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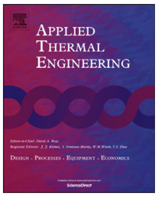

Research paper

New analysis method to reduce the industrial energy requirements by heat-exchanger network retrofit: Part 2 — Stepwise and graphical approach

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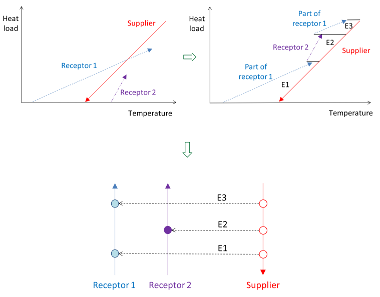
HIGHLIGHTS

- A bridge is necessary to reduce thermal energy consumption.
- A graphical tool to identify heat-exchanger configuration is presented.
- Modifications to reduce investment costs are classified by main categories.
- A stepwise procedure for heat-exchanger network retrofit is proposed.

GRAPHICAL ABSTRACT



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ABSTRACT

In the first part of this paper, concepts supporting a new analysis method to reduce energy consumption by heat-exchanger network (HEN) retrofit were presented. These include the definition of necessary conditions to achieve heat savings, which are expressed in the formulation of the bridge concept, the use of the Energy Transfer Diagram (ETD) to identify bridges, and a procedure to enumerate and evaluate these. In this second part, a graphical approach for the identification of exchanger configurations is presented, which can be used for modifications to the HEN to save energy or to reduce investment costs. A stepwise procedure for HEN retrofit is described; it includes identification of bridges, of actual modifications in the network to reduce the energy consumption, and of modifications to reduce the investment costs. Modifications to reduce the investment costs are classified by main categories. Examples are presented to illustrate each category and cover a broad spectrum of situations. The method has been applied for retrofitting the HEN of a kraft pulp mill, and it is found that the proposed approach has directly identified all possible heat-savings projects known in this industry. The method is practical, visual and user-friendly, and its principles can be used in optimization-based approaches.

1. Introduction

Over the past few decades, methods have been developed to reduce energy consumption in industrial processes by heat-

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exchanger network retrofit; these approaches are based on pinch analysis or numerical optimization. In practice, pinch analysis is the most widely used method for industrial applications. The main advantages of pinch analysis are its simplicity, its graphical representations, and the possibility for the design engineer to interact and influence the solution process at each step [1]. The use of composite curves makes it possible to evaluate energy targets and to identify cross-pinch transfers in an existing HEN. Pinch analysis recommends to eliminate these heat exchanges and to rebalance the resulting systems below and above the pinch via network modifications. The first complete method based on pinch technology for HEN retrofit targeting and design was presented by Tjoe and Linnhof [2]. Although many developments have been achieved in the applications of pinch analysis to HEN retrofit, difficulties in data extraction, targeting and redesign of the network are still encountered [3,4]. Numerical optimization models for HEN retrofit, based on deterministic or stochastic methods, are highly complex and do not guarantee reaching the global optimum [5–10]. Solving the present models is a non-deterministic polynomial-time hard problem, and this can limit the use of deterministic methods. Another approach, termed “network pinch” combines the use of heuristics to identify and create heater-cooler paths, and numerical optimization [11–13]. However, this approach encounters difficulties to solve even simple problems [14]. A more in-depth literature review about methods for HEN retrofit is included in Part 1 of this paper.

The concepts of a new method to reduce thermal energy consumption have been presented in Part 1. Reducing energy demand implies reducing the flow rate of heat cascaded from the heating utilities to the environment through the existing exchangers. The set of modifications necessary to reduce this flow rate of cascaded heat is termed “bridge”. Bridges can be identified with a grid diagram, an energy transfer diagram [15,16], a table, or a formal algorithm. A method for bridge enumeration and the use of an evaluation table have been proposed. The bridge principle can be applied to insight- or optimization-based approaches for HEN retrofit.

The objective of this paper is to present a graphical approach to identify a proper exchanger configuration corresponding to bridge modifications, a stepwise procedure for HEN retrofit, and to illustrate the method through examples covering a broad spectrum of different situations.

For didactical purposes, all graphical tools in this second part use “shifted temperature scales”; i.e., heat sources and heat sinks have already been shifted by their individual contribution to a minimum temperature difference, evaluated according to one of the approaches proposed in the literature [4,17]. As a consequence, the following constraint regarding the minimum temperature difference between a source and a sink is applied: this temperature difference must be greater or equal to zero. Also for clarity, matches are written without superscripts. For example, a match between supplier of exchanger E_1 and receptor of exchanger E_2 was written $e_1^s e_2^r$ in Part 1 of this paper; hereafter, this match is written more simply by $e_1 e_2$; i.e., the supplier is always written before the receptor.

2. Graphical tools

Beside the Energy Transfer Diagram ETD which is composed of exchanger transfer curves whose equation is hereafter expressed, two supplementary graphical tools are proposed for retrofit: a HEN representation and a Heat-Exchanger Load Diagram (HELD) to identify a convenient exchanger configuration. The axis orientation in these diagrams is consistent; the vertical axis represents change in enthalpy, while the flow of transferred heat is represented in the horizontal dimension.

2.1. Energy transfer diagram

To reduce energy consumption by HEN retrofit, it is necessary to reduce the flow rate of heat cascaded from the hot utility to the environment through heaters, process–process exchangers, and coolers. The ETD shows the flow rate of heat cascaded as a function of temperature and provides a global view on all possible bridges. The diagram is composed of energy transfer curves (ETC) representing the flow rate of heat cascaded through each exchanger, which can be a heater, a process–process exchanger, or a cooler. The energy transfer curve of exchanger *i* is expressed by Equation (1), where FCp_i^s and FCp_i^r refer to the heat capacity of the supplier and the receptor in the exchanger, respectively.

$$\mathrm{ETC}_i(T) = \mathrm{ETC}_i(T+1) + FCp_i^s(T) - FCp_i^r(T) \qquad (1)$$

The flow rate of cascaded heat at temperature *T* is equal to the flow rate of cascaded heat at temperature $(T + 1)$ plus the heat released by the supplier minus the heat captured by the receptor at temperature *T*. Equation (1) results from the general formulation relative to the ETC of a system. That is, the flow rate of transferred energy through temperature *T* is equal to the difference between the outlet cumulative heat flow rate and the inlet cumulative heat flow rate at temperature *T*, with the environment chosen as the reference [15]. In the ETD, the energy transfer curves are added according to a stacked arrangement. The total flow rate of cascaded heat is termed “network curve” and is expressed by Equation (2). The minimum of the network curve indicates the theoretical heat-savings potential without consideration of connection constraints.

$$\text{Network curve}(T) = \sum_{i=1}^{\text{Exchangers}} \mathrm{ETC}_i(T) \qquad (2)$$

2.2. HEN representation: vertical orientation of sinks and sources

The classical grid diagram was developed for the design of new networks, not for the retrofit of HEN. The following HEN representation in combination with the heat-exchanger load diagram can be used for the design of new networks and for HEN retrofit. Fig. 1 shows the HEN representation proposed for HEN modifications in a retrofit scenario. In short, this representation corresponds to the classical grid diagram (e.g. the one shown in Figure 1 of Part 1) after a clockwise rotation by 90° and a vertical flip. Sinks are placed on the left; sources are placed on the right. Cold and hot utilities are placed on the extreme left and right, respectively. Showing all cold and hot utilities on the diagram is important since these are fully included in the network; furthermore, utilities can be placed at different temperature levels, and loops may involve coolers or heaters beside process–process exchangers. Arrows oriented to the top or the bottom represent positive or negative changes in enthalpy, respectively. Heat is transferred from right to left. The cold-end and hot-end temperatures (°C) of each receptor and supplier are indicated at the left and right of the circles, respectively. For example, process source 2 is cooled from 145 to 115 °C through exchanger E1. The heat load (kW) corresponding to each exchanger is indicated inside the rectangles. It is proposed to index each exchanger in the initial network according to increasing hot-end temperature of its supplier; for example, the relative indexes of E1 and E2 imply that the hot-end temperature of the supplier of E2 is greater than the one of the supplier of E1; as a consequence, bridge matches that are favourable from the thermodynamic point of view are clearly identified (e.g., $e1e2$ is favourable, while $e2e1$ is unfavourable). It is also proposed to order all sinks and sources according to their hot-end temperatures.

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