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ISSN 0543-5846
METABK 54(3) 499-502 (2015)
UDC – UDK 669.1.05:669.162.2.083.3:622.62=111

METHODS OF MATHEMATICAL MODELING FOR EVALUATION OF ENERGY MANAGEMENT OF BLAST-FURNACE PLANT

Received – Prispjelo: 2014-07-21
Accepted – Prihvaćeno: 2015-01-10
Preliminary Note – Prethodno priopćenje

The reduction of energy consumption in the blast furnace is still the subject of investigations using mathematical modelling of a blast furnace plant. Theoretical-empirical hybrid models of a blast furnace and its equipment have been presented. This model is built based on the mass and energy balances of furnace zones and empirical data from the measurement of a blast furnace. The results of a numerical simulation of the injection of auxiliary fuels and the top-gas recirculation after the removal of CO_2 to the blast furnace have been presented.

Keywords: metallurgy, blast-furnace process, mathematical modelling, auxiliary fuels

INTRODUCTION

The technology “blast furnace – LD (Linz- Donawitz) converter” dominates in the production of steel all over the world, where the blast furnace is the main operational unit producing pig iron. In the blast furnace process a large amount of energy is consumed. It is primarily a coke and alternatively auxiliary fuels [1 - 3]. Pig iron is achieved by the reduction of the iron oxides contained in the iron ore [4]. Liquid pig-iron contains about 96 % iron. The reduction process of the iron oxides takes place at high temperature generated by the combustion of coke and auxiliary fuels in the lower part of the furnace [4,5]. Blast is heated to a high temperature in Cowper stoves fired by a product of the process – the top gas [6,7]. In the modern blast furnace process sinter is used instead of raw ore. The blast-furnace process by using the principle of counter-current gas flow relative to the charge material is characterized by relatively low exergy losses. Exergy efficiency of a modern blast-furnace, reaches up to 80 % [7]. So far, on the industrial scale, this has been the cheapest and most effective method of iron ore reducing [4]. Energy improvements in the blast-furnace technology are mainly associated with the reduction of coke consumption. The chemical energy of coke constitutes the prevailing position (about 70 %) to the total energy supplied to the blast furnace process [4,7]. The share of the blast-furnaces process in energy consumption by the iron works, based on the level of fossil fuels using indicators of cumulative energy consumption is now over 60 %. The reduction of coke consumption can be achieved by an increase of blast parameters (temperature, pressure and oxygen enrichment) and applying auxiliary fuels [6]. However, the amount of coke, which is essential as the bearing structure and as a carburizing pig agent is the limit in the efforts to reduce the consumption of coke in the blast-furnace. The minimum requirement for coke is dependent on the quality of charge and coke. It is estimated at around 250 - 300 kg/t p.i. in the case of a high-quality coke and with optimal distribution of charge materials in a blast furnace throat [1]. The reduction of energy consumption in the blast furnace is still the subject of investigations that can be based in most cases on mathematical modelling of a blast furnace plant. Blast furnace literature presents different mathematical modelling methods [8 - 10]. In this paper selected mathematical models (input-output model [6] and zone-balance model [7]) have been presented and results of numerical simulation of injection of auxiliary fuels and the top-gas recirculation after the removal of CO_2 to the blast furnace have been showed.

MATHEMATICAL MODELING OF BLAST FURNACE

Thermal and chemical processes in the blast furnace are very complex. Mathematical modelling of these processes in theoretical way is very difficult [5,10]. The applied method of predicting the direct energy effects of a blast-furnace is based on information concerning the input and output of the process [6]. Theoretical-empirical hybrid model basing on the principle of the conservation of mass and energy in the steady state of blast furnace has been used. The balances of the elements C + S, H, O and N and energy balance equations have been set up for a blast-furnace process. Each equation, except the nitrogen balance, contains an individual constant. In the empirical part there is calculated the effect of changes of the thermal parameters of a blast-furnace, first of all auxiliary fuels, on the composition and temperature of the

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top-gas, as well as on the amount of flue dust. Each of these empirical equations contains one parameter, which is unknown a priori. The experimental part of this method includes also one single thermal measurement of the investigated blast-furnace. The results of this measurement are used to determine the process constants in the balance equations and the unknown parameters in the empirical equations. In this way one can obtain individual equations to predict the energy characteristics of the investigated blast-furnace, that means the specific consumption of coke (K) and blast (D), specific production of the top-gas (G) and its chemical energy (E), as well as the chemical energy of the top-gas feeding the gas-system (E_z) and the production of electric energy by the recovery turbine of the top-gas (E_{el}). This model is based on the assumption that the conditions of the blast-furnace charge are kept constant [6,7]. It has also been assumed in the balance equations that the following quantities, related to a pig iron unit are constant [6]: the difference between the amount of carbon and sulphur in non-energetic products (without flue dust) and substrates (process constant α in example balance presented by Equation 1), moisture of the charge (without moisture of coke), difference between the amount of oxygen in non-energetic products and substrates, difference between the physical and chemical enthalpy of non-energetic products and substrates, the loss of heat to the environment and cooling water in the blast-furnace. For example the carbon element balance is presented by Equation 1, and the example of empirical characteristic of CO_2 and CO content in the top-gas is presented by Equation 2.

$$\left(K - P\frac{c_P}{c_K}\right)\left(\frac{c_K}{12} + \frac{s_K}{32}\right) + \\ + F\left(\frac{c_F}{12} + \frac{s_F}{32}\right) = \alpha + G(CO_2 + CO) \qquad (1)$$

$$\varphi = \frac{CO}{CO_2} = a_1 exp(a_2 F) + \\ + a_3 exp[a_4(T_D - 273)] + \\ + a_5(O_{2D} - a_6)^2 + \varphi_0 \qquad (2)$$

where:

K, *F*, - specific consumption of coke, and auxiliary fuel / kg/t p.i.,

G, *P* - specific amount of the top gas and dust / kg/t p.i.

c_P, c_K, c_F - mass fraction of carbon in the dust, coke and auxiliary fuel,

s_F, s_K - mass fraction of sulphur in auxiliary fuel and coke,

CO_2, CO - volume fraction of CO_2, and CO in the top-gas,

O_{2D}, - volume fraction of O_2 in the blast,

T_D, - blast temperature,

a_i , φ_0 - empirical coefficients.

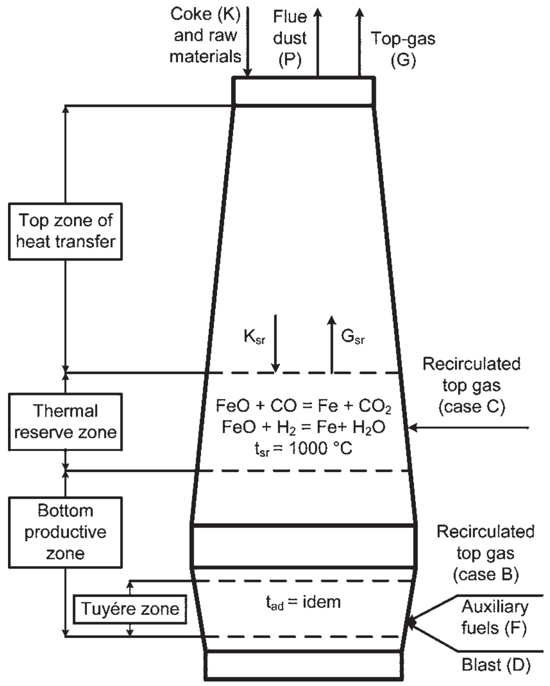

Figure 1 Temperature zones of a blast furnace.

More complex and advanced is the theoretical - empirical zone balance mathematical model of a blast furnace [7]. This model is built based on the mass and energy balances of blast furnace zones, whose main principles are similar to those of the previously discussed model. The balances of the elements C,S,H,O and N, and also energy balance equation have been set up separately for the top zone of heat transfer and for the lower zone of production together with the thermal reserve zone (see Figure 1). Approaching thermodynamic equilibrium makes it possible to apply chemical equilibrium equations in order to determine the composition of gas phase in the thermal reserve zone. The balance of elements and the energy balance also for the tuyére zone have been applied.

The empirical part of the zone method may be reduced to the experimental factor characterizing the deviation from the state of thermodynamic equilibrium in the thermal reserve zone and the equation expressing the amount of flue dust. The example of the carbon element balance for the bottom zone (productive zone) together with the thermal reserve zone and for the top zone (see Figure 1) is described by Equation 3 and Equation 4.

$$K_{sr}\left(\frac{c_{K_{sr}}}{12} + \frac{s_{K_{sr}}}{32}\right) + F(C_F + S_F) + \\ + G_{rec}(CO_{rec} + CO_{2rec}) = \frac{c_N}{12} + \\ + G_{sr}(CO_{sr} + CO_{2sr}) \qquad (3)$$

$$\left(K - P\frac{c_p}{c_k}\right)\left(\frac{c_K}{12} + \frac{s_K}{32}\right) + \\ + G_{sr}(CO_{sr} + CO_{2sr}) + \alpha_p = \\ = G(CO + CO_2) + K_{sr}\left(\frac{c_{Ksr}}{12} + \frac{s_{Ksr}}{32}\right) \qquad (4)$$

The meaning of the main symbols is similar to the case of Equation 1 and Equation 2. Additionally, the lower index "*sr*" concerns the thermal reserve zone of the blast-furnace, the lower index "*rec*" concerns the re-circulated top-gas. In the case of the zone-balance model, the mass fraction of carbon in the pig iron c_N is included in the carbon balance. For this reason the zone balance model requires the introduction of process constant only in the case of the top zone of heat transfer (see Figure 1). In the example of Equation 4 this is included as the constant $\alpha_{P.}$

The results of modelling by means of both presented models of the blast furnace process can be linked with the modelling of the system of Cowper-stoves and the top-gas recovery turbine. The energy efficiency of the Cowper stoves is determined by means of the energy balance equation [7]:

$$\eta_N = 1 - \varepsilon_{ot} - \frac{S(t_{sw} - t_{ot})}{W_d} \tag{5}$$

where:

ε_{ot} - relative heat losses,

S, W_d - heat capacity of flue gasses and lower heating value of fuel,

t_{sw}, t_{ot} - temperature of flue gasses and ambient temperature.

For this purpose the mean temperature of flue gases from Cowper stoves must be known. This temperature is described by the empirical formula [7]. The index of gas consumption per unit of pig iron E_N is expressed by the formula:

$$E_N = \frac{D(\Delta i_D + X_D \Delta i_{XD})}{\eta_N} \tag{6}$$

Δi_D, Δi_{XD} - the increase of enthalpy of blast and moisture in the blast,

X_D - the amount of moisture per unit of dry blast.

If no enrichment is required, the index of the consumption of the fuel gas expresses directly the consumption of the blast-furnace gas for Cowper stoves firing.

EXAMPLE RESULTS AND DISCUSSION

The authors considered the comparison of injection of pulverized coal (A) and the recirculation of the top-gas after the removal of CO_2 and H_2O. In the case of recirculation two cases have been investigated: (B) the injection of re-circulated gas into the tuyére zone and (C) the injection of the re-circulated gas into the thermal-reserve zone. The case (A) has been modelled by means of the input-output balance model. Cases (B) and (C) have been modelled by means of the zone-balance model. Figures 2 – 5 presents the influence of the injection of considered auxiliary fuels on:

- coke consumption K,
- blast consumption D,
- production of top gas chemical energy E,
- production of electricity in the top-gas recovery turbine E_{el}.

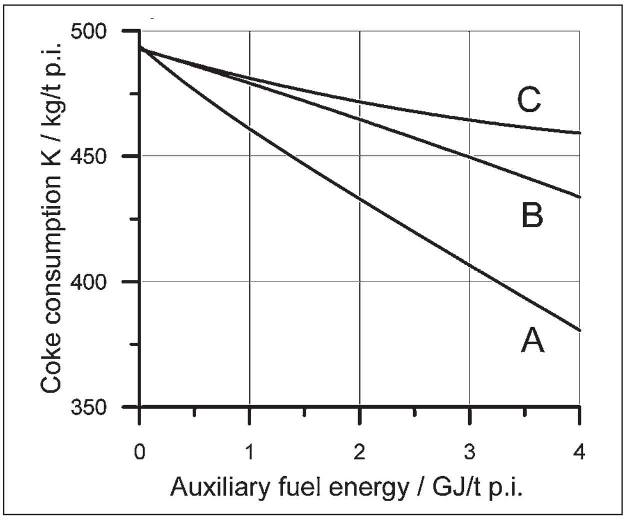

Figure 2 Influence of auxiliary fuel injection on coke consumption

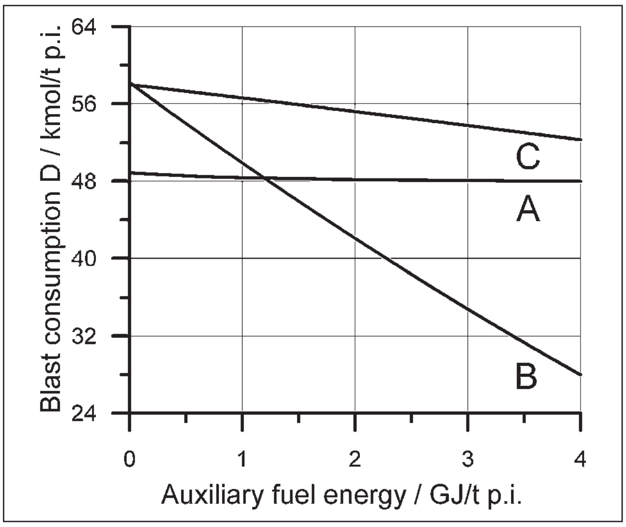

Figure 3 Influence of auxiliary fuel injection on blast consumption

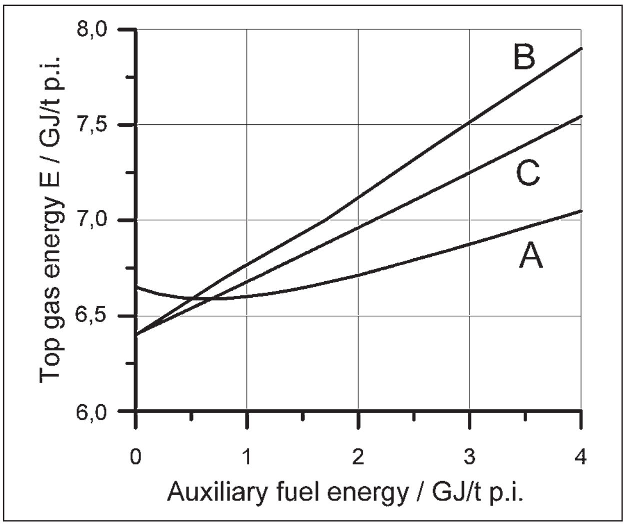

Figure 4 Influence of auxiliary fuel injection on top-gas production

It can be observed that the injection of pulverised coal leads to higher coke savings than in the case of the recirculation of the top-gas. However, it should be taken into account that coal represents non-renewable prima-

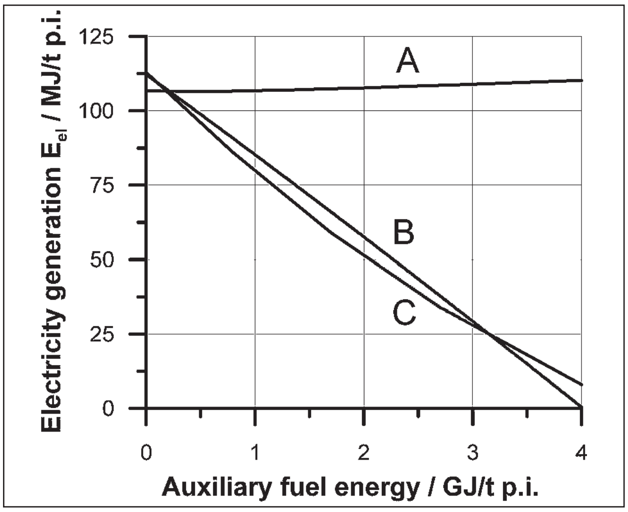

Figure 5 Influence of auxiliary fuel injection on electricity production in recovery turbine

ry energy and the recirculation of the top gas can be qualified as the utilisation of waste energy generated in the same technological process. As a result it leads to savings of non-renewable resources. Moreover, the recirculation of the top-gas in case B leads to a significant decrease of blast consumption, which finally results in an additional reduction of primary energy consumption. In the case of the top gas production, both injection technologies lead to quite similar effects. In the case of recirculation, the increase of injection leads to a decrease of the amount of the top-gas that can be used in the recovery turbine. From this point of view more profitable is the injection of coal. The presented models can be additionally applied to the investigation of the influence of increasing blast temperature and oxygen enrichment on the energy indices of the blast-furnace process. The presented results can be qualified as local effects. They can be applied for system energy, exergy and ecological analysis. Such analyses are possible thanks to the application of the cumulative calculus as presented in [7].

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Note: Anna Rudek-Gazda is responsible for English language, Gliwice, Poland.