THERMODYNAMIC ANALYSIS OF THE BLAST FURNACE PROCESS UNDER THE CONDITIONS OF TOP GAS RECIRCULATION AND HIGH OXYGEN ENRICHMENT OF THE BLAST

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Abstract

The blast furnace process is the dominant technology in worldwide iron metallurgy. The basic fuel in this process is coke. However, coke production is associated with several adverse environmental impacts. The reduction of coke consumption in a blast furnace can be achieved by injection of auxiliary fuels or by changing the parameters of the blast. The recirculation of the top gas into the process after CO_2 and H_2O removal and the high enrichment of the blast with oxygen are considered to be future technologies conducive to the reduction of coke consumption. The paper presents the influence of the above-mentioned technologies on the operating parameters of the blast furnace plant. The simulation calculations were performed using the formulated theoretical-empirical mathematical model of the blast furnace plant. The mathematical model of the blast furnace is built based on the mass and energy balances of its separated temperature zones. The balances of the elements and also the energy balance equation have been set up separately for the top zone of heat transfer and the lower zone of production together with the thermal reserve zone. The balances of elements and the energy balance also for the tuyére zone have been applied. The advanced data validation and reconciliation method to eliminate incompatibilities of selected balances of mass and energy of the temperature zones of the blast furnace for the so-called basic measurement of its raw materials and energy consumption indicators in the steady state of operation has been applied. The carried-out simulation calculations showed a significant saving of coke in the process under top-gas recirculation after CO_2 and H_2O removal and oxygen enrichment of the blast conditions.

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Introduction

The blast furnace process is the first stage in the production of iron alloys [2, 7]. The dominant technology of steel production in the two-stage "blast furnace – oxygen-blown converter" process means that there is a constant need to improve the blast furnace process. In addition to the improvements consisting of the appropriate preparation of the iron-bearing charge in the form of a self-fusing sinter and coke fractionation, improvements are made to reduce the energy consumption of the process [3, 4, 9, 13]. These projects are primarily related to the desire to save coke because its chemical energy is approximately 70% of the total energy supplied to the blast furnace process. Nowadays, the reduction of coke consumption in the process is achieved by increasing the parameters of the blast furnace - temperature, pressure, and amount of oxygen, and the use of additional fuel reduction factors in the form of alternative fuels. Currently, the alternative fuel, which is most often used in the process for economic reasons is coal dust. In recent years many further activities have been observed to improve blast furnace technology. The research was made on the use of blowing hot reducing gases into the shaft or blast furnace nozzle zone and recirculation to the top gas process after removing CO_2 and H_2O from it [3, 15]. Recently, there have been and still are studies made on the significant enrichment of the blast with oxygen with the simultaneous injection of various fuel-reduction factors [4, 14]. These activities are primarily aimed at reducing the energy consumption of the process due to the reduction of the amount of primary fuel resources and the requirements of environmental protection.

To verify the benefits of the proposed improvements to the blast furnace process, experimental studies of new technologies or mathematical modeling techniques are required [1, 5, 6]. The use of verified mathematical models to analyze the predicted energy effects of proposed improvements can replace long-term experimental studies that are sometimes impossible due to the lack of sufficient financial resources. Modern computer technology and the available software, along with the availability of measurement data, create great opportunities in the mathematical modeling of the blast furnace process [12, 13]. Following the principle that a good mathematical model of the process is expected to have predictive ability, i.e. to predict the quantitative side of the occurring processes, to study the impact of new technologies on energy and ecological indicators of the blast furnace process, and to further system analyses, a zone divided mathematical model of a blast furnace can be used [11, 15, 16]. This model in its basic version was validated and applied to the study of the influence of recirculation of blast furnace gas in the process [15]. The zone-divided mathematical model of the blast furnace is based on the equations of mass and energy and can be included in the class of theoretical and empirical models. The basic assumption of this model is the calculation in the so-called "on-design" mode of empirical constants of the process, first of all, to reproduce the fixed parameters of the non-energy raw materials assumed in the model of the process in substances and energy balance equations based on base measurement of its raw material and energy consumption indicators in a fixed state. As part of the extension and improvement of the model, the calculation of the process constants was replaced by the inclusion of measurement data of non-energy factors in the model. However, this results in the occurrence of measurement redundancy, resulting in the incompatibility of selected model balance equations. Therefore, in the "on-design" calculation mode based on the data of the base measurement, the advanced data validation, and reconciliation method (DVR) was applied [8, 10]. The usage of this method is aimed at improving the reliability of the measurement data of the process and selected empirical coefficients used further for simulation calculations in the so-called "off-design" mode.

Mathematical model of the blast furnace

The working and supervision of each thermal process is controlled by direct and indirect measurements. Based on the results of measurements balance equations of chemical compounds in the case of physical processes and balance equations of elements in the case of chemical processes as well as energy balance equations in the fixed state of operation of the device are prepared. They are most often used to calculate unmeasured variables. The results of measurements and balance calculations are then used to determine energy efficiency, energy losses, and technical indicators in the analyzed thermal process. In thermal engineering usually there is a case where the number of unmeasured variables (unknowns) is smaller than the number of balance equations describing the process. It goes with the situation, that a part of the balance equations is unused. If the results of measurements and the calculation results of unknowns received from non-redundant equations are substituted for the redundant balance equations, the result will be the incompatibility of the redundant equations. It is a result of unavoidable errors in measured variables and calculation errors of unknowns. The excess balance equations can be used to calculate the corrections of the measured variables and the pre-calculated unknowns, which leads to the elimination of incompatibilities of all balance equations describing the process. The procedure of calculation of these corrections is called, as mentioned earlier, advanced data validation and reconciliation [8, 10].

From mathematical point of view advanced data validation is defined as the issue of minimizing the sum of the weighted squares of the corrections of measurements with constraints, resulting from the maximization of the Gauss reliability function:

$$min\left\{\sum_{i=1}^{m}\left(\frac{\hat{x}_i - x_i}{\sigma_i}\right)^2\right\} \qquad (1)$$

for

$$g_l(\hat{x}_i, \hat{y}_j) = 0, \quad where \quad l = 1,\dots,r \qquad (2)$$

where: x_i – measured variables, $\hat{x}_i, \hat{y}_j$ - measured and unmeasured variables validated after advanced data validation, σ_i - uncertainties of measurements.

Equation (2) defines a set of equality constraints of the model - the so-called condition equations. These limitations in thermodynamic analyzes are the previously mentioned equations of the substance and energy balance equations of the process.

To solve the optimization issue (1) with the equality constraints (2) the method of indeterminate Lagrange multipliers is mostly used [8]. It is presented in many publications about this issue shown in [10]. The solution with the use of matrix calculation consists of calculating the corrections of the measured variables v_{xi} and pre-calculated unmeasured variables v_{yi} and next their authenticated values in the form:

$$\left.\begin{array}{l} \hat{x}_i = x_i + v_{xi} \\ \hat{y}_i = y_i + v_{yi} \end{array}\right\} \qquad (3)$$

where: y_i – pre-calculated values of unmeasured variables.

The main beneficial effects of using advanced data validation include:
- value reconciliation of the measured variables,
- reduction of inaccuracies (uncertainties) in authenticated measurement results,
- calculation of the most probable values of unmeasured variables,
- keeping the assumed accuracy of measurements under control,
- identification of the probable places of occurrence of the gross errors.

As presented, the advanced data validation method was used to reconcile (eliminate incompatibilities of) the substance and energy balance equations of the blast furnace in the "on-design" calculation mode and to calculate the empirical process constants, which are used in the "off-design" simulation model.

The mathematical model of a blast furnace is based on the foundations of the blast furnace process theory, which distinguishes two temperature regions in a blast furnace separated by a thermal reserve zone [2, 7]. The balance equations of elements, chemical compounds, and the energy balance in the furnace model are prepared separately for the upper heat flow zone (preparation zone) and the lower zone (producing zone) together with the thermal reserve zone. Conditions close to the state of thermodynamic equilibrium that prevails in the zone of thermal reserve allow for the formulation of chemical equilibrium equations to determine the composition of the gas phase in this zone. Additionally, a substance and energy balance are formulated for the adiabatic combustion chamber of the blast furnace nozzle zone. The empirical part of the model includes additional equations that are complementary to the balance equations of substances and energy of the separated temperature zones to obtain the consistency of the number of equations and unknowns in the model. These equations contain in their mathematical form empirical coefficients, which are calculated based on the so-called base thermal measurement of the blast furnace [9, 16]. In the current model assumptions, the variables used in this measurement were limited only to measurements involving energy carriers in the process. The elements included in the non-energy carriers (raw materials and products) in the process, i.e., sinter, pig iron, and slag, and the energy effects related to the reduction of ore were not balanced. This problem was solved, as mentioned earlier, by calculating based on the data obtained as part of the base measurement, the so-called process constants occurring in the selected model substance and energy balance equations. The improvement of the mathematical model is based on the elimination of the calculation of these constants in favor of using the measurements of the parameters of non-energy factors received in the base measurement in an equal way with the measurements of energy carriers and their further application in the simulation calculations.
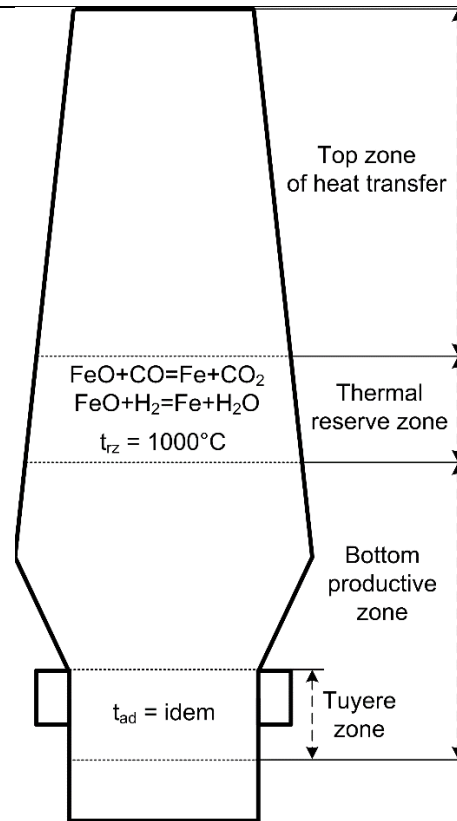

Figure 1: Temperature zones of a blast furnace

Conditional equations of the advanced data validation method

The introduction to the calculations of data characterizing non-energy carriers in the process, received in the base measurement, results in measurement redundancy resulting in the incompatibility of selected model balance equations. Therefore, for the base measurement data of the blast furnace, mentioned before, the DVR method was applied. The selected equations of the mass and energy balances of the mathematical model of the blast furnace with no unknown variables were adopted as the conditional equations (equality constraints). These equations, in their basic form, were part of the developed zone mathematical model of the blast furnace [16], but without distinguished components of non-energy raw materials – which included the previously mentioned so-

called process constants. These equations are balance equation of carbon of the upper heat flow zone, of hydrogen of the upper heat flow zone, of the difference between hydrogen and oxygen of the upper heat flow zone, of energy of the upper heat flow zone, of the difference between hydrogen and oxygen of the bottom heat flow zone and balance equation of energy of the bottom heat flow zone. After introducing the measurement components for non-energy raw materials into the equations, their mathematical form is text missing?

In the equations below index sr represents the inlet or outlet substances from the bottom heat flow zone along with the thermal reserve zone.

- the balance equation of carbon of the upper heat flow zone:

$$\left(K - P \cdot \frac{c_P}{c_K}\right) \cdot \left(\frac{c_K}{12} + \frac{s_K}{32}\right) + G_{sr} \cdot (CO_{sr} + CO_{2sr}) + Sp \cdot \frac{c_{Sp}}{12}$$
$$= G \cdot (CO + CO_2) + K_{sr} \cdot \left(\frac{c_{K\,sr}}{12} + \frac{s_{K\,sr}}{32}\right) \quad (4)$$

where: K - specific coke consumption, P - dust exhaust from the blast furnace, c_P - mass fractions of carbon in the dust, c_K - mass fractions of carbon in the coke, s_K - mass fractions of sulfur in the coke, , Sp – specific amount of sinter, c_{Sp} - mass fractions of carbon in the sinter, G- specific production of blast furnace gas, CO_2 - volumetric (molar) fractions of carbon dioxide in the blast furnace gas, CO - volumetric (molar) fractions of carbon monoxide in the blast furnace gas.

- the balance equation of hydrogen of the upper heat flow zone:

$$\left(K - P \cdot \frac{c_P}{c_K}\right) \cdot \left(\frac{h_K}{2} + \frac{w_K}{18}\right) + G_{sr} \cdot (H_{2\,sr} + X_{z\,sr}) + Sp \cdot \frac{h_{Sp}}{2}$$
$$= G \cdot (H_2 + X_z) + K_{sr} \cdot \frac{h_{K\,sr}}{2} \quad (5)$$

where: h_K - mass fractions of hydrogen in the coke, w_K - mass fractions of moisture in the coke, h_{Sp} - mass fractions of hydrogen in the sinter, H_2 - volumetric (molar) fractions of hydrogen in the blast furnace gas, X_Z – moisture level of the blast furnace gas.

- the balance equation of the difference of hydrogen and oxygen of the upper heat flow zone:

$$\left(K - P \cdot \frac{c_P}{c_K}\right) \cdot \left(\frac{o_K}{32} - \frac{h_K}{4}\right) + G_{sr} \cdot [0,5 \cdot (CO_{sr} - H_{2\,sr}) + CO_{2\,sr}]$$
$$+ Sp \cdot \left(\frac{o_{Sp}}{32} - \frac{h_{Sp}}{4}\right) + K \cdot a \cdot \frac{o_a}{32}$$
$$= Sp_{sr} \cdot \frac{o_{Sp\,sr}}{32} + K_{sr} \cdot a_{sr} \cdot \frac{o_{a\,sr}}{32} + G$$
$$\cdot [0,5 \cdot (CO - H_2) + CO_2] - K_{sr} \cdot \frac{h_{K\,sr}}{4} \quad (6)$$

where: o_K - mass fractions of oxygen in the coke, o_{Sp} - mass fractions of oxygen in the sinter, a - mass fraction of mineral substance in coke, o_a - mass fractions of oxygen in the mineral substance in coke.

- the balance equation of energy of the upper heat flow zone:

$$\left(K - P \cdot \frac{c_P}{c_K}\right) \cdot d_K + G_{sr} \cdot (W_{d\,sr} + i_{sr} + X_{z\,sr} \cdot i_{X\,sr}) + Sp \cdot$$
$$\left(d_{Sp} + i_{Sp}\right) + K \cdot a \cdot (d_a + i_a) = Sp_{sr} \cdot$$
$$\left(d_{Sp\,sr} + i_{Sp\,sr}\right) + K_{sr} \cdot a_{sr} \cdot (d_{a\,sr} + i_{a\,sr}) + (1 - \xi_q) \cdot \quad (7)$$
$$\dot{Q}_{ow} \cdot \frac{D}{\dot{D}} + G \cdot (W_{dG} + i_G + X_z \cdot i_{XG}) + K_{sr} \cdot (d_{K\,sr} + i_{K\,sr})$$

where: d_K - enthalpy of devaluation of the coke, W_{dsr} - calorific value of the gas in the inlet or outlet from the bottom heat flow zone along with the thermal reserve zone, i_{sr} – specific enthalpy of the gas in the inlet or outlet from the bottom heat flow zone along with the thermal reserve zone, i_{Xsr} – specific enthalpy of the moisture in the gas in the inlet or outlet from the bottom heat flow zone along with the thermal reserve zone, d_{Sp} - enthalpy of devaluation of the sinter, i_{Sp} – specific enthalpy of the sinter, d_a - enthalpy of devaluation of the mineral substance in coke, i_a – specific enthalpy of the mineral substance in coke, ξ_q - distribution of heat loss between temperature zones, $\dot{Q}_{ow}$ - heat losses from the blast furnace to the cooling water and the environment, $\dot{D}$ – the flux of the blast, D - the specific amount of blast, W_{dG} - calorific value of the blast furnace gas, i_G – specific enthalpy of the blast furnace gas, i_{XG} – specific enthalpy of the moisture in the blast furnace gas, i_{Ksr} – specific enthalpy of the coke in the inlet or outlet from the bottom heat flow zone along with the thermal reserve zone.

- the balance equation of the difference of hydrogen and oxygen of the bottom heat flow zone:

$$D \cdot O_{2D} - K_{sr} \cdot \frac{h_{K\,sr}}{4} + F \cdot (O_{2F} - 0.5 \cdot H_{2F}) + G_{rec} \cdot$$
$$\left(0.5 \cdot (CO_{rec} - H_{2_{rec}}) + CO_{2_{rec}}\right) + Sp_{sr} \cdot \frac{o_{Sp\,sr}}{32} + K_{sr} \cdot a_{sr} \cdot \frac{o_{a\,sr}}{32} = \qquad (8)$$
$$Zu \cdot \frac{o_{Zu}}{32} + G_{sr} \cdot [0.5 \cdot (CO_{sr} - H_{2\,sr}) + CO_{2\,sr}]$$

where: O_{2D} - volumetric (molar) fractions of oxygen in the blast, F - specific amount of alternative fuel, O_{2F} - volumetric (molar) fractions of oxygen in alternative fuel, H_{2F} - volumetric (molar) fractions of hydrogen in alternative fuel, G_{rec} - amount of gas for recirculation, CO_{2rec} - volumetric (molar) fractions of carbon dioxide in the recirculating gas, CO_{rec} - volumetric (molar) fractions of carbon monoxide in the recirculating gas, Zu – specific amount of slag, o_{Zu} - mass fractions of oxygen in the slag.

- the balance equation of energy of the bottom heat flow zone,

$$K_{sr} \cdot (d_{K\,sr} + i_{K\,sr}) + D \cdot (i_D + X_{zD} \cdot i_{XD}) + F \cdot (d_F + i_F) + Sp_{sr} \cdot (d_{Sp\,sr} +$$
$$i_{Sp\,sr}) + K_{sr} \cdot a_{sr} \cdot (d_{a\,sr} + i_{a\,sr}) + G_{rec} \cdot \left(W_{d_{rec}} + i_{rec} + X_{z_{rec}} \cdot i_{X_{rec}}\right) = \qquad (9)$$
$$Su \cdot (d_{Su} + i_{Su}) + Zu \cdot (d_{Zu} + i_{Zu}) + \xi_q \cdot Q_{ow} \cdot \frac{D}{D} + G_{sr} \cdot$$
$$(W_{d\,sr} + i_{sr} + X_{z\,sr} \cdot i_{X\,sr})$$

where: i_D – specific enthalpy of the blast, i_{XD} – specific enthalpy of the moisture in the blast, d_F - enthalpy of devaluation of alternative fuel, i_F – specific enthalpy of alternative fuel, Su – specific amount of pig iron, d_{Su} - enthalpy of devaluation of pig iron, i_{Su} – specific enthalpy of the pig iron, d_{Zu} - enthalpy of devaluation of the slag, i_{Zu} – specific enthalpy of the slag.

The basic set of conditional equations of the DVR procedure is also supplemented with dependencies that bind the balance values concerning the thermal reserve zone and the blast furnace outlet. The equations of the balance equations of elements and energy constitute equality constraints in the DVR optimization task. As a result of the application of this method, the variables appearing in the equations to which a specific measurement uncertainty was assigned are corrected, which eliminates the inconsistencies of the right and left sides of these equations. The measurable effect of applying the method is receiving authenticated parameters of non-energy factors, i.e., parameters characterizing the properties of the charge in the model for simulation calculations.

Validation of empirical coefficients in the equations of the mathematical model

The use of the DVR method for the analysis of the blast furnace process brings additional benefits.

As presented, the zone balance model of the blast furnace as a whole contains, in addition to the balance equations (mass and energy balances), additional dependencies resulting from theoretical considerations, but including empirical coefficients in their mathematical form. These dependencies include:

- the equation to calculate the content of the main gas components in the outlet of a blast furnace:

$$\frac{G \cdot H_2}{\left(K - P \cdot \frac{c_p}{c_K}\right) \cdot \frac{h_K}{2} + D \cdot X_{zD} + F \cdot H_{2F}} \qquad (10)$$
$$= \frac{-C_{sr}}{1 + \frac{CO}{CO_2}} + \psi_0$$

where:

$$C_{sr} = \frac{K_{p_{H_2}} \cdot \left(1 + K_{p_{CO}}\right)}{K_{p_{CO}} \cdot \left(1 + K_{p_{H_2}}\right)} \qquad (11)$$

where: $K_{p_{H_2}}$ – the chemical equilibrium constant corresponding to the reduction reaction of FeO by use of H_2 in the thermal reserve zone, $K_{p_{CO}}$ - the chemical equilibrium constant corresponding to the reduction reaction of FeO by use of CO in the thermal reserve zone.

- the equation describing the amount of dust blown from the throat of a blast furnace as a function
of the average speed of its outflow [17]:

$$P = (58.24 + 2.65 \cdot P_0) \cdot u_G + P_0 \qquad (12)$$

where the average velocity of gas outflow from the blast furnace outlet u_G results from dependence:

$$u_G = \frac{(MR) \cdot G \cdot \dot{D} \cdot T_G}{p_G \cdot A_G \cdot D} \tag{13}$$

where: (MR) - universal gas constant, T_G – temperature of the top gas, p_G – top gas pressure, A_G - the area of gas outflow.

- the connection between the charge sagging index and the mass density index of gases and liquid smelting products to calculate the blast flux:

$$\left(G_g \cdot \frac{\dot{D}}{D}\right)^3 \cdot \left(\frac{M_g}{p_D}\right)^{\frac{3}{2}} = C_D \tag{14}$$

where: G_g – gas in the blast furnace tuyére zone, M_g - specific amount of molar mass in the area of blast furnace nozzles, p_D – pressure of the blast.

- dependencies describing the connection of blast pressure p_D with a pressure of reducing gases
in the thermal reserve zone p_{sr} and gas pressure in the outlet of the blast furnace p_G:

$$p_D{}^2 - p_{sr}{}^2 = C_{sw} \cdot \left(G_w \cdot \frac{\dot{D}}{D}\right)^2 \cdot T_w \cdot M_w \tag{15}$$

$$p_{sr}{}^2 - p_G{}^2 = C_{sp} \cdot \left(G_p \cdot \frac{\dot{D}}{D}\right)^2 \cdot T_p \cdot M_p \tag{16}$$

where: T_w – mean value of the temperature of gases in the blast furnace producing zone, T_p - mean value of the temperature of gases in the blast furnace top zone.

The empirical coefficients: $\psi_o, P_o, C_D, C_{sw}, C_{sp}$ appearing in the equations (10), (12), (14)-(16) are calculated for validated blast furnace base measurement data. This is the mentioned benefit of using the advanced DVR method. The values of the coefficients calculated for unreliable data and after applying advanced DVR (for receiving the consistency of the balance equations) are presented in Table 1.

The equation included in the mathematical model is also the balance of the adiabatic combustion chamber energy for the blast furnace tuyére zone:

In the equations below index g represents the tuyére zone.

$$K_g \cdot (d_{K\,sr} + h_{K\,g}) + D \cdot (h_D + X_{zD} \cdot h_{XD}) + F \cdot (d_F + h_F)$$
$$= G_g \cdot (W_{d\,g} + h_g) \tag{17}$$

After completing the energy balance (17) with the balance equations of the elements like carbon, oxygen, hydrogen, and nitrogen (assuming that the reduction gases in the nozzle zone include CO, H_2, and N_2), the only unknown in the created set of equations is the adiabatic combustion temperature. In blast furnace practice, this temperature reflects the thermal state of the blast furnace nozzle zone and keeping it unchanged is one of the conditions for the proper performance of the process. That's why, in simulation calculations and material and energy balances of a

blast furnace, it is usually assumed that the adiabatic temperature is a constant value. The usage of advanced data validation allows, as in the cases of empirical coefficients, to authenticate the value of this temperature. The results of the calculations are presented in Table 1.

The results of calculations of the empirical coefficients of the mathematical model

Table 1 presents the selected results of calculations of the parameters of the developed mathematical model of the selected blast furnace based on the base measurement data. The data for the base measurement of the blast furnace are primarily the variables contained in equations mentioned in point 2.1 in the form of the so-called specific indicators (specific consumption or production energy carriers) of blast furnace operation related to coke consumption K, auxiliary fuel F, blast D, sinter Sp, total production of the top-gas G, dust P and production of pig iron Su and slag Zu. These indicators are supplemented with data about the chemical compositions of the above-mentioned energy and raw materials factors. Base measurement data was adopted based on [9, 16, 17]. They were developed for a selected 3200 m³ blast furnace. As the source materials were used measurement and production data collected in reports on the operation of the furnace. To meet the fixed state conditions of the process, these

data were collected under the conditions of stable operation of the furnace over a sufficiently long time.

The most important results are presented. These results were obtained before and after the application of the advanced data validation method. The values of empirical coefficients and adiabatic temperature presented in column 3 of Table 1 were calculated for the data of the base measurement of the blast furnace and the values of other variables calculated on its basis. Column 4 contains the values of these coefficients and variables calculated with the use of the base measurement data validated with the advanced data validation method. In this case, the calculations of the empirical coefficients and the adiabatic combustion temperature in the nozzle zone are based on the validated data of the base measurement of the blast furnace, for which the equations of balances of elements and energy of its temperature zones are fulfilled.

temperature values from the energy balance of the blast furnace nozzle zone are also a part of the validation procedure. From here, the value of this temperature is also subject to reconciliation. As shown in Table 1, its value obtained from calculations is coherent with the literature data, which gives its value in the range of 2200°C-2300°C [2].

Table 1: Empirical coefficients of the selected mathematical model equations before and after the application of the advanced measurement validation method

No.		Value for the base measurement data	
	An empirical factor or process parameter	Without using the advanced data validation method	After using the advanced data validation method
1	2	3	4
1	ψ_0	1.286	1.317
2	P_0	-15.197 kg/t p. i.	-15.458 kg/t p. i.
3	C_D	2.059 $(kmol \cdot m)^{\frac{3}{2}}/s^{\frac{1}{2}}$	2.029 $(kmol \cdot m)^{\frac{3}{2}}/s^{\frac{1}{2}}$
4	C_{sp}	0.10210 $kPa/(kmol \cdot K \cdot m)$	0.09321 $kPa/(kmol \cdot K \cdot m)$
5	C_{sw}	0.02979 $kPa/(kmol \cdot K \cdot m)$	0.02843 $kPa/(kmol \cdot K \cdot m)$
6	T_{ad}	2542 K	2520 K

The values of the base measurement data of the blast furnace used to calculate the adiabatic

Table 2: Input data of the mathematical model before and after the application of the advanced measurement validation method

Variable	Value before advanced validation method	Value after advanced validation method	Unit
$g_{Fe_2O_3}$ – mass fraction of hematite in sinter	0.1668	0.1666	$\dfrac{kg}{kg\ of\ sinter}$
$g_{Fe_3O_4}$ – mass fraction of magnetite in sinter	0.5203	0.5201	$\dfrac{kg}{kg\ of\ sinter}$
g_{FeO} – mass fraction of iron oxide in sinter	0.0870	0.0870	$\dfrac{kg}{kg\ of\ sinter}$
g_{CaO} – mass fraction of calcium oxide in sinter	0.0940	0.0942	$\dfrac{kg}{kg\ of\ sinter}$
g_{MgO} – mass fraction of magnesium oxide in sinter	0.0135	0.0135	$\dfrac{kg}{kg\ of\ sinter}$
g_{CaCO_3} – mass fraction of calcium carbonate in sinter	0.0100	0.0100	$\dfrac{kg}{kg\ of\ sinter}$
g_{SiO_2} – mass fraction of silicon oxide in sinter	0.0740	0.0742	$\dfrac{kg}{kg\ of\ sinter}$
$g_{Al_2O_3}$ – mass fraction of aluminum oxide in sinter	0.0115	0.0115	$\dfrac{kg}{kg\ of\ sinter}$
g_{H_2O} – mass fraction of water in sinter	0.0230	0.0230	$\dfrac{kg}{kg\ of\ sinter}$
$g_{C_{SUR}}$ – mass fraction of carbon in pig iron	0.0500	0.0500	$\dfrac{kg}{kg\ of\ pig\ iron}$
$g_{Si_{SUR}}$ – mass fraction of silicon in pig iron	0.0050	0.0050	$\dfrac{kg}{kg\ of\ pig\ iron}$
Fe_{ZUZ} – molar fraction of free iron in slag	0.0060	0.0060	$\dfrac{kmol}{kmol\ of\ slag}$
K - coke	485.00	491.49	$\dfrac{kg}{t\ of\ pig\ iron}$
c_K – mass fraction of carbon in dry coke	0.8890	0.8793	$\dfrac{kg}{kg\ of\ coke}$
h_K – mass fraction of hydrogen in dry coke	0.0050	0.0050	$\dfrac{kg}{kg\ of\ coke}$
w_K – mass fraction of water relative to dry coke	0.0400	0.0403	$\dfrac{kg}{kg\ of\ coke}$

Variable	Value before advanced validation method	Value after advanced validation method	Unit
o_K – mass fraction of oxygen in dry coke	0.0080	0.0080	$\dfrac{kg}{kg\ of\ coke}$
n_K – mass fraction of nitrogen in dry coke	0.0100	0.0097	$\dfrac{kg}{kg\ of\ coke}$
s_K – mass fraction of sulfur in dry coke	0.0050	0.0050	$\dfrac{kg}{kg\ of\ coke}$
g_{SiO_2K} – mass fraction of silicon oxide in mineral fraction of coke	0.5950	0.5950	$\dfrac{kg}{kg\ of\ m.f.of\ co}$
g_{MgOK} – mass fraction of magnesium oxide in mineral fraction of coke	0.0160	0.0160	$\dfrac{kg}{kg\ of\ m.f.of\ co}$
$g_{Fe_2O_3K}$ – mass fraction of hematite in mineral fraction of coke	0.0370	0.0370	$\dfrac{kg}{kg\ of\ m.f.of\ co}$
g_{CaOK} – mass fraction of calcium oxide in mineral fraction of coke	0.0290	0.0290	$\dfrac{kg}{kg\ of\ m.f.of\ co}$
$g_{Al_2O_3K}$ – mass fraction of aluminum oxide in mineral fraction of coke	0.3230	0.3230	$\dfrac{kg}{kg\ of\ m.f.of\ co}$
T_{SP} – temperature of the sinter	333.00	331.17	K
T_{SUR} – temperature of the pig iron	1723.0	1739.0	K
T_G – temperature of the top gas	439.00	445.22	K
T_D – temperature of the blast furnace blast	1392.0	1378.2	K
ξ_q – multiplier of the distribution of heat losses to the environment and cooling water for the blast furnace zones	0.7000	0.6985	–
D – amount of the blast furnace blast	49.670	47.983	$\dfrac{kmol}{ton\ of\ pig\ iron}$
$\dot{D}$ – flux of the blast furnace blast	3.8900	3.8789	$\dfrac{kmol}{s}$

Variable	Value before advanced validation method	Value after advanced validation method	Unit
$\dot{Q}_{ow}$ – flux of the heat losses to the environment and cooling water	30000	30081	$\dfrac{kJ}{s}$
X_{z_D} – molar degree of moisture in the blast furnace blast	0.0149	0.0149	$\dfrac{kmol\ H2O}{kmol}$
O_{2_D} – molar fraction of the oxygen in blast furnace blast	0.2685	0.2644	$\dfrac{kmol}{kmol}$
G – Amount of the top gas	76.770	77.197	$\dfrac{kmol}{ton\ of\ pig\ iron}$
CO – molar fraction of carbon oxide in the top gas	0.2719	0.2506	$\dfrac{kmol}{kmol}$
CO_2 - molar fraction of carbon dioxide in the top gas	0,1884	0.1867	$\dfrac{kmol}{kmol}$
H_2 - molar fraction of hydrogen in the top gas	0.0547	0.0551	$\dfrac{kmol}{kmol}$
X_z - molar degree of moisture in the top gas	0.0600	0.0605	$\dfrac{kmol\ H2O}{kmol}$
F – amount of the natural gas	2.8200	2.7970	$\dfrac{kmol}{t\ sur.}$
P – amount of dust	6.000	5.9997	$\dfrac{kg}{ton\ of\ pig\ iron}$
c_P – mass fraction of carbon in the dust	0.4300	0.4300	$\dfrac{kg}{kg\ of\ dust}$

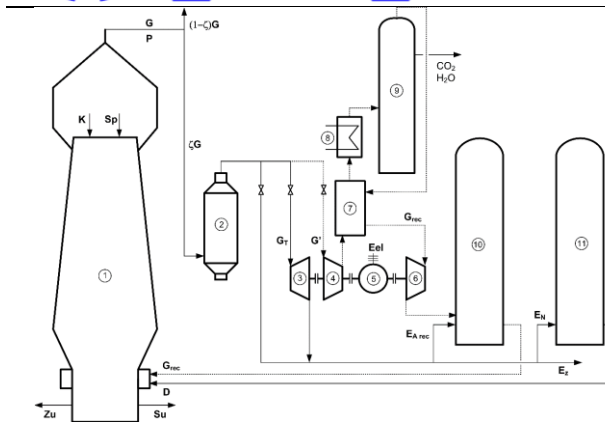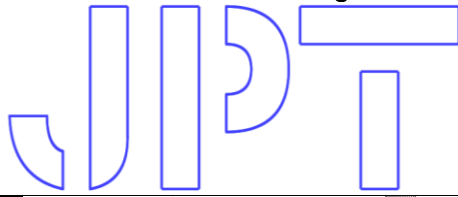## Mathematical model of the equipment of the set of devices for the blast furnace

Figure 2: Schematic diagram of the blast furnace plant. Designations: 1 – blast furnace, 2 – top-gas clearing plant, 3 – recovery turbine of top gas, 4 – compressor of recirculated gas, 5 – electric generator, 6 – recovery turbine of purified recirculated gas, 7 – recuperator, 8 – preheater, 9 – installation of CO2 and H2O removal, 10 – preheater of purified recirculated gas, 11 – Cowper stove

The blast furnace to work correctly needs a set of devices that take care of the products and substances delivered to the process. One of the devices is used to recover the energy from the top gas and produce electricity from it. We can do so because the parameters of the top gas are higher than the environment, for that we use a wet recovery turbine. We also need to prepare the air for the blast by making the pressure higher in the blast compressor and heating it in the Cowper stove. Another Cowper stove is used to heat the recirculating top gas which was previously cleaned.

Besides calculations made to the blast furnace itself the model also needs to include a calculation for the additional equipment necessary for the correct work of the blast furnace.

The specific effective work of blast furnace gas expansion in a wet recovery turbine results from the equation:

$$L_{eT} = G_T \cdot l_i \cdot \eta_{mT} \tag{18}$$

where: G_T – part of the top gas that goes to the wet recovery turbine, η_{mT} - the mechanical efficiency of the wet recovery turbine.

For that purpose, the specific internal work l_i is calculated by the following:

$$
\begin{aligned}
l_i = (h_1 - h_{2s}) \cdot \eta_i \\
= \{(c_{pG} + X_1'' \cdot c_{pH_2O}) \cdot (T_1 - T_{2s}) + (X_1'' - X_2'') \\
\cdot [r_0 - (c_{pw} - c_{pH_2O}) \cdot (T_{2s} - 273.15)]\} \cdot \eta_i
\end{aligned}
\tag{19}
$$

where: index 1 - represents the gas at the inlet of the turbine, index $2s$ - represents the gas at the exit of the turbine, h - physical specific enthalpy, c_p - specific heat, X - degree of dryness of the steam, T – temperature, r_0 - enthalpy of evaporation, η_i - the internal efficiency.

The blast compressor is calculated as a two-step blower with the internal cooling for which the specific effective work is calculated as:

$$l_{eD} = \frac{c_{pD} + X_{ot} \cdot c_{pH_2O}}{\eta_{mD}} \cdot (\Delta T_1 + \Delta T_2) \tag{20}$$

where: c_{pD} - specific heat of the blast, X_{ot} - molar degree of moisture in the air, c_{pH_2O} - specific heat of the water, η_{mD} - the mechanical efficiency of the blast, ΔT_1 - blast temperature rise in the first stage of the compressor, ΔT_2 - blast temperature rise in the second stage of the compressor.

Blast heaters and recirculation blast furnace gas heaters (Cowper stoves) are calculated as the regeneration heat exchangers. For the chemical energy needed for heating the recirculation top-gas is used:

$$E_{Arec} = \frac{G_{rec} \cdot \Delta h_{rec}}{\eta_{Arec}} \tag{21}$$

where: Δh_{rec} – increase of the specific enthalpy of the recirculating gas, η_{Arec} – the efficiency of the recirculation blast furnace gas heater.

and for the chemical energy needed for heating of blast

$$E_N = \frac{D \cdot (\Delta h_D + X_{zD} \cdot h_{XD}) \cdot W_{dG}}{\eta_N \cdot W_{dG}} \tag{22}$$

For the correct calculation of the variables above it is necessary to find the value of the energetic efficiencies of the heaters:

$$\eta_N = 1 - \varepsilon_N - \frac{n_{sG} \cdot h_{swG}}{W_{dG}} \qquad (23)$$

where: ε_N - the relative heat losses of the heater, n_{sG} – amount of the flue gases received from burning of 1 kmol of the top gas, h_{swG} - the specific enthalpy of flue gases that exit the heater.

Specific electric energy production in the set of devices for the blast furnace is calculated as a balance of the specific work of the wet recovery turbine and usage of the specific work needed in the unit for preparing the recirculating top gas:

$$E_{el} = (L_{eT} - |L_n|) \cdot \eta_{me} \qquad (24)$$

where: η_{me} - electromechanical efficiency of the electric generator.

Specific work of $|L_n|$ is due to the difference between the compressor driving work and the expansion work of the purified recirculating gas according to the equation:

$$|L_n| = G' \cdot |l_{eS}| - G_{rec} \cdot l_{eR} \qquad (25)$$

where: G' - amount of the dry gas that goes to the cleaning installation, $|l_{eS}|$ - specific work of the compressing of the recirculating top gas, l_{eR} - specific work of the expansion of the purified recirculating gas.

The relation between amount of gas that goes to the compressor, to the wet recovery turbine and the bypass valve:

$$G_{zo} - G_T = \zeta G - G' \qquad (25)$$

where: G_{zo} – amount of the gas that goes to the bypass valve, ζG – amount of top gas after considering the losses.

Simulation calculations

Using the developed mathematical model of the analyzed system, simulation calculations were made of the influence on the energy consumption of the process of significant enrichment of the blast with oxygen and the recirculation of the cleaned top gas to the blast

furnace nozzle zone. An independent value, which was set for simulation calculations, was the mole fraction of oxygen in the blast. The amount of recirculating top gas in the mathematical model is not an independent quantity. Its quantity results from the condition of keeping the adiabatic combustion temperature constant in the area of the blast furnace nozzles. Simulation calculations were carried out until all the top gas was used for recirculation.

Results of the simulations

A range of simulations for different input temperatures was made. The temperature of the blast and of recirculation cleaned top gas were changed. The range of values for these temperatures is from 350 K to 1373 K for the recirculating top gas [18] and from 1178 K to 1478 K for blast [19]. The calculations were carried out until all the top gas was used for recirculation or the molar fraction of oxygen in the blast reached 95%. The results are shown in the figures below.
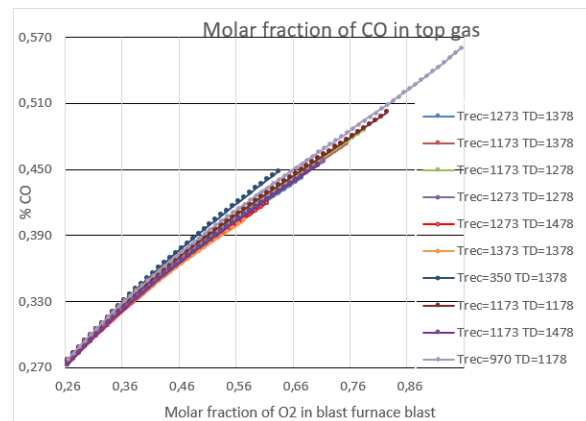

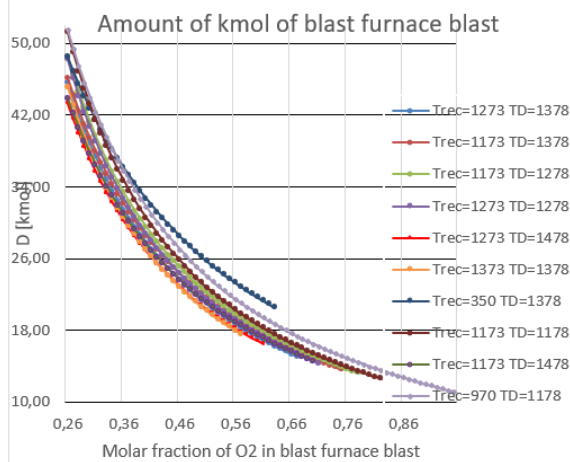Figure 3: Molar fraction of CO in top gas

Figure 4: Amount of kmol of blast furnace blast
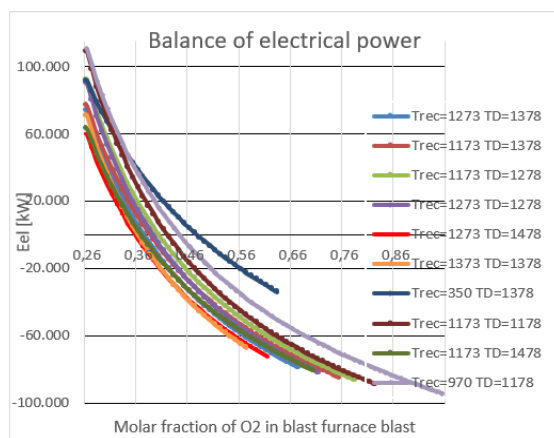

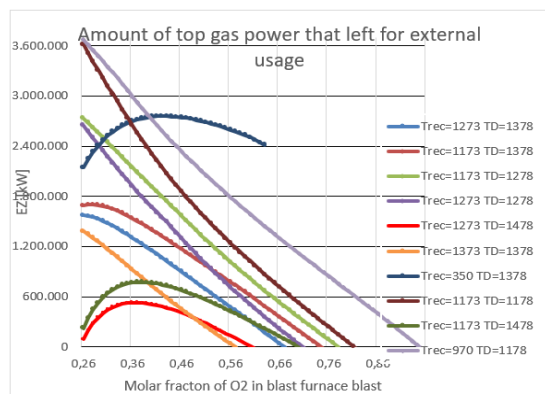Figure 5: Balance of electrical power

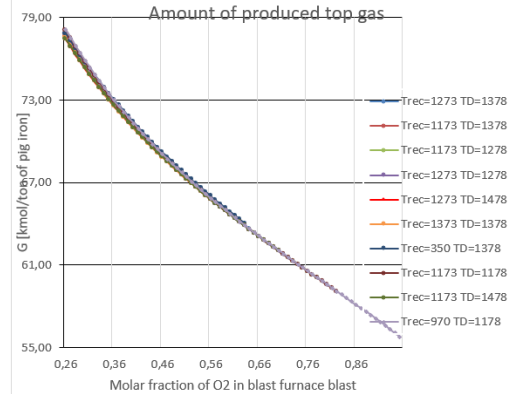Figure 6: Amount of top gas power left for external usage
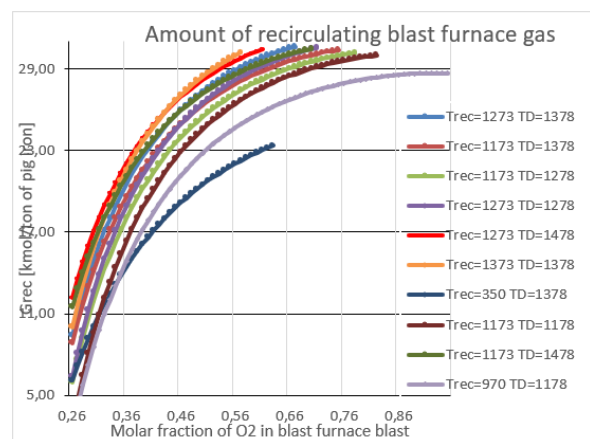

Figure 7: Amount of produced top gas
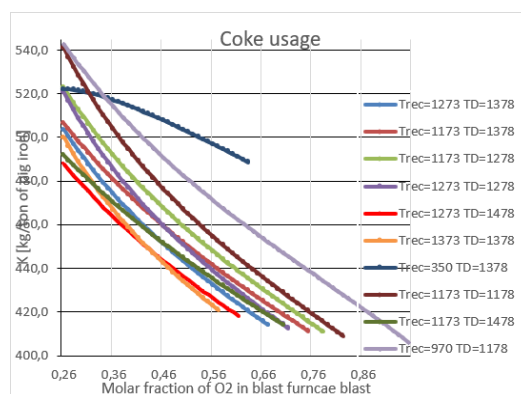

Figure 8: Amount of recirculating blast furnace gas

Figure 9: Coke usage

Thermo-ecological cost

Currently, it is important to know what the value of the thermo-ecological cost (TEC) of the process is [20]. Thanks to it we can optimize our models by changing the input data and receive more efficient results that are cheaper and less harmful to the environment. TEC is an indicator that allows us to verify the usage of exergy needed for the whole process of production of the particular product, in this case the pig iron. It includes the exergy of the natural resources and the effort that we have to put to acquire them, the intermediate stages of production, and the production of the final product. It also includes the exergy of the by-products and their impact on the environment [20]. The thermo-ecological cost of the pig iron is calculated using the equation:

$$\rho_{SUR} \cdot a_{SUR} = \rho_{SP} \cdot a_{SP} + \rho_D \cdot a_D + \rho_{O_2D} \cdot a_{O_2D}$$
$$+ \rho_K \cdot a_K + \rho_F \cdot a_F + \rho_{Ps} \cdot a_{Ps}$$
$$- \rho_{E_{el}} \cdot a_{E_{el}} - \rho_{G''} \cdot a_{G''} \qquad (26)$$

where: ρ - thermo-ecological cost, a – amount of a substance, index SP – sinter, index D – blast furnace blast, index O_2D – amount of oxygen in the blast with the level above the molar fraction of oxygen in the air, index K – coke, index F – alternative fuel, index Ps – steam, index E_{el} - electrical power, index G'' - top-gas emitted from the system.

Equation (26) takes into account the exergy carriers delivered to the blast furnace and discharged from the blast furnace unit. To be able to calculate the TEC value just like before the calculation is made for 1000 kg of produced pig iron a_{SUR} = 1000 kg. The TEC value for particular variables is [20]: r_{SP} = 6.8 MJ/kg p.i., r_D = 29.7 MJ/kmol blow, r_{O_2D} = 153 MJ/kmol O₂, r_K = 46.1 MJ/kg coke, r_F = 835.7 MJ/kmol nat. gas, $r_{E_{el}}$= 2.81 MJ/MJ el. power, $r_{G''}$ = 835.7 MJ/kmol nat. gas, r_{Ps} = 1.8 MJ/kg steam. Values a for coke, blast, steam, sinter, oxygen, additional fuel, and electric energy are calculated in the mathematical model. Value a for top gas emitted from the system has to be corrected by recalculating it to natural gas [20].

$$a_{G''} = G'' \cdot \frac{W_{d_G}}{d_F} \cdot 0.7 \qquad (27)$$

where: G'' - top gas emitted from the system, that means blast-furnace gas produced in the blast furnace that is left after losses, recirculation and heating stoves of blast and recirculation gas.

Results of the TEC value from one simulation are shown in Figure. 10. The figure shows how the TEC is changing its value compared to the base simulation. Base simulation is a simulation without the recirculation of the top gas and on the figure below it is represented as value 1.
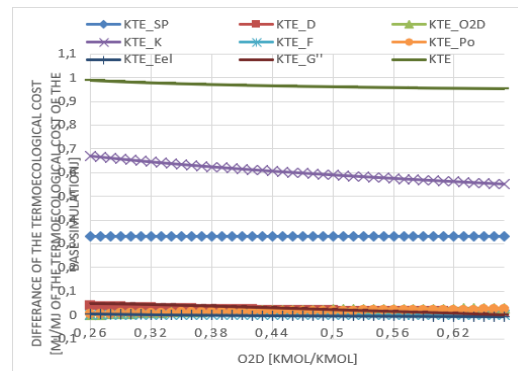

Figure 10: Thermogeological cost of the production of the pig iron for Trec=1273 K, TD=1378 K

Conclusions

The correct mathematical model of the process should be predictive, i.e., it should predict the correct quantitative side of the phenomena. The developed mathematical model of the blast furnace based on zone balance equations has this ability. Simulation calculations allow us to determine the effect of the use of additional various fuel-reduction factors and changes in the parameters of the blast on the energy performance indicators of the furnace. To improve the prediction of these indicators, the base measurement data of the blast furnace was validated using the advanced data validation method, which were then used to calculate the values of variables assumed as constant values in simulation modeling and empirical coefficients appearing in the presented equations of the mathematical model of the process. The validated values of the empirical coefficients of the mathematical model will be the input data for the target simulation calculations of the impact

of additives of various fuel-reduction factors and blast parameters on the energy consumption indicators of the blast furnace process and system effects.

The conclusion after reviewing the results shown in table no. 2 is that it is possible to simplify the advance validation method. It is not needed to include all the input date (all variables) in the algorithm. Like it is shown in table no. 2 the significant changes were made only in values of amount of coke, the mass fraction of carbon in the coke, temperatures of sinter, pig iron, top gas and blast furnace blast, amount of blast furnace blast, amount of natural gas, amount of top gas and composition of the top gas. It is possible to achieve similar results of the advanced validation method by considering only the variable listed above in the algorithm.

The increase in the molar fraction of oxygen in the blast furnace blast reduces the amount of the blast furnace blast itself. This is due to the oxygen demand of the blast furnace process. The amount of oxygen required for chemical reactions is provided by an increase in its share in the blast. It also results in lowering the temperature of the top gas and reducing its amount. The reduction of the amount of gas results directly from the reduced amount of blast, while the reduction of its temperature results from the necessity to find the energy balance - in order to ensure that the charge in the preparation zone is heated to the temperature in the thermal reserve zone, a smaller amount of gas is cooled to a lower temperature.

Lowering the temperature of the blast furnace blast as well as the recirculating blast furnace gas (reducing their physical enthalpies) increases the demand for the blast in order to meet the energy balance requirements for the assumed required adiabatic combustion temperature in the zone of the blast furnace nozzles.

The molar fraction of carbon monoxide in the top gas increases with the increase in the proportion of oxygen in the blast furnace blast, simultaneously increasing its calorific value. The reason for this change is the reduction of the amount of nitrogen supplied in the blast furnace blast, which in the blast furnace does not take part in chemical reactions but is only the carrier of the physical enthalpy. As the temperature of the blast or the recirculating blast furnace gas supplied to the process decreases, the molar fraction of carbon monoxide in the top gas, for the assumed oxygen fraction in the blast, increases slightly (Figure. 3). The reason for this situation may be the increased demand for coke to meet the energy balances of the furnace temperature zones. Hence, a greater coke requirement results in a greater amount of CO in the top gas.

The set of devices for the blast furnace in the conditions of cleaned top gas recirculation must be equipped with a turbine set using, on the one hand, the physical exergy of the top gas, and on the other hand, providing energy carriers for the process itself (Figure. 7). As presented earlier, an increase in the molar fraction of oxygen in the blast furnace blast causes a decrease in the amount of top gas produced with a simultaneous increase in the demand for recirculated cleaned gas. Up to the oxygen content in the blast of approx. 40% (this value depends on the temperatures of the energy carriers supplied to the blast furnace), there is a surplus of power in the turbine set shown in Figure. 5, which can be used, as in the modern blast furnace process, to drive the electric generator. Above this value of oxygen fraction, due to the decreasing amount of produced top gas, the recovery turbine does not have enough power to drive other machines - it is necessary to supply electricity to the system, which increases with the increase of oxygen fraction in the blast furnace blast.

The increase in the proportion of oxygen in the blast causes an increased demand for clean recirculating blast furnace gas with a simultaneous reduction in coke consumption. The chemical energy of the coke supplied to the blast furnace is replaced by the chemical energy

of the recirculating gas. The carbon monoxide in the recirculating gas replaces the coke carbon element needed for the iron oxides reduction reaction.

Calculations, as mentioned earlier, were performed until the top gas balance was zero. This means that they were carried out until there was no gas left that could be led out of the system balance shield.

Depending on the value of the blast temperature and the temperature of the recirculating blast furnace gas set for the simulation calculations, different values of coke savings are obtained. The maximum reduction in coke consumption reaches about 18% for the oxygen content in the $O_{2D} = 95\%$. For setting higher values of the temperature of the blast and the recirculating top gas, a greater reduction of the coke, demand is obtained for the same value of the molar fraction of oxygen in the blast (Figure. 9). At the same time, the system uses all the available top gas with a lower fraction of oxygen in the blast. This does not allow the reduction of coke consumption to reach the values achievable for the lower temperatures of the blast and recirculating gas supplied to the blast furnace.

In the simulation calculations, too much reduction of the temperatures of the blast and the recirculating gas supplied to the blast furnace resulted in obtaining the temperature values of the top gas produced in the blast furnace inconsistent with the physics of the process. As a result of this physical limitation, no further numerical simulations were performed.

The thermo-ecological cost of pig iron production in a blast furnace depends on the parameters and the number of substrates supplied to it. For the adopted assumptions, top gas recirculation allows for its reduction by about 4.8%. This is the minimum value achieved for the simulation, in which the minimum temperature of the blast set for calculations was $t_D = 1178\,K$, and the recirculating gas t_{rec} = 970 K. For the above temperatures, the minimum value of the coke demand is also achieved, which is K = 406.2 kg/t p. i.

Both the blast furnace temperature of 1387 K and the recirculating blast furnace gas temperature of 1273 K as well as for the lower values of these temperatures, one value of the thermo-ecological cost reduction was achieved, which can be considered as minimum under the model assumptions. This value was about 4.8% lower compared to the value of the thermo-ecological cost obtained in the calculations carried out with the use of data obtained from the baseline measurement of the blast furnace. This constant value was almost the same for the simulations performed, which may be due to the energy and chemical requirements of the blast furnace. The lower temperatures of the gases (blast and recirculating gas) supplied to the blast furnace allowed for greater oxygen enrichment of the blast without the need to provide additional fuel, increased the calorific values of the top gas and recirculating blast furnace gas at the same time reducing the demand for blast and coke. It follows that the higher thermo-ecological cost of oxygen needed to enrich the blast and the greater electricity demand are balanced with the lower thermo-ecological cost of coke consumption and the amount of blast for lower gas temperatures input to the system.

After the simulations, in which the blast furnace gas is fully used for firing the heating stoves and recirculation, it can be concluded that lowering the gas temperatures – blast and recirculating gas (while maintaining physical constraints) does not reduce the thermo-ecological cost by more than the previously presented value of 4.8 % compared to the value obtained from the base measurement. This means that from the temperatures of the blast and the recirculating gas for which, with the full utilization of the top gas, a value of oxygen content in the blast of 95% and higher temperatures the achieved thermo-ecological cost is the same. Increasing these temperatures is undesirable due to the use of all the available top gas with low oxygen enrichment of the blast, which does not allow the energy supplied in the coke to be adequately replaced by the recirculating top gas. This is due to the reduction of the efficiency of the blast and the recirculating top gas heaters because the increase in the assumed temperatures increases

the temperature of the exhaust gases flowing from the heaters. When the temperatures of the blast and recirculating gas are increased in the simulations, the minimum technically possible temperatures of the exhaust gases from the heaters are not achieved.

Acknowledgments

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