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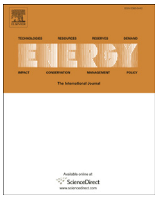

Simultaneous synthesis of utility system and heat exchanger network incorporating steam condensate and boiler feedwater

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ABSTRACT

A heat exchanger network (HEN) is an important part in processing plants used to recover heat from process streams. A utility system supplies heating and cooling utilities and introduces additional hot and cold streams for the processes. The HEN and utility system (e.g., Rankine cycle-based cogeneration system) are closely interconnected primarily through steam, steam condensate leaving the turbines, and process surplus heat. The recovery of the sensible heat from the steam condensate and process surplus heat through an integration technique may contribute significantly to the reduction of the heating and cooling utility consumption in the heat exchanger network as well as in the primary energy consumption in the utility system. In this paper, a systematic methodology for the simultaneous synthesis and design of a utility system and HEN is proposed. The heat recovery from the steam condensate and boiler feedwater preheating are integrated into the HEN synthesis together with the design optimization of a Rankine cycle-based utility system. In addition to the simultaneous design of the utility and heat-recovery systems, the optimization variables include the steam condensate target temperature, the steam level for process heating, the energy demand for the utility system, the returning temperature of the steam condensate, and the final temperature of the boiler feed water. The total site HEN is composed of several interlinked sub-HENs. A model for the new hot utility-process cold stream HEN is formulated together with the hot -cold process streams of the HEN. The linking constraints between sub-HENs and the utility system are formulated. Several case studies are elaborated to demonstrate the effectiveness and applicability of the proposed methodology. Compared with the former design methods without integrating steam condensate sensible heat and boiler feedwater preheating, meaningful economic benefits can be achieved by applying the proposed framework.

1. Introduction

The growing emphasis on sustainable design is leading industrial facilities to conserve energy and reduce greenhouse gas emissions. Heat exchanger networks (HENs) form an important part in the energy management system for a process plant. The goal of the HEN design is to recover energy from the process by economically matching hot streams with cold streams. Any energy still needed is then supplied by hot and cold utilities. The utility system undertakes the role of supply hot and cold utilities for the HENs in a form of multiple pressure levels of steam and cooling water. In the process industries, the HEN and utility system are usually treated as two separate parts and sequentially designed. In fact, most of the steam streams used in HEN as hot utility may return to the utility system in a form of condensate water after heating the cold streams. The recovery of steam condensate sensible heat is helpful in reducing the consumption of steam as hot utility in the HEN and steam as heat source for boiler feedwater (BFW) preheating. In addition, the surplus heat of process hot stream can be used as heat source for utility streams (boiler feed water preheating, cold utility generation and power generation) of the utility system instead of directly cooled by additional cold

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utility. The HEN and utility system are close interacted and the simultaneous synthesis of the HEN and utility system is crucial to improve the energy efficiency and economic competition of process industry. In this paper, there is presented a new methodology based on a new superstructure and a mathematical model for the simultaneous synthesis and optimization of integrated HEN and utility systems accounting for practical and feasibility considerations.

2. Literature review

The goal of the synthesis and design of HEN is to recover heat from the process by matching hot streams and cold streams to minimize the economic objective. Hot and cold utilities are imported to supply any energy requirement for the HEN after the energy recovery between hot and cold streams. The synthesis and design methodology of HEN was introduced by Hohmann [1] and later improved by Linnhoff and Flower [2,3]. Since then, the synthesis and design of HEN has been very well studied.

The solution approach for the HEN synthesis problem can be generally grouped into pinch analysis approaches, sequential approaches, and simultaneous approaches [4–6]. According to the pinch analysis approach, a HEN can be designed following a series of rules based on the first and second law of thermodynamics. The objective of the pinch analysis is to maximize the heat recovery and at the same time minimize the total hot and cold utilities. Any violation of these rules results in an increment in the utility consumption. The pinch analysis is a powerful tool that can provide targets through a graphical interpretation and visualization for the problem, and makes the HEN problem easier to understand [5].

The sequential synthesis approaches decompose the HEN design problem into sub-problems. For example, the targets for the minimum utility requirement, the minimum number of exchanger units and the minimum capital cost of the network are obtained sequentially [7]. Mathematical programming based on pinch theory is usually used in sequential synthesis approaches. Papoulias and Grossmann [8] developed a transshipment model to predict the minimum utility consumption using linear programming and the minimum number of units using mixed-integer linear programming (MILP). Cerda et al. [9] proposed a transportation model for determining the minimum utility cost using a linear programming technique. Floudas et al. [10] proposed a model to minimize the total annual cost (TAC) of a HEN in a two-stage procedure. A mixed-integer linear programming model was first formulated to minimize the number of heat exchangers and a non-linear programming model was used to obtain the minimum TAC of the network by fixing heat exchanger structure. Zhu [11] proposed an automated sequential synthesis approach for the HEN. In their approach, an MILP model was formulated to select the matches and a mixed-integer non-linear programming (MINLP) model for determining the cost-optimal network.

The simultaneous optimization techniques solve the HEN synthesis problem without any decomposition. The trade-offs between the capital and operational costs of the HEN can be handled by MINLP formulations. Simultaneous approaches have shown to be superior to sequential approaches in most of the cases. Ciric and Floudas [12] combined the transshipment model [8] with a nonlinear programming model [10] into one MINLP formulation for a specified minimum temperature difference. In this method, all the involved variables were optimized simultaneously. At the same time, Yee et al. [13] developed a stage-wise simplified superstructure formulation and then Yee and Grossmann [14] extended it to the HEN synthesis. Subsequent works incorporated different assumptions and considerations, such as isothermal mixing [15,16], non-isothermal mixing assumption [17,18] and multiple utilities [19].

In the past decades, the synthesis and design of HEN have been well studied and applied in the practical design. To further recover energy or improve the energy utilization for a total site, there has been considered the integration between the HEN and its associated energy system accounting for the integration of HEN with organic Rankine cycles (ORC) [20,21], absorption cycle [22] trigeneration systems [23], thermal membrane distillation systems [24], and water network [25].

It is worth noting that any additional energy needed after the HEN synthesis is supplied by hot and cold utilities generated from the utility system. The utility system is the heart of an industrial site energy system. Fig. 1 shows a close interconnection between the HEN and the utility system. The synthesis and optimization of the utility system has been the focus of many researchers [26]. Particularly, the integrated design of a utility system and a HEN has been accepted and more attention and various powerful methodologies have been developed over the recent years.

Klemeš et al. [27] extended the pinch analysis methodology to the total site plant by incorporating multiple processes linked by a common central utility system. The cogeneration potential and the emission from a centralized utility system were achieved using the proposed methodology. Liew et al. [28] proposed an improved Total Site Sensitivity Table (TSST) to determine the optimal size of a utility generation system, to design the backup generators and piping in the system and to assess external utilities that might need to be bought and stored. Zhang et al. [29] proposed a coupled mixed integer nonlinear programming model to integrate process plants and utility systems. The mathematical model includes three parts: the heat integration of the process plants, the optimization of the utility system, and the coupling equations for the site-scale steam integration. Later, Zhang et al. [30] proposed a multi-period mathematical model for the simultaneous optimization of materials and energy on a refining site scale. A bi-level MILP framework was presented to minimize the total hot and cold utilities of the up and down plants and to maximize the steam generation in the total site. Goh et al. [6] proposed a multiple cascades automated targeting method to determine the minimum total operating cost of a trigeneration system.

The above mentioned researches aim to find a cogeneration potential of a total site or a design scheme with the minimum operating cost. Other works are focused on the simultaneous minimization of investment and operating costs or the environmental impact for the utility system and the HEN. Chen and Lin [31] presented a systematic methodology for the synthesis of an entire energy system for chemical plants. The entire energy system is composed of a gas-steam cycle-based utility network and a HEN. Bamufleh et al. [32] presented a multi-objective optimization approach for the design of a cogeneration system accounting for

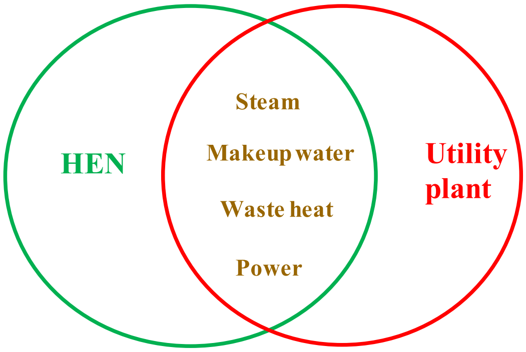

Fig. 1. Interaction between the HEN and the utility system.