Computers and Chemical Engineering 82 (2015) 216–227

Contents lists available at ScienceDirect

Computers and Chemical Engineering

journal homepage: www.elsevier.com/locate/compchemeng

A new methodology combining total site analysis with exergy analysis

Alaa Farhat[a,b,*], Assaad Zoughaib[a], Khalil El Khoury[b]

[a] PSL, Mines Paristech, Paris, France
[b] Lebanese University, Engineering Faculty 2, Roumieh Lebanon

ARTICLE INFO

Article history:
Received 1 December 2014
Received in revised form 13 July 2015
Accepted 17 July 2015
Available online 28 July 2015

Keywords:
Total site analysis
Heat integration
Exergy analysis
Heat transfer networks
Shaft work targeting

ABSTRACT

Total site analysis allows determining the potential heat transfer between multiple plants to obtain further energy savings to the process integration in industrial plants. Exergy analysis offers a clear understanding of the integration of thermodynamic systems in process integration. A new methodology that combines total site analysis and exergy analysis is presented. The methodology allows for simultaneous use of both thermodynamic systems and heat transfer networks. The combination of the two types of utilities allows for better exploitation of the plants' energy profile. In addition, the methodology allows specifying the networks' and thermodynamic systems characteristics and number. The capacities of this methodology are tested on a case study where different combinations of systems are studied to determine their behavior with variable parameters.

1. Introduction

Heat integration on a site scale (between multiple plants), was treated originally by Dhole and Linnhoff (1993), by introducing the method of total site analysis. To this method are associated the sites sources and sinks profiles, these profiles are built from the synthesis of grand composite curves of the plants subject to heat integration in a site; this method is further explained by the work Klemeš et al. (1997). These profiles are used to determine the site energy demands. It is worth noting that the non monotonous parts of these curves, which consist of self sufficient pockets, were omitted in the construction of the profiles despite their heating potential.

The TSA method was the basis for development of other methodologies and techniques used to study issues of multiple plants energy integration such as planned or sudden shutdowns and their impact (Liew et al., 2012) or process modifications to reduce the general utility size (Chew et al., 2014). In general, the TSA allows determining the energy savings, cogeneration potentials and information about the utilities needed to allow heat exchange between plants. In general heat exchange between different plants is done using steam but liquids such as water can be used for lower temperatures heat exchange as stated by Hackl et al. (2011).

The works of Maréchal and Kalitventzeff (1998), Rodera and Bagajewicz (1999), Bagajewicz and Rodera (2001), and Bagajewicz and Rodera (2002), treat heat integration of multiple plants using mathematical programming techniques (MILP), adding another layer to the initial mathematical representation of heat integration proposed by Papoulias and Grossmann (1983). Rodera and Bagajewicz (1999) introduced the idea of using intermediate fluids in the liquid phase since their heat recovery potential is higher than steam; however at high temperatures this implicates the use of complicated systems and non conventional fluids.

The consideration of energy conversion systems in a heat integration problem was done both on process scale problems and on site scale problems (TSA). Exergy is usually used as a comparison criterion since it can account for and compare between different heat production mechanisms e.g. boilers and heat pumps. On a process scale: cogeneration systems, heat pumps and refrigeration systems among others were considered to improve energy recovery. Linnhoff and Dhole (1992) presented a method that combines pinch analysis and exergy analysis on low temperature applications; it allows the user to specify a refrigeration system while increasing its exergy efficiency. Becker et al. (2012) proposed the use of a mathematical programming method to assess the advantages of heat pumps in upgrading low grade heat and the use of cogeneration for electricity production as well as process modification.

On a site scale, energy conversion systems, mainly cogeneration, were also considered initially with (Dhole and Linnhoff, 1993) where exergy analysis in the total site helped assessing cogeneration targets. Bagajewicz and Barbaro (2003) proposed a non linear mathematical model to solve for heat pump integration in the total site. The capacity of heat pumps in "debottlenecking heat transfer

---

* Corresponding author at: PSL, Mines Paristech, Centre efficacité énergétique des systèmes (CES), 5 rue Léon Blum, 91120 Palaiseau, France. Tel.: +33 1 69194512.
E-mail address: alaa.farhat@mines-paristech.fr (A. Farhat).

http://dx.doi.org/10.1016/j.compchemeng.2015.07.010
0098-1354/© 2015 Elsevier Ltd. All rights reserved.

Nomenclature

T	temperature (K)
$Q_{p,i}$	sum of stream enthalpies in plant p at interval i [kW]
$R_{p,i}$	cascaded energy in plant p at interval i [kW]
Ex	exergy consumption [kW]
H_p	default hot utility at plant p [kW]
C_p	default cold utility at plant p [kW]
$Ehp_{p,i,j}$	heat pump's evaporator capacity, at plant p, withdrawing heat at temperature T_j, where the condenser supplies heat at temperature T_i [kW]
$Chp_{p,i,j}$	heat pump's condenser capacity, at plant p, supplying heat at temperature T_i, where the condenser withdraws heat at temperature T_j [kW]
$Gabs_{p,i,j}$	absorption chiller's generator capacity, at plant p, withdrawing heat at temperature T_i, where the evaporator withdraws heat at temperature T_j [kW]
$Eabs_{p,i,j}$	absorption chiller's evaporator capacity, at plant p, withdrawing heat at temperature T_j, where the generator withdraws heat at temperature T_i [kW]
$Eorc_{p,i,j}$	organic Rankine cycle's evaporator at plant p, withdrawing heat at temperature T_i, where the condenser rejects heat to the surroundings [kW]
$Corc_{p,i,j}$	organic Rankine cycle's condenser at plant p, rejecting heat to the surroundings, where the evaporator withdraws at T_i [kW]
COP	coefficient of performance
η	efficiency
$Qh_{net,p,i}$	heat transferred from a network *net* toward a plant p at interval i [kW]
$Qc_{p,net,i}$	heat transferred from a plant p toward a network *net* at interval i [kW]
Np	total number of plants
NET	total number of networks
N	total number of temperature intervals

Subscripts

p	plant
net	network
i, j	temperature indices

between plants" is shown, and the authors adopted an operational cost analysis to determine the best solution. However, they did not consider simultaneously the heat transfer network needed for such integration. Later, Hackl and Harvey (2013) expanded the use of exergy analysis in the total site to target shaft work for sub-ambient processes, which limits the energy consumption of the total site. Pouransari et al. (2014) performed site-scale process integration on a large chemical plant having three different process operation units. To improve the total site energy recovery and the heat exchange between different units, the authors integrated mechanical vapor recompression systems as well as heat pumps.

This work presents a methodology that performs heat integration and exergy consumption minimization using heat transfer networks between multiple plants while simultaneously integrating thermodynamic energy conversion systems. The methodology couples both heat transfer networks and conversion systems to provide wider energy recovery possibilities and propose solutions otherwise unattainable. In addition, the methodology is able to specify the type, number and operating conditions of any heat transfer systems and conversion systems needed to attain an optimal solution, while taking into consideration technological limitations.

Mixed integer and linear programming (MILP) is used leading in one-step to an optimal solution. The resulting computerized algorithm can treat TSA cases resulting in a heat network synthesis as shown in a first case study but also treat low temperature systems such as ethylene and propylene process plants as it is shown in the second case study. The second case study from the petrochemical industry is analyzed where energy conversion systems are compared and those most compatible with the plants requirements are selected based on exergy consumption minimization.

2. Method

The proposed method combines heat transfer networks with energy conversion systems. The integration of energy conversion systems might create new pinch points or pseudo pinch points hence creating more heat exchange areas between plants. Therefore the existence of heat transfer utilities cannot be limited to designated regions as originally proposed in TSA. Rodera and Bagajewicz (1999) and Bandyopadhyay et al. (2010) noted that the inclusion of self sufficient pockets increases the heat transfer between two plants. As mentioned before, this was dismissed by Kemp (2007) and Liew et al. (2012) as uneconomical and technically difficult. But with the integration of multiple plants the latter may become applicable since the heat transfer from the self sufficient heat pocket becomes part of a larger system and not the reason of existence of that system. In the proposed method, heat transfer regions exist along the temperature scale to cover all possibilities. Initially, interactions and utilities inside a single plant are described with all their necessary constraints and equations. Streams belonging to different plants cannot exchange with each other directly due to practical reasons stated earlier, hence any exchange possibility is restricted as proposed by Becker and Maréchal (2012). Energy transfer systems between different plants are described along with their requirements.

3. Mathematical formulation

3.1. Heat exchange formulation within a plant

Temperature intervals are built using the process' streams data of each plant, using the method of (Papoulias and Grossmann, 1983). In addition sub-divisions are introduced in each interval. Those sub intervals allow exploring different configurations for thermodynamic systems and networks. Eventually, fine divisions will increase the total number of intervals and the calculation time.

Fortunately, a thorough analysis of the grand composite curves allows restraining the possibilities of thermodynamic systems in general and heat pumps in particular to the relevant zones. This is studied comprehensively by Thibault et al. (2014) concerning optimal the placement of heat pumps.

The adopted approach will end up in creating a unique temperature set for each plant. For the sake of simplicity and uniformity, the temperature intervals are combined, while conserving singular temperatures for all streams, to obtain a unique temperature set for all plants. The temperatures are indexed such as the interval having the highest temperatures shall have the index $i = 0$, while the lowest temperatures has the highest index $i = N$.

Hot streams inject heat into to the interval while cold streams withdraw heat from the interval as shown in Fig. 1. At the highest intervals hot utilities can be added while at the lowest intervals cold utilities could be added.

Heat integration between streams belonging to the same plant and defined in the same temperature interval is assumed accomplished; therefore each interval is represented by the sum of streams' enthalpies $Q_{p,i}$, hot streams enthalpies are considered to