



Environment and Risks of Iron Production

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1. Introduction

The blast furnace plant includes not only the operation of its own blast furnaces but also many preparatory and auxiliary operations with relative autonomy (Fig. 1). The operation of the blast furnace is then continuous. The feedstocks must also be prepared and replenished continuously, and iron will be tapped at regular intervals (Kret 2013).

Blast furnace operation is an important source of pollutants that affect the working environment, but also the surroundings of the company. Most relevant studies focus on the secondary consequences that deal with the production of specific pollutants. However, higher fuel consumption, higher energy performance, repeated entry of raw materials into the process (sintering) can be affected by differences in the reducibility of individual ore raw materials. Significant differences in the degree of reduction of ore raw materials can fundamentally affect the technological process of iron production. The research goal of the article can be classified into two levels. The first one concerns the analysis of current scientific work and the definition of the main sources of pollutants in the blast furnace process. The experimental part was focused on the production of pollutants in the agglomeration process and evaluation of the degree of reducibility for three types of ore raw materials. The research was carried out in the environment of the selected metallurgical company in the Czech Republic. The evaluation of the reducibility of the monitored ore raw materials was focused on finding possible deviations in the degree of ore reduction. Significant variations in this technological parameter can contribute to the production of pollutants in the production of iron and inefficiencies in the production process.

In addition to controlling the technological process of the blast furnace itself, other operations connected with material preparation, transport, blast furnace product processing and other related activities are essential. A separate part of the production plant deals with the processing and preparation of the metal-bearing component (mainly ore). Sintering or palletizing processes are used for their treatment.

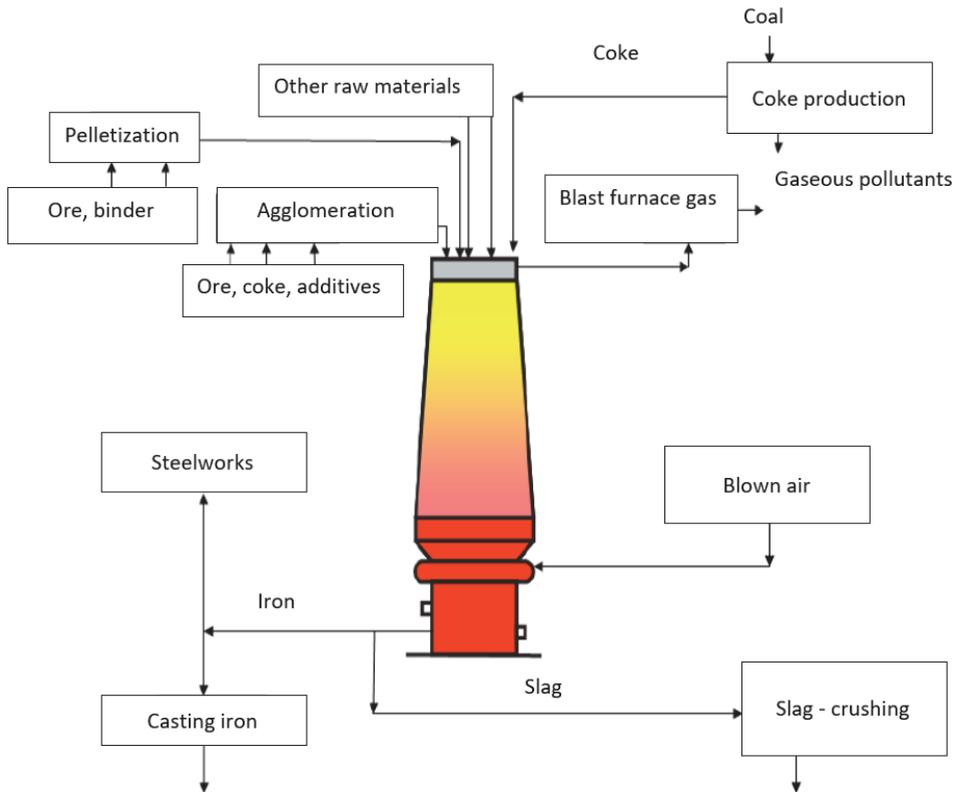


Fig. 1. General diagram of the blast furnace plant (Kret 2013, Besta & Lampa 2019)

Agglomeration or sintering of iron ores is the heating of the powder agglomeration mixture (ore, fuel, additives) to such a temperature that the surface of the individual grains of the charge is melted and the resulting melt forms liquid bridges between the grains which ensure that solid porous material is formed after solidification). The feedstock thus prepared is then used in the blast furnace process (Brož 1998). Agglomeration processes can be divided into cold and warm sections according to their character. The cold section serves to feed raw materials and to adjust grain size and to average the chemical composition of the

material (tipplers, crushers, screens, homogenization heaps). The task of the warm section is to produce the agglomerate of the required quality from the supplied ores, concentrates, fuel and additives (daily reservoirs, mixture preparation and batching, pre-pelletizing equipment, sintering belts, sinter coolers).

Blast furnace coke is used as fuel in the blast furnace process. Coke is a solid, porous, degassed residue from coal carbonization leading to temperatures of 950 to 1050°C (Kret 2013). Coke production can, therefore, be another related manufacturing operation. Slag-forming additives are the alkaline additives (limestone, dolomitic limestone and dolomite), which form slag during the transition to the liquid phase in order to permanently bind the acidic tailings of the ores and other undesirable additives (Smallman 2013). If the metallurgical plant uses fuel supplies and slag-forming additives, it is usually necessary to adjust their granulometric homogeneity (Najafabadi et al. 2018).

The profile of the blast furnace and its dimensions are adapted to the production technology. The lower cylindrical portion of the profile is called the hearth. Here, pig iron and slag accumulate and are periodically discharged through tap holes (Kret 2013). The upper part of the hearth is interrupted by the blast tuyeres for blowing hot air and additional fuels (Besta & Lampa 2019). The hearth is followed by a saddle in the shape of a truncated cone with the upper wider base (Geerdes et al. 2010). This shape of the saddle provides the necessary deflection of the hot gas streams from the oxidation compartments from the furnace lining, which would otherwise be prematurely destroyed. The gradual transition of the saddle into the shaft is secured by the belly. The most capacious part of the blast furnace is the shaft in the shape of a truncated cone or two truncated cones. Preheating of raw materials, decomposition of carbonates, and indirect reduction take place in the shaft. The upper part of the furnace is called the furnace top and serves to charge the furnace with a charge and to conducting the charge gas away from the furnace. Output products and wastes (agglomeration dust, blast furnace discharge, blast furnace sludge, slag) are also subject to processing. Waste treatment is given by the possibilities of their further use in other industrial areas (Fahimnia et al. 2015), but also by their possible re-use in the production of iron or other metallurgical processes. The production and processing of waste are also demanding due to the quantity. Only in the case of slag, it is 200-400 kg (Wu et al. 2018) per tonne of pig iron produced.

The metal-bearing burden portion of the batch is usually formed by iron or manganese ore, but also metal-bearing waste from industrial production. The metal-bearing constituents can be contained in the blast-furnace burden in the form of natural or sorted ore, but more often as blast furnace ore treatment products, i.e. agglomerates or pellets. From the chemical point of view, we distinguish four groups of iron ores (Brož 1998):

- Anhydrous oxides – ferric oxide Fe_2O_3 – hematite or bloodstone with the iron content of 70% in pure state, in nature up to 60%, ferrous-ferric oxide Fe_3O_4 – magnetite or lodestone with the iron content of 72.4%, pure, in nature 68%.
- Hydrated iron oxides $\text{Fe}_2\text{O}_3 \cdot n\text{H}_2\text{O}$ – limonites or brown hematites, hydro hematite $\text{Fe}_2\text{O}_3 \cdot n\text{H}_2\text{O}$, where $n < 1$, contains in the pure state 62-69% of Fe, götit $\text{Fe}_2\text{O}_3 \cdot \text{H}_2\text{O}$, where $n = 1$, i.e. $\text{FeO} \cdot \text{OH}$ contains in the pure state 62.9% of Fe, hydrogötitite or limonite $\text{Fe}_2\text{O}_3 \cdot n\text{H}_2\text{O}$, where $1 < n < 1.5$, contains in the pure state 59.8 to 63% of Fe.
- Carbonates, iron spar or siderite FeCO_3 , contains up to 50% of Fe in the pure state.

In many deposits, ore minerals occur in a combined composition. We can talk about belt deposits. In that case, the individual layers can contain different types of ores (Clout et al. 2015). Besides the content of the metal itself, the content of pollutants and other negative substances is a key factor. All of these aspects can influence not only the iron oxide reduction process, but the production technology as a whole.

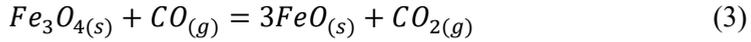
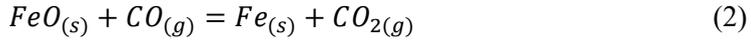
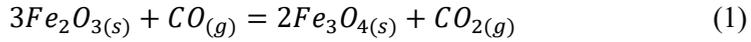
The iron ore burden brings the required amount of iron to the blast furnace in the form of its oxides or other compounds that replace these oxides. The main components of the iron ore burden are agglomerate, pellets and lumpy ore. The main reducers of iron oxides in the blast furnace are carbon monoxide, carbon and hydrogen (Shamsuddin 2016). The carbon reduction is referred to as direct, while the reduction with hydrogen and carbon monoxide as indirect. The reduction with carbon monoxide is predominant, accounting for a total volume within the range of 50-70%. The hydrogen reduction has the smallest effect, which can be 5-15% (Hosford 2011) depending on the type of fuel used. The importance of the hydrogen reduction increases significantly with the higher use of hydrocarbon fuels.

The iron reduction from its oxides proceeds gradually from the higher oxides to the lower ones in two planes (Brož 1998):

- $\text{Fe}_2\text{O}_3 \rightarrow \text{Fe}_3\text{O}_4 \rightarrow \text{Fe}_{1-y}\text{O} \rightarrow \text{Fe}$ (oxidation reduction order at temperatures above 570°C).
- $\text{Fe}_2\text{O}_3 \rightarrow \text{Fe}_3\text{O}_4 \rightarrow \text{Fe}$ (at temperatures below 570°C).

The highest percentage of the iron oxide reduction is with carbon monoxide. This reduction occurs throughout the height of the blast furnace. The direct reduction with carbon is less frequent due to imperfect contact between the two solid phases. The area of contact of the solid materials is inadequate and does not allow a higher proportion of the direct reduction with coke carbon (Kret 2013).

The reduction of iron oxides with carbon monoxide takes place at a temperature above 570°C according to the following structure (1), (2), (3):



The reduction of iron oxides with carbon monoxide takes place at a temperature below 570°C as follows (4), (5):

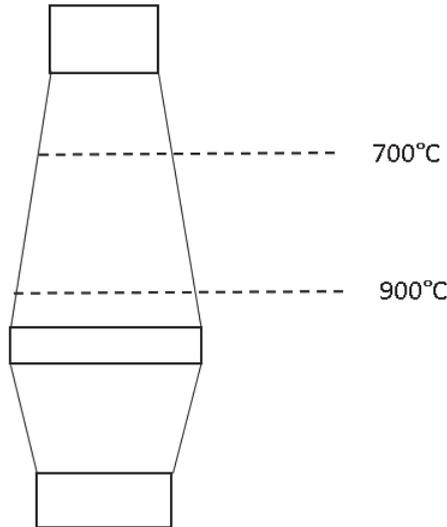
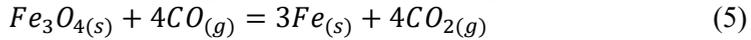
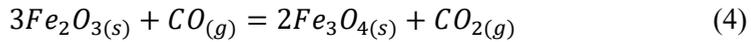


Fig. 2. Blast furnace monitored area defined by the given temperatures

The reduction of iron oxides takes place over the entire height of the blast furnace. The carbon monoxide reduction at the gas-solid interface has special significance. This gas is produced by exothermic reactions in the lower parts of the blast furnace (Bechara et al. 2018). It then rises to the higher parts of the furnace, which results in a large portion of iron oxide reduction. A significant part of the reduction processes takes place in the largest part of the blast furnace (shaft). The key area is the temperature range of 700-900°C (Fig. 2), which is located in the largest part of the blast furnace in terms of volume.

2. Methods

The research goal of the article has an analytical and experimental level. Knowledge about the harmfulness of individual parts of the blast furnace process was evaluated analytically. Part of the blast furnace plant, which is one of the largest producers of pollutants, is the sintering of iron ore. Within this section, the share of individual dust parts was determined on the basis of records of long-term measurements in the monitored company, and on the basis of chemical analysis, the concentration of selected key elements in agglomeration dust. The degree of reduction of iron ore from deposits in Russia (Kursk), South Africa (Sishen), Ukraine (Krivoy Rog) was then evaluated in the laboratory. The degree of reduction was determined for the samples in laboratory conditions using homologous equipment. The reduction processes were evaluated for three specific temperatures, in relation to the individual parts of the blast furnace and to the ore sintering process. The evaluation of the degree of reducibility of iron ores was carried out with regard to their consequences in the blast furnace and agglomeration process, which adversely affect the ecological impacts of iron production.

3. Negative impacts of individual parts of the production plant on the environment

Iron production can have a very negative impact on the environment and can be considered a major polluter. Emissions from iron production can be divided according to the state into solid and gaseous. In the case of solid emissions, it is an airborne material (dust). The gaseous pollutants that pollute the environment are mainly SO₂, CO, NO_x (Ubando et al. 2019). These gases are produced not only in the blast furnace process itself but also as products of other operations (e.g. ore sintering). In addition to these pollutants, increased attention is currently being paid to heavy metal contamination of the environment (As, Hg, Pb, Zn, Cr or Cd). The risk of contamination with these elements is mainly due to the possible contamination of soil material.

In terms of the structure of the blast furnace plant, the following are the key components that produce the most significant amount of pollutants:

- blast furnace,
- agglomeration,
- foundry processes,
- slag processing.

The negative aspect related to environmental pollution is the frequent use of waste materials in the blast furnace process (Wu et al. 2018). Metallurgical companies are constantly trying to reduce production costs, especially in the area

of expenditure on raw materials (Piecyk et al. 2015). Therefore, blast furnace wastes which contain a certain amount of iron or manganese, as well as the necessary basic components such as MgO and CaO, are reused. However, the waste materials also contain many of the pollutants mentioned above, which in this way repeatedly enter the production process. The main wastes of blast-furnace production that are reused are mainly: slag, iron scales, blast furnace slopping, agglomeration dedusting.

4. Negative consequences of the agglomeration process

Sintering processes involve sintering of ores, alkaline additives and fuel in the form of coke. The produced material has a porous character and is subsequently fed into the blast furnace (Besta et al. 2017, Haverland et al. 2018). The sintering mixture is ignited by means of blast furnace gas at a temperature of 1 300°C. Gradually, the individual grains of the agglomeration mixture are melted, and the whole layer is gradually burnt (Vilamova et al. 2016). This is due to the vacuum suction of air, which supports the shift within the combustion front. After the entire agglomeration mixture is completely burned, a solid porous material, called agglomerate, is formed. The quality requirements for the size of the agglomerate produced are above 5-6 mm.

Emissions arising from agglomeration processes can be divided in terms of their place of origin. The first area concerns the preparation of the sinter mixture, furthermore the emission of sintering itself, and the third important place is in the cooling and treatment of the sinter. The preparation of the agglomeration mixture includes mainly transport, storage, treatment and preparation of ore materials before sintering. According to the research carried out, the dominant negative effect is primarily dustiness, which arises during mechanical processes. Dust emission reduction is achieved by hermetization and extracting of dust from transport routes and transfer points. Dust and dust particles from this production segment mainly affect the working environment and hygiene conditions. The environmental impact is limited.

The main proportion of emissions from sintering processes, as analysed in the research conducted, are waste gases, which are generated during sintering. These waste gases pass through electrostatic precipitators, and waste dust is formed, which can be returned to the production process. The average amount of waste gases is in the interval 2 500-4 500 m³ per tonne of sinter mixture produced. The amount of dust particles in these waste gases range from 0.5-3.5 g/m³. The composition of the sintering waste dust according to the particle size is shown in Table 1.

The largest proportion is within the smallest dimension of dust particles, i.e. in the interval 0-0.1 mm. This places high demands on the capture of these

microscopic dust particles. In terms of their impact on the human organism, they can be considered the most dangerous because of their size. Due to their size, these small particles can pass through the respiratory system into the body. The use of electrostatic separator is necessary for their capture in the production process. These then allow the concentration of dust particles to be reduced to 40-60 mg/m³. When using mechanical separators, their efficiency is 20-30% lower. A significant problem with mechanical separators is the fact that it is much less challenging to capture small fractions below 0.1 mm.

Table 1. Share of individual dust particle sizes

Size (mm)	Proportion within the total quantity (%)
0-0.1	86.8
0.1-0.25	5.8
0.25-0.5	2.9
0.5-0.75	2.6
above 0.75	1.9

Table 2. Contents of some elements in sintering waste dust

Element	Content (%)
Fe	52.8
Mg	2.1
Ca	2.8
S	0.35
Zn	0.020
Pb	0.34
Cd	0.008
As	0.002

The captured waste (Table 2) is rich in iron content and is therefore often reused in the production. An advantage is also the content of alkaline substances and their compounds based on magnesium and calcium. The negative aspect is the content of pollutants that are returned to the process.

5. Reducibility of iron oxides for the types of ores used

Another critical parameter is the quality of the raw materials, especially the ores used. The key is the content of pollutants such as sulphur, phosphorus or silicon compounds. At the same time, the degree of iron oxide reduction, which contributes to the efficiency of the technological process, is essential. An

adequate technological process enables the efficient use of resources, reducing fuel consumption and ultimately, the overall environmental burden.

Ore minerals may contain different types of ores, different amounts of the metal in question, but also a variety of harmful elements. Everything can fundamentally influence the technological parameters of the blast furnace process. The chemical composition of the selected three types of ore minerals is shown in Table 3.

Table 3. Chemical composition of selected types of ore

Content of elements	Ore minerals – kind		
	Russia – Kursk –Magnetite	Republic of South Africa – Sishen – Hematite	Ukraine – Krivoy Rog – Magnetite
Content of Fe (%)	61	69	60
Content of P (%)	0.069	0.039	0.025
Content of S (%)	0.019	0.005	0.016
SiO ₂ (%)	5.2	1.3	4.1
Al ₂ O ₃ (%)	3.8	0.85	5.0
SiO ₂ + Al ₂ O ₃ (%)	9.0	2.15	9.1

In the case of different types of ores (hematite, magnetite), there will be a different ratio of the reduction of oxides in relation to the given boundary temperature. At the same time, the ore mineral from South Africa contains a significantly larger proportion of the metal-bearing part. Ore minerals within individual deposits are often formed by more kinds of oxides. A very important aspect is the content of harmful substances, but also the character of ore minerals in terms of alkalinity. This can be measured as the proportion of basic and acidic components. We consider ore minerals containing a larger proportion of SiO₂ and Al₂O₃ to be acidic. This is especially the case with ore from deposits in Russia, Ukraine, but also in some Baltic states. Ore minerals from Australia, Brazil, but also South Africa have a basic character (higher share of CaO, MgO). Table 3 shows that ore minerals from Russia and Ukraine contain several times higher levels of SiO₂ and Al₂O₃ than ore from South Africa.

The types of ores under review were analysed by a laboratory with respect to their degree of reducibility. Ore raw materials were heated in the furnace to the temperature of 700-900°C. This temperature range is significant in terms of location in the blast furnace. For most of the blast furnaces, the largest part of the blast furnace in the shaft is used to heat the charge to this temperature.

Dimensionally, this part of the furnace is the largest in terms of the blast furnace structure, and a significant amount of carbon monoxide reductions occur here.

The heating rate was 90°C per minute. The reduction processes were evaluated for the time of 20, 60, 80, 100 minutes. After this time, the corresponding ore samples were removed from the furnace and cooled to the ambient temperature. Subsequently, the weight loss of the ores was determined. This was done as a proportion of weight loss to the total weight of removable oxygen in the form of iron oxides. Table 4 shows the results of the laboratory measurements.

Table 4. Determined values of the degree of reduction of the selected ore raw materials

Time (min.)	Temperature (°C)	Ore minerals – kind		
		Russia – Kursk – Magnetite	South African Republic – Sishen – Hematite	Ukraine – Krivoy Rog – Magnetite
		Degree of reduction (%)		
20	700	19.2	20.9	18.9
40	700	27.6	29.8	28.6
60	700	34.3	36.7	34.5
80	700	36.1	42.8	37.6
100	700	42.1	54.3	44.1
20	800	26.5	28.1	25.3
40	800	34.3	36.2	32.6
60	800	41.6	42.3	40.8
80	800	47.1	53.2	46.5
100	800	54.8	62.9	56.8
20	900	35.4	38.7	35.9
40	900	47.5	50.1	47.1
60	900	56.1	59.7	58.2
80	900	61.9	68.5	60.6
100	900	66.8	74.3	68.1

The degree of reduction (%) was determined for all three ore raw materials from Russia, South Africa and Ukraine. Graphically, the results are shown in Fig. 3 (for 700°C). The degree of reduction is shown separately for each boundary temperature (700, 800, 900°C).

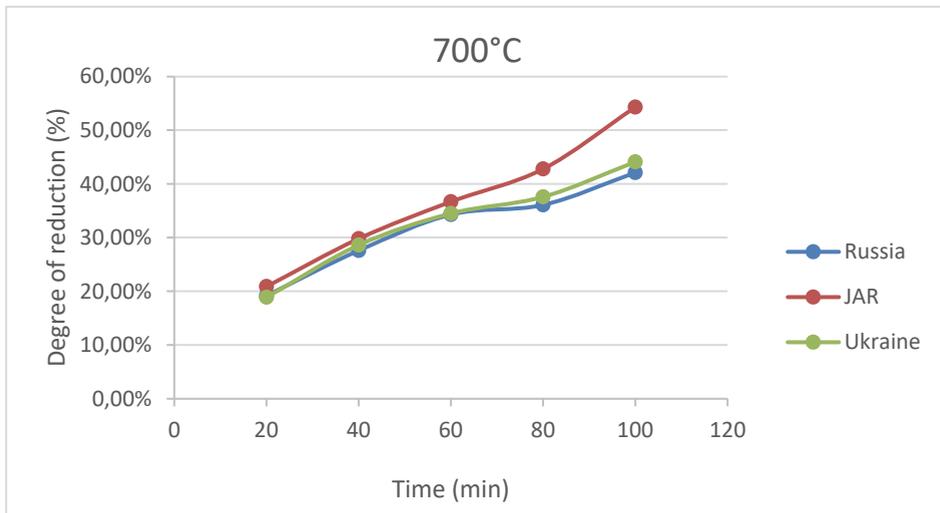


Fig. 3. Development of reducibility for the temperature of 700°C

In the laboratory research, the reducibility was analysed for three types of ore raw materials. Hematite and magnetite ore raw materials from different sites were compared. The degree of reducibility was determined separately for temperatures of 700, 800 and 900°C and for the times of 20, 40, 60, 80 and 100 minutes. The furnace heated ore samples were divided into several working vessels according to the classification mentioned above. They were heated to the corresponding temperatures for specified time intervals. Subsequently, they were gradually withdrawn from the furnace and evaluated for weight change after cooling to the ambient temperature. The reducing abilities of different ores were compared. The progression and intensity of the reducing abilities shown in Figure 3 show high similarity. There are a few key facts to identify. Hematite (South Africa) showed a higher degree of reducibility for all temperatures studied. At the same time, Hematite tended to form messy and easily reducible FeO compounds. This could affect the higher degree of reduction in this ore raw material. A significantly higher degree of reduction was then found for the heating times of 80 and 100 minutes. For Hematite, a higher degree of reduction at these times can be clearly identified for all the temperatures monitored. In the case of Magnetite from both sites under review, the reduction degrees for the indicated heating times were very similar. Therefore, a simple arithmetic mean for the indicated heating times was set for both Magnetite-based ore raw materials (Russia, Ukraine). The value thus obtained was compared with the ore raw material from South Africa. This comparison, which compares Magnetite and Hematite, is shown in Table 5. In the case of the heating times of 20, 40, 60 minutes, the reduction degree of

Hematite is higher in the range of 2.6-8.9%. Significantly higher differences was found in the case of the times of 80 and 100 minutes. Here the degree of Hematite reduction is higher than that of Magnetite in the interval of 9.2-20.6%. This may also be due to the fact that, for longer heating times, a larger proportion of fine-grained portions was formed in the case of Magnetite. For these fine-grained portions, it is more difficult to accurately determine the degree of reduction. The formation of a fine-grained fraction results from cracking, which is caused by higher local stresses due to rapid changes in the volume of the material.

Table 5. Comparison of reducibility for Magnetite and Hematite

Time (min.)	Temperature (°C)	Degree of reduction		Difference (%)
		Magnetite – average (%)	Hematite (%)	
20	700	19.05	20.9	8.9
40	700	28.1	29.8	5.7
60	700	34.4	36.7	6.3
80	700	36.85	42.8	13.9
100	700	43.1	54.3	20.6
20	800	25.9	28.1	7.8
40	800	33.45	36.2	7.6
60	800	41.2	42.3	2.6
80	800	46.8	53.2	12.0
100	800	55.8	62.9	11.3
20	900	35.65	38.7	7.9
40	900	47.3	50.1	5.6
60	900	57.15	59.7	4.3
80	900	61.25	68.5	10.6
100	900	67.45	74.3	9.2

Heating Hematite and Magnetite-based ore raw materials had essentially a similar effect on the reduction character. The highest degree of reduction was found in ore raw material from South Africa (Hematite). In the monitored range of heating times, there were the highest differences in the heating times of 80 and 100 minutes. These facts can be used not only in the blast furnace process of iron production but especially in the process of preparation of ore raw materials in the sintering process. In optimizing the sintering belt performance, it is necessary to

effectively control the sintering time relative to the type of ore raw material used in addition to other relevant parameters. Other consequences of the reduction of ore raw materials are then due to technical aspects of the blast furnace operation. Inefficiency in ore sintering means: higher CO production, higher SO₂ production, higher energy consumption. Ineffectiveness in ore sintering therefore negatively affects the environment.

From the point of view of the defined research goal, the detected deviations in the reducibility of the monitored iron ores can be considered less significant. According to the performed laboratory measurements, the ores showed a very comparable degree of reduction. The measured and evaluated deviations would not mean a disturbance of the technological conditions of the blast furnace operation and would not represent an increase of the ecological burden for the environment. Within the research goal, not only ore raw materials from different deposits but also raw materials with different chemical composition were evaluated. In the case of Hematite, a higher degree of reduction was found compared to ore raw materials based on Magnetite. Given the research goal, this difference can be assessed as moderately significant. With a fundamentally significant difference in the composition of the blast furnace charge, this difference can affect the operation of the blast furnace and have environmental consequences. If the monitored ore raw materials are adequately homogenized, the differences found will not have a major impact. If the rules for the treatment of ore raw materials are observed, their processing will not significantly affect the production technology or increase the ecological burden.

6. Conclusions

From the point of view of individual parts of the blast furnace plant and their impact on the environment, the agglomeration processes during ore sintering can be considered particularly harmful. The problem is the production of gaseous and solid pollutants. In the case of dust particles, the largest proportion is fine-grained material, which is the most negative in terms of human health. Installation and use of electrostatic precipitators are necessary to reduce emissions. These make it possible to filter emissions according to environmental requirements. However, in the case of using these separators, it is important to maintain the constant composition of the sinter batch and to use quality fuel and its adequate quality.

From the point of view of the analytical goal of the article, sintering can, therefore, be considered as an important source of pollutants in the blast furnace plant. The main problem is mainly in the production of fine-grained dust parts. As the research has shown, this is by far the largest part.

The experimental goal of the article focused on the evaluation of the degree of reducibility did not confirm large differences for individual ore raw materials. No major differences were identified in terms of different chemical

composition (Magnetite, Hematite). The processing of different ore raw materials in different proportions will not mean problems in the technology of iron production and will not be secondarily a source of higher environmental burden. Nevertheless, in the case of using a larger number of ores, quality homogenization can be recommended to the maximum. Overall, from the point of view of the degree of reducibility, the monitored ore raw materials can be evaluated very comparably. The utilization of all monitored ore materials should not mean a deterioration of the technological parameters of the blast furnace process, and therefore, no higher environmental burden. In the case of ore materials, however, it is necessary to monitor their quality continuously, especially in relation to the content of pollutants. Any harmful substances that will enter the blast furnace process will then be allocated in the metal, production waste, or in the form of emissions. In the case of processing of ore materials of different quality, more attention should be paid to the tailings selection and material homogenization. Overall, current iron producers must take into account not only technological, cost, but also environmental requirements.

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Abstract

Iron production is one of the production processes that create a large number of negative externalities towards their surroundings. Iron production is based on the use of a wide range of production operations, which include not only the blast furnace process but also the treatment and processing of ores, sintering, pelletizing and processing of metallurgical waste and its possible storage. All parts of the blast furnace process can have a negative impact on the environment. Within the individual parts of the blast furnace plant, a number of pollutants are produced which negatively affect the environment. They can have both solid and gaseous states. In the case of solid emissions, it is airborne dust, and the gaseous form represents pollutants in the form of sulphur, nitrogen or carbon oxides. From the point of view of the blast furnace plant structure itself, blast furnace, agglomeration processes, palletization processes or the processing of waste from production can be classified as emission points. The article deals with the classification of basic impacts of blast furnace production on the environment. It analyses in detail the negative externalities in ore sintering. It also deals with the analysis of research, which was focused on the degree of reduction of iron oxides ore. The efficiency of the reduction process is crucial in terms of resource use, but also the overall amount of negative externalities. The research was carried out in the environment of a selected iron producer in the Czech Republic.

Keywords:

environment, iron, ore sintering, blast furnace, cost