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Premises for a combined Exergy and Pinch Optimization within ProSimPlus® simulator

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Abstract

The recent increase in fossil fuel prices and the more and more stringent environmental regulations have stimulated the search for further improvements. A short term and sustainable solution consists in improving energy efficiency of industrial processes. To tackle this challenge, a combined exergy and Pinch Analysis has been developed for industrial process' optimization. To summarize the presented methodology, the Exergy Analysis firstly aims at making a diagnosis of the existing process by identifying the major inefficiencies; then based upon this diagnosis; the Pinch Analysis enables to give concrete solutions to improve its energy efficiency. Moreover, the strength of this work relies in the implementation of this Exergy Analysis and Pinch Analysis methodologies in the process simulation software ProSimPlus® which provides an efficient support to the engineer.

Keywords: Exergy Analysis, Pinch Technology, Process optimization, Process simulation.

1. Introduction

Industrial sector accounts for one third of global energy consumption. The recent increase in fossil fuel prices and the more and more stringent environmental regulations have stimulated the search for further improvements. A short term and sustainable solution consists in improving energy efficiency of industrial processes. Process Integration may be used to tackle this challenge (Klemeš et al., 2013). Among the several methodologies of process integration, one can find the Pinch Technology and the Exergy Analysis. While the latter (Ghannadzadeh et al., 2012) can be applied to identify thermodynamic imperfections (exergy losses) of a given process and to propose some hints to reduce such losses, Pinch Technology (Klemeš and Kravanja, 2013) aims at improving heat-exchanger network of a process, solely dealing with heat transfers, excluding chemical or pressure changes. To overcome these limitations, it seems appropriate to implement a methodology combining Exergy Analysis and Pinch Technology as shown in the literature (Marmolejo-Correa and Gundersen, 2012).

The purpose of this paper is to present a new general approach for optimizing an industrial process from an exergy point of view as well as an energy efficiency view point. More emphasis is placed on the retrofitting and improvement of existing processes operating under steady-state conditions. The concepts of exergy load, and exergy efficiency are combined to the Pinch methodology. The general procedure for process optimization and improvement is described through a very simple cogeneration case study. This paper is part of the COOPERE ANR project involving several partners (Veolia Environnement Recherche et Innovation, Prosim SA, AgroParisTech' and Laboratoire de Génie Chimique).

2. Methodology

The Computer-aided Exergy and Pinch Analysis (PA) methodology (CEPA) is primarily based on the ProSimplus® environment's ability to make Pinch and exergy calculations. Therefore, the studied process needs first to be modeled and simulated in ProSimPlus®.

2.1. Exergy Analysis

The Exergy Analysis, which has been proved to be an efficient tool for the energy diagnosis of industrial processes, especially relies on the computation of internal losses and exergy efficiencies. The Exergy Analysis first enables to perform an energy diagnosis of the existing process by evaluating several efficiencies representing the thermodynamic performance from different points of view. By offering the possibility to make automatic calculation of exergy of material and heat streams, ProSimPlus® simulation software (ProSim S.A., 2014) facilitates Exergy Analysis of industrial processes (Ghannadzadeh et al., 2012). As a reminder, the amount of exergy destroyed, I, also known as irreversibilities or exergetic internal losses, of a system is obtained by a simple exergy balance – Eq (1) – where B_{in} and B_{out} respectively represent the whole exergy entering and leaving the system.

$$I = B_{in} - B_{out} \tag{1}$$

An in-depth study of exergy based efficiencies has been undertaken. It highlighted that the intrinsic efficiency – Eq (2) - (Sorin et al., 1998) is the general way to compute a significant exergy efficiency.

$$\eta = \frac{Exergy\ produced}{Exergy\ consumed} \tag{2}$$

The intrinsic efficiency must be combined to the exergy load concept in order to compute an exergetic efficiency of a multiple unit operation system – Eq (3).

$$\eta = \sum_{i=1}^{N_{UO}} \left[\lambda_i^p . \eta_i - \lambda_i^{1-p} . (1 - \eta_i) \right] \tag{3}$$

The computation of the intrinsic efficiency η_i, exergy load coefficients λ_i^p and λ_i^{1-p} which rely on a general methodology is beyond the scope of the study, thus the reader is recommended to consult references (Gourmelon et al., 2013). For a given unit operation, it is also possible to define the relative exergy loss as the ratio of exergy loss and exergy consumed – Eq (4).

$$I_{rel} = \frac{Exergy loss}{Exergy\ consumed} \tag{4}$$

All of these coefficients are part of the exergy based tools package used by engineer to make a process energy diagnosis.

2.2. Complementarity between Pinch and Exergy Analysis

The analysis of these thermodynamic criteria permits to suggest modifications aimed at reducing irreversibilities (exergy internal losses) and to maximize the reuse of external losses (waste streams). The decomposition of exergy into thermal, mechanical and chemical terms enables to get a clear vision of the potential of reuse of waste streams. The way of using such waste streams depends on the contribution of each term (T, P, z) in the exergy balance.

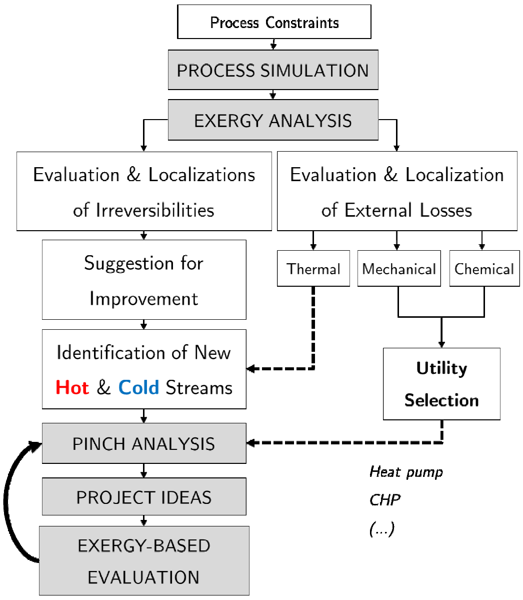

Figure 1: CPEA methodology diagram

As presented in Figure 1, thermal exergy losses should be recovered as hot or cold streams. For chemical exergy losses, some recycling solutions could be considered such as methanisation or combustion. In the case of high mechanical exergy loss, it might be possible to produce power.

Pinch Analysis provides an efficient tool to generate a heat exchanger network in order to maximize the internal heat load reuse. However it is sometimes difficult to decide which heat exchanger, heat pump… represents the best investment for a more efficient energy use in the industrial process. Finally, calculation of the exergetic efficiency and other exergy based coefficients of the different configurations can help the process manager to make a choice between several solutions.

3. Case study description

Air entering the cogeneration system (**Erreur ! Source du renvoi introuvable.**Figure 2) is compressed up to 25 atm and is sent to the combustion chamber. Natural gas (NG), supplied by stream S03, is burnt to produce hot gases. The latters are expanded down to 1 atm and recycle to produce steam (E101). The power produced by the turbine T101 is partly used to fulfill the needs of the compressor C101. The rest is sent to another system.

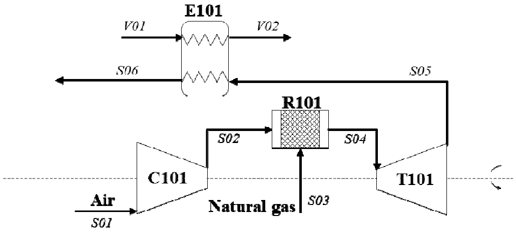

Figure 2: Heat and power cogeneration system

The natural gas and air flowrate are computing according to equation (5). The temperature of steams leaving the evaporator E101 is equal to 773.15 K. Stream S06 is assumed to be a waste stream.

$$F_{Natural\,Gas} = 0.047.F_{Air} \tag{5}$$

4. Heat and power cogeneration system analysis

4.1. Exergy analysis

The first step of the methodology consists of proceeding to an Exergy Analysis of the studied process. Exergy balance is reported in Table 1 and Figure 3 summarizes the results of the exergy analysis by detailing the irreversibility and the exergy efficiency on unit operations. The overall efficiency is 55.22 %.

Table 1: Exergy balance of the cogeneration system

Streams	S01	S02	S03	S04	S05	S06	V01	V02
Temperature (K)	298.15	797.17	298.15	1762	915.03	520.71	298.15	773.15
Pressure (atm)	1	25	25	24.5	1	1	15	15
Total exergy (MW)	0.40	74.06	202.86	224.09	53.32	13.53	1.06	26.92
Physical exergy (MW)	0.00	73.66	1.90	220.99	50.22	10.43	0.03	25.89
Thermal exergy (MW)	0.00	32.69	0.00	182.13	50.22	10.43	0.00	25.86
Mechanical exergy (MW)	0.00	40.96	1.90	38.86	0.00	0.00	0.03	0.03
Chemical exergy (MW)	0.40	0.40	200.96	3.10	3.10	3.10	1.03	1.03

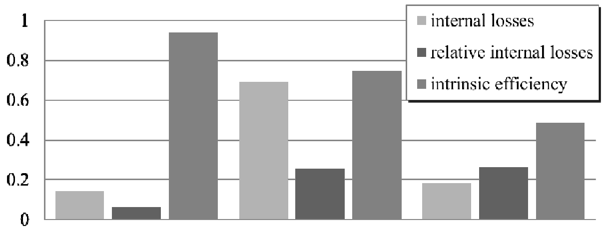

Figure 3: Exergy efficiencies and internal losses on unit operations

As shown in Figure 3, even though the exergy destroyed represents about 30 % of the exergy consumed by the combustion chamber, chemical reaction is the most significant source of exergy destruction in the cogeneration system. As noticed by Cziesla et al. (Cziesla et al., 2006), the thermodynamic inefficiencies may be reduced by preheating the air or increasing the fuel/air ratio. Consequently, a heat exchanger dedicated to the preheating of air should be introduced in the flowsheet after the compressor. The maximum input temperature is set at 947 K in order to keep the output temperature below 1900 K.

As the stream S06 is a waste stream, and despite the low relative internal losses, the exergy efficiency of the heat exchanger E101 is very low. In fact, the formulation of intrinsic efficiency allows taking into account the difference between waste and utilized streams. When analysing the values of the three components of exergy of the stream S06, it would be interesting to reuse the thermal exergy rather than reject it to the environment.

4.2. Pinch analysis

The new process flowsheet with the air preheater, the updated fuel/air ratio and the cooling down of the stream S06 to the ambient temperature is modeled using ProSimPlus®.Then, applying the automatic Pinch calculation, the process Composite Curve and the Grand Composite Curve are drawn in Figure 4. As illustrated in Figure 4, the S05 hot stream leaving the T101 turbine is sufficient to meet the global hot utility requirement of the cogeneration system. It can be concluded from the design of the new heat exchanger network that a preheater has to be placed before the E101 heat exchanger in the S05 stream flow.

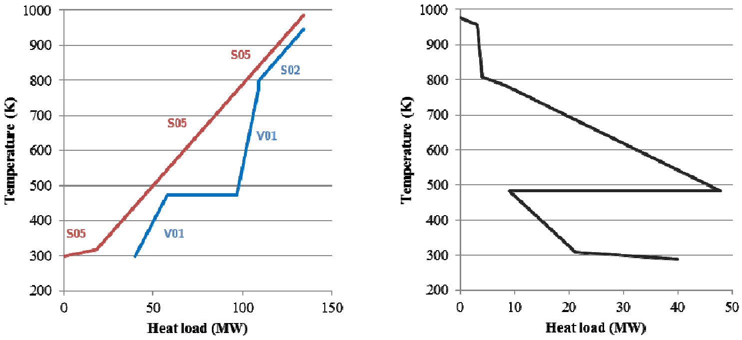

Figure 4: (a) Composite curve and (b) grand composite curve of the cogeneration system

4.3. Retrofitted process

The retrofitted cogeneration system, represented in Figure 5, has been simulated in ProSimPlus® modeling and simulation software.

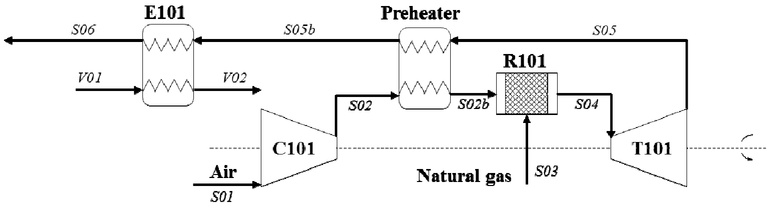

Figure 5: Retrofitted cogeneration system

. In addition, exergy efficiency is increased as external is reduced by recycling the thermal exergy loss.

Table 2 compares the performances of the retrofitted process with the base case cogeneration system. The increase of generated power and the decrease of irreversibilities are obvious. In addition, exergy efficiency is increased as external is reduced by recycling the thermal exergy loss.

Table 2: Base case vs. Retrofitted case

	Base case process	**Retrofitted process**
Generated Power (MW)	86.39	98.20
Overall exergy efficiency (%)	55.22	61.03
Overall internal losses (MW)	76.42	69.23
Overall relative internal losses (%)	37.60	34.06
External losses (MW)	13.53	8.90

5. Conclusions

This paper presents a general methodology for computer-aided process improvement tool combining the Pinch Technology and the Exergy Analysis. The Exergy Analysis first enables to make a diagnosis of a process proposing then solutions to recover external losses or to reduce internal losses. Here, with the cogeneration system, we have illustrated the case of thermal losses. In such a case the concerned streams become hot or cold streams for the Pinch Analysis. A more in-depth study could have been done to determine the best input temperature and air/fuel ratio of the combustion chamber. Then starting from cold and hot streams, power sinks and sources deduced from a previous Exergy Analysis, the Pinch methodology proposes different solutions to optimize both process and utility. The next step is to extend the scope of this methodology to industrial scale processes.

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