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SUPPORT ALGORITHM FOR BLAST FURNACE OPERATION WITH OPTIMAL FUEL CONSUMPTION

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Abstract

Fuel consumption in blast furnaces depends on many factors that are mainly conditioned by the technological level of a given blast furnace, the steel mill in which it operates, and the type and quality of ferrous feed, coke, and additional reducing agents. These are global factors which a furnace crew cannot control during operation. On the other hand, using their own experience and decision-making software, a crew can run a blast furnace with minimal fuel consumption under current batch and process conditions. The paper presents a model-based algorithm for optimizing the operation of blast furnaces to achieve the lowest fuel consumption. The algorithm allows the heat demands to be continuously calculated and highlights any wastage that could be reduced without affecting the stable operation of the blast furnace.

Keywords: *Blast furnace fuel rate; Ironmaking; Direct reduction of wustite; Model-based control*

Abbreviations

COG - coke oven gas;
BF - blast furnace;
BFOP - blast furnace operation point;
BOF - basic oxygen furnace;
FRMM - fuel rate minimization model;
HB - hot blast;
HM - hot metal;
PCI - pulverized coal injection;
tHM - ton of hot metal.

Nomenclature

C_{DR} - carbon demands for direct reduction of FeO, *kgC/tHM*;
d_{DR} - FeO direct reduction rate, *%*;
d_{DRopt} - optimal direct FeO reduction rate, *%*;
d_{IR} - indirect FeO reduction rate, *%*;
Fe_{HM}, Si_{HM} - respective share of Fe and Si in hot metal, *wt.%*;
H_2O_{HB} - moisture content in hot blast, *g/m³*;
M_{Fe} - molar weight of Fe, *t/mol*;
O_{2HB} - oxygen content in hot blast, *vol.%*;
Q_{CL} - cooling losses and top gas enthalpy, *MJ/tHM*;
Q_{CmHn} - heat demands of volatiles of PCI or COG decomposition, *MJ/tHM*;
Q_{H2O} - heat demands of HB moisture decomposition, *MJ/tHM*;
Q_{HB} - hot blast enthalpy, *MJ/tHM*;
Q_{HM} - hot metal enthalpy, *MJ/tHM*;
Q_{PCI} - heat demands of PCI preheating, *MJ/tHM*;
Q_{slag} - slag enthalpy, *MJ/tHM*;
RAFT - raceway adiabatic flame temperature, ^0C;
y1, y2, y3, y4 - ordinates of points 1, 2, 3 and 4 for FRMM, *kgC/tHM*.

1. Introduction

Hot metal (HM) production is the most energy-consuming step in the steel production cycle. In turn, fuel consumption in a blast furnace (BF) depends on many factors that directly or indirectly influence this process. Reducing fuel consumption by even several kilograms per tonne of hot metal (tHM) brings measurable benefits; for example, reduced costs and emissions of carbon dioxide.

Despite a long history of hot metal production, blast furnace optimization is still a difficult task due to the complexity of the process, the geometry of BFs, and the variety of physicochemical processes that simultaneously take place in the three states of matter. In addition, there is a considerable range of gas and batch residence times in the furnace: gas flows

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through the furnace in seconds, while the tapped hot metal and slag only appear a few hours after the materials are loaded into the BF. All these factors make it impossible to control processes in the BF in a simple way; thus, it is difficult to optimize HM production.

Therefore, for many years research centers have tried to facilitate control of the BF process by modelling particular phenomena and analyzing the entire process. Apart from the usual monitoring of real BF processes [1,2] and mathematical and numerical models [3–7], which can be supported by physical cold models [8–11], the common use of neural networks for controlling hot metal quality and temperature [12–17] should be mentioned. Advanced methods such as genetic algorithms [18, 19], subspace methods [20–22], or fuzzy clustering [23] are also reported.

After several years of observation of blast furnaces in Krakow and Dabrowa Gornicza, it may be said that fuel consumption largely depends on factors that a technologists cannot currently control. On the other hand, the correct operation and optimum fuel consumption of a blast furnace is a result of the crew's knowledge and experience. Thus, with only the batch in the storage area and variation of the blast parameters, minimum fuel consumption can be achieved for the current operating conditions.

This paper shows a support algorithm for controlling the optimal share of indirect and direct reduction as a way to achieve minimum fuel consumption in a blast furnace.

2. Factors that influence fuel consumption in blast furnaces

The production cost of hot metal directly depends on fuel consumption (coke only or coke with additional reducing agents) in a blast furnace. This parameter depends on many factors, such as:

- the quality and method of preparing iron-bearing feed, the proportion of sinter in the batch, the technological level of the ore yard, the technical condition of the sinter plant, the quality of the sinter (Fe content, harmful elements content, mechanical properties);
- the temperature of the hot blast and the technical condition of the blast stoves and their heating surface;
- the technical condition of the refractory lining and the cooling system and their effect on heat losses in the BF process;
- physicochemical parameters of coke conditioning;
- the technological level of the control and measurement apparatus of the blast furnace;
- the logistic and technological conditions of the steel mill, such as the technical condition and type of the ladles used, the distance from the blast furnace to the basic oxygen furnaces (BOF), the use of secondary hot metal desulfurization, the share of metal scrap in steel production, etc.;
- external conditions which indirectly influence the continuity of operation of the BF, such as market demand for steel products.

From the above, it follows that decades-old blast furnaces – as are commonly found in Poland – may require significant investment to be adapted to the use of modern cost-effective technologies. Modernization, on the other hand, is carried out gradually over considerable time intervals – most often when worn-out equipment is being replaced. Modernization is often unprofitable, resulting in the closure of individual blast furnaces.

However, mathematical modelling of the blast furnace process can help in understanding and highlighting shortcomings in BF technology.

3. Fuel rate minimization model

3.1 Reduction of iron oxides

The main chemical process in a BF is the reduction of iron oxides. Figure 1 shows the operation of a blast furnace, idealized from the perspective of the presence of iron oxides. In the real-world process, the amount of iron oxide cannot be accurately determined due to variations in batch quality [24–27].

However, it is certain that iron oxides in a BF are changed during reduction according to the scheme from the top of the furnace:

$Fe_2O_3 \rightarrow Fe_3O_4 \rightarrow FeO \rightarrow Fe$

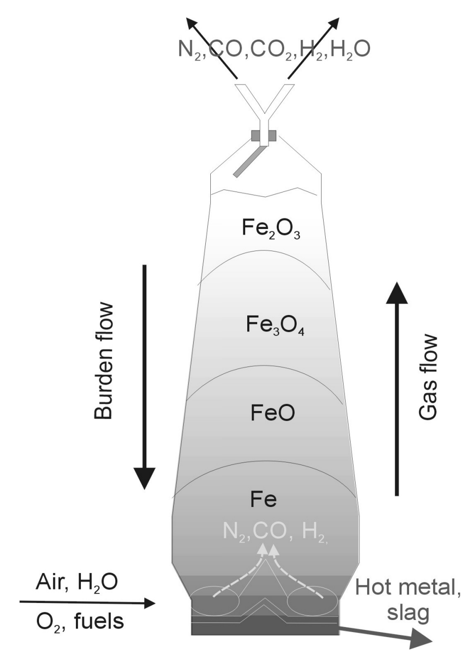

Figure 1. *Blast furnace process with idealized locations of iron oxides*

The most thermochemically demanding aspect is the reduction of wustite to iron (FeO→Fe); this occurs directly when the reducer is carbon and indirectly when the reducer is CO. The reduction of higher iron oxides – hematite to magnetite (Fe_2O_3→Fe_3O_4) and magnetite to wustite (Fe_3O_4→FeO) – can only occur indirectly when the reducer is CO or hydrogen. However, H_2 and the CO remaining after wustite reduction are sufficient for the reduction of magnetite and hematite. Moreover, during the reduction, there is a lower demand for heat than during the direct reduction of wustite (reaction I). For reaction (I), in addition to carbon for chemical requirements, heat should be also provided for the endothermic reaction.

$$FeO+C=Fe+CO \quad \text{(I)}$$

It should be noted that when carbon is playing the role of reducer in reaction (I), it does not descend to the flame zone and cannot be a source of heat in a BF according to reaction (II):

$$C+0.5O_2=CO \quad \text{(II)}$$

So, overall carbon demands for reaction (I) can be calculated as:

$$C_{DR}=\frac{d_{DR}}{100}(215+(\frac{154\cdot10^{-3}}{M_{Fe}}\cdot\frac{1}{9.196})\cdot\frac{Fe_{HM}}{100} \quad (1)$$

Where:

215 - stoichiometric demand of reaction (I) for carbon, kg C/t Fe; $154\cdot10^{-3}$ - enthalpy of endothermic reaction (I), MJ/mol Fe; 9.196 - enthalpy of exothermic reaction (II), MJ/kg C.

In a real BF, the direct FeO reduction rate is in the range 40–60%. According to equation (1) and at 94 wt.% iron share in hot metal, the carbon requirement for direct reduction is about 193–290 kgC/tHM. It seems that limiting direct reduction of wustite contributes to reducing the fuel rate for the whole BF; however, it should be noted that decreasing direct reduction also increases indirect reduction of wustite:

$$FeO+2.5CO=Fe+CO_2+1.5CO \quad \text{(III)}$$

Although reaction (III) is exothermic ($17\cdot10^{-3}$ MJ/mol Fe), it demands about 2.5 times more reducer than direct reduction [28]. This means that the required CO can be obtained by burning about 537 kgC/tFe. However, CO may also be derived from direct reduction (reaction I). Therefore, there must be such an optimal division of both types of wustite reduction at which the carbon rate is sufficient for thermal and chemical processes in a blast furnace.

3.2 Model building

The principles of the optimal division of direct and indirect reduction in a BF are based on the theory of A.N. Ramm [29], who proposed building a diagram of the dependence of carbon consumption on chemical and thermal demands. Similar or extended balances were presented [7, 30–32].

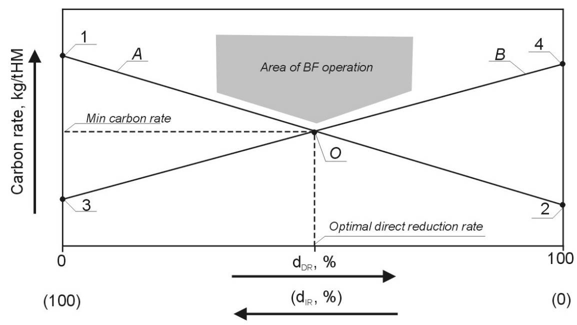

Figure 2. *Carbon rate – FeO reduction ratio diagram for coke-only technology*

Figure 2 shows the diagram used in the present algorithm, as is described below. The boundary conditions for building a diagram of heat and chemical demands are calculated for 100% indirect and 100% direct reduction, despite the fact that in a real BF the reduction of wustite occurs in both ways.

The ordinates of points '1' and '4' reflect overall carbon demands at d_{IR}=100% and d_{DR}=100%, respectively; however, the ordinates of '2' and '3' determine the course of straight lines 'A' and 'B', respectively. The slope of 'A' reflects the carbon requirement decrease due to reduced chemical requirements, while the slope of 'B' reflects reduced thermal requirements. The intersection of the lines at point 'O' shows the minimum carbon rate at the optimal share of both types of FeO reduction. The broken line '1-O-4' is the boundary, below which blast furnace operation is impossible.

Taking the aforementioned factors into account, the ordinates of points 1–4 may be calculated:

$$y_1=537\cdot Fe_{HM}\cdot0.01 \quad (2)$$

$$y_2=215\cdot Fe_{HM}\cdot0.01 \quad (3)$$

$$y_3=\frac{Q_{HM}+Q_{slag}+Q_{H_2O}+Q_{PCI}+Q_{CmHn}+Q_{CL}-Q_{HB}}{9.196} \quad (4)$$

$$y_4=(215+\frac{154\cdot10^{-3}}{M_{Fe}}\cdot\frac{1}{9.196})\cdot\frac{Fe_{HM}}{100}+y_3 \quad (5)$$

3.3 The role of hydrogen in wustite reduction

Besides carbon and carbon monoxide, there is one more reducer in the blast furnace process – hydrogen [33–36]. As has already been mentioned, hydrogen can replace CO in magnetite and hematite reduction processes. However, in wustite reduction hydrogen plays the role of oxygen carrier from the condensed phase to the gas phase; in the presence of carbon and at a temperature above 610^{0}C, H_2O as a reduction product turns into H_2 according to reaction (IV).

$$H_2O+C=H_2+CO \tag{IV}$$

Therefore, hydrogen only enhances indirect reduction and thus decreases direct reduction [37]. This means that the minimum amount of carbon which has to be burnt to obtain CO for indirect reduction is reduced. For instance, 537 kgC/tFe of carbon (equation 2) in coke-only technology is reduced to 528 kgC/tFe when about 70 kg/tHM PCI is introduced thanks to the higher hydrogen content in the bosh gas. In consequence, the optimal direct reduction ratio is achieved and fuel consumption is minimized, as shown in Figure 3.

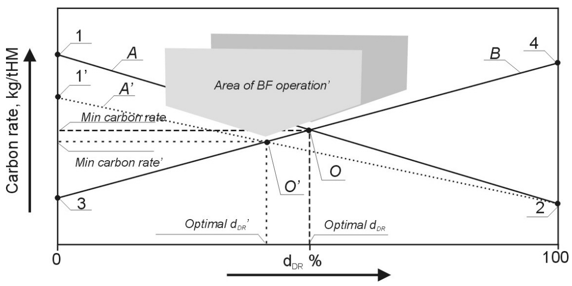

***Figure 3.** Changing the carbon rate to FeO reduction ratio with the introduction of hydrogen to the BF bosh gas; the new state is marked as (')*

Also, a blast furnace operation area can be adjusted to a lower direct reduction rate range and carbon ratio.

4. Algorithm overview

4.1 General schema

Figure 4 shows the general schema of the parent algorithm. Calculations are conducted for 1h intervals. Because the charge goes through the furnace in about 6 hours, it takes approximately 3–4 hours to descend to the direct reduction area. This means that the current top gas reflects the reduction processes of the batch which was loaded 3–4 hours ago. Therefore, there is a need to create an array from gas data which is taken from the last hour of BF operation and the charge data taken from 3 hours earlier. When the array is not full for the last 4 hours, the algorithm does not work and it shows the BF status as 'Stop' or 'Boot'. Next, material and heat balances are calculated. The raceway adiabatic flame temperature (RAFT) is calculated separately from the fuel-rate minimization model (FRMM), but they are connected by the hot blast parameters and the raceway gas phase composition. This is additional security to prevent accidental incompatibility between the types of regulation d_{DR} and correct BF operation. However, the RAFT must be in the range 2000–2100^{0}C, especially when additional fuels are blown into tuyeres.

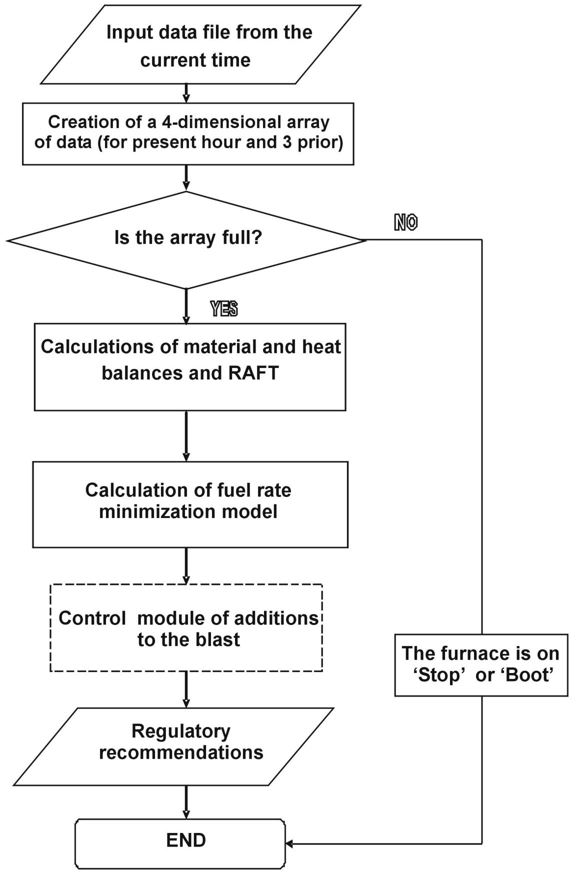

***Figure 4.** General schema of the parent algorithm*

Subsequently, the d_{DRopt}, the operation point of BF and the possible blast adjustment parameters are calculated. Oxygen or moisture levels can be adjusted in order to set the operation point of the BF close to the optimal direct FeO reduction rate in the current state. The next step is to decide whether to change the BF charge. These steps will be described in detail.

4.2 Detailed schema and building FRMM using real data

In a real BF, the model must include:

- the requirements for carbon to be dissolved in hot metal;
- carbon blown out with the top dust;
- carbon requirements for the direct reduction of the amount of Si, Mn and P which passes to HM;
- heat requirements to cover possible divergences in BF operation, such as output inhibition, descent of

alkaline growths to the hearth, deviations in gas and burden flow, unforeseen breakdowns and planned repairs, etc.

Figure 5 shows the FRMM using real data. Carbon needs are recalculated for dry coke consumption, which is a more convenient parameter.

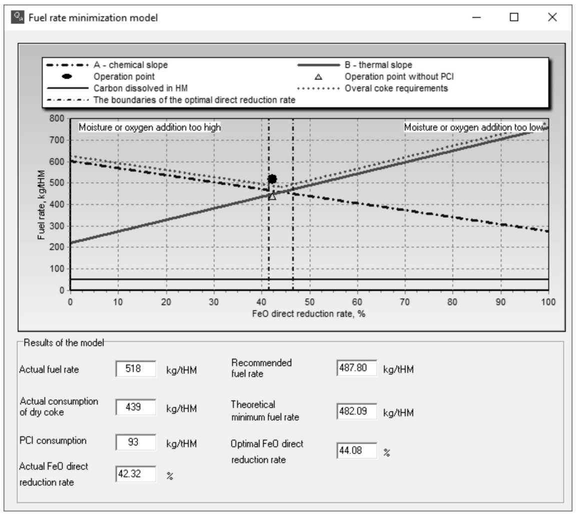

Figure 5. *An example of the fuel rate minimization model working on real data*

In addition to what is described in Figure 2, the following is shown in Figure 5:

- BF operation point (black dot);

- BF operation point without additional reducing agents (triangle);

- Boundaries of optimal direct FeO reduction rate; these are set as ±2.5% deviation from the optimal direct reduction rate (two vertical dotted/dashed lines);

- Boundary of overall coke requirements. Therefore, in the real process the operation point must not be below this line at any d_{DR} (broken dotted line). This also means that if BF operation were represented by only a triangle, the furnace would become dangerously cold;

- Carbon dissolved in hot metal (black horizontal straight line).

It should be noted that according to equation (1), for every 1% that d_{DR} is greater than d_{DRopt}, the overall fuel consumption increases by about 5.4 kg/tHM. On the other hand, it can be seen by subtracting equation (3) from equation (2) that for every 1% that d_{DR} is lower than d_{DRopt}, overall fuel consumption increases by about 3.36 kg/tHM. So, the best position for the BF operation point is exactly on the bend of the broken dotted line. This can be achieved by adjusting the moisture or oxygen additive in the hot blast within an hour of the last run of the algorithm. It is hard to achieve the exact amount of additives, hence the limits of the optimal direct reduction rate are set to d_{DRopt}±2.5%. This range of deviation is not large but is achievable. This was also confirmed during industrial testing of the algorithm.

Summarizing, the increased or reduced addition of moisture or oxygen caused the operation point in Figure 5 to move to the left (d_{DR} decreasing) or right, respectively.

However, moving the operation point vertically is only possible if the top feed charge is changed. Increasing the mass of sinter or pellets in the top charge causes the operation point to move downwards, which directly contributes to reduced fuel consumption. The same effect may be obtained by reducing PCI mass. However, the intention of using PCI is to save coke and the mass of PCI should be as high as possible for the currently available technology and technical condition. Unloading of charge causes the operation point to move upward.

Figure 5 also shows a current example of actual overall fuel consumption calculated as 439+79·0.85=518 (coefficient of coke replacement by PCI is 0.85; 1 kg PCI replaces 0.85 kg of coke). Also shown is the possible theoretical minimal fuel consumption which can be obtained at dDRopt; however, the recommended fuel rate equals the minimum fuel rate at the actual d_{DR}. Therefore, this schema graphically represents the thermal state of the BF and reveals an eventual heat surplus or deficit. The crew can visually estimate whether there is a need to intervene in the operation of the BF.

Figure 6 shows a general schema of the adjustment of blast parameters that gives recommendations for BF operation depending on the d_{DR} value.

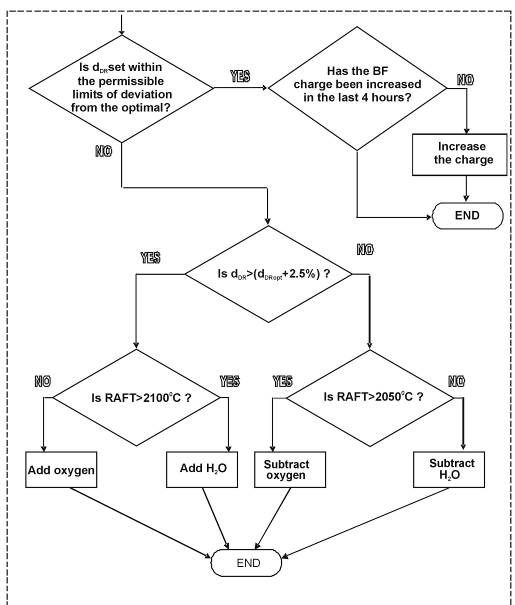

Figure 6. *Control module of the blast parameter adjustments*

It should be noted that the addition of oxygen has twice the effect on reducing d_{DR} (the black dot moving to left in Figure 5) than the addition of H_2O; however, as mentioned previously, the fact that H_2O contains hydrogen causes point y1 to move down (Figure 3). Moreover, there are inverse effects on the thermal state of the combustion zone: the addition of oxygen increases RAFT, but the addition of H_2O reduces RAFT. The exact amounts of added or subtracted H_2O, oxygen, or charge mass are calculated as the difference between the actual state of the BF's operation point (location of the black dot) and d_{DRopt}. However, adjusting blast parameters and especially charge could change the positions of points y1–y4 in the next BF operation cycle (1 hour). Thus, eventual recommended operation changes are halved.

5. Model testing and verification in real conditions

For model testing, data describing the miscellaneous use of fuels and reducing agents from about a one-month period of work were gathered for each item:

- BF No. 5 in Krakow when only coke was used;
- BF No. 5 in Krakow when coke and PCI were used,
- BF No. 2 in Dabrowa Gornicza when coke and COG were used.

Table 1 shows the average monthly basic working parameters.

Table 1. *Average monthly working parameters used in the verification*

Parameters		BF No. 5 Krakow Working volume 2,000 m^3		BF No. 2 Dabrowa Gornicza Working volume 3,200 m^3
		Coke only	Coke +PCI	Coke +COG
Dry coke consumption	kg/tHM	481.31	472.9	467.08
PCI consumption	kg/tHM	0	42.18	0
COG consumption	m^3/tHM	0	0	75.92
HB volume	m^3/h	179,995.32	181,837.32	247,683.96
HB oxygen	vol. %	21	21.23	22.58
HB moisture	g/m^3	22.54	24.74	1.71
HB temperature	^{0}C	940.02	994.57	1,050.00
Si_{HM}	wt.%	0.72	0.89	0.51
HM temperature	^{0}C	1,437.94	1,444.50	1,446.44
RAFT	^{0}C	2,078.88	2,090.97	2,235.86
Slag mass	kg/tHM	392.96	381.43	393.62
CO_2 in top gas	vol. %	19.52	19.48	19.49
CO in top gas	vol. %	22.75	22.74	24.91
H_2 in top gas	vol. %	2.07	1.87	4.55
Top gas temperature	^{0}C	203.69	212.06	65.27

The presented algorithm aims to control the optimal direct reduction rate. Blast furnace operation can be adjusted by changing the blast parameters (also known as 'control from the bottom' in ironmaking) or by changing the top charge (referred to as 'control from the top').

Control of the furnace 'from the top' and 'from the bottom' works closely with the fuel consumption minimization model. The minimization model sets trends for BF operation which should be used to achieve the lowest fuel consumption. However, striving to achieve minimum fuel consumption as the main goal may lead to contrary results. Excessively interfering with the blast and charge parameters, as might be advised by the minimization model, could undermine stable operation of the BF; this has undesirable economic consequences as the furnace is the key link in the whole production chain. Thus, there is a need to calibrate the regulatory recommendations system to other indicators, such as hot metal tap temperature and hot metal silicon content, and also to take into account changes in the control parameters in the cycles that preceded the current state. Figure 7 shows the recommendations control module.

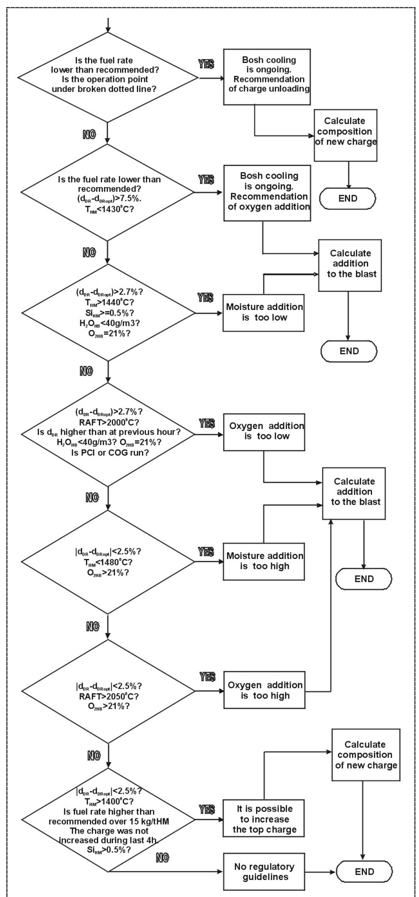

Figure 7. *Regulatory recommendations module*

It can be seen that the module that is directly responsible for decreasing the fuel rate is the last element in the chain. Before the top charge is increased, there must be certainty that the BF is not underheated. Table 2 shows calculated characteristics according to the calibrated recommendation control module.

Table 2. *Average monthly actual and recommended characteristics calculated by the support algorithm*

Support algorithm characteristics		BF No. 5 Krakow Working volume 2,000 m^3		BF No. 2 Dabrowa Gornicza Working volume 3,200 m^3
		Coke only	Coke +PCI	Coke +COG
d_{DR}	m^3/tHM	51.46	44.96	62.07
d_{DRopt}	m^3/h	55.76	46.3	54.66
Actual fuel rate	kg/tHM	481.31	508.74	508.96
Minimum fuel rate	kg/tHM	448.48	478.25	461.24
Actual t H_2O_{HB}	g/m^3	22.54	24.44	1.71
Recom. H_2O_{HB}	g/m^3	17.87	22.75	1.72
Actual O_{2HB}	vol. %	21	21.23	22.58
Recom. O_{2HB}	vol. %	21	21.23	22.62
Actual top charge	–	3.59	3.37	3.44
Recom. top charge	–	3.61	3.38	3.5

From Table 2 it can be seen that in every case the fuel rate is about 30-40 kg/tHM more than the minimum that could be achieved. However, it should be remembered that this means that the black dot must be located exactly on the bend of the dotted line (Figure 5). Such a low fuel rate is hard to achieve and it is hard to maintain because, if even the direct reduction remains the same in the next hour, the BF condition could change and the bend of dotted line moves. In this case, the operation point may be outside the narrow safe BF heat-state area. It is more important to set the value of d_{DR} within ±2.5% of the optimum, and then to consider if the fuel rate should be reduced. This is why the recommendation control module mostly 'advises' the addition or subtraction of moisture or oxygen and then evaluates the necessity of increasing the top charge. Therefore, the recommended fuel rate was calculated by FRMM when the BF reached the acceptable range of d_{DR}. Thus, minimal fuel consumption during tests could be reduced by about 5–30 kg/tHM at corresponding d_{DR}.

6. Conclusions

The paper describes the construction of a blast furnace technology support algorithm, in particular the fundamentals of the fuel rate minimization model based on carbon balance and the share of the direct reduction rate of wustite. On the basis of measurements and chemical analyses obtained online, the support algorithm adjusts the blast furnace operation so that at any given moment, with the current batch and technical conditions, the total fuel consumption is minimized. The algorithm has been tested in real conditions. Verification showed that when blast furnaces reach an acceptable range of direct reduction rate, they can be operated with a 5–30 kg/tHM lower fuel rate; however, final decisions about the operation of a BF are always taken by the furnace crew.

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ALGORITAM PODRŠKE ZA RAD VISOKE PEĆI SA OPTIMALNOM POTROŠNJOM GORIVA

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Apstrakt

Potrošnja goriva u visokim pećima zavisi od mnogo faktora koji su uglavnom uslovljeni tehnološkim nivoom date peći i železare u kojoj se ta peć koristi, kao i vrstom i kvalitetom železonosnih sirovina, koksa i dodatnih redukujućih agenasa. Ovo su opšti faktori koje osoblje koje radi na visokoj peći ne može da kontroliše tokom rada. S druge strane, oslanjajući se na svoje iskustvo i softvere za donošenje odluka, osoblje može da upravlja visokom peći uz minimalnu potrošnju goriva za postojeću šaržu i uslove procesa. U ovom radu je predstavljen algoritam za optimizaciju rada visoke peći kojim se postiže minimalna potrošnja goriva. Algoritam neprekidno izračunava potrebnu toplotu i određuje toplotne gubitke koji bi mogli da se smanje, a da se ne poremeti rad visoke peći.

Ključne reči: *Potrošnja goriva kod visoke peći; Proizvodnja gvožđa; Direktna redukcija vistita; Kontrola zasnovana na modelu.*