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THERMO-ECOLOGICAL COST (TEC) EVALUATION OF METALLURGICAL PROCESSES

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Metallurgy represents a complex production system of fuel and mineral non-renewable resources transformation. The effectiveness of resource management in metallurgical chains depends on the applied ore grade and on the irreversibility of components of the system. TEC can be applied to measure the influence of metallurgy on the depletion of natural resources. The paper discusses the possibility of application of TEC in metallurgy and presents illustrative example concerning blast-furnace process.

Key words: metallurgy, blast-furnace, thermo-ecology, exergy, non-renewable resources

INTRODUCTION

The world-wide iron metallurgy is still mainly based on the blast-furnace technology. The blast-furnace process is characterized by high exergy efficiency because the counterflow of heat and substance is realised in the shaft of this furnace [1]. The exergy efficiency of the blast furnace plant (including Cowper stoves) reaches the level of about 65 % [2]. In the case of the blast-furnace process only (without Cowper stoves), the exergy efficiency can be even higher and reach 70 %. Two-stage “blast furnace – converter” technology of steel production is at present dominating all over the world, and endeavours are to be observed aiming to an improvement of the blast-furnace process [1], e.g. by the injection of auxiliary fuels into the tuyére zone [3-5]. From the thermodynamic point of view fuel injection is not an improvement because it leads to a disturbance of the counterflows in the blast furnace and deteriorates its exergy efficiency. However, from economical point of view it is justified because the injection of cheaper auxiliary fuels in comparison with expensive coke decreases the costs of the blast furnace plant operation [4, 5]. The main purpose of economical improvements is to save coke, because its cost is the predominant item of the input of the blast-furnace plant and significant position in balance of the whole ironwork. Besides changes in the saving of coke, also the consumption of blast, the production of the chemical energy of blast-furnace gas and its consumption in Cowper stoves, as well as the production of electricity in the recovery turbine utilising the top-gas exergy are changed. These values, determined per unit of pig-iron, are called energy and exergy characteristics of the blast-furnace plant and serve as a measure of the thermal improvement of the blast-furnace process (B-F) [2, 3].

The complexity of connections in the energy and technological system requires application of advanced evaluation tools based on thermodynamics. Energy and exergy system analyses can be numbered among this group of investigations. Thermoeconomic analysis (TEA) based on exergy cost theory [6] goes an step further to exergy analysis by introducing systems perspective and the concept of cost. Thermoeconomics has been applied widely for the analysis, optimization and diagnosis of energy intensive systems, but now is also starting being applied to the analysis of industrial symbiosis [7, 8] which is a key part of industrial ecology [7], looks for the reduction of resources consumption and waste generation by transforming present linear productive chains into closed material loops. As the classic TEA measures only the transformation of resources, for the environmental evaluations it should be extended also to the wastes causing the environmental losses, should reach the common level of non-renewable resources extraction and cover the whole life cycle [9]. The general method for environmental evaluation of any production system based on exergy was proposed by Szargut as the Thermo-Ecological Cost (TEC). The TEC application can be amply found in publications of Szargut and Stanek e.g. [3, 10]. In this paper this method will be discussed as powerful tool to evaluate the full environmental impacts of B-F

DIRECT EXERGY ANALYSIS OF BLAST-FURNACE PROCESS

As ferrous and non-ferrous metallurgy represent complex energy-technology systems and is characterised by mutual connections. Some of them are of the feed-back character. Moreover the flows connecting components of

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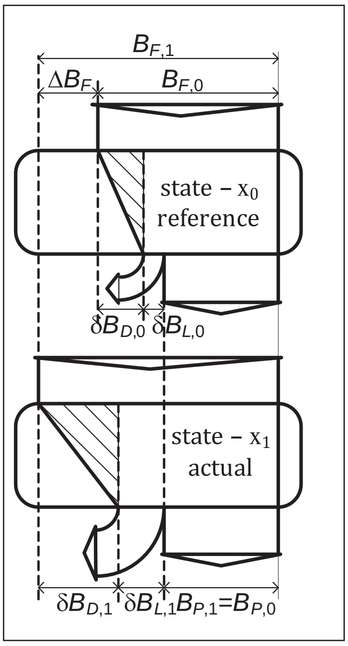

Figure 1 Exergy balance for reference and actual operational state

such systems are of different quality. For this reason simply analyses based only on the first law of thermodynamics and energy balance are far not enough. First of all the common measure of quality of different flows has to be introduced. The quality results from difference in thermal parameters as well as composition of flows in respect to the dead state found in the common environment. Such quality can be measured by means of exergy [10, 11]. Exergy is the thermodynamic property of matter and energy and results from combination of first and second law of thermodynamics. Besides the quality of matter and energy exergy can measre also the perfection of and production processes. The internal exergy losses $\delta\dot{B}_D$ can be calculated from the Guy-Stodola equation or form the exergy balance of the investigated process presented in Figure 1. It can be easily concluded, that each increase of internal exergy losses $\delta\dot{B}_{D,0} \rightarrow \delta\dot{B}_{D,1}$ which is the result of operational parameters changes between x_0 – reference state and x_1 – operational (actual) state leads directly to the increase of demand for exergy of process driving resources $\delta\dot{B}_{F,0} \rightarrow \delta\dot{B}_{F,1}$.

Consumption of resources, especially primary energy, caused by increase of irreversibility leads indirectly to the increase of waste emission to the environment. In the presented paper the exergetic evaluation of production process will be explained in the case of blast-furnace process. In

Non energy (mineral) materials and products are sinter, limestone, ferromagnetic and blast furnace slag, pellets, and pig iron. Its exergy can be determined by means of so-called single thermal measurement of the blast furnace [1, 2]. The example exergy balance of the blast furnace obtained by means of Equation 1 is presented in Figure 2.

The results confirmed that the B-F process is characterised by relatively high exergy efficiency about 63 %.

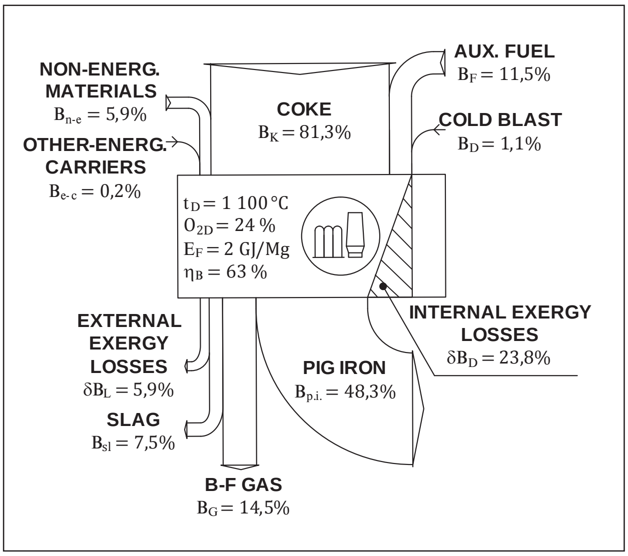

Figure 2 Exergy balance of blast-furnace plant

It results from the realisation of counter current flow in the blast furnace during mass and heat transfer.

THE EXERGY COST ANALYSIS

The presented direct exergy analysis is useful but far not enough. 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 [6, 11]. 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_T) through the production chain. Increase of irreverasability in single component influences the resources demand in all preceding links of the production chain as depicted in Figure 1.

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

$$k_i^* = \frac{B_i^*}{B_i} = \frac{R}{P_i} = 1 + \frac{\Sigma I_i}{P_i} \qquad (2)$$

where:

B_i^* – cumulative exergy consumption burdening the fabrication of *i*-th product exergy,

B_i, P_i – exergy of *i*-th useful product,

R – total exergy of resources feeding the whole production chain,

I_i – irreversibility (exergy losses) of *i*-th component of production chain.

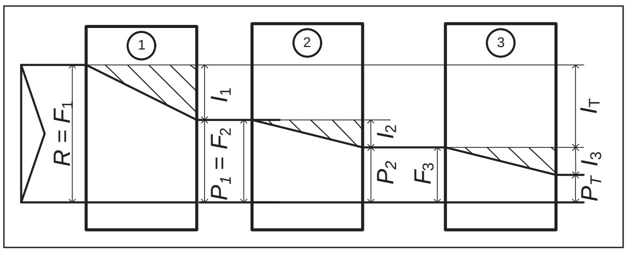

Figure 3 Exergetic cost formation

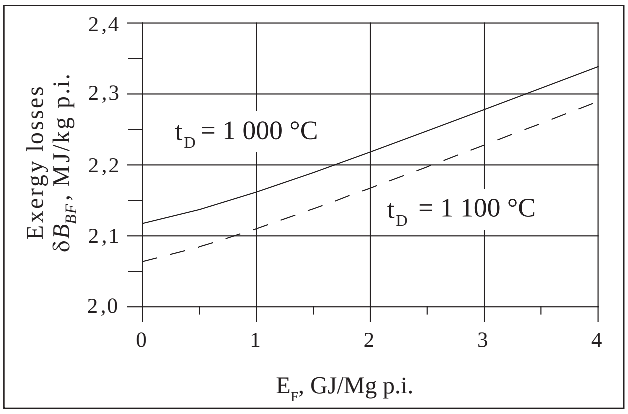

Figure 4 Exergy losses in blast furnace

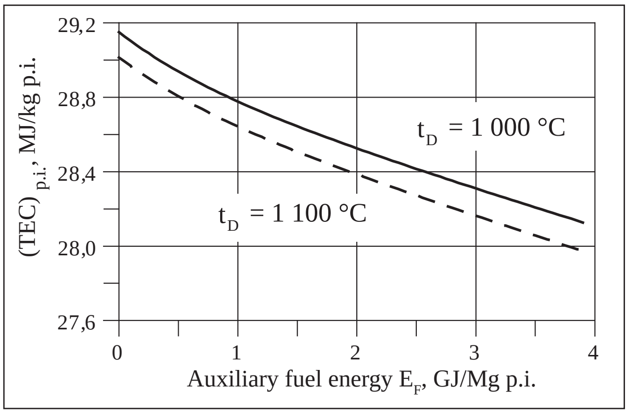

Figure 5 TEC of pig iron

The detailed algorithm for the determination of this cost is described in [6 - 8]. The ecological effects evaluation is possible with the application of the TEC [10, 11]. TEC is defined [11] as defined as a cumulative consumption of non-renewable exergy connected with the fabrication of a particular product. The TEC is calculated from set of balances presented by Equation 3.

$$\rho_j + \Sigma_i (f_{ij} - a_{ij}) \rho_i = \Sigma_s b_{sj} + \Sigma_k p_{kj} \zeta_k \qquad (3)$$

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. 3) included the chemical exergy $b_{ch\,j}$ and concentration exergy $b_{c\,j}$ [11, 12].

EXAMPLE RESULTS AND CONCLUSIONS

Coke characterised by relatively high TEC index can be partly replaced in blast-furnace by injection of pulverized coal with lower TEC. However, injection of cold coal leads to the increase of internal exergy losses in blast furnace. This effect for injection of coal in the range E_F= 0 - 4 GJ/Mg p.i. is presented in Figure 4.

Taking into account the criterion of direct exergy efficiency we reached from Figure 4 the conclusion, that the injection of coal is not-favourable. However, this statement is a wrong and misleading conclusion. Figure 5 shows clearly that the TEC decreases with the increasing amount of injected coal. We reach the savings in natural non-renewable resources not locally but in other point of complex systems of processes connected with B-F process. Presented results of TEC analysis show that for the presented minimization, entropy generation criterion is not correct. In the systems with strong connections between particular processes the cumulative calculus should be taken into account.

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Note: The responsible for English language is P. Nowak, Katowice, Poland