CHEMICAL ENGINEERING TRANSACTIONS

VOL. 35, 2013

A publication of
AIDIC
The Italian Association
of Chemical Engineering
www.aidic.it/cet

Guest Editors: Petar Varbanov, Jiří Klemeš, Panos Seferlis, Athanasios I. Papadopoulos, Spyros Voutetakis

ISBN 978-88-95608-26-6; **ISSN** 1974-9791

DOI: 10.3303/CET1335028

A Techno-Economic Analysis of Using Residual Top Gases in an Integrated Steel Plant

Hamid Ghanbari, Henrik Saxén

Thermal and Flow Engineering Laboratory, Department of Chemical Engineering, Åbo Akademi University,
Biskopsgatan 8, FI-20500 Åbo, Finland
hghanbar@abo.fi

This paper presents a process integration approach to analyze and evaluate usage of residual gases from coke oven, blast furnace and basic oxygen furnace in a primary steelmaking integrated with a carbon dioxide capturing and a polygeneration plant. Mathematical programming is applied to find the optimal operation of the integrated system for a given time horizon, where the polygeneration system produces methanol, electricity and district heat as by-products. As alternative technologies for steelmaking, blast furnace top gas recycling with three different integration scenarios for compressing and heating of the top gas and the blast have been studied. This includes an evaluation of the technical potential to enrich the oxygen content of the blast to full oxygen (i.e., nitrogen-free) injection operation.

The results illustrate the optimal states and technologies under different external energy demands. Medium blast oxygen enrichment and top gas recycling with preheating for cold season and cold oxygen injection with preheated high top gas recycling rate is suggested for warm season.

1. Introduction

The iron and steel industries are the largest energy consuming manufacturing industry in the world, particularly in developing countries where inefficient technologies are still used in purpose of higher production. These sectors are also one of the largest carbon dioxide producers due to coal based operation. Environmental restriction, social demands and economic crisis in developed countries has made a difficult time and brings motivation to research for next generation of steelmaking. For instance, ULCOS -Ultra low carbon dioxide (CO_2) Steelmaking- program is consortium of 48 European companies and organizations from 15 European countries that have lunched a cooperative research and development initiative to enable drastic reduction by at least 50 percent of carbon dioxide emission from steel production sectors.

Researchers have been focused on both new iron and steelmaking routes and also improving energy efficiency of the available processes (Elfgren et al., 2010). Blast furnace ironmaking and basic oxygen furnace steelmaking are still the most common way to produce pig iron and raw steel which have large amount of off-gases as byproduct contributing in emissions from the plant. The main investigation in this area is concerning by partial replacing coke with other low carbon barrier fuels as auxiliary reductant in the blast furnace. These reducing agents could be oil, natural gas, coke oven gas, blast furnace top gas, pulverized coal and biomass (Ghanbari, et al., 2012). Implying new operational technologies such as blast furnace top gas recycling and blast oxygen enrichment (Wang, Sandberg and Larsson 2011) has been investigated by simulation (Helle et al., 2011), experiment (Zuo and Hirsch, 2009) and tested in industrial practice (Tseitlin et al. 1994).

The authors have been used a process integration approach to studying all the possible potentials to increase energy efficiency and suppress emissions from the system. They also suggested utilizing the residual off gases in a polygeneration system instead of a combined heat and power plant to produce methanol, electricity and district heat. Ghanbari et al. studied the effect of integration under novel blast furnace operation (Ghanbari et al. 2011, 2012); at the next step the effect of different auxiliary fuel injection on carbon dioxide emission and methanol production investigated (Ghanbari et al., 2012) and a

Please cite this article as: Ghanbari H., Saxen H., 2013, A techno-economic analysis of using residual top gases in an integrated steel plant, Chemical Engineering Transactions, 35, 169-174 DOI:10.3303/CET1335028

superstructure suggested to find the optimal design and operation of the integrated system (Ghanbari et al., 2013).

In the present study, the model is extended to estimate the optimal design and operation for the integrated system according to the different seasonal demand for electricity and district heat. Section 2 represents the problem statement and mathematical model developed in Thermal and Flow Engineering Laboratory. It includes the new operation state for blast furnace under three different top gas recycling, oxygen enrichment and blast/recycled gas preheating scenarios. In section 3, the result of a case study for specific cost/price for feedstock materials and products is presented by maximizing the net present value of the integrated system.

2. Problem statement

2.1 Background

The model (Ghanbari et al., 2013) was developed to describe primary steelmaking under novel blast furnace operation scenarios. It includes top gas recycling and blast oxygen enrichment together with preheating of both recycled top gases and oxygen enriched blast (state no.1) and either preheating of oxygen enriched blast (state no.2) or recycled top gas (state no.3). Figure 1a shows the block flow diagram for integrated steel plant including Coke Plant (CP), Sinter Plant (SP), Hot Stoves (ST), CO_2 Capturing Plant (CCP), Blast Furnace (BF), Basic Oxygen Furnace (BOF), Combined Heat and Power Plant (CHP), PYRolysis Unit (PYRU), Air Separation Unit (ASU) and Methanol Plant (MP).

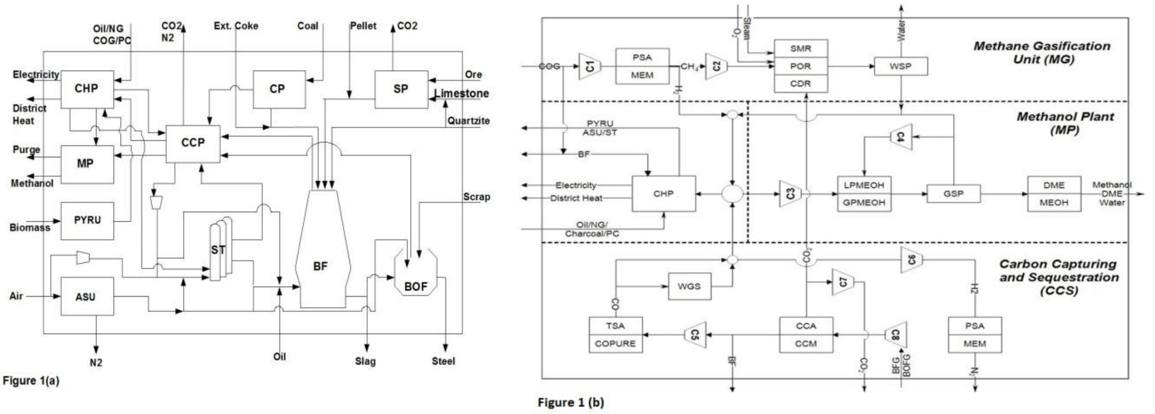


Figure 1(a)

Figure 1 (b)

Figure 1: (a) Integrated Steel Plant. (b) Superstructure for suggested polygeneration plant.

Figure 1b represent the suggested superstructure for carbon capturing, methane gasification and methanol plant with the common possible available technologies which has shown as Pressure Swing Adsorption (PSA), MEMbrane adsorption (MEM), Steam Methane Reforming (SMR), Partial Oxidation Reactor (POR), Carbon Dioxide Reforming (CDR), Water Separation (WSP), Liquid Phase methanol reactor (LPMEOH), Gas Phase methanol rector (GPMEOH), Gas Separation unit (GSP), Dimethyl Ether purification (DME), Methanol purification (MEOH), Temperature Swing Adsorption (TSA), Chemical absorption unit (COPURE), Water Gas Shift reactor (WGS), CO_2 Chemical Absorption (CCA), CO_2 Capturing membrane (CCM) and C1-C8 are Compressors. The figures show the main flows in the system.

Oil is considered the only reducing agent to the blast furnace while oil, natural gas, pulverized coal, coke oven gas and biomass can be supplied as external fuel to polygeneration system. Short-cut models and empirical equation based on Finnish steel plant is used to estimate the material and energy balance in the system. Due to complexity of the blast furnace, available model was used to generate a surrogate model based on multi-linear regression for a data set of feasible operational states. Because of the nonlinear behaviour of the produced data set, it divided to three different criteria for oxygen enrichment and top gas recycling operational state (Table 1).

These states are defined as conventional blast furnace operation (no top gas recycling), low recycling rate (80 - 100 knm^3/h) and high recycling rate (180 - 200 knm^3/h). In terms of oxygen enrichment, low blast oxygen enrichment (21 - 32 %) is considered based on upper limit for heating blast in hot stoves, medium oxygen enrichment through lances (55 - 65 %) and high oxygen enrichment assumed to be between lower bound of 84 and upper bound of 99 % (nitrogen free operation). For thirteen different states, we have found feasible solutions and surrogate models have produced by regression for those data sets.

Part of stripped carbon dioxide blast furnace top gas is sent back to blast furnace for injection between the upper and lower bound for different states.

A network of heat exchangers is considered to reach in operational condition for different units. The utilities such as electricity and steam are produced in polygeneration system according to internal/external demands and costs. The investment cost is considered for new process units which are gasification, carbon dioxide capturing and methanol plant. A pressurized (100 atm) captured carbon dioxide pipeline is sent to sequestration unit.

Table 1 availability of feasible data set used to generate surrogate model

		Top gas recycling degree (knm^3/h)		
		0	80-100	180-200
Oxygen enrichment (%)	21-32	State no.2 State no.3	State no.1 State no.2	-
	55-65	-	State no.1 State no.3	State no.1 State no.3
	84-99	-	State no.1 State no.2 State no.3	State no.1 State no.3

2.2 Mathematical Model

Mixed integer nonlinear programming (MINLP) is used to express the suggested superstructure. The model has 86 binary variables, 2,797 continuous variables and 4,475 constraints. The problem is nonconvex due to bilinear terms in mass balances and in the enthalpy calculations in the energy balances. The generalized disjunctive formulation is represented in the following of this section and bigM method is used to reformulate the problem to MINLP. The problem is implied in General Algebraic Modelling System (GAMS) (GAMS Development Corporation) and SBB (Standard Branch and Bound) is used as solver to find the optimal solution.

$$\bigvee_{\substack{tech\\fuel}} \begin{bmatrix} Y(tech, fuel, t_i) \\ hm(f_j, x_j, t_i) \\ he(f_j, H_j, t_i) \end{bmatrix} = 0 \qquad \begin{array}{c} j \in \{BF, CHP, PYRU\} \\ fuel \in \{COG, BM, OIL, NG, PCI\} \\ tach \in \{state\ no.1, state\ no.2, state\ no.3\} \end{array}$$

$$\begin{array}{l} A^j f(j, t_i) = b^j \\ hc(f_j, t_i) = 0 \end{array} \qquad \begin{array}{c} j \in \left\{ \begin{array}{c} ASU, WSP, GSP, C1, C7, \\ MEOH, COG, BOF, SP, HS \end{array} \right\} \\ j \in \{ASU, WSP, GSP, C1, C7, MEOH\} \end{array}$$

$$\begin{bmatrix} Y(PSA, t_i) \\ hm(f_{PSA}, R_{PSA}, t_i) = 0 \\ hp(f_{PSA}, x_{PSA}, R_{PSA}, \beta_{PSA}, t_i) = 0 \\ he(f_{PSA}, T_{PSA}, t_i) = 0 \\ hc(f_{PSA}, t_i) = 0 \end{bmatrix} \vee \begin{bmatrix} Y(MEM, t_i) \\ A^l f(MEM, t_i) = b^l \\ hp(f_{MEM}, x_{MEM}, t_i) = 0 \\ he(f_{MEM}, T_{MEM}, t_i) = 0 \\ hc(f_{MEM}, t_i) = 0 \end{bmatrix}$$

$$\bigvee_{reac} \begin{bmatrix} Y(reac, t_i) \\ A^{reac} f(reac, t_i) = b^{reac} \\ he(f_{reac}, T_{reac}, t_i) = 0 \\ hc(f_{reac}, t_i) = 0 \end{bmatrix} \qquad \begin{array}{c} \forall\, reac. \in \{SMR, CDR, POR\} \\ \forall\, reac. \in \{LPMEOH, GPMEOH\} \end{array}$$

$$\bigvee_{sep} \begin{bmatrix} Y(sep, t_i) \\ A^{sep} f(sep, t_i) = b^{sep} \\ he(f_{sep}, T_{sep}, t_i) = 0 \\ hc(f_{sep}, t_i) = 0 \end{bmatrix} \qquad \begin{array}{c} \forall\, sep \in \{TSA, COPURE\} \\ \forall\, sep \in \{CCA, CCM\} \end{array}$$

$$\begin{bmatrix} Y(DME, t_i) \\ A^{DME} f(DME, t_i) = b^{DME} \\ he(f_{DME}, T_{DME}, t_i) = 0 \\ hc(f_{DME}, t_i) = 0 \end{bmatrix} \vee \begin{bmatrix} \neg Y_{DME} \\ f_{DME} = 0 \\ he = 0 \\ hc = 0 \end{bmatrix}$$

$$\bigvee_{comp} \begin{bmatrix} Y(comp, t_i) \\ A^{comp} f(comp, t_i) = b^{comp} \\ hp(P_{comp}, T_{comp}, t_i) = 0 \\ he(f_{comp}, T_{comp}, P_{comp}, t_i) = 0 \\ hc(f_{comp.}, t_i) = 0 \end{bmatrix} \qquad \forall\, comp \in \{C2{:}\,C6\}$$

$$Y_{sep} \Rightarrow \left(P^{min} \le P_{sep} \le P^{max}, \qquad T^{min} \le T_{sep} \le T^{max}\right) \qquad \forall\, sep$$

$$Y_{reac} \Rightarrow (P^{min} \leq P_{reac} \leq P^{max}, \quad T^{min} \leq T_{reac} \leq T^{max}) \qquad \forall\ reac$$
$$\neg Y_{sep} \Rightarrow Y_{comp} \qquad \forall\ sep, comp$$
$$\neg Y_{reac} \Rightarrow Y_{comp} \qquad \forall\ reac, comp$$
$$Y_{GPMEOH} \Rightarrow Y_{DME}$$
$$Y_{sep}, Y_{comp}, Y_{reac}, Y_{DME}, Y_{PSA}, Y_{MEM}, Y_{fuel} \in \{True, False\} \qquad \forall\ sep, comp, reac, fuel, PSA, MEM, DME, CHP, BF$$
$$f^{L} \leq f \leq f^{U}$$
$$x^{L} \leq x \leq x^{U}$$

where *sep* are the separation units, *comp* are the compressors, *reac* are the reactor units, *fuel* are different fuels, *tech* are the blast furnace operational states and *Y* is a Boolean variable.

Table 2 reports the feasible ranges of some variables, dictated by operational condition in the steelmaking process. Details about the models of the unit processes can be found in (Ghanbari et al., 2013).

In order to find the optimal design and operation of the suggested superstructure, considering 40 % tax rate, 12 % annual discount rate, 10 and 30 y life and depreciation time of the project and 7,500 h annual operating time, the maximum Net Present Value (NPV) defined as -0.893 times the total capital investment costs of equipment for gasification, carbon capturing and sequestration and methanol units which are expressed by a linear approximation with fixed cost charge in Guthrie’s modular method (Biegler et al., 1997) with cost update factor for 2010 and the annual net profit of the integrated system by a factor of 5.65 (Ghanbari et al., 2013).

The annual net profit is estimated from the profit of the product reduced by the sum of operating costs (including carbon sequestration costs) and carbon emission tax.

Table 2 Feasible range for some variables

Variable	Range
BF specific oil rate	$0-120\ \mathrm{kg/t_{hm}}$
No top gas recycling	$0\ \mathrm{km^3n/h}$
Low top gas recycling	$80-100\ \mathrm{km^3n/h}$
High top gas recycling	$180-200\ \mathrm{km^3n/h}$
Low oxygen enrichment	$21-32\ \%$
Medium oxygen enrichment	$55-65\ \%$
High oxygen enrichment	$84-99\ \%$
Blast/recycled top gas temp.	$20-1200\ ^{\circ}\mathrm{C}$
BF specific pellet rate	$0-600\ \mathrm{kg/t_{hm}}$
BF flame temperature	$1750-2300\ ^{\circ}\mathrm{C}$
BF top gas temperature	$115-250\ ^{\circ}\mathrm{C}$
BF bosh gas volume	$150-220\ \mathrm{km^3n/h}$
BF solid residence time	$6.0-9.5\ \mathrm{h}$
BF slag basicity	$1.0-1.2$
BF sinter feed flow	$0-160\ \mathrm{t/h}$
Own coke feed flow	$0-55\ \mathrm{t/h}$
External fuel flow	$0-50\ \mathrm{t/h}$
Electricity demand	$0-100\ \mathrm{MW}$
Pressure	$1-100\ \mathrm{bar}$
Adsorbent selectivity	$0.02-2$
Hydrogen recovery	$0.8-0.92$

3. Case study representation

The system is studied for steel production rate of 170 (t_{ls}/h) under three different top gas recycling and blast oxygen enrichment scenarios considering all possible mass and energy flow integrations in the superstructure to find the optimal design and operation.

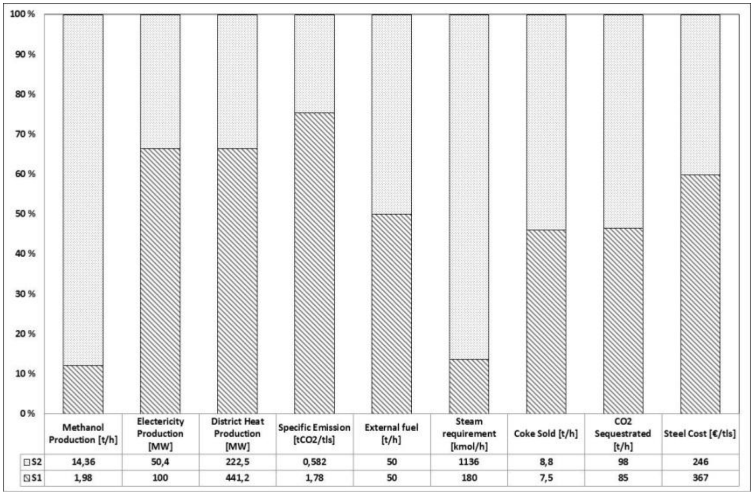
The fixed cost factors used are c_{ore} = 104 \$/t, c_{pel} = 156 \$/t, c_{coal} = 143 \$/t, c_{coke} = 390 \$/t, c_{quartz} = 39 \$/t, c_{lime} = 39 \$/t, c_{scrap} = 130 \$/t, c_{ls}= 550 \$/t, c_{MeOH} = 325 \$/t, c_{el} = 65 \$/MWh, c_{dh} = 13 \$/MWh, $c_{emission}$ = 52 \$/t, $c_{sequestration}$ = 26 \$/t and c_{fuel} = 195, 260, 230 and 65 \$/t for oil, natural gas, pulverized coal and biomass, respectively. Lower bound for electricity demand in cold season is considered to be 100 MW and in warm season relaxed.

3.1 Seasonal optimal design and operation

The result shows the net present value of 2.06 G\$ with the average specific carbon dioxide emission of 1.184 (tCO_2/tls). Partial oxidation reactor for gasification, temperature sewing adsorption for carbon monoxide removal, chemical absorption for carbon dioxide capturing and pressure swing adsorption for methane separation are the main unit processes for both seasons and membrane unit in CCS and gas phase methanol are determined for season one (cold) while pressure sewing adsorption and gas phase methanol reactor for season two (warm).

Table 3 shows some of optimal variables and Figure 2 represents a comparison of polygeneration properties in different operational season for the system. The operational cost is estimated to be about twice in cold season in compare of warm season.

The results show the flexibility of a polygeneration system to distribute the top gases in the system according to get highest profit. Methanol production is estimated 7 times more for warm season in compare of cold season which could result lower specific emission and steel production cost due to biomass supply as external fuel. In both case the maximum amount of external fuel is used which shows the necessity usage of renewable resources to reduce emission in an integrated system.



	Methanol Production [t/h]	Electericity Production [MW]	District Heat Production [MW]	Specific Emission [tCO2/tls]	External fuel [t/h]	Steam requirement [kmol/h]	Coke Sold [t/h]	CO2 Sequestrated [t/h]	Steel Cost [€/tls]
□ S2	14,36	50,4	222,5	0,582	50	1136	8,8	98	246
▨ S1	1,98	100	441,2	1,78	50	180	7,5	85	367

Figure 2: Comparison of polygeneration properties in different operational season for the system for cold (S1) and warm (S2) season

Two different operations are selected for blast furnace. In period one state no.1 preheating of low top gas recycling rate and medium blast oxygen enrichment is selected while for period two state no.3 i.e. high top gas recycling rate and cold oxygen injection is suggested. The preheating temperature is in its upper bound which illustrations the importance of preheating to optimal solution.

In both case top gas recycling and oxygen enrichment is proposed to improve profitability in compare of conventional blast furnace operation. It is estimated that considering different operational states can increase 20 % net present value for the system.

Table 3: Optimal process variables for the system for cold (S1) and warm (S2) season. Boldface denotes values at their constraints

Variable	(S1)	(S2)
Oxygen volume [$\text{km}^3\text{n/h}$]	34.4	35.6
Specific coke rate [kg/t_{hm}]	270	261
Specific oil rate [kg/t_{hm}]	**120**	42.1
Specific pellet rate [kg/t_{hm}]	456	456
Coal flow rate [t/h]	81.5	81.5
Ore flow rate [t/h]	153	153
Limestone Rate [t/h]	21.3	21.3
Quartzite Rate [t/h]	1.1	9.6
Sinter flow rate [t/h]	**160**	**160**
Flame temperature [ºC]	2,067	**1,750**
Blast/Recycled top gas temp. [ºC]	**1,200**	**1,200**
Recycled top gas volume [$\text{km}^3\text{n/h}$]	86	**180**
Bosh gas volume [$\text{km}^3\text{n/h}$]	162	181
Top gas temperature [ºC]	**115**	194
Burden residence time [h]	8.5	8.7
Slag rate [kg/t_{hm}]	211	213
COG volume [$\text{km}^3\text{n/h}$]	17.5	17.5
BOFG volume [$\text{km}^3\text{n/h}$]	6.1	6.1

The carbon dioxide emissions from the system are calculated on the basis of a carbon balance equation, including all fossil carbon-bearing inputs (coal, oil, natural gas, external coke, pulverized coal and limestone) and excluding the outflows of carbon with liquid steel, methanol, coke sold and CO_2 in the carbon dioxide pipeline. The emissions associated with the production of external raw materials (e.g., pellets) were not considered, as the units were outside the balance boundaries of the system. The specific emission from the system is estimated three times more for cold season with external energy demand in compare of warm season.

Figure 3 shows the carbon flow percentage in the system for cold period (left) and warm period (right). For cold season (S1) natural gas is chosen to be an external fuel supply to the system while biomass for the warm season (S2).

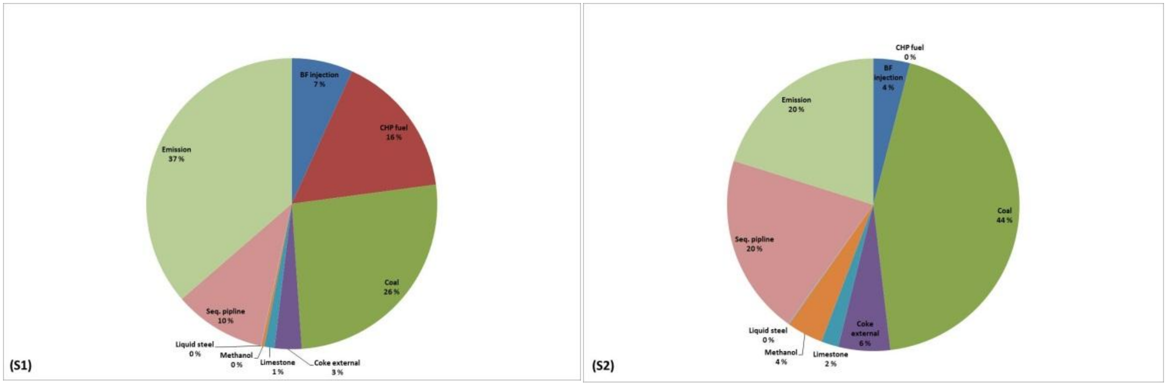


Figure 3: Carbon flow percentage in the system for liquid steel production rate of 170 t/h for cold (S1) and warm season (S2). The percentage of emission from non-fossil fuels carbon carrier is excluded

4. Conclusion

The optimal design and operation of an integrated steelmaking with different available technologies has been studied. The goal is to find possible strategies to suppress emission from conventional steelmaking, still keeping the system economically feasible. Mathematical programming is used to develop a mixed integer nonlinear model of the system, which is solved by maximizing net present value considering altered energy demand in cold and warm season in a time horizon. The results show that optimal design and operation for process units highly depend on external constraint in an integrated plant and different strategies are evaluated for blast furnace operation in different season.

References

Biegler L.T., Grossmann I.E., Westerberg, A.W. (eds) 1997, Systematic Methods of Chemical Process Design, Prentice Hall PTR, USA.

Elfgren E., Grip C., Wang C., Karlsson J., 2010, Possibility to Combine Exergy with other Process Integration Method for a Steel Case, Chem. Eng. Trans. 21, 1375-1380, DOI: 10.3303/CET1021230.

GAMS Development Corporation *GAMS* (General Algebraic Modeling System) Software v23.7.3.

Ghanbari H., Helle M., Pettersson F.,,, Saxén H., 2012, Steelmaking Integrated with a polygeneration plant for improved Sustainability, Chem. Eng. Trans.. 29(2),1033, DOI: 10.3303/CET1229173.

Ghanbari H., Helle M., Pettersson F., Saxén H., 2011, Optimization Study of Steelmaking under Novel Blast Furnace Operation Combined with Methanol Production, Ind. Eng. Chem. Res. 50(21),12103.

Ghanbari H., Helle M., Saxén H., 2012, Process integration of steelmaking and methanol production for suppressing CO2 emissions—A study of different auxiliary fuels, Chem. Eng. Process. 61, 58-68.

Ghanbari H., Saxén H.,Grossmann I.E., 2013, Optimal design and operation of a steel plant integrated with a polygeneration system, AIChE J, DOI: 10.1002/aic.14098.

Helle H., Helle M., Saxen H., 2011, Nonlinear optimization of steel production using traditional and novel blast furnace operation strategies, Chem. Eng. Sci.. 66(24), 6470-6481.

Tseitlin M.A., Lazutkin S.E., Styopin G.M., 1994, A Flow-Chart for Iron Making on the Basis of 100-Percent Usage of Process Oxygen and Hot Reducing Gases Injection, ISIJ International 34(7), 570-573.

Wang C., Sandberg J., Larsson M., 2011, Analysis of OXygen Enrichment and its Potential Influence on the Energy System in an Integrated Steel Plant Using a New Solution Space Based Optimization Approach, Chem. Eng. Trans.25, 87-92, DOI:10.3303/CET1125015.

Zuo G., Hirsch A., 2009, The Trial of the Top Gas Recycling Blast Furnace at LKAB's EBF and Scale-up, Revue De Metallurgie-Cahiers D Informations Techniques, 106(9), 387-392.