CHEMICAL ENGINEERING TRANSACTIONS Volume 21, 2010
Editor J. J. Klemeš, H. L. Lam, P. S. Varbanov
ISBN 978-88-95608-05-1 ISSN 1974-9791
DOI: 10.3303/CET1021230

Possibility to Combine Exergy with other Process Integration Methods for a Steelmaking Case

Erik Elfgren[1]*, Carl-Erik Grip[1,2], Chuan Wang[3], Jonny Karlsson[4]
[1]Luleå University of Technology Dept. Energy Engineering, 971 87 Luleå, Sweden
Erik.Elfgren@ltu.se
[2]SSAB until 2007, [3]Swerea MEFOS, [4]SSAB

The energy system of Luleå consists of the steel plant, a local CHP using process gases from the plant and the district heating system. Process integration work to improve the efficiency of the system is presently carried out by mathematical programming using a MILP tool (reMIND). Further improvements would need an improved possibility of the tool to consider the thermodynamic quality of the energy flows. This project aims to include exergy parameters in the node equations and object functions. This has been carried out for a test case, including a part of the system. Programming principles and some results are described.

1. Introduction

1.1 The energy system in Luleå

The Luleå energy system consists of three major parts: the SSAB steel plant, the LuleKraft CHP (combined heat and power) plant and the local district heating system (Luleå Energi), see Figure 1.

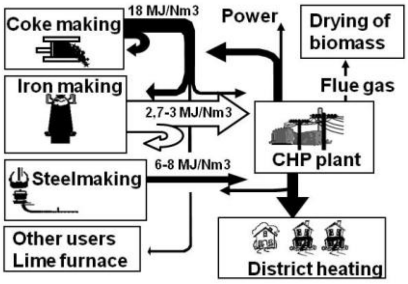

Figure 1: Overview of the energy system in Luleå.

The process gases, coke oven gas (COG), blast furnace gas (BFG) and basic oxygen furnace gas (BOFG) are generated at SSAB. These energy rich processes gases are partly used within SSAB and partly sent to the CHP plant, where they are combusted in the boiler, creating 520 °C steam that goes to a turbine system. The output from the turbine system is sequentially 300 °C process steam, 95 °C steam, 80 °C steam and 30

Please cite this article as: Elfgren E., Grip C-E., Wang C. and Karlsson J., (2010), Possibility to combine exergy with other process integration methods for a steelmaking case, Chemical Engineering Transactions, 21, 1375-1380 DOI: 10.3303/CET1021230

°C steam. It also generates about 80 MW of power. The 300 °C steam is process steam, which is used in SSAB. The 95 °C steam and the 80 °C steam are used for district heat production via a two-steps heat exchanger, for example to preheat the hot water from 50°C to 90 °C before delivering to the district heating system. The district heating system then provides heating to the whole municipality of Luleå, around 700 GWh per year. The remaining steam is condensed at the end of turbine. All temperatures are approximate but represent winter conditions.

1.2 Process integration on the Luleå system

The energy system is complicated and a global approach is needed to reach energy efficiency. Process integration studies on the Luleå system (SSAB Steel plant- CHP plant of the LuleKraft-district heating) have been practiced for several years. Most studies are carried out by mathematical programming, using a MILP method (Mixed Integer Linear Programming) tool. The tool itself is a software shell, the thermodynamics, energy and material balances are inherent in the equations and data put in the nodes and connections of that shell. The method and tool is used to analyze and improve the system(s) for several parameters, e.g., energy use, emissions, material efficiency, cost etc, see for example (Larsson and Dahl, 2003), (Ryman et al., 2007), (Ryman and Larsson, 2006) and (Wang et al., 2008). The process integration techniques are further developed within the excellence centre PRISMA. The standard procedure used for process integration at LTU and PRISMA is mathematical programming using the MILP based tool reMIND. The tool was initially developed by Linköping Universty (LiU). Further development was carried out in cooperation between LiU, LTU and PRISMA. The programming language is Java. In reMIND the cases are modeled in a graphical interface showing the process units as nodes and the flows as arrows between them. The nodes can be raw materials, energy, process units or product. They are linked by flows based on mass and energy balance in between. The equations expressed in the relevant nodes are linear as the MILP programming use linear equations. The flows have a magnitude e.g. unit/s. They also carry properties, e.g. energy/unit, kg/unit, content of chemical elements etc. They are included as a matrix of several properties. This is because of the multiproperty characters of steelmaking flows. The properties are constant values, not variables. Once again, this is because of linearity demand, otherwise (flow*property) would be a 2nd degree expression. The reMIND tool converts the node and flow parameters into an equation matrix, which is treated by a commercial solver, CPLEX, for optimization work. The output data from the solver is then converted into practically useful results in an evaluation model, which in the reMIND case is in Excel format.

Process integration often involves optimization of energy systems. A solution has to be found that optimizes the system within the frame stipulated by first and second law of thermodynamics. The 2nd law criteria could be exergy or even entropy. Exergy is chosen as criteria in this study, mainly because SSAB and LTU have a long experience and ongoing work in using exergy for mapping and evaluating the steel plant energy system. The exergy of a system can usually be described as

$$E = \Delta H - T_0 \cdot \Delta S, \tag{1}$$

where E is the exergy content, ΔH and ΔS are the change in enthalpy and entropy from the reference state in J/kg and T_0 is the temperature of the reference state. For a temperature change of solids and liquids without chemical reactions ΔS can be described as

$$\Delta S = m \cdot C_p \cdot \ln(T/T_0), \tag{2}$$

while for an ideal gas

$$\Delta S = m \cdot C_p \cdot \ln(T/T_0) + m \cdot R \cdot \ln(p_0/p), \tag{3}$$

where m is the weight in kg, C_p is the heat capacity at constant pressure in J/(kg·K), T is the temperature in K and p is the pressure in Pascal.

1.3 Previous use of exergy at SSAB

Combined energy and exergy studies have been practiced intermittently at SSAB since 1989. Principally the studies have given two types of useful answers, see Figure 2.

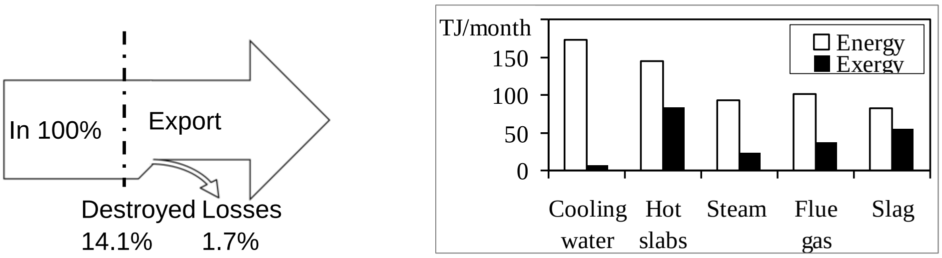

Figure 2: Exergy balance for blast furnace (left) and exergy content in different energy Media (right).

The general balance for a unit or the whole system gives efficiency, losses and destroyed exergy. The destroyed exergy is the part that is irreversibly destroyed in the process. It is an expression of the efficiency of the process itself. The exergy loss is an expression of the remaining exergy in the waste flows. It can give an indication of the possibility to use it elsewhere. The right diagram in Figure 2 shows the energy- and exergy contents in some flows. The cooling water represents the highest amount of rest energy but it is hardly recoverable because of the low exergy quality. Hot slabs seems most promising from an exergy point of view. Further details see (Grip et al., 2009).

1.4 Scope of paper

The scope of this paper is to present the ongoing work on including exergy criteria in reMIND along with some preliminary results.

2. Creating a “thermodynamic MILP”

The reMIND model consists of nodes interacting through their in- and outputs and their transport flows.

2.1 Node equations and flows

The nodes contain equations describing process units. These equations are based on mass, energy and exergy balance. Sometimes existing knowledge, experiences and models used in process computers and in offline evaluations by plant or institute engineers are also needed. The steel industry is based on thermo-chemical processes, and thus these process models are also based on thermodynamic. The interaction is taken care of by in- and outputs that are transported by flows. These flows are described by their magnitude and by content properties, e.g. energy in J/unit.

2.2 Formulating thermal exergy expressions for a linear equation matrix

The node calculations can be expected to give output consisting of mass flows combined with accompanying energy flows. In a normal excel sheet the exergy flow could easily be calculated from these data by using the temperature and material properties. In a MILP model this cannot be done directly because of the non-linearity. The calculation of temperature involves a division of energy flow with mass flow and C_p, and the determination of exergy from those data is definitely non-linear. In this work an interpolation technique has been chosen, based on splitting one flow into two (or more) virtual flows. Take as an example a case where water with a certain content of mass and thermal energy leaves the node. Chose one virtual flow of "cold water" and one of "hot water", both having a precalculated enthalpy and exergy per mass unit. Use a mass-heat balance to calculate the amount of the two virtual waters that would give a mix with the mass- and enthalpy content of the real water. Make a weighed mean of the "cold" and "hot" water precalculated exergies to get the exergy of the "real" water. As the exergy curve is non-linear this is applicable only if the interpolation area is of limited width (see Figure 3).

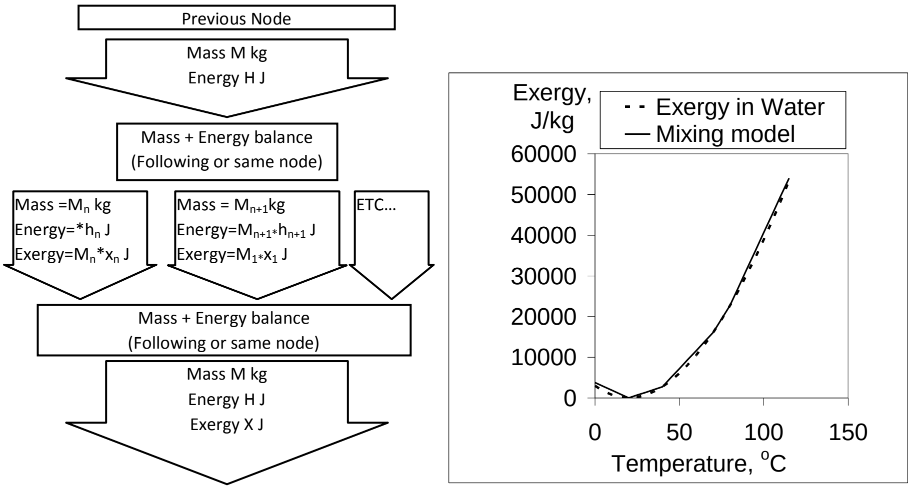

Figure 3: Linear approximation of thermal exergy. Left: virtual mixing method. Right: comparison of modelled and real exergy for a six-component case.

If the width is more large the problem can be solved by choosing several virtual waters and letting the program chose the two closest (see Figure 3). Such a choice can be made using the integer facility in the MILP tool. An example using six components is shown in Figure 3. The choice and interpolation were simulated in excel. The calculation was made for a reference temperature of 20 °C. Like any interpolation of non-linear functions it is not perfect, there is always a difference between the calculated and real exergy. In our case the difference is principally a function of the entropy when mixing the two components.

3. Exergy reMIND model for the Luleå system

3.1 Model

The Luleå energy system has been partly modeled, focusing on the CHP plant, shown in Figure 4. The CHP plant is interesting both from an exergy point of view (the water temperature is the dominant exergy term) and also from the point of view of the industry, since cost can be reduced at Luleå Energi by lowering the flow line temperature.

Each node (the boiler, the turbine system and the heat exchangers) has mass, energy and exergy balance. The destroyed exergy is also calculated (flows F17, F18 and F19 in Figure 4) in each of these nodes.

The water flows passing through the condensers (called heat exchangers in Figure 4) from the turbines (F13 and F16 in Figure 4) do not change their temperatures significantly but transfer energy by changing from steam phase to water phase.

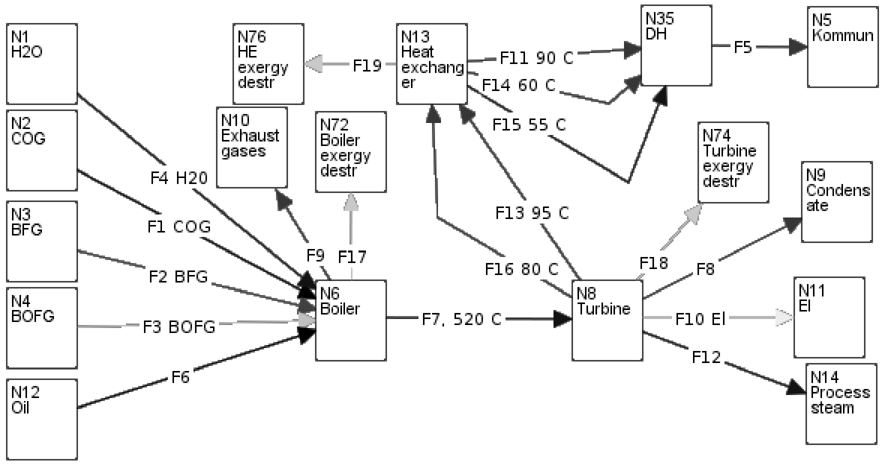

Figure 4: Model of the CHP plant, showing the different nodes and flows.

3.2 Preliminary results

Currently, all parts of the CHP plant are not included in the prototype model but some encouraging preliminary results can still be obtained. When exergy destruction is minimized, it is found that the 80 °C (F16 in Figure 4) steam only destroys roughly a third of the exergy in the heat exchanger as compared to the 95 °C steam (F13 in Figure 4). In consequence, more electricity can be generated in the turbine instead. This result can be understood from the higher exergy content in high temperature steam compared to steam with lower temperature.

Furthermore, when exergy destruction is minimized and the optimizer can choose between the three different flow line temperatures, 55, 60 and 90 °C (F15, F14 and F11 in Figure 4), it chooses the 90 °C water. The reason for this is that the higher the temperature, the more exergy can be transported away, thereby reducing the exergy destruction. The 55 and 60 °C flows give roughly three times higher exergy destruction as compared to the 90 °C flow. Obviously, the major part (about 90 %) of the exergy destruction always occurs in the boiler since that is where the combustion occurs.

4. Discussion

4.1 Exergy in reMIND

Including exergy calculations in the reMIND program can give valuable insights into the possibilities of optimizing an industrial system. Furthermore, including it does not seem to require any significant extra effort. With exergy included, both the exergy waste and the exergy destruction can be monitored and optimized. Different cases can easily be studied and the most beneficial selected.

4.2 Other combination methods

Gong and Karlsson (2004) proposed a coordination of exergy analysis and MILP method for the pulp and paper industry. In their work, some process improvements from the exergy analysis have been used as different investment alternatives in the optimization model, therefore, the cost optimization can be made to find out the cost-efficient alternatives.

Acknowledgements

We wish to thank the Swedish Energy Agency for funding this research.

References

Gong M. and Karlsson M., 2004, Coordination of exergy analysis and the MIND method - applied to a pulp and board mill, International Journal of Exergy 1, 289-302.

Grip C .E., Dahl J and Söderström M, 2009, Exergy as a means for process integration in integrated steel plants and process industries, Stahl und Eisen 129, S2–S8

Larsson M. and Dahl J., 2003, Reduction of the specific energy use in an integrated steel plant – The effect of an optimization model, ISIJ International 40, 1664-1673.

Ryman C, Grip C.E. and Larsson M, 2007, Model based evaluation of sustainability indicators in integrated steelmaking: A Swedish case study, AISTech 2007, The Iron & Steel Technology Conference and Exposition, May 7-10, Indianapolis, Ind., USA.

Ryman C. and Larsson M., 2006, Reduction of CO2 emissions from integrated steel-making by optimised scrap strategies: Application of process integration models on the BF-BOF system, ISIJ International 46, 1752-1758.

Wang C., Larsson M., Ryman C., Grip C-E., Wikström J-O., Johnsson A. and Engdahl J., 2008, A model on CO2 emission reduction in integrated steelmaking by optimization methods, International Journal of Energy Research 32, 1092-1106.