

W. STANEK^{*#}, M. SZEGA^{*}, L. BLACHA^{**}, M. NIESLER^{***}, M. GAWRON^{****}

EXERGO-ECOLOGICAL ASSESSMENT OF AUXILIARY FUEL INJECTION INTO BLAST-FURNACE

OCENA EGZERGO-EKOLOGICZNA WDMUCHIWANIA PALIW ZASTĘPCZYCH DO WIELKIEGO PIECA

Metallurgy represents complex technological chain supplied with different kinds of primary resources. Iron metallurgy based on blast-furnace process, dominates in world steel production. Metallurgical coke is the basic fuel in this case. Its production is connected with several environmental disadvantageous impacts. One of them is the extended production chain from primary energy to final energy. The reduction of coke consumption in the process can be achieved e.g. by injection of auxiliary fuels or increasing the thermal parameters in the process. In present injection of pulverised coal dominates while recirculation of top-gas seems to be future technology. However, the latter one requires the CO₂ removal that additionally extended the production chain. The evaluation of resources management in complex energy-technological systems required application of advanced method based on thermodynamics. In the paper the system exergo-ecological assessment of pulverised coal injection into blast-furnace and top-gas recirculation has been applied. As a comparative criterion the thermo-ecological cost has been proposed.

Keywords: Blast-Furnace (BF), Pulverised Coal Injection (PCI), Top-Gas Recirculation (TGR), Thermo-Ecological Cost (TEC)

Metalurgia reprezentuje złożony łańcuch technologiczny zasilany różnymi rodzajami zasobów pierwotnych. Proces wielkopiecowy jest dominującą technologią w światowej metalurgii żelaza. Podstawowym paliwem w tym przypadku jest koks metalurgiczny. Produkcja koksu jest związana jednak z szeregiem niekorzystnych oddziaływań środowiskowych. Jednym z nich jest wydłużony łańcuch przemian od pozyskania zasobów energii pierwotnej do wytworzenia koksu. Redukcję zużycia koksu w wielkim piecu można osiągnąć przez wdmuchiwanie paliw zastępczych lub przez zwiększanie parametrów termicznych dmuchu wielkopiecowego. Obecnie w nowoczesnym procesie wielkopiecowym dominuje wdmuchiwanie pyłu węgla kamiennego. Jako technologię przyszłościową zaś wymienia się recykulację gazu wielkopiecowego do strefy dysz wielkiego pieca. Recykulacja gazu wymaga jednak zastosowania usuwania CO₂, co wiąże się z dodatkowymi nakładami energii. Ocena efektywności gospodarki zasobami w złożonych systemach energo-technologicznych wymaga zastosowania zaawansowanych metod opartych o prawa termodynamiki. W pracy zaprezentowano systemową egzergo-ekologiczną ocenę wdmuchiwania pyłu węglowego oraz recykulacji gazu gardzielowego do wielkiego pieca. Jako kryterium porównawcze zastosowano wskaźnik kosztu termo-ekologicznego.

1. Introduction

The world iron metallurgy is still mainly based on Blast Furnace (BF) technology (Fig. 1), that share in total production amounts to 95% [1]. A large amount of energy has to be delivered to the blast furnace. It is primarily metallurgical coke, and alternatively auxiliary fuels [2,3,4]. Moreover hot blast is introduced into the tuyere zone. The quality of resources, as well as, thermodynamic perfection of the process can be properly measured by means of concept of exergy. *Exergy* is alternatively defined as [5]:

- maximum ability of substance to perform work in relation to the environmental “*dead state*”,
- minimum amount of work necessary to produce a mater-

ial of given parameters from components common in the natural environment.

The second definition is especially useful for evaluation of quality of mineral resources with known ore grade [6].

Exergy efficiency, expressing the ratio of exergy of useful product (*P*) to exergy of resources (*F*) delivered to the process characterises the local thermodynamic efficiency of resources management in the process.

The blast furnace is characterized by relatively high exergy efficiency that can reach the level of about 70%. The exergy efficiency of the whole blast furnace plant, including Cowper stoves, (Fig. 2) reaches the level of about 65 % [7,8]. Such high thermodynamic effectiveness of the process is possible

* SILESIAN UNIVERSITY OF TECHNOLOGY, INSTITUTE OF THERMAL TECHNOLOGY, GLIWICE, POLAND

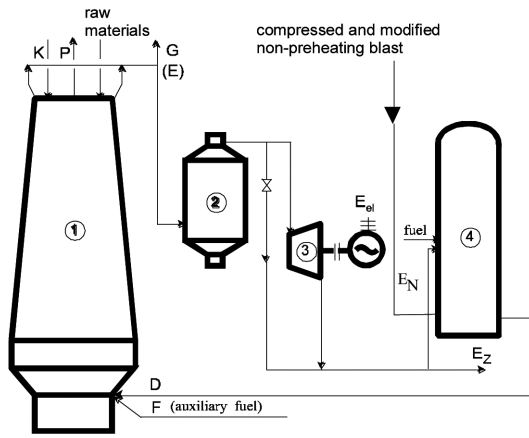
** SILESIAN UNIVERSITY OF TECHNOLOGY, INSTITUTE OF METALS TECHNOLOGY, KATOWICE, POLAND

*** INSTITUTE FOR FERROUS METALLURGY, DEPARTMENT OF PRIMARY PROCESSES, GLIWICE, POLAND

**** ARCELORMITTAL POLAND S.A.

Corresponding author: wojciech.stanek@polsl.pl

because the counter flow of heat and substance is realised in the shaft of this furnace [9].



1 - BLAST FURNACE, 2 - GAS CLEANING PLANT, 3 - RECOVERY TURBINE OF TOP GAS, 4 - COWPER STOVE

Fig. 1. Scheme of blast-furnace plant

The example exergy balance of the blast furnace is presented in Figure 2.

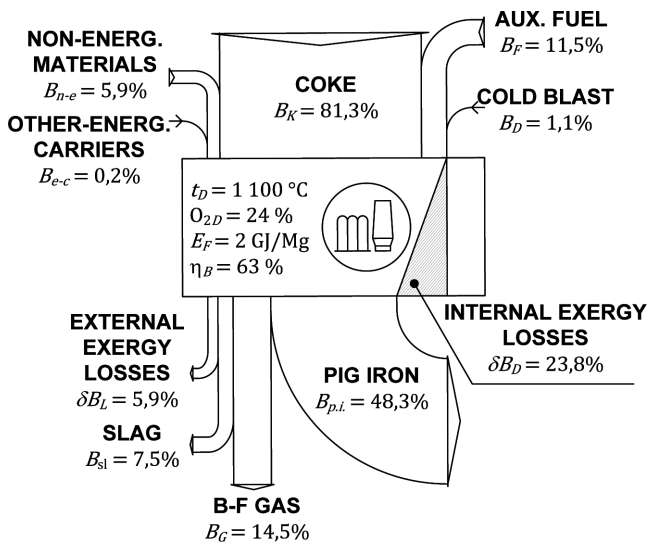


Fig. 2. Exergy balance of B-F plant

Over 80% of consumed exergy of resources results from the consumption of coke. Improvement of resource management of blast furnace plant is aiming mainly at reduction of coke consumption. This reduction can be achieved by means of an increase of blast parameters (temperature, pressure and oxygen enrichment) and applying an auxiliary fuels [9] or recirculation of top-gas. Each change of operational parameters \$x_0 \to x_1\$ can lead to changes in the exergy losses and to changes in the exergy efficiency and decide on the effectiveness of resource management in the considered component of production system (Fig. 3).

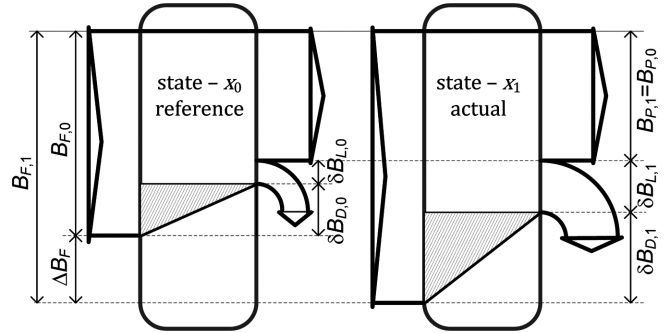


Fig. 3. Influence of operational parameters on exergy balance

The increase of consumption of resources exergy \$\Delta B_F\$ by constant output of the process \$B_{P,0} = B_{P,1}\$ in general can be the result of two reasons:

1) changes of operational parameters \$x_0 \to x_1\$ leads to increase of the external exergy losses:

$$\delta B_{L,0} \to \delta B_{L,1}$$

2) changes of operational parameters \$x_0 \to x_1\$ leads to increase of the internal exergy losses due to entropy generation in the considered process:

$$\delta B_{D,0} \to \delta B_{D,1}$$

In general the “fuel impact” due to \$x_0 \to x_1\$ is expressed as:

$$\Delta B_F = (\delta B_{L,1} - \delta B_{L,0}) + (\delta B_{D,1} - \delta B_{D,0}) \quad (1)$$

The example of influence of changing the operational parameters on local exergy losses will be presented in the paper for the case of pulverised coal injection (PCI) into the blast furnace.

Direct exergy analysis performed for the single component of the system is useful but far not enough. For the analysis of resource management efficiency the system analysis based on the concept of Exergetic Cost (ExC) has to be applied. Because of interconnections between processes there are also strong interconnections between exergy losses. To detect these effects the concept of the exergy cost or cumulative exergy consumption has to be applied [10,11]. The concept of exergy cost is presented in Fig. 4. The total resources input (\$R\$) depends not only on single irreversibility (\$I\$) but on the cumulation of irreversibility (\$I^*\$) through the production chain. Increase of irreversibility in single component influences the resources demand in all preceding links of the production chain.

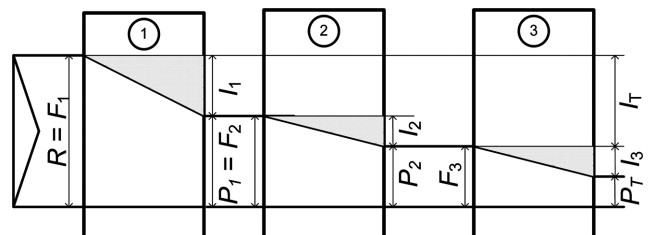


Fig. 4. Exergetic cost formation

The unit exergy cost of \$i\$-th component is defined as:

$$(ExC)_i = \frac{B_i^*}{B_i} = \frac{R}{P_i} = 1 + \frac{\sum I_i}{P_i} = 1 + \frac{I^*}{P_i} \quad (2)$$

Exergy Cost (ExC) analysis reaching the level of primary non-renewable resources can be the measure of influence of production technology on the depletion of non-renewable natural resources and in literature [12,13] is defined as Thermo-Ecological Cost (TEC).

In the presented work the authors briefly discussed two balance models of blast furnace (BF) with the model of Cowper stoves (CS). These models in details has been discussed e.g. in [7,8,14]. Results of modelling, so called *energy characteristics* of blast furnace plant represents input data for both – direct and cumulative exergy analysis by means of TEC. Presented example results of direct exergy analysis confirmed that in complex energy-technology systems such approach is far not enough. For this reason to compare the effects of pulverized coal injection (PCI) and top-gas recirculation (TGR) the authors proposed to apply system TEC analysis. Example results of this analysis are included and discussed. The exergy analysis and TEC analysis require the characteristic or mathematical models of particular components to determine the influence of operational parameters change on the exergy losses and on the exergetic cost formation.

2. Blast Furnace Modelling

For the purpose of Exergy and TEC analysis the “input-output” model [7,8] has been applied for prediction of PCI direct effects and zone balance model [14] for simulation of direct effects of top-gas recirculation. The scheme of blast furnace with assumed temperature zones for modelling purposes has been presented in Fig. 5.

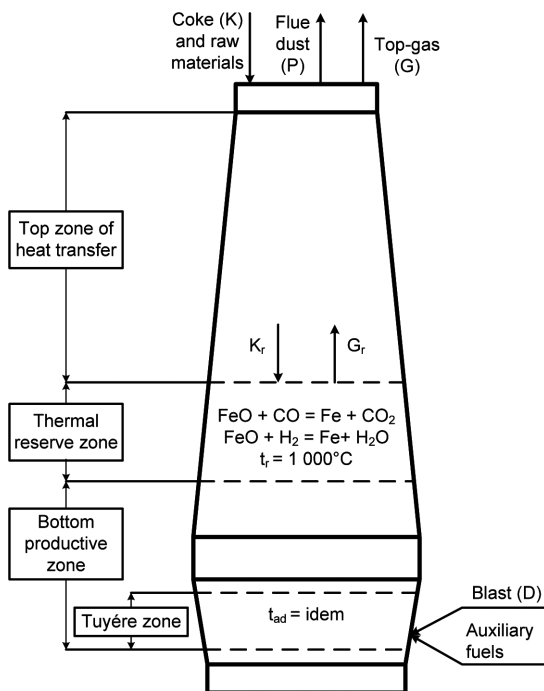


Fig. 5. Temperature zones of a blast furnace

Theoretical-empirical hybrid (I-O) model basing on the principle of the conservation of mass and energy in the steady state of blast furnace. The balances of the elements C+S, H, O and N and energy balance equations have been derived for

balance boundary covering whole blast-furnace. Each equation, except the nitrogen balance, contains an individual constant. Empirical part describes the effects of changes of the thermal parameters of a blast-furnace, and auxiliary fuels injection on the composition and temperature of top-gas. Each of these empirical equations contains one parameter, which is unknown a priori. The experimental part of I-O model 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. The I-O model let to predict the influence of operational parameters changes $x_0 \rightarrow x_1$ on energy characteristic of BF plant including: consumption of coke (K) and blast (D), production of top-gas (G) and its chemical energy (E), as well as, the chemical energy of the top-gas feeding the gas-system (E_Z). Moreover the model of top-gas expansion turbine [7,8,14] let to evaluate the production of electric energy by the recovery turbine of top-gas (E_{el}). For example the carbon element balance is presented by Eq. 3, and the example of empirical characteristic of CO_2 and CO content in top-gas is presented by Eq. 4.

$$\left(K - P \frac{c_P}{c_K}\right) \left(\frac{c_K}{12} + \frac{s_K}{32}\right) + F \left(\frac{c_F}{12} + \frac{s_F}{32}\right) = \alpha + G (CO_2 + CO) \quad (3)$$

$$\phi = \frac{CO_G}{CO_{2G}} = 0.1174 \exp(-0.0364F) + 8.93 \exp[-0.0053(T_D - 273)] + 69.01(O_{2D} - 0.2576)^2 + \phi_0 \quad (4)$$

where:

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

G, P – specific amount of 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.

The more complex and advanced is the theoretical-empirical zone balance mathematical model of a blast furnace [14]. This model is built based on the mass and energy balances of blast furnace zones depicted in Fig. 5. The main principle of which are similar as 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. Approaching thermodynamic equilibrium make it possible to apply chemical equilibrium equations in order to determine the composition of gas phase in the thermal reserve zone. Balance of elements and energy balance also for tuyère 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 carbon element balance for bottom zone (productive zone) together with thermal reserve zone and for top zone (Fig. 5) is described by Eq. 5 and Eq. 6.

$$K_{sr} \left(\frac{c_{Ksr}}{12} + \frac{s_{Ksr}}{32} \right) + F (C_F + S_F) + G_{rec} (CO_{rec} + CO_{2rec}) = \frac{c_N}{12} + G_{sr} (CO_{sr} + CO_{2sr}) \tag{5}$$

$$\left(K - P \frac{c_p}{c_k} \right) \left(\frac{c_K}{12} + \frac{s_K}{32} \right) + G_{sr} (CO_{sr} + CO_{2sr}) + \alpha_p = G (CO + CO_2) + K_{sr} \left(\frac{c_{Ksr}}{12} + \frac{s_{Ksr}}{32} \right) \tag{6}$$

The meaning of the main symbols is similar as in the case of Eq. 3 and Eq. 4. Additionally the lower index “sr” concerns the thermal reserve zone of the blast-furnace, lower index “rec” concerns re-circulated top-gas. In the case of 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 (Fig. 5).

The results of modelling by means of both presented models of blast furnace process can be linked with modelling of the system of Cowper-stoves and top-gas recovery turbine. The energy efficiency of the Cowper stoves is determined by means of the energy balance equation [15]:

$$\eta_N = 1 - \varepsilon_{ot} - \frac{S(t_{sw} - t_{ot})}{W_d} \tag{7}$$

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.

Main parameter deciding on the energy efficiency of Cowper stove is flue gas temperature, that depends on the operational parameters of blast furnace as [15]:

- blast temperature t_D ,
- flux of blast, n_D ,
- net calorific value of top-gas, W_{dG} .

Empirical characteristic of Cowper stove used in the mathematical model of BF plant has been identified by means of neural network [15], which simplified structure is presented in Fig. 6.

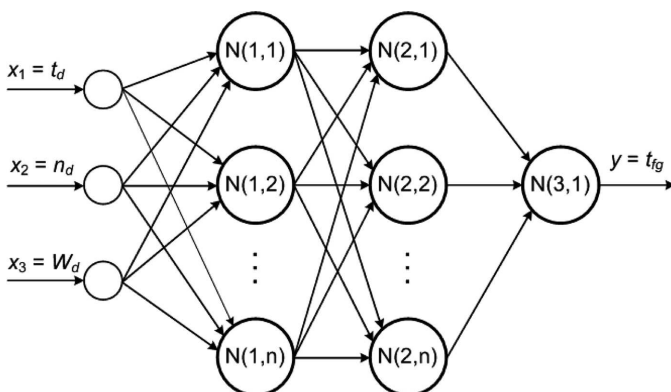


Fig. 6. Mean temperature neural model

Knowing the flue gas temperature and energy efficiency of CS (Eq. 7) the index of gas consumption per unit of pig iron E_N is expressed by the formula:

$$E_N = \frac{D(\Delta i_D + X_D \Delta i_{XD})}{\eta_N} \tag{8}$$

where:

$\Delta i_D, \Delta i_{XD}$ – the increase of enthalpy of blast and moisture in the blast,

X_D – amount of moisture per unit of dry blast.

The amount of gas transferred to the gas system of iron-work results from the difference:

$$E_Z = E - E_N \tag{9}$$

If no enrichment is required the index of the consumption of fuel gas expresses directly the consumption of blast-furnace gas for Cowper stoves firing. If the temperature constrains of CS is exceeded the BF gas for firing CS has to be enriched. In the considered case the coke-oven gas is assumed as rich fuel. The consumption of rich fuel is minimised by means of control of the following condition:

$$t_{fg} = t_{fg,max} \rightarrow E_{Nb} = E_{Nb,min} \tag{10}$$

The discussed models of B-F plant have been used for simulation of the influence of

- A) pulverized coal injection (PCI), and,
- B) top-gas recirculation (TGR)

on energy characteristics of blast furnace process. Results of these simulations are presented in Figs. 7÷11. Figs. 9 and 11 concerns the case of TGR. In Fig. 9 the influence of injection of top gas after CO₂ removal on additional consumption of oxygen is presented. The simulations for coal have been carried out for constant oxygen content in the blast at the level 24%. In the case of top gas recirculation this value is varying from 22% for $E_F = 0$ GJ/t to 49% when 4 GJ/t of recirculated top gas is injected into BF. Fig. 11 presents the presents the production of top-gas for the case of TGR and additionally presents the amount of CO₂ that has to be removed.

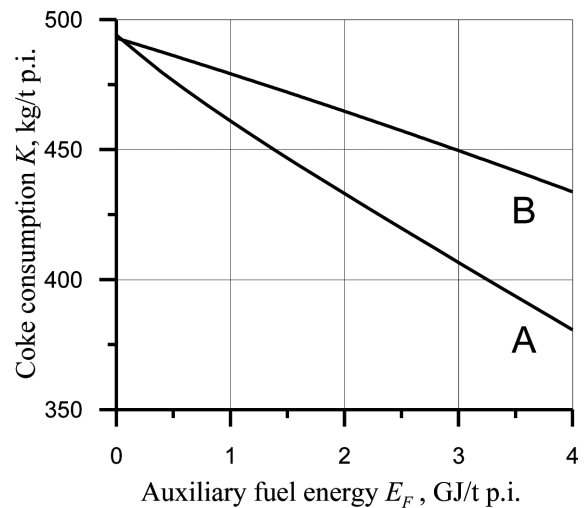


Fig. 7. Coke consumption

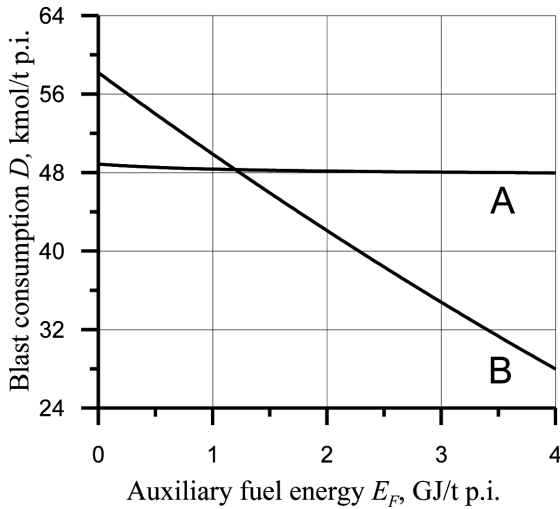


Fig. 8. Blast consumption

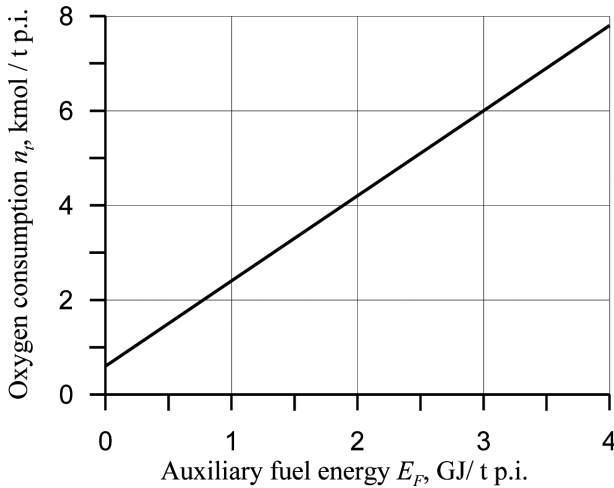


Fig. 9. Oxygen consumption

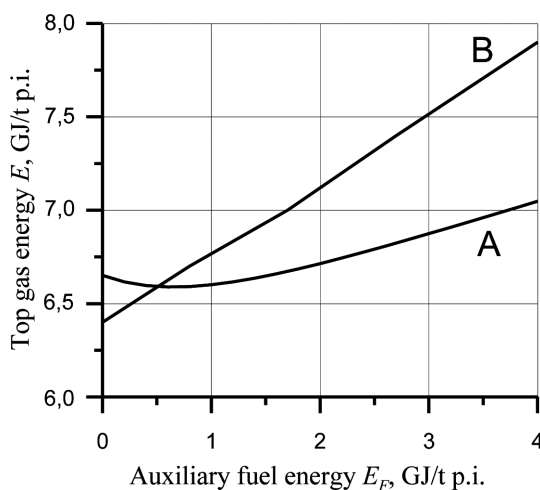
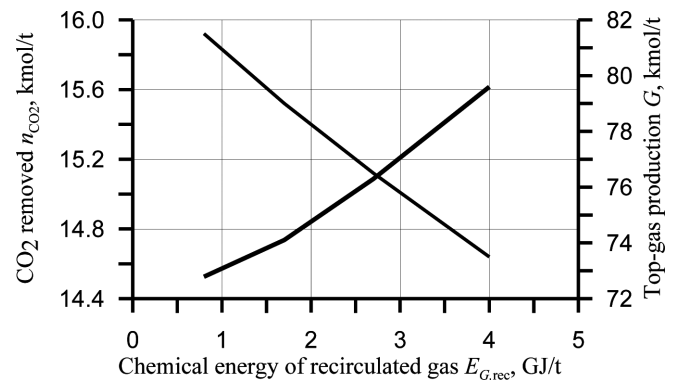


Fig. 10. Top-gas energy

The results of direct effects shown that first of all higher savings of coke is obtained in the case of pulverized coal injection. From other hand recirculation technology uses waste energy of top-gas instead of non-renewable primary energy of fossil fuels as in the case of PCI. Recirculation requires lower amount of compressed and preheated blast when the

chemical energy of injected fuel is higher than 1 GJ/t. From other hand recirculation requires significantly higher consumption of oxygen (Fig. 9) and additional energy consumption for CO₂ removal (Fig. 11). Concluding, due to multiplication of different effects accompanying the injection of auxiliary fuels it is difficult to evaluate the thermodynamic effectiveness and resource management efficiency basing purely on direct effects depicted in Figs. 7÷11. For proper and comprehensive evaluation the system analysis based on TEC concept is necessary. Such analysis includes all mentioned partial effects and brings all of them to one common measure which is the influence of operational parameters changes on the consumption of exergy of non-renewable resources. Assumptions and results of TEC analysis is presented in next section of the paper.

Fig. 11. Top-gas production and amount of CO₂ removed

As it has been pointed out in the introduction, also the direct exergy analysis could be far not enough when the complex metallurgical system is investigated. To prove this thesis the paper includes additionally example results of direct exergy effects determined using the exergy balance of BF and results presented in Figs. 7÷11. The exergy balance of the blast furnace plant takes the following form:

$$B_K + B_F + B_D + B_{n-e} + B_{e-c} = B_{p.i.} + B_G + B_{sl} + \delta B_L + \delta B_D \quad (11)$$

In the case of injection of auxiliary fuel to blast furnace the decrease of exergy efficiency is observed because injection leads to disturbance of counter current exchange of heat and mass in the furnace. The influence of pulverised coal injection on changes of exergy losses in blast furnace is illustrated in Fig. 12.

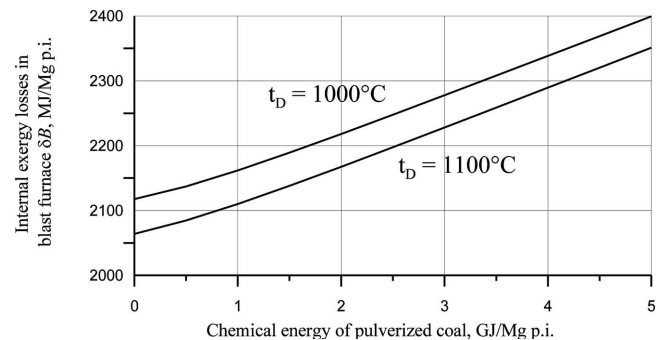


Fig. 12. Influence of PCI and blast temperature on exergy losses in BF

At first glance it can be concluded that the injection of auxiliary fuels into BF is not thermodynamic improvement

when leads to the exergy losses. However, the presented direct exergy analysis is useful but far not enough. For the analysis of resource management efficiency the system analysis based on the concept of Thermo-Ecological Cost (TEC) has to be applied. Because of interconnections between processes there are also strong interconnections between exergy losses. To detect these effects the concept of the exergy cost or cumulative exergy consumption has to be applied (Fig. 4) [6,8,9,12,13]. The concept of exergy cost is presented in Figure 3. The total resources input (R) depends not only on single irreversibility (I) but on the cumulation of irreversibility (I^*) through the production chain. Increase of irreversibility in single component influences the resources demand in all preceding links of the production chain as depicted in Figure 4.

3. Thermo-Ecological Cost (TEC) analysis

The system ecological effects including the evaluation of natural resource management is possible with the application of the TEC [5,6,12,13,16]. TEC is defined [5,12] as a cumulative consumption of non-renewable exergy connected with the fabrication of a particular product with inclusion of the additional demand for resources necessary to compensate of losses due to rejection of wastes to the natural environment. The TEC is calculated from set of balances which structure is explained Fig. 13.

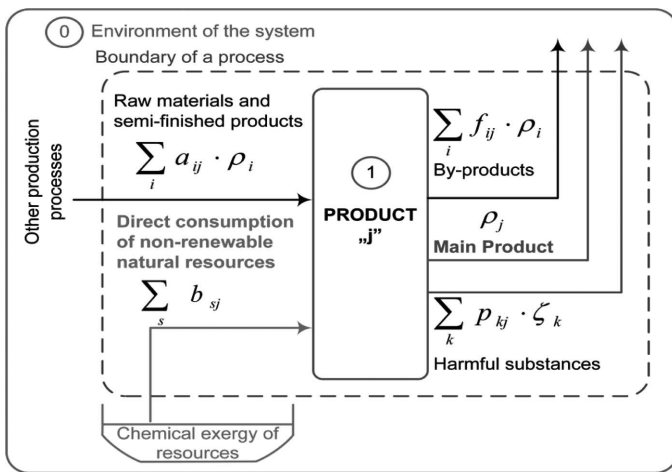


Fig. 13. Concept of TEC balance

The TEC balance for j -th production branch takes the following form:

$$\rho_j + \sum_i (f_{ij} - a_{ij}) \rho_i = \sum_s b_{sj} + \sum_k p_{kj} \zeta_k + p_{CO_2, j} \sigma_{CO_2} \quad (12)$$

where:

ρ_j, ρ_i – total value of the TEC of major product of the j th considered process, of the remaining processes belonging to the system,

b_{sj} – exergy of the fuel and of the mineral raw material immediately extracted from nature, per unit of the j th major product,

a_{ij}, f_{ij} – coefficient of the consumption and by-production of the i th domestic semi-finished product per unit of the j th major product,

p_{kj} – coefficient of the production of the k th rejected waste product per unit of the j th major product,
 ζ_k – total TEC of compensation of the deleterious impact of the k th rejected waste product

The exergy of mineral non-renewable resources appearing in the TEC balance (Eq. 12) b_{sj} includes the chemical exergy b_{chj} and concentration exergy b_{cj} [5,6]. The chemical part results from the equation [5]:

$$(Mb)_{chj} = \sum z_i (Mb)_{chi} - T_0 (MR) \ln z_i \quad (13)$$

where:

z_i – molar fraction of i -th component of solution,

$(Mb)_{chi}$ – molar chemical exergy of i -th component of solution,

(MR) – universal gas constant.

In the case of mineral natural resources, e.g. metal ores, the concentration part of chemical exergy is important. The higher is the ore grade (concentration of i -th component) the lower is the exergy (theoretical minimal work) required to separate the component from the solution (lower is the concentration exergy). The analysis done by Szargut and Stanek [13] shown that taking only chemical part of exergy of resource, the TEC of mineral resources is in most cases negligible. From other hand it is obvious that the more concentrated mineral the higher is the value of the ore. The worthless substance is that of the composition equal to the composition of completely degraded planet where all elements are mixed. From this point of view the concentrated ore represents some natural bonus. The higher the concentration the lower energy input is necessary to obtain the ore for metallurgical processes. In [6] it was proposed that the exergy mineral resources should contain not only chemical exergy but also concentration exergy resulting from the entropy of solution:

$$Mb_{cj} = -T_0 (MR) \left[\ln z_i + \frac{1 - z_i}{z_i} \ln(1 - z_i) \right] \quad (14)$$

The influence of ore grade x_i on the concentration exergy b_{ci} (calculated by Eq. 14) that expresses the physical value of the mineral ore is presented in the case of Fe in Figure 14.

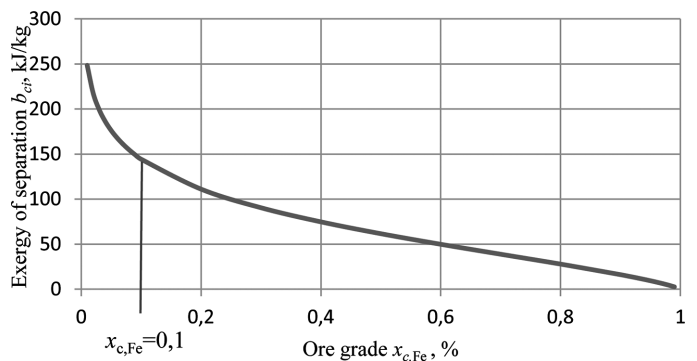


Fig. 14. Influence of the ore grade on concentration exergy

Not only consumption of resources to drive the processes but also negative effects resulting from the rejection of harmful waste substances to the natural environment has to be taken into account in the TEC index. TEC (ζ_k) burdening the k -th waste substance determine the additional requirement for resources in order to compensate the ecological losses due

to waste rejection. To calculate the index ζ_k Szargut [5] proposed the simplified method based on monetary indices of harmfulness w_k :

$$\zeta_k = \frac{Bw_k}{GDP + \sum_k P_k w_k} \quad (15)$$

where:

B – annual domestic consumption of non-renewable resources,

P_k – annual of waste substances released to the environment,

GDP – gross domestic product.

In [17] the new attitude to the blast-furnace process project realised under ULCOS programme – Top

Gas Recycling (TGR) and Carbon Capture and Storage (CCS) technology has been presented. The idea of the project [18,19] is to replace hot blast necessary for combustion of coke and production of reduction gas with oxygen. Then CO_2 is removed from the blast-furnace gas. The reduction gas prepared like this is blown again into the blast furnace. Tests carried out in the Experimental Blast Furnace at MEFOS – Metallurgical Research Institute AB in Luleå (Sweden) showed that 24% reduction in coke consumption with 90% share of blast-furnace gas recycled into the process is possible. Recirculation of top-gas to BF requiring additionally CO_2 removal also influences the total TEC index because of requirement for energy in the CO_2 removal installation. In general the proposed and applied CO_2 removal methods can be divided into the following group [20]:

- 1) post-combustion separation of CO_2 ,
- 2) pre-combustion separation of CO_2 ,
- 3) oxy-combustion with CO_2 recirculation.

For top-gas recirculation technology the first group is appropriate. In this group the following methods can be distinguished:

- 1) physical and chemical absorption of CO_2 ,
- 2) adsorption,
- 3) membrane separation,
- 4) cryogenic separation.

Within the TEC analysis presented in this paper the chemical adsorption of CO_2 by monoethyloamine (MEA) has been assumed. The simplified scheme of this process has been presented in Fig. 15.

In [20] the energy consumption in the presented process is estimated at the level of 0,3 do 0,8 kWh/kg CO_2 . To include the effects accompanying the removal of CO_2 before recirculation of top-gas, the abatement exergetic cost [21] has to be taken into account within the TEC analysis by means of balance (Eq. 12). The abatement thermo-ecological cost of CO_2 removal can be calculated by means of the following formula:

$$\sigma_{CO_2} = \frac{\sum_j a_j CO_2 \rho_j}{m_{CO_2}} \quad (16)$$

where:

$a_j CO_2$ – amount of j -th material or energy carrier consumed in the installation of CO_2 removal,

m_{CO_2} – amount of removed CO_2 .

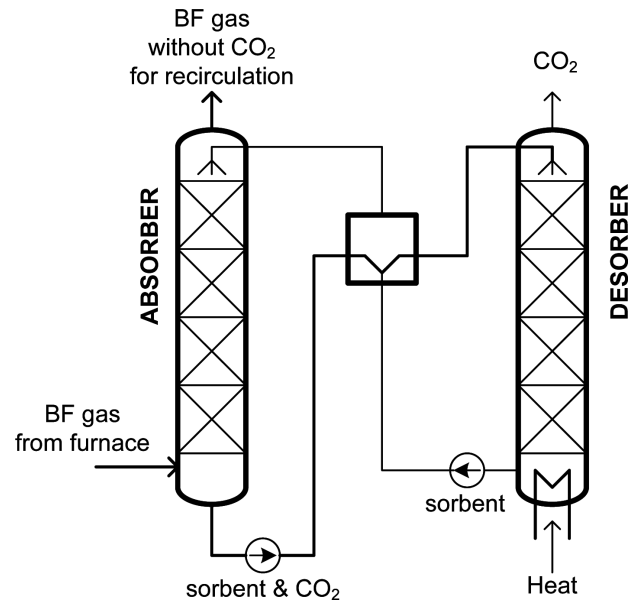


Fig. 15. Process of CO_2 removal from top-gas

The indices of thermo-ecological cost ζ_k and abatement cost σ_k for harmful substances and for CO_2 are summarised in the Table 1.

TABLE 1

Thermo-Ecological Cost and Abatement Cost of wastes

Substance	Abatement Cost σ_k	Thermo-ecological Cost ζ_k
	MJ/kg	MJ/kg
CO_2	4.4	-
SO_x	17.5	45.0
NO_x	26.0	45.0
Dust	0.5	9.5

Table 2 included the values of TEC indices [22, 23] for products delivered to the ironwork from outside the balance boundary.

TABLE 2

Thermo-Ecological Cost indices

Product	Unit	TEC
Coal	MJ/kg	27.1
Coke	MJ/kg	46.1
Natural gas	MJ/kmol	835.7
Electricity	MJ/MJ	3.6
Iron ore	MJ/kg	0.5
Sinter	MJ/kg	6.8
Oxygen	MJ/kmol	153.0

The results of simulation of direct effects of PCI and TGR presented in section 2 have been used for thermo-ecological assessment. As has been proven the injection of auxiliary fuel into BF leads to decrease of exergetic efficiency and to increase of exergy losses (Fig. 12). Thus, from the point of view

of direct exergy analysis the local effectiveness of resources management has been worsened. Simultaneously it is evident that PCI and TGR leads to coke savings, but local exergy evaluation doesn't take into account the internal losses generation in interconnected links. For this reason TEC has been determined by means of set of equation described by (Eq. 12) with application of data from Table 1 and 2. In Fig. 16 three cases are presented:

A) top-gas recirculation (TGR) connected with CO₂ removal,

B) pulverized coal injection (PCI) by blast temperature $t_D = 1000^\circ\text{C}$,

C) pulverized coal injection (PCI) by blast temperature $t_D = 1100^\circ\text{C}$.

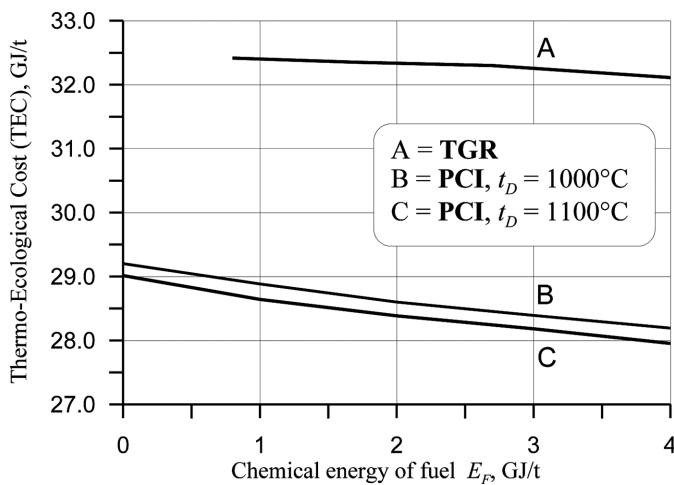


Fig. 16. Thermo-Ecological Cost of pig iron

First of all the opposite conclusion in comparison with results of direct exergy analysis can be reached – the injection of both PCI and TGR leads to the decrease of TEC and finally to savings of primary non-renewable resources. Thus, complex energy-technology systems can't be evaluated purely by means of local exergy efficiency or entropy generation methods. It can be observed that in the case of PCI it is possible to achieve significantly lower TEC than that corresponding to TGR. The difference is of magnitude about 4 GJ/t. It can be first of all the reason of necessity of CO₂ removal (Fig. 11) but also because of significantly higher demand for oxygen in the case of TGR (Fig. 9). Production of oxygen is burdened with relatively high index of TEC (Table 2). To detail analysis of mentioned reasons it could be useful to calculate the partial TEC for the case of TGR technology. The total TEC is influenced in the analysed cases by the following partial impacts: K – coke consumption, D – blast consumption, O2D – oxygen consumption, Eel – production of electricity in top gas recovery turbine, EZ – energy of blast furnace gas for external consumers, RAW – raw non-energetic material, CO2 – removal of CO₂. Results of such calculations are presented in Fig. 17.

In the cases with recirculation of top-gas the share of coke consumption in total TEC is between 57% and 52%. The second important position is the consumption of sinter which share in total TEC is about 34% when TGR is applied. The production of electricity in recovery turbine decreases the total TEC less than 1% in all cases and is negligible. Also

with the increase of chemical energy of recirculated gas the positive effect of transfer of surplus of gas to the ironwork gas system is decreasing up to 2%. The share of CO₂ removal in total TEC is about 10% and additionally in the case of TGR at the level of 4 GJ/t the share of oxygen is increased to about 4%. Two factors are then decisive for higher value of TEC in comparison with PCI. First of all the necessity of CO₂ removal that require about 3.2 GJ/t and secondly because the increased demand for oxygen that in the case of 4 GJ/t TGR is equivalent to 3.7 GJ/t of the total TEC.

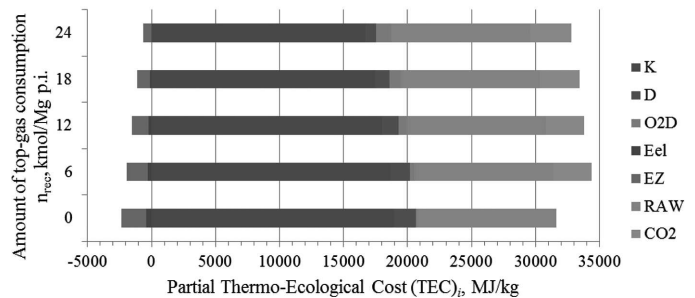


Fig. 17. Partial TEC

4. Summary and conclusions

The paper discussed the comparison of pulverised coal injection (PCI) and top-gas recirculation into blast furnace. To compare the thermodynamic effectiveness of both technologies the exergy analysis has been applied. Moreover system exergo-ecological assessment has been carried out. Exergy analysis has been based on the results of Blast-Furnace plant modelling based on input-output and zone balance models. On the example of (PCI) the authors demonstrated that in the case of complex energy-technological systems the direct exergetic evaluation is far not enough and can lead to false conclusions as depicted in Fig. 12. For this reason the algorithm of Thermo-Ecological evaluation of both technologies has been developed and applied for comparative analysis.

First of all the opposite conclusion in comparison with results of direct exergy analysis can be reached – the injection of both PCI and TGR leads to the decrease of TEC and finally to savings of primary non-renewable resources. It proved the thesis that complex energy-technology systems can't be evaluated purely by means of local exergy efficiency or entropy generation methods. It can be observed that in the case of PCI it is possible to achieve significantly lower TEC than that corresponding to TGR. The difference is of magnitude about 4 GJ/t. It can be first of all the reason of necessity of CO₂ removal in the case of TGR but also because of significantly higher demand for oxygen in this technology. In order to analyse both technologies more detailed it has been proposed to calculate the partial TEC for the case of TGR technology.

In the cases with recirculation of top-gas the share of coke consumption and consumption of sinter is dominant in the total TEC. The production of electricity in recovery turbine decreases the total TEC at negligible level. The share of CO₂ removal in total TEC of TGR technology is about 10% and additionally in the case of TGR at the level of 4 GJ/t the share of oxygen is increased to about 4%. These two factors are then decisive for higher value of TEC in comparison with PCI.

REFERENCES

- [1] <http://www.worldsteel.org/statistics>. Last assessed September 2014.
- [2] G. Hanniker, J.C. Davidson, Toward 300 kg/thm coke rate with granular coal injection, *Ironmaking Conference Proceedings* **50**, 503-516 (1991).
- [3] J.C. Agarwal, F.C. Brown, D.L. Chin, The role of oxygen-plus-fuel injection in increasing of the productivity of the blast furnace, *Proceedings of Ironmaking Conference* **51**, 139-147 (1992).
- [4] R.F. Hall, D.E. Heinz, K.S. Nanavati, Blast furnace operation with high oxygen and fuel injection rates, *Iron and Steel Maker*, August **18** (8), 35-39 (1991).
- [5] J. Szargut, *Exergy Analysis, Technical and Ecological Applications*. WIT-press, Southampton, (2005).
- [6] A. Domínguez, L. Czarnowska, A. Valero, W. Stanek, A. Valero, Thermo-ecological and exergy replacement costs of nickel processing, *Energy* (2014).
- [7] A. Ziębik, W. Stanek, Energy and exergy system analysis of thermal improvements of blast-furnace plants, *International Journal of Energy Research* **30**, 101-114 (2006).
- [8] A. Ziębik, W. Stanek, Influence of blast-furnace process thermal parameters on energy and exergy characteristics and exergy losses, *International Journal of Energy Research* **30**, 203-219 (2006).
- [9] J. Szargut, A. Ziębik, The influence of the blast parameters and of the injection of auxiliary fuels and hot reducing gas on the energy characteristics of a blast furnace plant (in Polish), Ossolineum, (1983).
- [10] J. Szargut, Analysis of cumulative exergy consumption, *Energy Research* **4**, 541-547 (1987).
- [11] A. Valero, Exergy accounting: capabilities and drawbacks, *Energy* **31**, 164-80 (2006).
- [12] J. Szargut, A. Ziębik, W. Stanek, Depletion of the non-renewable natural exergy resources as a measure of the ecological cost, *Energy Conversion and Management* **43**, 1149-1163 (2002).
- [13] J. Szargut, W. Stanek, Fuel part and mineral part of the thermoecological cost, *International Journal of Thermodynamics* **15** (4), 187-190 (2012).
- [14] A. Ziębik, M. Szega, Zone-balance method of predicting the energy characteristics of a blast-furnace plant, *Bull. Pol. Acad. Sci. Techn.* **42** (4), 521-539 (1994).
- [15] W. Stanek, H. Rusinowski, Identification of the energy characteristics of a cowper stove with the application of neural modelling, *Energy Conversion and Management* **48**, 2810-2817 (2007).
- [16] W. Stanek, Examples of application of exergy analysis for the evaluation of ecological effects in thermal processes, *International Journal of Thermodynamics* **15** (1), 11-16 (2012).
- [17] M. Niesler, New attitude to blast-furnace process in ulcos project, *Prace IMZ3* (2009) (in Polish).
- [18] <http://www.ulcos.org/en/>.
- [19] ULCOS, the European initiative for CO₂-lean steelmaking. Newsletter from MEFOS – Metallurgical Research Institute AB, Luleå, Sweden, December (2006).
- [20] J. Kotowicz, K. Janusz, Ways to reduce CO₂ emissions from energetic processes (Sposoby redukcji emisji CO₂ z procesów energetycznych). *Rynek Energii* **1**, (2007) (in Polish).
- [21] A. Valero, E. Botero, An assessment of the earth's clean fossil exergy capital based on exergy abatement cost., *Proc. Conf. ECOS'2002*, Berlin (2002).
- [22] W. Stanek, Method of evaluation of ecological effects in thermal processes with the application of exergy analysis, Silesian University of Technology Press, (2009) (in Polish).
- [23] W. Stanek, L. Blacha, M. Szega, Thermo-ecological cost (TEC) evaluation of metallurgical processes, *Metalurgija* **54** (1), 270-272 (2015).