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Flexibility Assessment of Heat Exchanger Networks: From a Thorough Data Extraction to Robustness Evaluation

Lucille Payet, Raphaële Thery Hétreux, Gilles Hétreux, Florent Bourgeois, Pascal Floquet*

Laboratoire de Génie Chimique, Université de Toulouse, CNRS, INPT, UPS, Toulouse, France

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ABSTRACT

Due to process variabilities and operational modifications, operating parameters of Heat Exchanger Network (HEN) may alter its output temperatures. Nevertheless, the impact of these disturbances depends largely on the topology of the HEN. As a consequence, it can be relevant to evaluate the flexibility of a HEN after its synthesis. Flexibility of a HEN refers to the ability of a system to operate at a finite number of set points. In this framework, the implementation of this property is broken down into several aspects. In this contribution, the first level of flexibility concerning the robustness (ability of the system to absorb disturbances without changing utility flowrates) is addressed and compared to other contribution, this criterion is not formulated as a generic one but as a criterion that strongly depends on the studied process. As a consequence, to evaluate its value, the first step is to perform an enhanced data collection by identifying the most frequent disturbances and by pointing out the critical streams i.e. the streams whose output temperature absolutely needs to be kept into a strict interval; then, given this information, a robustness criterion can be formulated for a given HEN. In this paper, a methodology relying on several models is developed to address this issue: a Mass Equilibrium Summation enthalpy non-linear model (MESH) dedicated to the enhanced data collection, a Mixed Integer Linear Programming (MILP) model used for the HEN synthesis and finally a linear model developed for the modeling of the HEN response to disturbances. This methodology is first illustrated through a basic academic example and finally applied to an industrial case study.

1. Introduction

The energy issue is paramount to improving the performances of industrial processes as it impacts their economic profitability and environmental footprint. One of the most effective strategies to improve the energy efficiency of industrial sites is to maximize heat recovery by *Process Integration (PI)*, as still pointed out recently by Pereira et al. (2017). Indeed, PI is an essential concept which consists in coupling the hot and cold streams internal to the process rather than consuming external utilities. The PI methodology is based on the Pinch Analysis (PA) (Linnhoff and Hindmarsh, 1983) and leads to the Heat Exchanger Network (HEN) as a final solution to achieve a significant reduction of energy consumption.

By design, a HEN leads to a stronger integration of hot and cold streams. There is a substantial literature on HEN design methods, as reflected in Furman and Sahinidis (2002), which lists and analyses as many as 461 articles from the late 40s to 2000. This study highlights different methodologies that were carried out. The approaches concern algorithmic methods, methods based on heuristics or mathematical programming techniques. According to the authors, in recent

* *Corresponding author*.
E-mail addresses: lucille.payet@ensiacet.fr (L. Payet), raphaele.thery@ensiacet.fr (R. Thery Hétreux), gilles.hetreux@ensiacet.fr (G. Hétreux), florent.bourgeois@ensiacet.fr (F. Bourgeois), pascal.floquet@ensiacet.fr (P. Floquet).
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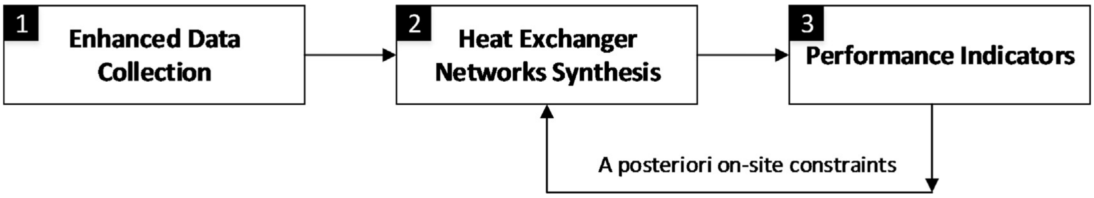

Fig. 1 – RREFlex methodology.

years, the latter predominates and the need for more robust formulations and more efficient global optimization algorithms is all the more crucial. In this framework, Escobar and Trierweiler (2013) displays a case study comparison between several mathematical models: Mixed Integer Non Linear Programming *(MINLP)*, Non Linear Programming *(NLP)*, Mixed Integer Linear Programming *(MILP)* and Linear Programming *(LP)* to test their efficiency on a few examples. Simultaneous and sequential methods are also compared in this study. The authors concludes that whereas *sequential methods*, which solve the problem step by step, are easier to solve, *simultaneous methods*, which solve the problem in one step, provide better solutions. Another observation is that most of the proposed methodologies aim to derive solutions that minimize the site's energy consumption by achieving the best compromise between the capital expenditures (CAPEX) and the operational cost (OPEX) (Gundersen and Naess, 1990; Barbaro and Bagajewicz, 2005; Björk and Westerlund, 2002; Escobar and Trierweiler, 2013; Isafiade and Fraser, 2008; Mehta et al., 2001; Mikkelsen and Qvale, 2001; Morar and Agachi, 2010; Yee and Grossmann, 1990). However, these solutions do not always give rise to a concrete implementation on industrial sites. As suggested in Sreepathi and Rangaiah (2014), a single optimal solution is generally not sufficient for the industrial feasibility of the HEN due to unforeseen on-site constraints. The challenge with designing viable HEN is that it is simply not possible to identify and formulate all constraints out of hand. Sreepathi and Rangaiah (2014) concluded that it would be better to provide several optimal solutions so that experienced engineers can select the most practical HEN. To address this issue, this paper presents a computational framework developed as part of the RREFlex project (Software for the Robust Synthesis of Flexible HEN). This tool proposes an original approach, which consists in an iterative process relying on 3 major points as shown in Fig. 1:

- The analysis of the process historical data to identify precisely the on-site constraints.
- The proposal and evaluation of several configurations of HEN achieved by an optimization approach based on Mixed Integer Linear Programming (MILP).
- The a posteriori evaluation of the performances of these configurations: performance indicators are relative to on-site considerations such as topology of the HEN or its flexibility in addition to more traditional indicators like energy consumption and global costs. The analysis of these solutions by the engineer leads to the formulation of new constraints and the synthesis of new HEN. The procedure is run until finally obtaining configurations which fulfill all the industrial constraints correctly.

Thus, the methodology proposed in this work consists in providing the site engineer with several HEN solutions and letting him post-evaluate the performance of each one using key performance indicators (KPIs) based on economical, topological, practical and operational considerations. The method therefore assigns the end-user a pivotal deciding role, and new improved HEN solutions are designed iteratively as the end-user adds in additional on-site constraints. With such a scheme, one HEN solution provides the basis for the next one, and the design process stops when KPIs can no longer be improved and on-site constraints have all been accounted for.

As mentioned, a multi-criteria evaluation of each proposal is carried out in the RREFlex tool. Among these KPIs, flexibility appears as one of the most crucial ones. Many definitions of HEN flexibility can be found in the literature for continuous processes (Escobar et al., 2013; Verheyen and Zhang, 2006; Chen and Hung, 2004). Nevertheless, a common definition of flexibility is the ability of a system to operate for a finite number of operating points. Moreover, it is often referred as resilience index (Saboo et al., 1985) or controllability for dynamic and steady-state regime of processes (Swaney and Grossmann, 1985; Pintarič and Kravanja, 2004; Masoud et al., 2016). In Escobar et al. (2013), a two-stage methodology is reported for designing of a flexible and controllable HEN. Their first stage consists in the design of an optimal HEN that minimizes the CAPEX and OPEX, using the SYNHEAT non-linear model from Yee et al. (1990). Their second stage deals specifically with the flexibility issue by minimizing the sensitivity of the HEN to disturbances. The methodologies to establish directly resilient HEN for grass-root cases was thus well studied. For the post-evaluation of the flexibility of HEN in retrofit cases, this notion has to take into account batch processes but still including the notion of resilience. Moreover, the definition of HEN resilience as *the ability to cope with inlet and target temperature changes* in Saboo et al. (1985) required to be divided into two notions. In all cases, such a flexibility analysis clearly requires accounting for all the relevant process uncertainties. Whereas, the design of robust HEN for green or new projects can be considered mature as new facilities offer the maximum design flexibility for heat integration, this is not the case however for brown or existing projects. As highlighted by Smith et al. (2010), retrofitting a flexible HEN to an operating plant remains a complex and critical problem.

In our methodology, the general property of flexibility has been subdivided into 4 layers:

- *Robustness* (or inherent resilience): the intrinsic ability for the HEN to cope with inlet temperature small changes with no topological changes.
- *Potential resilience*: the ability to achieve the resilience by acting on the utility flow rates or/and introducing by-passes solutions in order to make the HEN able to absorb the disturbances.
- *Adaptability*: the ability of a system to operate at a finite set of operating points.
- *Intermittency management*: the ability to overcome temporal mismatches between hot and cold heat sources (summer/winter operation, batch processes, etc...) by means of storage tanks that must be characterized.

In view of the complexity of the subject, only robustness property (first layer of the HEN flexibility) is addressed in this paper and compared to existing methods, robustness criterion is defined as a specific one that strongly depends on the history of the considered process.

To enable RREFlex software to assess the robustness of the HEN for a given process, a three-step methodology has been developed starting from an enhanced data collection for the calculation of enriched data for pinch key values (mean values and standard deviation of temperatures) and ending with the definition of a robustness criterion. In this framework, disturbances on inlet streams have to be characterized and tolerance intervals on outlet values have to be established by engineers. In order to obtain the required information, a generic data extraction methodology based on process history is developed. For that purpose, physical data (as stream flowrate, heat capacity and inlet/outlet temperatures) are assumed to follow a normal distribution. This representation is widely used in data extraction and validation methodology in chemical processes (Romagnoli and Sanchez, 1999). The data are then modelled by its mean value and standard deviation which would be a thinner representation of the variations than