °C.

The dissociation of moisture blowing expends heat:

$$Q_b \cdot 10806 \cdot \varphi \text{, kJ,}$$

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

Melting and slagging of PC ashes consumes heat:

$$C_{sl} \cdot A_{PC} \cdot C \text{, kJ,}$$

where C_{sl} – heat capacity of slag formed during melting of PC ash, kJ/(kg· deg)), A_{PC} – ashes content in PC, unit fractions.

The output of the mine gas in the combustion of natural gas by reaction:

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

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

The output of the mine gas in the combustion of coke carbon and coal:

$$\left(2 + \frac{1 - O_2}{O_2} \right) \cdot \left[Q_b - Q_g \cdot \left(0.5 + \frac{1 - O_2}{2O_2} \right) \right] \cdot O_2 \text{, m}^3\text{/s,}$$

The output of the mine gas due to the dissociation of the blast moisture:

$$1.5 \cdot Q_b \cdot \varphi \text{ , m}^3\text{/s.}$$

A general equation for calculating the output of the mine gas during the fuel combustion:

$$V_g = Q_g \cdot \left(3 + \frac{1 - O_2}{2 \cdot O_2}\right) + \left(2 + \frac{1 - O_2}{O_2}\right) \cdot \left[Q_g - Q_g \cdot \left(0.5 + \frac{1 - O_2}{O_2}\right)\right] \cdot O_2 + 1{,}5 Q_b \cdot \varphi \, .$$

Along with the mine gas formed during combustion of carbon and hydrocarbons in the hearth of the blast furnace and the dissociation of moisture in the blast, the PC volatile substances and nitrogen, which performs the function of gas PC carrier, are added to the total volume of the mine gas. If we assume that the composition of the volatile substances released in the hearth of the blast furnace corresponds to the composition of the coke oven gas, then the heat capacity of the volatile substances can be calculated from the data of [9]:

Component	Content (X_i), %	Average A_v, kJ/m^3· deg In the temperature range 800-1227 °
H_2	57.9	1.406
CH_4	26.2	3.742
CO	6.0	1.502
N_2	4.6	1.490
CO_2	2.2	2.466
C_6H_6	2.5	9.372
O_2	0.6	1.589
Mixtures	100	2.252

That is, the average isobaric heat capacity of a mixture of gaseous compounds released in the hearth from pulverized coal in the temperature range of 800-1227 °C is 2.252 kJ/m^3· deg .

Taking into account the heat capacity of the gases of coal volatile substances emitted, the gas PC carrier (nitrogen) and the heat expended for the slag formation from the PC ashes, a general equation for calculating the theoretical combustion temperature when injecting natural gas and PC into the hearth of the blast furnace can be represented in the following form:

$$T_t = 273 + \frac{1700 \cdot Q_g + 10521.9 \cdot O_2\left[Q_b - Q_g\left(0.5 + \frac{1 - O_2}{2O_2}\right)\right] + 1{,}4 \cdot Q_b \cdot t_b + \ldots}{1{,}5 \cdot \left\{\left(3 + \frac{1 - O_2}{2O_2}\right) Q_g + \left(2 + \frac{1 - O_2}{O_2}\right) \cdot \left[Q_b - Q_g\left(0.5 + \frac{1 - O_2}{2O_2}\right)\right] O_2 + 1.5 \cdot Q_b \cdot \varphi\right\} + \ldots}$$

$$\ldots \frac{+ 2340 \cdot O_2\left[Q_b - Q_g\left(0.5 + \frac{1 - O_2}{2O_2}\right) - 0.67 \cdot Y\right] - 10806 Q_b \cdot \varphi - C_{sl} \cdot A_{PC} \cdot m_{PC}}{+ (1.42 \cdot Q_{N_2} + 2.252 \cdot V^c) \cdot m_{PC}}, \qquad (5)$$

Where 1.5 – heat capacity of the mine gas, kJ/m^3· deg; 1.42 – the average heat capacity of nitrogen in the temperature range 100-1227 °C, kJ/nm^3· deg; Q_{N2} – specific consumption of nitrogen carrier, m ^{3}/kg of PC; 2.252 – average heat capacity of dry coke oven gas in the temperature range of 800-1227 °C, kJ/nm^3· deg determined by the composition of the gas and the average specific heat of the components; V^c – output of coal volatile substances, unit fractions.

In order to assess the effect of the change in the flow rate of the PC on the value of the theoretical combustion temperature, we performed calculations for the operating conditions of blast furnace No. 1 with a useful volume of 1033m^3 of Donetsk Metallurgical Plant [10] using the proposed equation (5).

As the initial parameters for the calculation, the following actual indicators of the operation of blast furnace No. 1 were selected: Q_b – 2021 m^3/min; 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. As indicators of the quality of pulverized coal, the followings were accepted: ash content (A) – 9 %; output of the volatile substances (V^d) – 24 %; Q_{N2} – 0.75 m^3/kg PC.

Calculations of the theoretical combustion temperature were performed with a change in the flow rate of PC from 0 to 300 kg /t of pig iron with a pitch of 50 kg / t of pig iron for two variants of natural gas consumption: 75.2 and 0 m^3/t of pig iron. The results of calculations are given in the table:

Consumption of PC, kg/t	Theoretical combustion temperature, °C	
	Q_g = 75.2 m^3/t	Q_g = 0 m^3/t
0	2033	2301
50	1977	2233
100	1923	2170
150	1872	2109
200	1823	2051
250	1776	2096
300	1732	1944

Thus, with an increase in the flow rate of PC from gas coal from 0 to 300 kg/t of pig iron, the theoretical combustion temperature without blowing natural gas is reduced by 357 °C, at the natural gas consumption of 75.2 m3/t – by 301 °C, that, under other conditions being equal, corresponds to a decrease in 1.2 and 1.0 °C/kg PC from gas coal.

According to the data given in [8], when the coals are injected, the main component of the effect is the furnace heat transfer, which is the greater, the higher is the content of non-volatile and unbound carbon in the injected coal. For crushed anthracite (CA), this indicator determines the coefficient of replacement of coke 0.75-0.80 kg/kg, and for crushed gas coal (CGC) – 0.50-0.60 kg/kg. Coefficient of replacement of coke CA for different conditions of melting differs insignificantly and on the average is 1.0 kg / kg. With an increase in the consumption of CA for every 10 g/m^3 of the blast, the theoretical combustion temperature is reduced by 14-10°C. The temperature of the boundary between the heat transfer zones increases, and the top gas temperature also rises by 0.1 deg / kg.

In various variants and for its various expenses, coefficient of replacement of CGC coke is 0.8-0.86 kg / kg, that is changed insignificantly. For CGC, the radiator is much smaller due to the heat transfer of the CGC. With an increase in the consumption of CGC for every 10 g/m^3 of the blast, the theoretical combustion temperature is reduced by 22-26 °C. In the calculations performed according to the proposed procedure (5), without blowing natural gas, with an increase in the flow rate of PC from gas coal for every 10 g/m^3 of the blast, the theoretical combustion temperature is reduced by 19.4 °C, which is sufficiently close to the theoretical data of I. G. Tovarovsky [8].

Specification of the method for calculating the theoretical combustion temperature of fuels in the combustion zones of a blast furnace allows us to optimize the blowing mode of melting [1, 3], significantly reduces the specific consumption of coke and increase the productivity of the furnace.

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