Computers and Chemical Engineering 71 (2014) 426–445

Contents lists available at ScienceDirect

Computers and Chemical Engineering

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

Heat exchanger network design of large-scale industrial site with layout inspired constraints

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ARTICLE INFO

Article history:
Received 11 July 2014
Received in revised form
13 September 2014
Accepted 15 September 2014
Available online 30 September 2014

Keywords:
Heat exchanger network (HEN)
Heat load distribution (HLD)
Mixed Integer Linear Programming (MILP)
Large-scale industry
Plant layout
Piping cost

ABSTRACT

This paper presents a systematic approach for the synthesis of the heat recovery network in total site using a Mixed Integer Linear Programming model. This model returns a near-to-optimal network configuration with minimum utility cost while allows to select geographically closest matches. The Heat Load Distribution is the subproblem of the network design and has been reported to be quite expensive to solve for large-scale problems. The computational complexity of HLD resides in the number of streams and the feasible networks. An additional challenge, raising particularly in industrial problems, has been the intermediate heat transfer network which aggravates the combinatorial complexity. The presented methodology deals with those difficulties by priority consideration based on the location of process units. It helps significantly reducing the computational time and also comes with a realistic network sketch with respect to the plant layout. Several examples are discussed along with a real industrial case study.
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1. Introduction

In industrial energy saving projects with site-scale integration, the Heat Exchanger Network (HEN) retrofit or design is the major step. The Pinch Design Method (PDM), presented by Linnhoff and Hindmarsh (1983) for the heat exchanger network, has been successfully used in a large number of industrial companies around the world. Meanwhile, the methodologies based on the PDM suffer from a number of limitations (Klemes, 2013). They usually imply difficult manual procedures to generate a solution while there is no guarantee for the solution to be the optimal one. These limitations have been the motivation to alternatively use optimization methods for the HEN synthesis.

In Mathematical Programming (MP) approaches, the synthesis procedure of HEN generally includes three stages of problem analysis: minimum utility requirements calculation, Heat Load Distribution (HLD) and network layout synthesis (Floudas et al., 1986). The MP methods based on the sequential approach, solve those three stages of the HEN problem consecutively (Papoulias and Grossmann, 1983). The second stage, the HLD problem, can be formulated as a Mixed Integer Linear Programming model with the objective function to minimize the number of connections as shown by Papoulias and Grossmann (1983) and later by Maréchal and Boursier (1989). Meanwhile, the search space of the optimization problems with integer variables grows exponentially with the number of binary variables. Therefore in case of a large-scale industrial site, the correspondent MILP problem becomes either infeasible or very expensive to solve with the available mathematical software: it has been reported that dealing with problems with more than 30 streams is considered to be complicated (Klemes et al., 2013). Another issue in solving the HLD model is the number of feasible networks while each of them results into different total area and cost (Gundersen and Grossmann, 1990). In order to have an optimal solution with respect to the both operating and investment cost, simultaneous Mixed Integer Non-Linear Programming (MINLP) optimization models were developed (Yee and Grossmann, 1990). The simultaneous MINLP methods, however, turn out to be quite problematic due to the computational complexity that resides in the number of binary variables and also the numerical problem related to the non-convexity feature of the model that tends towards the local optimum rather than the global one.

Frequently in the literature, the HEN synthesis problem with MP is addressed by either sequential methods or simultaneous MINLP models with gradient-based or stochastic search algorithm. An extensive review of the main research in this area can be found in the annotated bibliography of Furman and Sahinidis (2002).

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http://dx.doi.org/10.1016/j.compchemeng.2014.09.012
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Available design methods with an evaluation on their usefulness and applicability are also presented by Van Reisen (2008) and recent publications on HEN synthesis are reviewed in Gundersen (2013), Klemes et al. (2013). Among recent works, Becker and Maréchal (2012) considered the heat exchange restrictions between process subsystems, by optimal integration of the intermediate heat transfer units. They approach a realistic network by improving the heat cascade model at targeting level. Anantharaman et al. (2010) explained the computational complexity of network design. They also managed to tighten the linear programming relaxation by modifying the HLD model to reduce the computation time. However in both methods (Becker and Maréchal, 2012; Anantharaman et al., 2010), the model solution times still remain too long to be practical in industrial-size problems having a large number of streams.

Another important issue in the synthesis of heat exchanger networks for industrial problems is the site layout that has the potential to have an influence on the economics, the safety and energy targets (Chew et al., 2013). The economic impact of the layout is explained by the piping cost which can be as high as 80 percent of delivered purchased equipment cost (Peters et al., 2003). The connection with a large distance implies high piping cost and consequently installation, maintenance, insulation and other auxiliaries such as hangers, fittings and valves. The space which should be allocated to the long pipeline and the new heat exchanger also increases the cost factor. The long pipe length aggravates the pressure drop in pipes which imposes additional pumps or compressors cost. Having an extended pipe networks also threatens the system safety by increasing the risk of a late pipe failure detection due to leakage, crack, rupture, plumbing or contamination (Chew et al., 2013).

The above cited insight have motivated us to propose a sequential methodology to design the heat recovery network for the large-scale industrial sites. The particular focus of our manuscript is on the HLD subproblem. We take into account a new parameter, the spatial location of units, in order to overcome the computational complexity of large-scale problems and to design more realistic networks.

2. Methodology

Our methodology is based on a sequential approach where the problem is systematically analyzed in three steps discussed in following lines, while minimizing the operating cost target.

- In the first step, a MILP problem for the total site heating and cooling requirement is solved to define the optimal flow rates of the utilities and the minimum operating costs.
- Once energy saving targets identified, in the second step, the location of every process or utility units is identified using the plant layout. Coordinates of locations, let us then calculate the implied distance between any possible matches of hot and cold streams. Zero distance is considered for the binaries including any heat transfer network streams and higher priority levels are also assigned to the connections with lower distance. A weight factor based on the priority level is attributed to every binary integer variables defined for the candidate matches. The HLD problem is then solved with an extended MILP model.
- Using the result of HLD, the HEN can be generated through manually or by help of a Non-Linear Programming optimization model.

Our focus throughout this manuscript has been on the second step, the HLD problem. Our results show a practical close-to-optimal heat integrated network, also satisfying the Minimum Energy Requirement (MER) target, since the optimum flow rate of the streams is fixed at the targeting level by the MILP optimization solved beforehand. The plant layout considered as one of the important design issues in an industrial problem, is well involved in our methodology to derive the location-based priorities. At the design stage, the layout has also an implication on the capital cost through the piping cost in the grassroots design and as the space constraints for the new equipment or piping modification in retrofit. At the targeting level the layout can additionally affect the decision whether to use direct or indirect heat recovery system (Chew et al., 2013).

It is important to point out that the HLD solution does not provide directly the heat exchanger network configuration. However, this solution contains all the necessary information to manually develop the network or to be transfered to NLP model for generating and optimizing the network.

3. Process integration and energy conversion units optimization

A MILP model proposed by Maréchal and Kalitventzeff (1998) is applied here to identify the optimal integration of the energy conversion units. The objective is to minimize the operating costs including fuel and electricity contributions (see Eq. (1))

$$F_{obj_{opt}} = \min\left(\left(\sum_{f=1}^{nf}\left(c_f^+\sum_{u=1}^{nu} f_u \dot{E}^+_{f,u}\right) + c^+_{el}\dot{E}^+_{el} - c^-_{el}\dot{E}^-_{el} + \sum_{u=1}^{nu} f_u c_u\right).\tau\right) \tag{1}$$

In the above expression f_u is the multiplication factor of unit u. The c^+_{el} and c^-_{el} are respectively the electricity purchase cost and selling price. The fuel price is c^+_f and the energy which is delivered to unit u by the fuel is noted as $\dot{E}^+_{f,u}$. The total electricity demand and supply of the system are respectively described by $\dot{E}^+_{el}$ and $\dot{E}^-_{f,u}$. Finally c_u is the operating cost of unit u per hour and τ is the yearly operating hours. Eqs. (2)–(6) are related to the heat cascade and are detailed in Pouransari et al. (2014a).

$$\sum_{h_k=1}^{ns_{h,k}} f_u \dot{Q}_{h,k,u} - \sum_{c_k=1}^{ns_{c,k}} f_u \dot{Q}_{c,k,u} + \dot{R}_{k+1} - \dot{R}_k = 0 \quad \forall k = 1,\ldots,nk \tag{2}$$

$$\dot{R}_1 = 0 \quad \dot{R}_{nk+1} = 0 \quad \dot{R}_k \geqslant 0 \quad \forall k = 2,\ldots,nk \tag{3}$$

$$\sum_{u=1}^{nu} f_u \dot{E}^+_{el,u} + \dot{E}^+_{el} - \sum_{u=1}^{nu} f_u \dot{E}^-_{el,u} \geqslant 0 \tag{4}$$

$$\sum_{u=1}^{nu} f_u \dot{E}^+_{el,u} + \dot{E}^+_{el} - \dot{E}^-_{el} - \sum_{u=1}^{nu} f_u \dot{E}^-_{el,u} = 0 \tag{5}$$

$$\dot{E}^+_{el} \geqslant 0 \quad \dot{E}^-_{el} \geqslant 0 \tag{6}$$

where $\dot{Q}_{h,k,u}$ is the heat load of hot (or cold $\dot{Q}_{c,k,u}$) stream in the interval k. The cascaded heat from the temperature interval k to lower temperature intervals is expressed by $\dot{R}_k$. $\dot{E}^+_{el,u}$ and $\dot{E}^-_{el,u}$ are the electricity consumption and production of unit u respectively. In this formulation, a unit can have the process or the utility type which respectively imply ($f_u = 1$) or ($f_u = variable$) for their corresponding multiplication factor. The flowrates of streams belonging to the utility units are proportional to the multiplication factor (f_u), which is bounded by a minimum ($f_u^{\min}$) and a maximum value ($f_u^{\max}$). The related integer variable y_u in Eq. (7) determines if the unit u is present in the system ($y_u = 1$) or not ($y_u = 0$). For all the process units ($y_u = 1$) is fixed. The multiplication factors are optimized during the process integration step and the flowrates, the

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