USE OF MATHEMATICAL TOOLS FOR EVALUATION OF THE QUALITY OF BLAST FURNACE COKE

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Abstract

Coke is one of the basic energy sources in the blast furnace process. Its quality essentially then determines the course of the blast furnace process. It is used both in the blast furnace and in the agglomeration processes. Coke also significantly affects the price of the produced raw metal. A number of different categorical criteria can be used for its evaluation. It may be the chemical, physical, technical, mechanical and logistic properties, but also cost. Apart from the chemical composition, typical properties of coke include also strength, grain composition, moisture content, heating value and a number of other parameters. If the evaluation of coke were based only on isolated criteria, finding the best possible choice would be complicated. One option for evaluating multidimensional problems are mathematical multi-criteria decision tools. These methods allow assessment of the difficult and complex issues through dozens of completely different criteria. As part of the research, these methods have been used to experimentally assess the quality of the supplied coke. The article deals with the analysis applied to the assessment process of the quality of blast furnace coke and use of this methodology in metallurgical enterprises.

Keywords: Iron, process, Sulphur, costs, production

1. INTRODUCTION

Coke is a porous solid, degassed residue of carbonization of coal charged at temperatures of 950°C - 1050 °C. Its main use is in blast furnace metallurgy. It is also used in the production of ferroalloys and nonferrous metals and in the energy and utility sector [1, 2]. Coke does not represent only fuel in the blast furnace process, but also a reducer and load carrying frame. Coke, after descent into the oxidation space of the blast furnace, burns intensively and the combustion products rise to the cooler parts of the blast furnace [3, 4]. Physically, the combustion of coke in the oxidation spaces can be regarded as gasification of solid coke, freeing space in the bottom of the furnace for the descent of another batch. Hearth gas leaving the oxidation space contains, in addition to CO, H_2, N_2, also SO_2 from oxidation of sulphur in coke burning in front of the tuyeres [5]. This gas component, however, dissolves in the dripping pig iron and returns to the hearth where the desulfurization occurs. The highest temperature of the gas in the oxidizing chamber, nearing 1800 - 2200 °C [6], is located in areas where the highest concentration of CO_2 is caused by the capacity and composition of the blast wind. On the other hand, the lowest temperature of the gas in locations where CO_2 disappears is generally on the boundary of the oxidizing chamber, and it is caused by the endothermic Boudouard reaction.

The technological aspects aside, coke also represent a significant cost. Fuel is currently and increasingly important in the production of iron and influences competitiveness [7, 8]. Demand for coke also significantly affects the availability of high-quality coking coal, whose price has seen great development in recent years [9].

As part of the research, the quality of coke from selected suppliers from Belgium, the Czech Republic and Poland has been experimentally assessed. The evaluation criteria were chosen from the areas of physics and chemistry, but also logistics and cost. The paper analyses the possible system of evaluation of blast furnace coke through multi-criteria decision methods. The analysed data was obtained within the research.

2. PROBLEM FORMULATION

Coke is the dominant part of the fuel necessary for making iron in a blast furnace. In the upper part of the hearth, about half a metre below the edge of the saddle there are openings circumferentially spaced around the hearth, through which by means of special devices (lances) the heated air - blast wind is injected into the blast furnace [10]. Coke, which along with other raw materials descends from the throat into the hearth, reaches the oxidizing space in front of the individual tuyeres where there is intense burning of coke carbon in the flow of the blast wind (1).

$$C(k) + O_2 = CO_2 \tag{1}$$

Due to excess of carbon in the hearth, the carbon dioxide is reduced to carbon monoxide and the product of Boudouard reaction (2) in the blast furnace is essential for the reduction zones of the blast furnace. CO then always leaves the oxidizing space as the product of burning of coke [11, 12].

$$C(k) + CO_2 = 2\ CO \tag{2}$$

In oxygen-deficient places the coke carbon burns imperfectly to CO, relation 3.

$$C(k) + 0.5\ O_2 = CO \tag{3}$$

The coke in the blast furnace acts as a heat source and a reducer of iron ores and its appropriate granulometric composition contributes to the required flow of gases through the blast furnace. Coke properties can be classified into the following groups: chemical, physical, and physico-mechanical. The organic mass of coke consists mainly of carbon and a small amount of hydrogen, oxygen, nitrogen and sulphur. Hydrogen and oxygen and part of carbon constitute the residual volatile matter, the content of which is around 0.8 to 1.4 % by weight of normal mature cokes. During the secondary heating of the coke, the resulting gaseous products occur, which are composed of 9-12 % of CO_2, 47-55 % of CO, and 30-40 % of H_2. From the physical properties, the key one is particularly the density. This can be divided into actual and apparent. The actual density represents the weight volume of units of the examined coke free of voids, pores and cracks and with a grain size under 0.2 mm. Its value is around 1.8 g/cm^3 and it in general indicates the degree of maturity and arrangement of the produced coke [13, 14]. The apparent density refers to the weight of a volume unit of real grains of coke formed during the carbonization process. Its value depends on the density of the charge, on the velocity and temperature of coking, and also varies over the width of the chamber. It is most often within 0.7-1.2 g/cm^3. From the physical and mechanical properties especially crucial are those related to the abrasion resistance of the coke. For determining the mechanical properties of coke, the Micum drum test is used due to the nature of the stress, where about 40% of the kinetic energy is transferred to the wear stresses and the remainder to fall.

3. EXPERIMNETAL WORK

The assessment of blast furnace coke and its properties can utilize many indicators and parameters. In order to select the ideal variant, it is necessary to take into account all the relevant parameters. This can be performed with methods based on the principle of multi-criteria decision. For the purposes of the research, these methods were applied to the monitored types of coke. Assessment of coke can be performed according to dozens of properties. Within the research, the individual features were divided into the following categories: physical, chemical and mechanical. At the same time, the supply conditions must be also taken into account, which are related to price, availability and logistics. Metallurgical enterprises, however, do not have the option of selecting a suitable supplier and type of blast furnace coke according to dozens of completely different criteria. Therefore 30 key criteria were selected from the above categories. Out of those, 4 of the most important have been chosen. This was accomplished using the method of paired comparisons. The research was attended by employees from different areas within a metallurgical company.

Using the method of paired comparisons, the following key criteria have been identified:
Criterion no. 1 - Price ($/t)
Criterion no. 2 - Store (t)
Criterion no. 3 - Lumpiness (%)
Criterion no. 4 - Calorific value (MJ/kg)

These are completely different categories of criteria. Therefore, it is also important to use multi-criteria decision methods. The following criteria were therefore identified as the most important: price, quantity of coke in a consignment store, lumpiness and calorific value. The price is a dominant cost criterion. The cost of coke is a significant component affecting the final cost of the produced iron. In general, fuel costs can constitute 20-30 % of all the production costs of raw metal. The second criterion concerns the amount of coke that the contractor is willing to allocate in the form of consignment stock. It is therefore a supply that is constantly available to the metallurgical company, which can draw from it according to its current needs. The third criterion concerns the lumpiness of the actual blast furnace coke. Lumpiness is rated in percent. The given value represents the homogeneity of a given fraction according to a given grain. The last criterion is the calorific value, which may represent a crucial influence on the technological parameters of the blast furnace process. The research compared three types of supplied coke. For the purposes of the research, the suppliers were identified according to the country of origin: the Czech Republic, Belgium and Poland. **Table 1** shows the values of all the monitored criteria.

Table 1 Values of criteria by coke supplier

Criteria		Coke suppliers		
		Czech Republic	Belgium	Poland
K1	Price ($/t)	140	165	151
K2	Store (t)	600	1,100	900
K3	Lumpiness (%)	89	91	95
K4	Calorific value (MJ/kg)	28.49	29.1	27.96

For comparison of specific types of coke, the method of the distance from dummy option was used. The method is based on measurement of the Euclidean distance in space. The evaluation is based on the quantification of distance of individual variants from the fixed option. This then represents such an alternative in which the values of all the criteria are perfect. The assessment of individual suppliers of coke can be then performed using equations (4, 5).

$$D_j = \sqrt{d_j} \tag{4}$$

$$d_j = \sum_{i=1}^{n} v_i \times \left(\frac{x_i^* - x_{ij}}{x_i^* - x_i^0} \right)^2 \tag{5}$$

The method of the distance from dummy option also uses the weight (importance) of individual criteria. In **Table 2** the specific weight for each of the monitored criteria is in column v_i. Weights for all criteria were determined using the team method, both on the basis of long experience and using the method of paired comparisons. The values then represent the weights of individual types of criteria and their value was determined as the arithmetic mean of the results of the paired comparison method. The observed value of the Euclidean distance is basically the partial sum of each criterion's deviations from the ideal value. The supplier of coke with the lowest value of this represents the most appropriate option based on this method. For all analysed coke suppliers the distance from dummy option (D_j) was determined according to relation (5). They were then evaluated based on this value (see **Table 2**). Lower distance D_j means a better variant. **Table 2** on line D_j shows the specific distance from dummy option for the coke suppliers from the Czech Republic, Belgium and Poland. Based on these values the final ranking of coke supplies has been determined. The total quality of coke from individual suppliers from these countries is ranked in decreasing order.

Table 2 Analysis and determination of the quality of individual types of coke

Criteria		v_i	x_i^*	x_i^0	d_{ij} for individual suppliers		
					Czech Republic	Belgium	Poland
K1	Price ($/t)	0.300	140	165	0	0.300	0.168
K2	Store (t)	0.100	1,100	600	0.100	0	0.040
K3	Lumpiness (%)	0.150	95	89	0.150	0.100	0
K4	Calorific value (MJ/kg)	0.450	29.10	27.96	0.240	0	0.300
				$\sum$	0.490	0.400	0.508
				D_j	0.700	0.632	0.712
				Rank	2.	1.	3.

The determined order of the coke suppliers inherently represents their suitability for use in the blast furnace process. The method of distance from dummy option allows taking all the criteria into account regardless of the units in which they are quantified.

4. DISCUSSION

For complex evaluation of the quality of blast furnace coke the method of the distance from dummy option was used. The evaluation was performed for suppliers from these countries: the Czech Republic, Belgium and Poland. Based on these criteria the overall quality of supplied coke was evaluated and ranking of individual suppliers was performed. Using applied mathematical methods, the following order of coke suppliers from individual countries was determined (see **Table 2**):

1) Option supplier - Belgium (0.632)
2) Option supplier - Czech Republic (0.700)
3) Option supplier - Poland (0.712)

Values in parentheses represent the optimal distance from the (dummy) option. The order based on this model is quite remarkable given the primary data. The best identified coke was the fuel from a supplier in Belgium, but it but had the highest price. The Belgian supplier also offered the highest amount of allocated coke in the consignment store. At the same time, the offered coke had clearly the highest calorific value according to the performed tests. These two aspects greatly influenced the result of the evaluation. In second place was the coke from a supplier in the Czech Republic. It had the significantly lowest price, but also worse performance in other criteria. In third place was the coke from a supplier in Poland. According to the performed measurements, this coke had the best lumpiness homogeneity of all the submitted samples. Its other parameters were then significantly worse. Based on the research, the metallurgical enterprise was advised to use the coke suppliers according to the determined rank. It is however important to note that the differences in the observed results were minuscule. It can therefore be recommended using the ranking when ordering coke, but at the same time continually evaluating the current values of the monitored criteria.

5. CONCLUSIONS

Producers of iron must increasingly use complex methods for analysis of a number of complex issues. Most raw materials can be characterized by many parameters. In the case of coke these properties can be physical, chemical, and mechanical but also logistical and costs. The logistics and price significantly affect the costs of the whole process and thus the price of the produced raw metal. In the event that the metallurgical company chooses for evaluation of coke only one isolated criterion and based its assessment of this, it may certainly not be the optimal variant. The proposed evaluation is based on synthesis and comparison of many criteria which evaluate the coke properties from many aspects. This can be seen as a major contribution of the proposed evaluation. In the production of iron, it is not possible to only evaluate technological attributes but it is also necessary to take into account other criteria which influence the overall cost of the process. In the case of coke, it is a dominant cost item in the production of iron. Metallurgical enterprises must therefore very accurately assess the potential quality of the offered raw materials. The applied methodology makes it very simple to evaluate a number of parameters of coke and transform these into one single indicator. This process may represent a simple tool for assessing the quality of blast furnace coke.

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