Energy Conversion and Management 89 (2015) 985–1000

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Heat recovery networks synthesis of large-scale industrial sites: Heat load distribution problem with virtual process subsystems

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ARTICLE INFO

Article history:
Received 19 August 2014
Accepted 2 November 2014

Keywords:
Heat Exchanger Network (HEN)
Heat Load Distribution (HLD)
Mixed Integer Linear Programming (MILP)
Large-scale industry
Heat Integration
Plant layout

ABSTRACT

This paper presents a targeting strategy to design a heat recovery network for an industrial plant by dividing the system into subsystems while considering the heat transfer opportunities between them. The methodology is based on a sequential approach. The heat recovery opportunity between process units and the optimal flow rates of utilities are first identified using a Mixed Integer Linear Programming (MILP) model. The site is then divided into a number of subsystems where the overall interaction is resumed by a pair of virtual hot and cold stream per subsystem which is reconstructed by solving the heat cascade inside each subsystem. The Heat Load Distribution (HLD) problem is then solved between those packed subsystems in a sequential procedure where each time one of the subsystems is unpacked by switching from the virtual stream pair back into the original ones. The main advantages are to minimize the number of connections between process subsystems, to alleviate the computational complexity of the HLD problem and to generate a feasible network which is compatible with the minimum energy consumption objective. The application of the proposed methodology is illustrated through a number of case studies, discussed and compared with the relevant results from the literature.

1. Introduction

Heat Integration has been a promising strategy to improve the energy efficiency of industrial processes. The Total Site targeting methodology initially presented by Dhole and Linnhoff [1] and later by [2,3] is an extension of heat integration concept. It considers the side-wide energy saving opportunities rather than those related to the single processes. Total Site Integration (TSI) has been broadly used in energy saving projects and has leveraged a high potential of heat recovery (e.g. [4–6]). In order to achieve the energy saving identified through the TSI, the Heat Exchanger Networks (HEN) have to be synthesized. The heuristic methods such as Pinch Design Method (PDM), presented by Linnhoff and Hindmarsh [7] in spite of their success through several industrial projects suffer from a number of limitations [8] mainly difficult manual procedures and no guarantee for the optimal solution. The optimization methods for design of the HEN are developed based on the simultaneous Mixed Integer Non-Linear Programming (MILNP) [9] or the sequential approach consisting of the Mixed Integer Linear Programming (MILP) [10] and Non-Linear Programming (NLP) models. The simultaneous MINLP methods mainly suffer from computational complexities because of the large number of binary variables involved in the solution procedure. There are also numerical problems related to the non-convex features of those MINLP models which might tend rather toward a local optimum instead of converging into the global one. An alternative approach has been proposed which consists of breaking down the MINLP problem and then solve the HENs problem in a sequential approach. In those sequential settings, solving the MILP step, referred to as the Heat Load Distribution (HLD) model, is also challenging in its place. In case of HLD problems with a large number of streams (as it is the case with the TSI), solving the HLD model can also be complicated because of the exponential growth of the optimization search space. In the basic HLD model a high number of binary variables have to be considered and at the end of the procedure, several number of feasible networks might exist, leading into an ill convergence. Additionally, each of those feasible network solutions to the HLD problem tend to have very different properties when it comes to account for the total area and the cost of the network [11]. Consequently for a large-scale industrial problem, the correspondent MILP model becomes either infeasible or very expensive to solve with available mathematical software. Gundersen [11] provides a complete description over heat recovery synthesis methods for both grassroots and retrofit situation and the difficulties and limitation of each methods.

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http://dx.doi.org/10.1016/j.enconman.2014.11.006
0196-8904/

Nomenclature

Subscripts

φ	subnetwork index
c	cold stream
h	hot stream
in	inlet
max	maximum
min	minimum

Superscripts

$*$	virtual
ξ	number of unpacked subsystems

Variables

$F_{obj^*_{hld}}$	objective function of the HLD problem between packed subsystems
$\Delta T_{lm,hex}$	logarithmic mean temperature difference
A_{hex}	heat exchanger area (m^2)
C_{hex}	heat exchanger capital investment ($/yr)
C_{opt}	operating cost ($/yr)
$F_{obj_{hld}}$	objective function of the basic HLD model
N_{Euler}	minimum number of connections by Euler's theory
nk	number of temperature intervals
ns	number of streams
nt	number of subnetworks
ny	number of process subsystems
Q	heat exchanged
Q_{ijk}	amount of heat transferring from the hot stream i to the cold stream j at the interval k or lower
Q_{ik}	heat content of the stream i in the interval k
$Q_{j\varphi}$	total amount of heat that should be provided to the stream j in subnetwork φ
$Q_{max,ij\varphi}$	maximum amount of heat that can be exchanged between the hot stream i and the cold stream j
T	temperature
TAC	Total Annualized Cost ($/yr)
$y_{ij\varphi}$	integer variable associated with the existence of connection between binary (i,j) in subnetwork φ

Related works several approaches have been proposed in order to simplify or relax the HEN retrofit and grassroots design problem by improving the exiting optimization models or combining the mathematical programming methods with the approaches based on the heuristics. Among the recent works, the deterministic approaches have been frequently raised. Barbaro and Bagajewicz [12] proposed a one-step MILP-based model following the transshipment concept that considers splitting and non-isothermal mixing. Nguyen et al. [13] further extended this former method to be used for the retrofit problems while additionally considering the case of addition and relocation of heat exchangers to control the piping cost as well as splitting. Kralj [14] extended the stage-wise MINLP model of [9] for the retrofit problems. Sequential approaches have raised additional interest because of their consistency with respect to the local convergence. Ciric and Floudas [15] proposed a two-stage optimization approach in the HEN retrofitting: a MILP model has first been solved in order to determine a superstructure, followed by a NLP problem in the second stage for the detailed solution. An improved sequential strategy for the synthesis of near-optimal HEN based on the vertical heat transfer concept [16] is also developed by Gundersen et al. [17]. Anantharaman et al. [18] explained the computational complexity behind the HLD model and succeeded to reduce it by tightening the linear programming relaxation. Pettersson [19], proposed a sequential match reduction approach which solved different subproblems in order to result in a close to optimal design for the large-scale problems. Pouransari and Maréchal [20] proposed a sequential approach that reduces the model size of HEN problem by taking the insight on the existing heat transfer interfaces early at the targeting level. Pan et al. [21] proposed an iterative MILP-based approach to retrofit the HEN with the network topology modifications using the concept of pinching match. Recently, Pouransari and Marchal [22] proposed a method where additional constraints have been proposed to help the convergence of the HLD problem based on an insight on the plant layout and spatial location of units. The stochastic or meta-heuristic methods have also been closely investigated (see, e.g., [23–26]). These methods are more likely to find the global optimum for HEN retrofits, but usually cost long computational times even for small problems. Some publication have additionally investigated the flexibility and controllability of the HEN design. A computation framework for the synthesis of flexible and controllable HENs is proposed by Escobar et al. [27] which yields a design operating with the control system that ensures the stream temperature targets and optimal energy integration under variable conditions.

In summary, most of the existing methods are applied on mid-scale problems but are still limited for an industrial large-scale application. Solving the HEN retrofit or the grassroots design optimization model needs further improvement for the large-scale problems with more than 40 streams [19]. The importance of dealing with the computational complexity of the HEN optimization problem would be even more highlighted when we aim to synthesize the heat recovery network between several sites. The issue raised while synthesizing the HENs for industrial size problems (mainly in the TSI) is the connection proposed between streams of the subsystems located farther on the site. The common tendency for an industrial application of TSI is to choose the solution with the minimum possible connections between different process system or subsystems geographically separated or in difficult-to-access locations. Having fewer long-distance connections, improves the economic and also increases the system safety. The drawback of the long pipelines can be explained by their piping cost which can be as high as 80 percent of delivered purchased equipment cost [28].

Our contribution knowing the difficulties behind designing the heat recovery network for the large-scale problems on one hand, and the economic and safety issues of the long-distance connections on the other hand, have motivated us to propose a new methodology to synthesize Total Site heat recovery networks. The focus of our methodology is on minimizing the number of connections between process subsystems while finding a close-to-optimal network with respect to the number of connections. Our methodology uses a sequential approach and this manuscript particularly seeks to address the computational complexity of the HLD subproblem with an step-wise procedure detailed in Section 2. The process subsystems can be defined on any characteristic of the existing plant or quite randomly. However, the choice of these subsystems has a direct influence on the configuration and cost of the generated network. Using the defined subsystems, some additional constraints are developed at each step of the methodology sequence. The last step of this sequence is identical to the original problem but with the benefit of having a significant number of match