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Choice of technological regimes of a blast furnace operation with injection of hot reducing gases(•)

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Abstract

Injection rate of fossil fuels is limited because of drop in the flame temperature in the raceway and problems in the deadman region and the cohesive zone. The next step for obtaining a considerable coke saving, a better operation in the deadman as an well as increase in blast furnace productivity and minimizing the environmental impact due to a decrease in carbon dioxide emission would be injection by tuyeres of hot reducing gases (HRG) which are produced by low grade coal gasification or top gas regenerating. Use of HRG in combination with high pulverized coal inyection PCI rate and oxygen enrichment in the blast could allow to keep and to increase the competitiveness of the blast furnace process. Calculations using a mathematical model show that the HRG injection in combination with pulverized coal (PC) and enriching blast with oxygen can provide an increase in PC rate up to 300-400 kg/tHM and a rise in the furnace productivity by 40-50 %. Blast furnace operation with full oxygen blast (100 % of process oxygen with the exception for the hot blast) is possible when HRG is injected.

Keywords

Ironmaking and steelmaking. Blast furnace. Raceway. Pulverized coal injection. Injection of hot reducing gases.

Elección de regímenes tecnológicos de un alto horno operando con inyección de gases reductores calientes

Resumen

La tasa de inyección de combustibles fósiles está limitada a causa de la caída de la temperatura de llama en el *raceway* (cavidad frente a las toberas) y a problemas en la región del "hombre muerto" y en la zona cohesiva. La inyección por tobera de gases reductores calientes (GRC), que se producen por gasificación de carbón de bajo grado o generación de gas de tragante, será la próxima etapa para lograr un considerable ahorro adicional de coque, una zona del "hombre muerto" bien definida, además de un aumento en la productividad del horno alto y para minimizar el impacto ambiental debido a una disminución de la emisión de dióxido de carbono. El uso de GRC en combinación con una tasa elevada de inyección de carbón pulverizado (ICP) con viento enriquecido en oxígeno, podrá permitir mantener y aumentar la competitividad del proceso del horno alto. Los cálculos, utilizando un modelo matemático, muestran que la inyección de GRC en combinación con la ICP y enriquecimiento del viento con oxígeno pueden suministrar un aumento en la tasa de carbón pulverizado hasta 300-400 kg/t arrabio y una elevación en la productividad del horno de 40-50 %. La operación del horno alto con un máximo de oxígeno en el viento (100 % del oxígeno del proceso con la excepción para el viento caliente) es posible cuando se inyecta GRC.

Palabras clave

Elaboración de arrabio y acero. Horno alto. *Raceway*. Inyección de carbón pulverizado. Inyección de gases reductores calientes.

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1. INTRODUCTION

One of the largest global challenges in this age is the preservation of the environment. The world-wide energy consumption is approx. 9.8 $*10^{18}$ J per year. The CO_2-emissions causing the greenhouse effect and coming out of human activities are approx. 860 Mt/year[1]. Regarding the agreement of Kyoto[2] the steel industry must find a compromise between environmental compatibility, economy, saving of resources and supply guarantee. The steel industriy is responsible for approx. 5 % of the world-wide energy consumption[3] (in Germany about 10 %) and therefore in the future have to deal more and more with the preservation of resources as well as the lowering of CO_2-emissions.

Currently approx. 96 % of the pig iron is made by blast furnace process, which in spite of modern technologies contributes considerably to the high energy consumption and environmental impact.

The blast furnace, sinter plant and coke oven plant consume 70-75 % of the entire energy consumption of an integrated steelwork (Fig. 1). In consideration of the linked energy, this value is since many years in the area of 11-12 GJ/t HM[4]. The main part of the required fuels is covered thereby by metallurgical coke, which makes up 40-50 % of the total fuel[5]. The CO_2-balance of the blast furnace process shows that the coke production with approx. 1450 kg CO_2-emission/t coke causes also in consideration of the linked products the largest ecological damage[6].

Apart from the ecological consequences, coke causes a majority of production costs of the pig iron. But despite all ecological and economical problems resulting from the coke use, the blast furnace route remains the most efficient way to produce crude steel. Only about 5 % of the primary metal is manufactured by alternative steelmaking processes such as direct- and smelting-reduction methods[7]. Thus the lowering of coke consumption, respectively total energy consumption at the blast furnace process is of large importance not only from aspects of environmental protection, but also from economic regard.

1.1. Previous development

Decreasing the coke rate has been a priority throughout the entire history of the blast furnace. Operating improvements have been remarkable over the years. The total fuel rate for example in all German blast furnaces was decreased from 800 kg/tHM in the 1960s to below 470 kg/tHM in 1999. As it is shown in figure 2, the coke rate was decreased to 340 kg. The mean coke rate of all European blast furnaces in 1998 was 364 kg/tHM; its minimum value was 286 kg/tHM[8].

These impressive achievements in coke consumption are still far from the theoretical minimum in the coke rate which makes up usually distinct less than 200 kg/tHM (according to calculations of A.Poos and N. Ponghis[10] even 102 kg/tHM).

Present burden and coke quality have reached at European blast furnaces such a high level that the reserves for coke saving by means of improvement of their preparation are almost exhausted. According to the statistical study, only about 10% of coke rate variation are explained by coke and ore burden properties[8].

Partial replacement of coke by other fuels has been within the last two decades the main way of coke saving. Auxiliary fuels as natural gases (NG), oil, pulverized coal (PC) and occasionally coke oven gases and organic wastes are injected via the

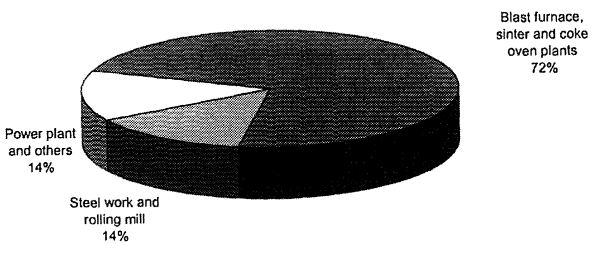

Figure 1. Structure of energy consumption in an integrated steel work[4].

Figura 1. Estructura del consumo de energía en una siderúrgica integrada[4].

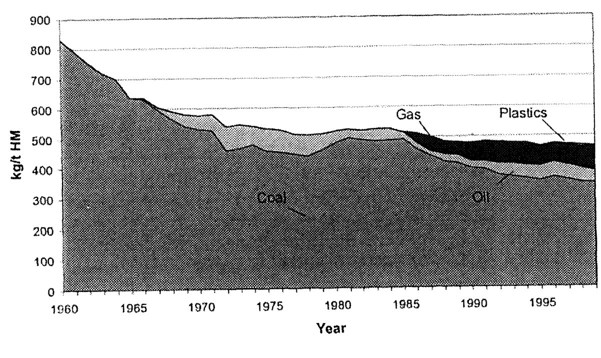

Figure 2. Average consumption of reducing agents per t HM (Germany)[9].

Figura 2. Consumo medio de agentes reductores por tonelada de arrabio (Alemania)[9].

tuyeres. Coke consumption of about 286-320 kg/tHM have been achieved at some blast furnaces by the PC injection of 170-200 kg/tHM[11-13].

Consumption of fossil fuels injected via the tuyeres is limited by their endothermic effect and by the oxidizing potential of the raceway which has to be able to provide a complete gasification of injectants within the raceway (see next section). Incomplete conversion of injected fuels leads to char generation and causes drop in the gas permeability, dirtying of the dead man and finally decrease in the furnace productivity and increase in the coke rate. In chapter 2, measures for increasing fossil auxiliary fuel efficiency are listed. Further ways for approach to the theoretical minimum of coke rate and for decrease in total energy consumption should be:

- optimization of hot metal temperature and Si-content
- improvement of process control
- decrease in heat losses
- injection of hot reducing gas (HRG) which is produced by fossil fuel gasification or top gas regenerating.

Numerous theoretical investigations as well as some pilot and industrial trials of the blast furnace technology with HRG-injection have been conducted in the former USSR, Belgium, Japan, the USA and other countries since the 1960s[10 and 14-20]. The results pointed out basic advantages of this technology, but further developments have not been proceeded due to the complexity of its realization. Beyond that, direct injection of fossil fuels was more economical and technologically simpler to implement at that time.

Since the injection rate of fossil fuels at some blast furnaces operating with super high PC or/and natural gas consumption is already close to the limit, an interest in the HRG technology has arisen again in the last few years. Different innovations of the blast furnaces technology which involve HRG injection have been recently worked out[21-23]. Calculations for injecting recycled top gas into the hearth on the basis of the kinetic "Four Fluid Model"[24], were made. Thereby the following four technology options were simulated[22]:

- conventional technology without gas recycling
- simple top gas recycling without CO_2 removal
- top gas recycling with O_2-enrichment of the blast
- top gas recycling after CO_2 removal at simultaneous O_2 enrichment

The calculation results show that simple and oxygen enriched recycling (variants b) and c)) lead to decrease in furnace efficiency and due to the cooling effects of CO_2 in the recycled gas. Using HRG recycling after cleaning from carbon dioxide, an increase of about 25 % in production and decrease in fuel rate of about 20 % can be achieved by high recycle fractions; stable furnace operation may be possible at 100 % HRG recycling (Fig. 3)[22].

Recently a process scheme for HRG injection based on the coupling of COREX –process and blast furnace was suggested[25]. In this technology the COREX-Export gas after the removing of CO_2, is heated up to 400 °C and then injected into the blast furnace (Fig. 4).

Despite considerable contribution of previoos and recent works, there are still many open questions to theory and practice of HRG-

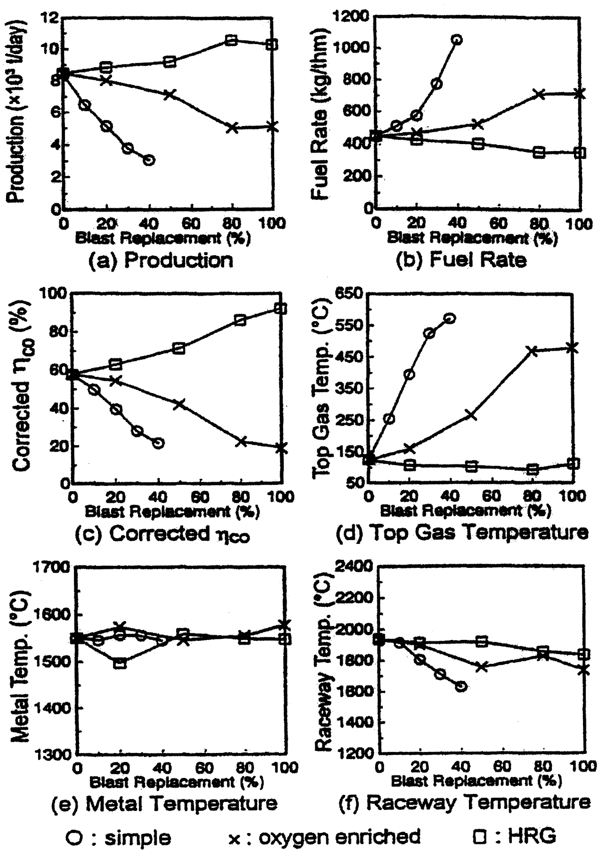

Figure 3. Calculated furnace parameters at fixed metal temperature[22].

Figura 3. Parámetros calculados del horno a la temperatura establecida de metal[22].

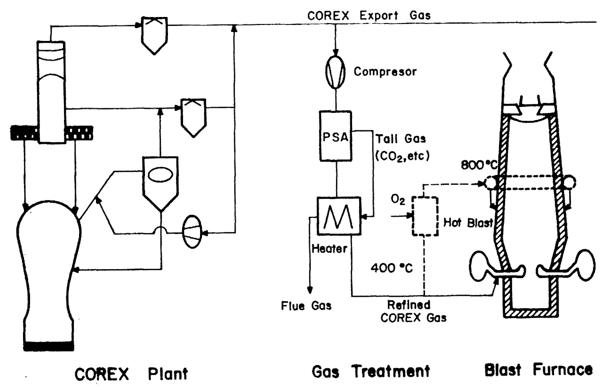

Figure 4. COREX-Export Gas Injection into the Blast Furnace.

Figura 4. Gas del proceso COREX suministrado para su inyección en el horno alto.

application. Due to this reason, the usefulness of this technology is still disputed also by experts.

In this paper limit conditions of blast furnace technology with fossil fuel injection are summarized and calculation results of technological regimes with HRG injection using a balance mathematical model are presented. Ways for realization of this technology are also proposed.

2. EFFECT OF FOSSIL AND ARTIFICIAL AUXILIARY FUELS ON THE BLAST FURNACE PROCESS

Injecting fossil reducing agents influences strongly the heat exchange, the gas permeability and the slag regime in the blast furnace. In numerous works both changes of the blast furnace operating condition as well as the conversion processes in the raceway have been investigated. From this reason only some aspects of the change in the raceway conditions, in the gas permeability and liquid product drainage as well as special features of HRG injecting are regarded here.

2.1. Flame temperature and oxidizing potential of the raceway

By injecting auxiliary fuels, flame temperature is reduced since the bosh gas volume rises more strongly than the quantity of heat generated by fuel gasification and carried by the hot blast. The amount of heat generated by combustion of auxiliary fuels decreases in comparison to the heat amount released by the coke combustion because of their pyrolysis and lower heat of incomplete combustion.

The difference in the decrease of the flame temperature for various fuels depends on the C/H ratio. Heat of decomposition increases with the drop of the C/H ratio in fuel. Therefore the less C/H ratio, the less heat is released in incomplete combustion (Table I).

Thus for example the decrease of the flame temperature makes up 350-450 °C per 100 m^3/tHM when injecting natural gas, 300-350 °C per 100 kg/tHM injecting heavy oil, 200-250 °C per 100 m^3/tHM injecting coke oven gas and with the use of pulverized coal 80-220 °C per 100 kg/tHM (80-120 °C for low-volatile and 150-220 °C for high-volatile types of coal)[5 and 28-33]. Using HRG flame temperature decreases less due to the insignificant pyrolysis as well as high temperature. Beyond that the problem of incomplete combustion does not apply. Compared to fossil fuels thereby a far higher quantity of HRG is applicable.

To keep, the flame temperature at a constant level is usual technological mode of blast furnace operation with combined blast. When injecting auxiliary fuels the decrease of flame temperature is adapted by enriching blast with process oxygen, incresase in blast temperature or decrease in humidity of the blast. Nevertheless the constant value of the flame temperature may not maintain the required temperature and composition of hot metal in changing technological conditions[34]. Following equation for flame temperature, needed to save initial temperature and composition of hot metal under changed technological conditions, was set up on the base of the heat balance in the lower blast furnace zone viewing two technological

Table I. Incomplete combustion heat of carbon in various fuels (depending on the C/H mass ratio)[26 and 27]

Tabla I. Calor de la combustión incompleta del carbono en varios combustibles (dependiendo de la relación en masa C/H)[26 y 27]

Fuel	C/H mass ratio	Heat released kJ/kg C	%
Coke	200-500	9800	100
Anthracite	33-50	9400	96
Fiery coal	10-12	8400	85
Fuel oil	7.7-9.0	7500	77
Hydrocarbons:			
pentane C_5H_{12}	5	6740	69
ethane C_2H_6	4	5650	58
methane CH_4	3	2970	30

regimes conditions - with (index 1) and without injecting reducing agents (index 0)[35]:

$$T_1=T_n+[1-A\ (r_{do}-r_{d1})/r_{do}]\ (K_o\ V_o\ /K_1V_1)\ (T_o-T_n) \quad (1)$$

where:

T: flame temperature, °C
T_n: temperature of burden and gases in the reserve zone of heat exchange (idle zone), °C
r_d : direct reduction rate, (-)
K : coke rate, kg/t HM
V: bosh gas volume, m^3/t coke
$A = 1 - 0.9 / W_b$
W_b : water equivalent of burden, kJ/t HM.

The necessary flame temperature as it follows from Eq. (1) depends on furnace operation conditions. E.g. a change in direct reduction rate, gas volume or coke rate requires correction in the flame temperature value. The PCI affects the necessary flame temperature not only because the drop in direct reduction rate but also due to the radiation of the coal particles within the raceway[34 and 36].

The oxidizing potential of the raceway at constant oxygen concentration in blast depends on the rate of injected fuels and can be maintained or changed controlling their ratio, according to the equation[37]:

$$\Delta S_2 = -\ (m/n)\ \Delta S_1 \ , \quad (2)$$

where:

S_1 and S_2: injecting rate of gaseous and liquid/solid respectively, m^3/kgHM (kg/kgHM)
m, n: theoretical oxygen consumption for combustion of 1 m^3 gaseous fuel and 1 kg liquid/solid fuel respectively, m^3.

The coefficients m and n are calculated by the equations[37 and 38]:

$$m = 2(H_2)+2(CO)+2(CH_4)+3.5(C_2H_6)+5(C_3H_8) +\dots \quad (3)$$

$$n = 1.8667\ C^w + 11.2\ H^w, \quad (4)$$

where:

H_2, CO, CH_4, C_2H_6, C_3H_8..: hydrogen, carbon monoxide, methane, ethane, propane and other components in gaseous fuel, %;

C^w, H^w : content of carbon and hydrogen in liquid / solid fuel, %.

To keep oxidizing potential e.g. for the case of simultaneous PC and NG injection, a PC consumption change by 10 kg should be accompanied according to eq. (2) by change in NG consumption in the opposite direction by 7-8 m^3. Injection of HRG does not require additional oxidizing potential of the raceway.

2.2. Gas permeability and drainage of liquid products

The lower the coke rate, the more difficult to maintain the gas permeability in the cohesive zone and in lower part of the furnace as well as the drainage of the melted products. The minimum coke rate which maintains the drainage of the liquid products in a counter flow corresponds to the critical voidage of 0,23-0,24 m^3/m^3 [39]. High coke qualitiy is necessary to limit the contamination of the furnace especially in the area of the dead man as well as to guarantee the necessary hydraulic and gas dynamic conditions in the hearth.

The following measures are necessary for the preservation of the gas permeability at the substantial decrease of coke rate[40]:

- the reverse V-profile of the cohesive zone
- the peak of the cohesive zone should be shifted possibly far upwards to maintain a sufficient number of coke windows and therefore the sufficient gas permeability in the cohesive zone (Fig. 5)

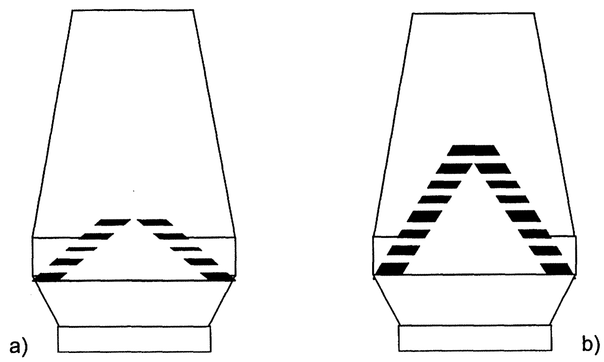

Figure 5. Desired shape of the cohesive zone at different coke rates. a) 500 kg/tHM; b) 250 kg/THM.

Figura 5. Forma deseada de la zona cohesiva para diferentes consumos de coque. a) 500 kg/ta; b) 250 kg/ta.

- during a retention of the coke layer thickness the ore layer thickness must be decreased.

These measures permit to enable the gas permeability of furnace during the coke replacement up to 40-50 %.

Injecting large quantities of fossil auxiliary fuels can worsen the gas permeability, the drainage of the hot metal and slag and the coke characteristics in the hearth, since the char or the unburned coal particles reduce the voidage in the lower part of the furnace as well as porosity and thus the reactivity of the coke. The contamination of the shaft increases and can lead to substantial disturbances of the blast furnace operation over months. The hydrodynamic conditions in the lower part of the blast furnace can be characterized by a Deadman Cleanliness Index (DCI): the higher this value is, the more favorably the conditions are[41].

Injecting the HRG could improve the conditions in the hearth, since it practically forms neither soot nor char or ash. The coke characteristics in the hearth can likewise improve.

Beyond that the use of HRG has a substantially smaller influence on the slag regime (physical characteristics, composition, quantity) as pulverized coal, oil or plastics.

2.3. Limit for fossil auxiliary fuels and fundamental advantages of HRG

The highest rate of NG injection of 155 m^3/tHM was achieved in USA (coke rate was 310 kg/tHM). In Russia and Ukraine its rate at some BFs was 150-170 m^3/tHM[5 and 42].

The higher NG rate leads to local supercooling of the hearth, an increment of slag viscosity, incompleteness of NG combustion with char generation, and worsening of melting products drainage.

The injection rate of coke oven gas (COG) (which is only injected occasionally in some blast furnaces because its free resources at an integrated plant are usually limited) is changed from 100 to 250-300 m^3/tHM[5,11 and 42]; the coke/COG replacement ratio makes up 0.4-0.45 kg/m^3 compare to 0.8-0.85 kg/m^3 for NG, and 0.9-1.1 kg/kg for PC.

PC is the most common auxiliary fuel. Its injection rate of 200-230 kg/tHM with the drop in coke consumption down to 280-300 kg/tHM has been achieved during trial periods at some BFs[11,12 and 43]. Theoretical, laboratory and pilot investigations as well as the latest industrial experience show that PC rate can be raised up to at least 250 kg/tHM and BF operating with coke/coal ratio = 50/50 (%) could be maintained.

On the other hand, average PC rate in Europe rarely exceeds 130-150 kg/tHM (in 1999 only IJmuiden 6, the Netherlands, operated with PC rate of 204 kg/tHM and coke rate of 316 kg/tHM[44]) mainly because of the problems with complete combustion within the raceway, gas permeability in the shaft, dirtying of the deadman and as a result irregular furnace operation and decrease in productivity. Increase in PC rate up to the record level of 266 kg/tHM even under perfect burden and operational conditions at Fukuyama No.3 BF (NKK, Japan) did not result in record low coke rates[45].

Total consumption of injected fuel at co-injection of NG, PC and /or oil does also not exceed 180-230 kg/tHM[5].

Considerable success in finding solutions to the above mentioned problems as

- the provision of the complete or at least high rate of auxiliary fuel utilization
- the provision of a suitable permeability under conditions of a very large decrease of the coke layer thickness and of the thickness of the coke windows in the cohesive zone
- the compensation for the negative changes of heat fluctuation and slag formation processes
- the maintenance of a uniform distribution of injected fuels by tuyeres around the furnace circumference

has been recently made. Further investigations and improvements of blast furnace operation with high rate of fossil fuel injection as well using of already developed measures (optimization of burden distribution, blast oxygen enrichment, improvement in delivery of oxidizing agent to the coal jet and their mixing, optimizing of coal grinding, use of catalysts, use of ionized air and injection of a gas-oxygen mixture for intensifying natural gas combustion etc[5,35 and 46]) could maintain a stable furnace operation at high PCI as well as NG or oil injection and increase the achieved average level of injected fuel rate.

It is necessary to clearly understand that all efforts in the direction of increasing the PC rate could shift the achieved limit of PCI to a higher level but not eliminate the limitation on fossil fuel injection generally.

Hot reduction gases have following fundamental advantages in comparison with the fossil auxiliary fuels:

- they enable to introduce a higher quantity of carbon monoxide and hydrogen, as fossil fuels,
- the quantity of hot reduction gas in combination with enriching blast with oxygen could be increased up to a nitrogen-free-process, because no (or almost none) heat is necessary for the splitting of the hydrocarbons and in the raceway no processes of combustion do take place
- the relative share of CO and H_2 increases because of reduction of the nitrogen quantity
- the furnace productivity increases, because in the fraction of time, more carbon converses and more raw material gets melted
- the mixing of the gas stream with the hot blast is improved. This leads to the increase of CO - and H_2- utilization rates
- the lower part of the blast furnace remains "cleaner" and the coke characteristics under the cohesive zone can be maintained.

The advantages of the HRG mentioned above refer on the injection by tuyeres into the hearth. When injecting into the shaft or belly, in the lower part of the blast furnace with reduced gas permeability the gas volume would not rise, so that an increase of the furnace productivity is possible; beyond that the physical heat of the HRG is entered at that point, where the temperature is low.

The decisive argument agaist the HRG injection into the shaft consisits of enormous difficulty to provide the necessary gas distribution in the shaft, especially in the cohesive zone. The distribution of the HRG all-over the furnace radius and the gas-penetrating up to the center will be one of the main problems of this method of HRG injection.

Further disadvantages of the HRG injection into the shaft consisit of the costly and complex constructional modifications; the shaft is more stressed by the additional tuyere rank.

3. CALCULATIONS OF TECHNOLOGICAL REGIMES FOR THE INJECTION OF HRG INTO THE BLAST FURNACE

3.1. Mathematical model

The calculations represented in the following were carried out using a mathematical model of the Donetsk State University of Technology[47]. This is a total balance model that does not require any input parameters to be assumed (e.g., the "Four Fluid Model"[24] needs raceway geometry, softening temperature of the burden, distribution of burden- and coke size all-over the furnace radius, coke size in deadman and other parameters of the inner state as input parameters).

The model calculates the coke rate, the blast volume, parameters of the inner state (bosh gas volume, flame temperature, direct reduction rate, heat generated and absorbed), and output parameters (slag volume, relative productivity, top gas composition and temperature, etc.). The model was developed on the base of a complex method of Prof. A.N. Ramm[26]. This method based on the interrelations of material and heat balances equations. Its characteristic feature is following: a system of equations of material balance of different input components according to a target hot metal chemical composition is formed; to this system one equation of heat balance is added which determines the correlation between coke rate and remaining components. The coke rate is introduced as unknown value in all equations of the material balance, rates of iron bearing and flux components in the heat balance equation.

The main steps of calculation are:

- O_2-quantity released during reduction
- useful heat output of physical and chemical conversions of burden, coke and coal ash
- total quantity of C, H, O and N in 1 m^3 or 1 kg of each injected fuel as well as the enthalpy and calorific value (by burning in the raceway)
- volume of bosh gas, direct reduction rate and top gas temperature
- coke and total fuel consumption, as well as blast volume
- needs of fluxes, slag volume, top gas parameter (volume, composition, calorific value)
- heat balance
- flame temperature
- change in the productivity and intensity of the coke combustion.

Furnace productivity is determined with the consideration of material gas permeability by the following equation[47]:

$$P = P^{\circ} \cdot (v_g^{\circ}/v_g) \cdot (d^{\circ} \cdot \Theta^{\circ} \cdot \gamma^{\circ}/ d \cdot \Theta \cdot \gamma)^{1/2} \quad (5)$$

where:

d = $[L (v_b/v_c + 1)] (v_b/v_c + 1)^{-1}$
P: blast furnace productivity, t / 24 h
Θ : average top gas temperature, K
v_g : wet top gas volume, m^3 / kg HM
γ: average gas density, kg / m^2
v_b, v_c : burden and coke volume respectively, m^3 / kg HM
L : ratio of gas pressure drop in the blast furnace. Superindex o refers to initial (base) conditions.

3.2. Calculation conditions

The injection of hot reducing gases with various parameters into the blast furnace hearth has been simulated. Calculations have been carried out for two blast furnaces operating under the different conditions. Blast furnace 1 (BF-1) with a working volume of about 1000 m^3 and 12 tuyeres represents the typical blast furnace with only coke operation without enriching blast with oxygen (21 % O_2). The hot blast temperature is 1080 °C. The produced pig iron contains 0.6 % Si and 0.040 % S. Blast furnace 2 (BF-2) (working volume of about 3800 m^3, 40 tuyeres) represents a modern blast furnace with PCI and O_2-enrichment of the hot blast. The hot blast temperature is in the range 1160 °C to 1180 °C and the produced pig iron contains about 0.37 % Si and 0.029 % S.

The iron bearing burden of BF-1 consists of 59.1 % sinters, 34.3 % pellets and 6.6 % lump ore. The S-content in the coke makes up 0.5 %. At the BF-2 the sinter/pellets ratio in the burden makes up 2:1. In tables II and III the burden and coke parameters for both blast furnaces as well as PC parameters for BF-2 are given.

3.3. Calculation results

3.3.1. *Influence of HRG-parameters*

The influence of HRG temperature and composition on blast furnace process has been investigated for the conditions of the BF-2 (hot blast temperature 1180 °C and PCI rate 160 kg/tHM). Four cases with the same injection rates of PCI and HRG (160 kg/tHM and 150 m3/tHM respectively) were examined and compared with the basic case. A constant flame temperature of 2150 °C was maintained by controlling the oxygen concentration in the blast.

The main results of the calculation are shown in table IV. While the HRGs of cases 1 and 2 are produced by coal gasification, in case 3 a HRG is used, which is generated by steam conversion of natural gas. The reducing gas used in case 4 is top gas, where CO_2 is stripped from the recycled gas.

Table III. Chemical analysis of coke and PC % mass

Tabla III. Análisis químico del coque y CP % masa

Analysis	Components	BF-1	BF-2	
		Coke	Coke	PC
Proximate	Fixed carbon	87.63	90.15	76.7
	Volatile matter	1.0	1.04	15.8
	Ash	11.37	8.8	7.5
	Moisture	5.0	3.3	1.0
Ultimate	Carbon	86.8	87.8	81.11
	Hydrogen	0.4	0.2	4.9
	Nitrogen	0.9	1.3	1.54
	Sulphur	0.5	1.09	0.98

Table II. Burden consumption and composition

Tabla II. Consumo y composición de la carga

Burden		Sinter		Pellets		Lump Ore		Limestone	
		BF-1	BF-2	BF-1	BF-2	BF-1	BF-2	BF-1	BF-2
Consumption, kg/t HM		935	923	543	437	104	189	–	38
	Fe	56.83	58.09	65.08	65.70	65.05	65.50	–	
	FeO	5.87	4.90	0.31	1.50	0.78	2.00	–	
	CaO	9.86	9.67	2.94	0.92	0.22	0.90	–	53.5
Composition, %	SiO_2	5.80	5.09	2.77	4.70	2.55	8.20	–	1.8
	MgO	1.65	1.54	0.09	0.26	0.04	0.90	–	0.7
	Al_2O_3	1.40	1.05	0.65	0.30	1.36	0.50	–	0.3
	MnO	0.52	0.22	0.17	0.07	0.15	0.10	–	0.05

Table IV. Influence of parameters of HRG on blast furnace operating parameters (BF-2)

Tabla IV. Influencia de los parámetros de GRC sobre los índices de operación del horno alto (HA-2)

Parameters		Base	1	2	3	4
				Blast		
Temperature, °C		1180	1180	1180	1180	1180
Oxygen, %		24.1	34.3	31.0	31.7	30.5
PC, kg/tHM		160	160	160	160	160
HRG, m^3/tHM		0	150	150	150	150
HRG composition, %	H_2		33.1	44.0	71.0	25.0
	CH_4		0.0	1.0	3.0	0.0
	CO		52.9	51.5	22.6	72.0
	N_2		0.0	0.0	1.0	0.0
	CO_2		7.0	3.0	3.0	1.5
	H_2O		6.5	0.5	0.0	1.5
HRG temperature, °C			700	1000	1000	1000
Direct reduction rate, %		52.9	44.7	44.0	40.8	46.3
Coke, kg/tHM		345	345	310	298	318
Total fuel, kg/tHM		511	511	477	464	484
Blast vol, m^3/tHM		1000	724	740	718	756
				Top gas		
Composition, %	CO_2	20.8	24.0	24.0	24.2	23.8
	CO	26.1	34.8	31.3	29.0	32.8
	H_2	3.5	6.5	6.7	8.6	5.5
	N_2	49.5	34.7	37.9	38.2	37.9
Calorific power, kJ/m^3		3685	5107	4685	4595	4733
Temperature, °C		166	107	125	126	125
CO utilization rate, %		43.7	40.2	42.8	44.8	41.5
H_2 utilization rate, %		46.1	42.3	45.1	47.3	43.8
				Heat balance kJ/kgHM		
Combustion of	C of coke	1420.0	1584.1	1301.0	1255.3	1319.3
	PC	1092.1	1092.1	1092.1	1092.1	1092.1
	HRG	0.0	-271.2	-64.1	-49.7	-57.2
Heat carried by	PC	11.5	11.5	11.5	11.5	11.5
	HRG	0.0	149.6	217.0	222.1	213.3
	the blast	1554.3	1124.2	1149.3	1114.4	1174.8
Oxidizing	C - CO	1096.3	934.4	920.1	855.6	964.9
	CO - CO_2	3969.9	4106.8	4035.8	3877.2	4120.0
	H_2 - H_2O	500.9	717.0	807.1	1075.2	643.0
Total in reduction area		5567.0	5758.2	5763.0	5808.0	5727.9
Total heat generated		9645.0	9448.5	9469.9	9453.8	9481.9
Useful heat absorbed		8868.8	8869.9	8852.5	8846.5	8856.0
Heat in top gases		370.4	214.3	249.7	244.9	253.6
External heat losses		407.8	369.0	370.7	364.6	375.4
Total heat absorbed		9647.0	9452.3	9472.9	9456.0	9485.0
Flame temperature, °C		2150	2150	2150	2150	2150
Productivity, %		100.0	111.3	110.9	114.8	108.4

The HRG in case 1 is characterised by a high content of oxidizing agents (CO_2+H_2O = 13,5 %) as well as a low temperature of 700 °C. It is shown, that the physical heat of the HRG can not compensate the lower heat entry with the hot blast (approx. by 430 kJ/kgHM in comparison to the basis case) and the heat consumption for the decomposition of carbon dioxide and water steam

(271 kJ/kgHM). For that reason the coke rate has not been changed despite the decrease in the direct reduction rate (r_d) by 8 % in comparison to the basis case. The furnace productivity increased by 11 %.

At reduction of the oxidising agents (CO_2+H_2O) up to 3,5 % and an increase of the blast temperature up to 1000 °C (case 2) the coke consumption was lowered by 35 kg/tHM and the furnace productivity increased around by 11 %.

The use of HRG with 3 % CO_2, 3 % CH_4, high H_2 - content and t = 1000 °C (case 3) makes possible to reduce the coke consumption by 47 kg/tHM, because of the strong decrease in direct reduction rate (by 12 %) and less needs of heat for the decomposition of CO_2 and H_2O (about 50 kJ/kgHM). The CO- and H_2- conversion degrees improve. The productivity was increased by 15 %.

The recycled top gas (after CO_2 removing) is characterised by a high content of CO and H_2 (72 and 25 % respectively) and low content of oxidixing agents (CO_2 + H_2O = 3 %). Injection of this gas with a temperature of 1000 °C into the hearth (case 4) makes possible a reduction of coke rate by 27 kg /tHM (8,5 %) as well as an increase in productivity by 8 %.

3.3.2. HRG injection and co-Injection of HRG and PC

In table V the calculation results for the BF-2 operating conditions are shown at simultaneous injection of PC and HRG. The parameters of HRG are equal for all cases:

- composition: H_2 = 33 %, CO = 60 %, CH_4 = 3 %, CO_2 = 4 %
- temperature: 1000 °C.

The cases 1 and 2 represent the partly and total substitution of pulverized coal by HRG. These technological regimes are of no interest for practice, since the modern blast furnace technology and equipment for PC preparation and guarantee an effective use of 150-180 kg PC/tHM, thus the advantages of HRG can not be realized. As consequence the coke rate rises.

Case 3 shows the co-injection of HRG and “standard level” of 150 kgPC/tHM + 150 m^3HRG/tHM. The direct reduction rate decreases by more than 8 % in comparison with the basis case because of the high content of reducing agents. This is the primary cause for the coke saving of approx. 35 kg/tHM despite the drop in heat supply. This technological regime is accompanied by lowering of the blast volume by 25 %, the bosh gas volume by 12 % and the top gas temperature by approx. 40 °C. The hydrogen content in the top gas rises in comparison with the basis case from 3.4 to 6.1 %; the nitrogen content decreases from 49.6 to 37.6 % because of the increased quantity of reducing agents and oxygen content in the blast. The calorific value of the top gas rises by 28 %. Other operating parameters (slag volume, flux consumption etc.) do not change. The furnace productivity increases by 10 %.

In cases 4-6 the increase in PCI by 50-100 kg/tHM and in the furnace productivity by 15-30 % were possible due to a rise in the oxygen concentration in the blast. Thereby an essential coke saving of 83-150 kg/tHM was reached. The efficiency of heat use rises from 91.9 % in the basis case to 94.2-96.0 %. When injecting 250 kg PC/tHM and 300 m^3 HRG/tHM (case 6), blast volume and O_2-enrichment of the blast make up 315 m^3/tHM and 75% respectively. The top gas has low temperature, contains 60 % (CO+H_2) and only 8 % N_2. Its calorific value makes up approx. 7350 kJ/m^3. The high thermal and reducing potential of this gas can be utilized in the blast furnace and/or other aggregates.

In chapter 2 it was shown, that with a change of parameters of the combined blast, the necessary flame temperature changes as well. The adjustment of flame temperature to the initial level is not necessary. The technological regimes for cases 7 and 8 were calculated using this principle. The HRG injection rate increases by 50-200 m^3/tHM. Coke rate reduced in case 7 by 14 kg/tHM (4.3 % in comparison to case 3) and by 13 kg/tHM (6.3 % in comparison to case 6) in case 8. The slag regime practically does not change in all cases.

Injection of HRG accompanying with enriching blast with process oxygen and PCI provides decrease in total energy consumption (by 450 MJ/tHM or 4.6 % when injecting 500-550 kg/tHM reducing agents). Total energy loss was dropped in this case by more than 400 MJ/tHM or 50 % (Fig. 6).

In table VI the results of similar calculations for conditions of BF-1 are shown. The HRG parameters are the same as for calculations discussed above (Table V). Cases 1-3 represent blast furnace operating parameters at only HRG (without PCI). At HRG-injection rates of 150, 300 and 600 m3/tHM the coke consumption decreases by 44.76 and 124 kg/tHM respectively.

Table V. Blast furnace operating results for BF-2

Tabla V. Datos de operación del HA-2

Parameters		Base	1	2	3	4	5	6	7	8
						Blast				
Temperature, °C		1160	1160	1160	1160	1160	1160	1160	1160	1160
Oxygen, %		24.1	24.1	26.5	31.2	36.7	44.1	75.0	31.2	75.0
Volume, m^3/tHM		1012	997	820	748	644	545	315	725	304
HRG, m^3/tHM		0	40	300	150	150	150	300	200	350
PC, kg/tHM		150	125	0	150	200	250	250	150	250
Direct reduction rate, %		53.2	53.0	49.0	45.0	41.3	38.0	32.1	42.5	30.4
Bosh gas flow, m^3/tHM		1376	1387	1388	1254	1177	1108	1025	1277	1060
Coke, kg/tHM		359	375	447	325	276	229	208	311	195
Total fuel, kg/tHM		514	504	443	481	485	491	471	467	458
Slag vol., kg/tHM		278	277	270	273	272	272	269	270	267
						Top gas				
Composition, %	CO_2	20.7	20.5	21.1	23.9	26.1	28.3	32.1	23.9	31.4
	CO	26.4	27.3	34.2	32.4	34.3	36.6	46.6	32.9	46.8
	H_2	3.4	3.6	5.5	6.1	7.4	8.9	13.4	6.9	14.3
	N_2	49.6	48.5	39.2	37.6	32.2	26.1	7.9	36.3	7.5
Calorific power, kJ/m^3		3705	3846	4920	4756	5136	5592	7344	4902	7459
Temperature, °C		165	165	149	123	100	80	68	126	69
CO utilization rate, %		43.3	42.2	37.6	41.9	42.6	43.1	40.2	41.6	39.7
H_2 utilization rate, %		45.6	44.5	39.6	44.2	44.9	45.4	42.4	43.8	41.8
						Heat balance, kJ/kgHM				
Combustion of	C of coke	1533.4	1681.2	237.7	1408.8	1059.0	720.5	661.0	1335.0	580.7
	PC	1023.9	855.6	0.0	1023.9	1365.2	1706.5	1706.5	1023.9	176.5
	HRG	0.0	-18.3	-137.4	-201.3	-68.7	-68.7	-137.4	-91.6	-160.3
Heat carried by	PC	10.8	9.0	0.0	10.8	14.4	18.0	18.0	10.8	18.0
	HRG	0.0	59.2	444.1	222.1	222.1	222.1	444.1	296.1	518.2
	the blast	1521.3	1499.7	1233.6	1124.9	967.7	819.3	473.0	1090.7	457.4
Oxidizing	C - CO	1102.8	1099.6	1019.5	939.2	866.6	799.9	683.0	890.5	648.2
	CO - CO_2	3973.3	3973.0	4032.2	4089.0	4128.7	4156.9	4222.7	4109.2	4223.9
	H_2 - H_2O	484.5	491.4	605.7	722.3	837.8	951.0	1135.3	805.3	1205.9
Total heat generated		9650.0	9650.4	9575.0	9472.3	9392.8	9325.4	9206.3	9469.8	9198.4
Useful heat absorbed		8871.3	8869.2	8851.7	8855.4	8852.7	8850.8	8841.1	884.9	8834.8
Heat in top gases		371.9	375.4	338.1	247.9	186.7	134.8	50.4	258.6	53.
External heat losses		408.9	408.6	391.8	372.2	356.0	341.8	316.5	366.5	312.0
Total heat absorbed		9652.1	9653.2	9581.5	9475.5	9395.3	9327.4	9208.0	9473.7	9200.6
Flame temperature, °C		2150	2150	2150	2150	2150	2150	2150	2079	2048
Productivity, %		100.0	100.3	105.7	110.1	114.9	119.5	130.2	109.8	128.5

An essential decrease of direct reduction rate (relatively by 20 and 43 % during injection of 300 and 600 m^3 HRG/tHM) allows to save still more coke. However the HRG must have thereby a temperature of more than 1000 °C. Injection of 150 m^3 HRG/tHM does not require perceptible changes in the combined blast parameters. At 300 m^3 HRG/tHM the blast moisture was reduced down to the atmospheric value and a blast volume to less than 800 m^3/tHM; the oxygen enrichment rises up to 27 %. At 600 m^3 HRG/tHM the blast volume decreases to approx. 330 m^3/tHM and the O_2-enrichment makes up 60 %. The furnace productivity rises in cases 1-3 by 3.5, 13 and 34 % respectively.

Cases 4-5 illustrate the operating parameters at co-injection of PC (150 kg/tHM) and HRG (150 and 300 m^3/tHM). Besides a considerable coke

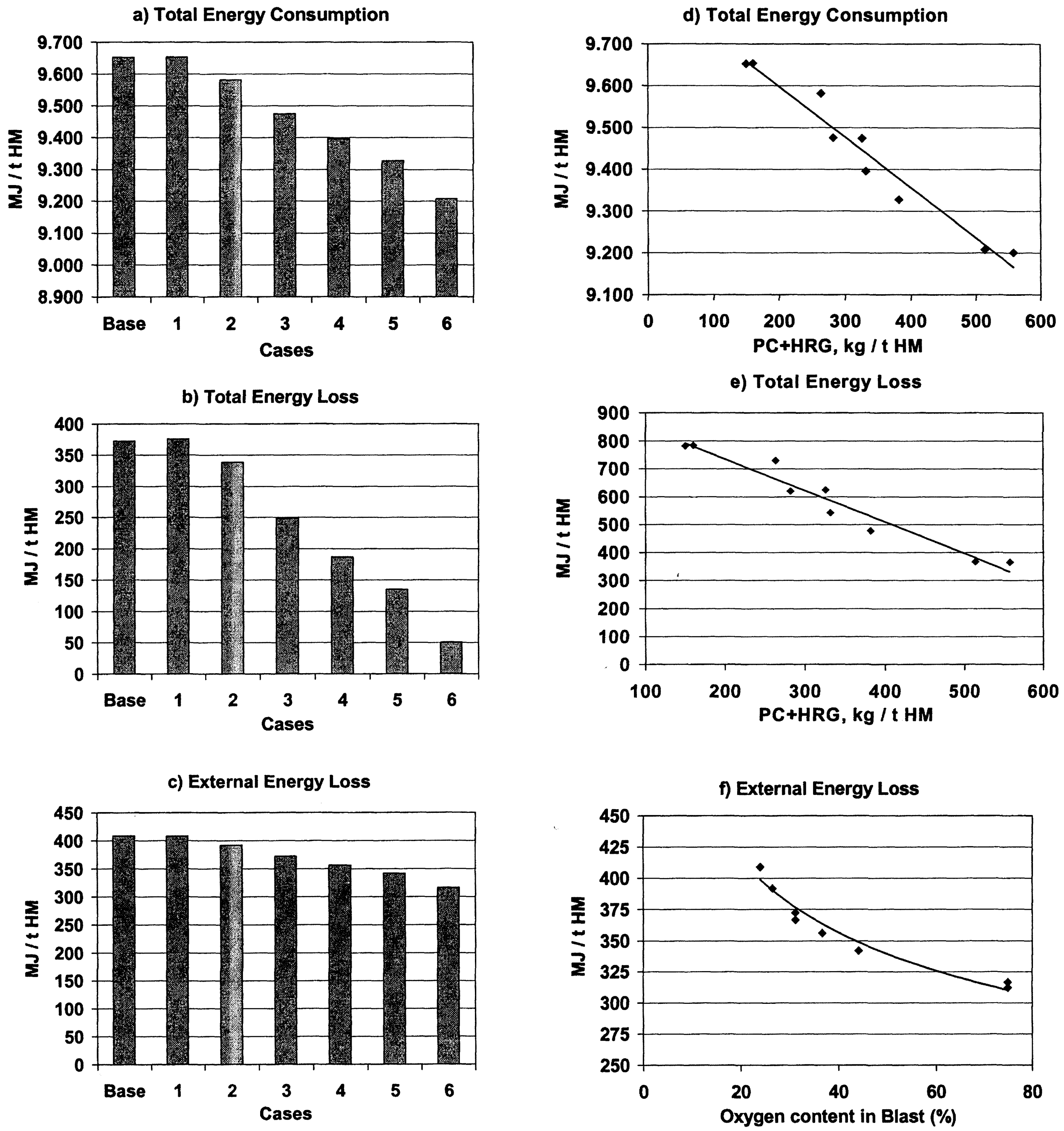

Figure 6. Total energy consumption structure of energy loss for BF-2 operation conditions.

Figura 6. Consumo total de energía y pérdida de energía para las condiciones de operación del HA-2.

saving of 160 (32 %) and 180 kg/t HM (37 %) these technological regimes provide an increase in furnace productivity of 24 and 36 % respectively. The effectiveness of heat use increases in case 5 by 3.3 %; the heat loss decreases from 5.5 % in the basis case to 4.5 %.

Case 6 represents a special technological regime, the so-called "Oxy-Coal-Process". Since in this process 100 % O_2 is injected i.e. no hot blast is used, neither cowpers are necessary nor other costs for the heating of blast arise. This regime enables coke saving of 182 kg/tHM and increase in furnace productivity by 52 %. Extra economic benefits could be derived by utilization of the top gas with a high calorific value which contains no nitrogen.

Total energy consumption decreases by 55-80 MJ/tHM for every 100 m^3/tHM of HRG. The higher value corresponds to the cases with PC

Table VI. Blast operating results for BF-1

Tabla VI. Datos de operación del HA-1

Parameters		Base	1	2	3	4	5	6
					Blast			
Temperature, °C		1080	1080	1080	1080	1080	1080	1080
Misture, g/m^3		32	12	8	8	8	8	8
Oxygen, %		21	22	27	60	32	45	100
Volume, m^3/tHM		1147	1024	792	327	730	503	248
HRG, m^3/tHM		0	150	300	600	150	300	450
PC, kg/tHM		0	0	0	0	150	150	150
Direct reduction rate, %		50.0	46.4	40.0	28.6	36.7	31.1	20.1
Coke, kg/tHM		489	445	413	365	330	308	307
					Top gas			
Composition, %	CO_2	20.5	21.6	24.1	29.9	26.5	29.5	35.5
	CO	23.0	25.4	30.5	45.6	28.7	36.3	47.8
	H_2	2.4	3.5	6.1	13.7	7.3	11.2	16.3
	N_2	54.1	49.5	39.3	10.9	37.4	23.0	0.4
Calorific power, kJ/m^3		3174	3589	4516	7243	4421	5799	7801
Temperature, °C		154	167	136	88	111	92	83
CO utilization rate, %		46.9	45.7	43.9	39.4	47.8	44.6	42.5
H_2 utilization rate, %		39.8	38.9	37.3	33.5	40.6	37.9	36.1
					Heat balance kJ/kgHM			
Combustion of	C of coke	2767.6	2452.5	2301.9	2109.8	140.2	1558.6	1775.5
	PC	0.0	0.0	0.0	0.0	744.1	744.1	744.1
	HRG	0.0	-68.7	-137.4	-274.8	-68.7	-137.4	-206.1
Heat carried by	PC	0.0	0.0	0.0	0.0	9.0	9.0	9.0
	HRG	0.0	222.1	444.1	888.3	222.1	444.1	666.2
	the blast	1352.5	1434.6	1145.0	473.1	1055.8	727.1	-31.8
Oxidizing	C - CO	1060.7	989.6	863.2	637.2	79.8	685.5	467.4
	CO - CO_2	4322.9	4373.8	4462.7	4609.8	4449.9	4512.1	4833.2
	H_2 - H_2O	290.8	393.5	577.8	917.2	722.9	901.1	1075.8
Total heat generated		9794.5	9797.4	9657.3	9360.5	9573.3	9444.2	9333.2
Useful heat absorbed		8894.4	8885.6	8879.3	8869.8	8892.2	8887.8	8887.8
Heat in top gases		367.6	391.7	297.4	80.5	217.8	126.8	65.5
External heat losses		535.6	525.3	488.0	415.5	468.3	434.9	384.4
Total heat absorbed		9797.7	9802.6	9664.7	9365.8	9578.3	9449.5	9337.7
Flame temperature, °C		2151	2138	2134	2105	2153	2143	2098
Productivity, %		100.0	103.5	113.0	134.0	124.4	136.0	151.9

co-injection (Fig. 7, e). Change in the value of energy loss is similar. E.g., external energy losses make up 20 and 28 MJ/tHM per 100 m^3/tHM of HRG for the cases without and with co-injection of PC respectively (Fig.7, f).

Further study of blast furnace operation with the injection of preheated top gas after CO_2 removal (HRG parameters are the same as in Table 4, case 4) has been carried out under BF-2 conditions for the wide range of oxygen enrichment of blast and PCI rate. Hot metal temperature has been kept on a constant level by maintaining the necessary value of flame temperature. Results are presented in figure 8.

Maximum coke saving of about 370 kg/tHM or more than 70 % has been achieved when injecting over 400 m^3/tHM HRG, 300 kg/tHM PC with blast consisting almost completely of cold process oxygen (80-90 % O_2). Decrease in direct reduction rate by 2.5 times is an important positive factor for the hearth operation, decrement of carbon consumption to direct reduction, improvement of heat of liquid products, operational conditions and hot metal desulphurization.

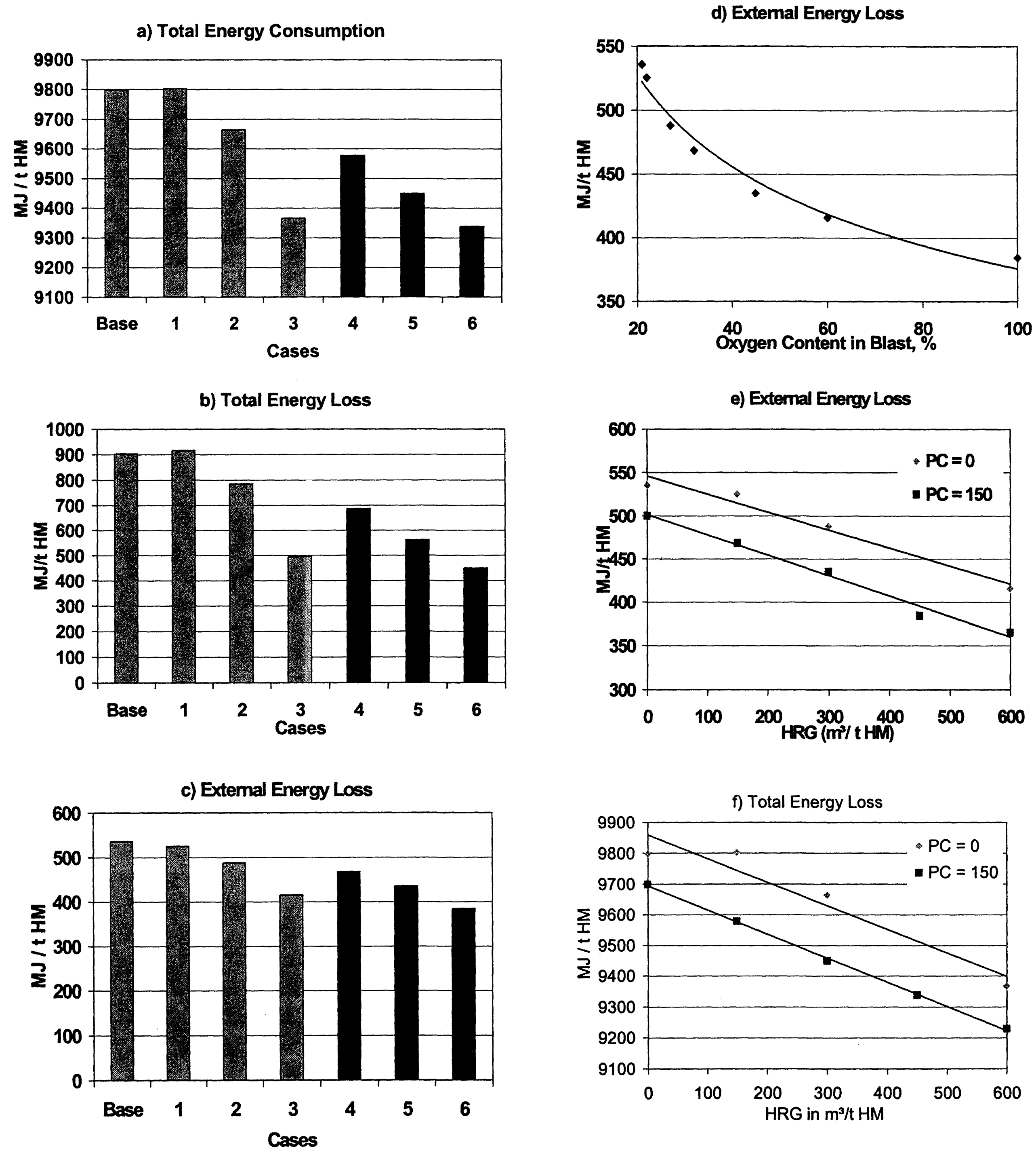

Figure 7. Total energy consumption and energy loss for BF-1 operation conditions
HRG injection. PC+HRG injection.

Figura 7. Consumo total de energía y pérdida de energía para las condiciones de operación del HA-1.
Inyección de GRC. Inyección de PC+GRC.

4. REALIZATION OF TECHNOLOGY WITH HRG INJECTION

4.1. Parameters of HRG

At a high CO_2+H_2O - content in the HRG (>7-9 %) and low temperature (< 700-800 °C) the physical heat of the hot reducing gas can not compensate the lower heat input with the hot blast as well as the cooling effects of CO_2 and H_2O. Therefore, in spite of the decrease of the direct reduction rate, none or only a small coke saving is possible whereas the furnace productivity can be increased depending on the oxygen concentration in the blast and other parameters.

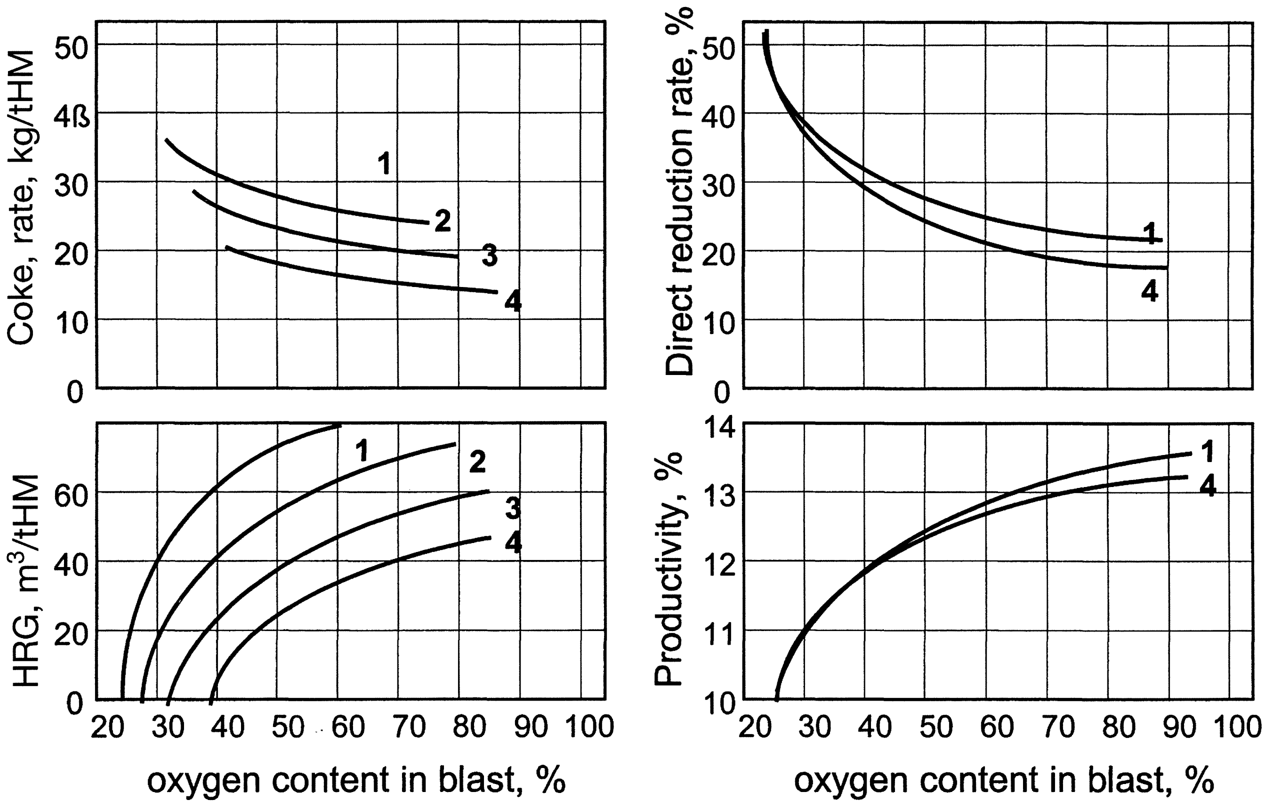

Figure 8. Dependence of operating parameters on oxygen content in blast. PC rate kg/tHM: 1 = 0; 2 = 100; 3 = 200; 4 = 300.

Figura 8. Dependencia de los parámetros de operación sobre el contenido de oxígeno en el viento. Tasa CP kg/t arrabio: 1 = 0; 2 = 100; 3 = 200; 4 = 300.

According to the calculations, with reducing the oxidants (CO_2+H_2O) down to 3,5-4,0 % and increasing the temperature of HRG up to 1000 °C the furnace productivity can be increased by 35 % when injecting 600 m^3 HRG/tHM. At the same time the coke consumption can be reduced by 120-130 kg/tHM. A further increase of the gas temperature by 100 °C leads to an additional coke saving of approx. 2.5 kg per 100 m^3 HRG/t HM.

Injection of HRG with high hydrogen content and a few percents of methane ensures the best operating results from the coke saving and productivity points of view. Such gas can be generated e.g. by steam-conversion of natural gas or coke-oven gas.

Effective use of HRG when injecting into the blast furnace hearth can be reached under following conditions:

- gas temperature should be on the level of the hot blast temperature, e.g. 1000-1250 °C; this requirement is important when injecting high amounts of HRG,
- a minimum content of oxidizing agents in the HRG (usually less than 3-5 % CO_2 + H_2O). Every one percent extra can cause an increase in coke consumption up to 3 %,
- a constant gas composition. Variations of the chemical analysis (particularly CO and CO_2) can disturb the process and lead to an excessive consumption of coke,
- economic manufacture of the HRG.

4.2. Production of HRG

At present time gasification of low coal grades and top gas regeneration are the most economic methods for HRG manufacturing.

For coal gasification effective methods should be chosen. 4 - 5 m^3 HRG from 1 kg coal can be generated by air- or steam-air-conversion of coal. Nitrogen in the reducing gas decreases the coke/HRG replacement ratio. However this can be compensated by increased gas temperature. The use of mini reactor / gasifiers incorporated into the tuyere apparatus allows HRG injection with temperature of 1800-2000 °C [18].

Various technologies for coal gasification in the fluidized bed, melting reactor and underground gasification were developed and investigated at the

Institute of Ferrous Metallurgy of the Aachen University of Technology[48-51].

Cleaning of top gas from CO_2 is usually accomplished by adding special chemical reagents (e.g., monoethanolamine); this technology is very complicated. The removal of carbon dioxide can also be done in gas scrubbers by solving the top gas in water at high pressure. This technology is used for example in the production of synthetic ammonia. The cowpers can be used for heating up the HRG up to 1000-1300 °C.

A technology with recycled top gas after its cleaning from CO_2 could also lead to additional cost saving. Carbon dioxide can be produced in gaseous or solid phase and utilized in the production of food, chemicals, in agriculture (increase in CO_2 in air by 2 % provides an acceleration in plants growth as twice. This fact could be used for the increase of harvest in hot houses or under glasses) metallurgy, etc.

The recirculation of top gas in the blast furnace without removal of the oxidizers can be used only in relatively low quantities, e.g. to compensate high temperature in the raceway and low gas volume when enriching blast with oxygen.

4.3. Blast furnace technology

Three technological variants with HRG injection were investigated:

a) the substitute of the pulverized coal (partly and completely) by HRG
b) the injection of HRG in addition to the reached level of PCI; the PC rate was kept on the constant level
c) the injection of HRG with simultaneous increase of the PCI due to the increased oxidation potential in the raceway.

Variant a) is of no interest for the practice because the existing equipment and technology maintains injection of 150-180 kg PC/tHM and the advantages of HRG can not be realized. The consequence is a rise of coke consumption. Variant b) ensures a coke saving of approx. 20-25 kg/tHM per each 100 m^3 HRG/tHM. Variant c) provides the highest efficiency. Maintaining the flame temperature at a necessary value, which keeps hot metal temperature and silica content, allows extra coke saving.

Total fuel rate at HRG injection decreases almost proportional to the drop in the coke rate: the difference corresponds to the heat generation by gasification of CH_4 and heat absorption by decomposition of CO_2 and H_2O.

A technology with the use of 100 % of cold process oxygen requires no hot stoves and causes no costs for the blast heating; it provides a high coke saving and an increase in productivity. In the investigated case these values amounted 182 kg/tHM and 52 % respectively. Additional benefit can be achieved by the use of the top gas as fuel or reductants, since it contains no nitrogen and has a high calorific value.

Nevertheless the optimal value of oxygen concentration in the blast should be determined because the disadvantage of the "oxy-coal process" is the absence of physical heat in the blast.

4.4. Tuyere apparatus design

Design of tuyere assembly for high amount of HRG, process oxygen and PC injection in the hearth should provide a complete mixture of PC with oxidizing agent, optimal kinetic energy of streams and reliability and simplicity in exploitation.

Conventional tuyere constructions with lances for auxiliary fuels inserted into the inner cavity of tuyere apparatus through the blowpipe or tuyere body as well as tuyeres with co-axial, double lances or separate lances for fuel and local oxygen delivery[52 and 53] cannot simultaneously fulfil two contradictory conditions: from the one hand, prevent ignition of super high amount of coal in high oxygen volume in the tuyere cavity and, from other hand, avoid the dilution of oxidizer with HRG before burning out of coal particles.

Following method and construction of tuyere apparatus can be suggested (Figure 9). PC with process oxygen and HRG with hot blast and/or additives (e.g., water steam, coke oven gas) are introduced into the hearth separately to improve combustion conditions of coal and to provide more rational use of oxygen. HRG and hot blast or HRG only in the case of "oxy-coal process" are introduced through the tuyere channel 5. Process oxygen and PC are entered through the lance 4 which is inserted in the water-cooled tuyere body 1. Oxy-coal mixture is formed in the lance cavity and delivered directly into the hearth. PC burnt with oxygen at the front of the tuyere nose in a local volume with very high temperature-oxidizing potential (gas temperature can achieve 3000 °C or more[54]). Coal gasification is accelerated sharply

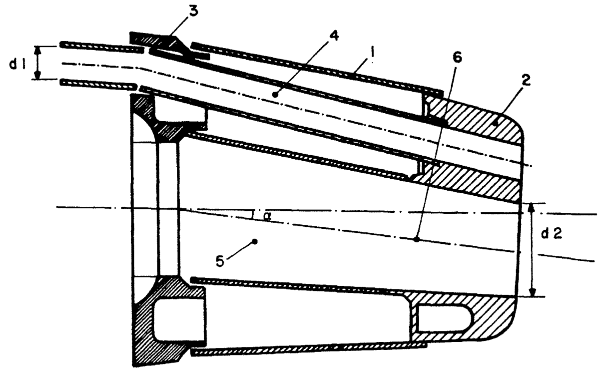

Figure 9. Tuyere assembly design[21]. 1. water cooled body; 2. nose; 3. flange; 4. lance; 5. tuyere channel; 6. axis of blast channel.

Figura 9. Diseño de la tobera[21]. 1. cuerpo enfriado por agua; 2. boca; 3. brida; 4. lanza; 5. canal de la tobera; 6. eje del canal de viento.

and complete combustion of super high PCI is maintained. HRG and combustion products of coal are mixed and form bosh gas with a very low content of nitrogen. Temperature of the mixture makes up 2100-2300 °C.

Flow rate through the tuyere channel is significant lower than using conventional blast furnace technology (e.g., 500-1000 m^3 HRG/tHM only or HRG with hot blast) and volume of oxy-coal stream is high (e.g., more than 200-250 kg PC and 100-400 m^3 O_2 per 1 tHM). The ratio of kinetic energy for both streams should not exceed a certain value in order to avoid:

- ignition of oxy-coal mixture inside the lance (velocity of stream outflow should be more than velocity of flame propagation)
- peripheral flow of PC combustion products with unburnt coal particles
- uneven mixture PC combustion products with HRG in the raceway.

To reach this goal, ratio of lance and tuyere diameters d_1/d_2 should be in the range 0.25-0.40.

5. CONCLUSIONS

The results of the work carried out allow us to draw the following conclusions:

- Injection of the hot reducing gas (HRG) generated outside the blast furnace and simultaneous enriching blast with oxygen should be regarded as a way for further coke saving and increase in the furnace productivity beyond the injection of fossil auxiliary fuels. Furthermore this technology promotes also decrease of the hearth contamination.
- The HRG should be heated to about 1000 °C and should have a minimal content of CO_2 and H_2O (< 3-5 %) as well as only minimal variations in the chemical analysis.
- HRG can be manufactured by air- or steam-air - conversion of coal or by top gas recycling. Low grade coals with a high ash content can be used for gasification, whereas rich coals with low ash content should be used for PCI.
- Co-injection of PC and HRG with simultaneous enriching blast with process oxygen is the most effective technology. The use of HRG, pulverized coal with low ash-content and O_2-enrichment of the blast up to 80-100 % can ensure an increase of the PCI rate up to 300-400 kg/tHM and productivity of 140-150 %. This technological regime provides decrease in total energy consumption of 55-80 MJ/tHM for every 100 m^3/tHM of HRG.
- Method and tuyere apparatus design for high amount of HRG, process oxygen and PC injection have been suggested.

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