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Research Paper

Methodological framework for economical and controllable design of heat exchanger networks: Steady-state analysis, dynamic simulation, and optimization

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HIGHLIGHTS

- HEN total annualized cost, heat recovery, and controllability are considered in the framework.
- Steady-state and dynamic simulations are performed.
- Effect of bypass on total annualized cost and controllability is reported.
- Optimum bypass fractions are found from closed and open-loop efforts.

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ABSTRACT

The problem of interaction between economic design and control system design of heat exchanger networks (HENs) is addressed in this work. The controllability issues are incorporated in the classical design of HENs. A new methodological framework is proposed to account for both economics and controllability of HENs. Two classical design methods are employed, namely, Pinch and superstructure designs. Controllability measures such as relative gain array (RGA) and singular value decomposition (SVD) are used. The proposed framework also presents a bypass placement strategy for optimal control of the designed network. A case study is used to test the applicability of the framework and to assess both economics and controllability. The results indicate that the superstructure design is more economical and controllable compared to the Pinch design. The controllability of the designed HEN is evaluated using Aspen-HYSYS closed-loop dynamic simulator. In addition, a sensitivity analysis is performed to study the effect of bypass fractions on the total annualized cost and controllability of the designed HEN. The analysis shows that increasing any bypass fraction increases the total annualized cost. However, the trend with the total annualized cost was not observed with respect to the control effort manifested by minimizing the integral of the squared errors (ISE) between the controlled stream temperatures and their targets (set-points). An optimal ISE point is found at a certain bypass fraction, which does not correspond to the minimal total annualized cost. The bypass fractions are validated via open-loop simulation and the additional cooling and/or heating utility requirements, in order to meet the target temperatures, are optimized. The optimum bypass fraction, which minimizes the additional utilities, is found to be the same as the one determined by minimization of ISE.

1. Introduction

High utility requirement and energy intensive nature of chemical and petrochemical processes have always stimulated practical and research investigations into energy recovery systems and heat integration for energy efficiency enhancement and operating cost minimization. In this context, heat exchanger networks (HENs) have received considerable attention over the past four decades [1]. The objective of a HEN is to minimize the capital cost and the heating and cooling utility consumption by matching the hot and cold streams within a process. Most techniques for HEN synthesis can be classified as either sequential or simultaneous synthesis methods [2]. Sequential synthesis method generally requires less computational effort and is based on pinch analysis [3]. This method decomposes the synthesis problem into a series

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of subproblems by dividing the temperature range into temperature intervals subject to thermodynamic constraints [4]. Generally, the three subproblems of minimum utility requirement, minimum number of matches, and minimum capital cost are solved successively [2,5]. However, the trade-offs between these three subproblems are not considered rigorously in sequential synthesis method. Due to this limitation, simultaneous synthesis methods have been reported to exhibit better performance compared to the sequential synthesis methods [6]. Simultaneous methods solve the synthesis problem using mathematical programming techniques, such as mixed-integer nonlinear programming (MINLP), without decomposing the problem [2]. Synthesis, design, and analysis of HENs has been studied extensively and the research efforts have been reviewed in Refs. [2,7–9].

Much of the early research on HENs focused on steady-state optimal design. As a result, conventional HEN synthesis methods are based on nominal or fixed values of flow rates and stream supply and target temperatures. However, stream supply temperatures and flow rates may act as inherent disturbances to the network. These disturbances propagate through the network and may result in offsets in the target temperatures. In addition, there exists an inextricable link between heat integration and controllability. Flexibility of any HEN is defined as its ability to withstand long-term desired changes in the inlet conditions [10,11]. Controllability, on the other hand, refers to the ability of HEN to tolerate short-term disturbances [12]. Complex HEN configurations can lead to process structures that are difficult to operate and control [13]. Thus, both flexibility and controllability of HENs become an important concern.

Several attempts have been made to address the flexibility of HENs without considering the control and dynamic aspects [11,14–18]. In order to account for controllability, Mathisen et al. [13,19–21] proposed addition of control-related constraints to HEN problem formulation. These studies concluded that all critical targets can be controlled by either bypass placement or addition of utility streams. Oliveira et al. [22] discussed the importance of controllability considerations in HEN synthesis. The study proposed a procedure to verify the controllability of HENs using relative gain array (RGA) and singular value decomposition (SVD) measures of controllability. The study suggested applying the procedure at each step of HEN synthesis in order to reject unfeasible structures or to perform modifications to make the structure feasible. Using MINLP, Papalexandri and Pistikopoulos [23,24] developed a method to design cost-effective HENs with satisfactory control scheme. Westphalen et al. [25] introduced a controllability index for the conceptual design of HENs. The index was independent of the control strategy and manipulated variables. Yang et al. [26] introduced a modeling approach to quantify the disturbance propagation in HENs. The model can be successfully used to predict the maximum deviation of the system outputs under the influence of the worst combination of disturbances. However, the model may lead to conservative network design since control actions for disturbance rejection were not considered. This model was extended by Yan et al. [12] to include both disturbance propagation and control action. A design procedure was developed to select the optimum locations and fractions of the bypass streams for complete disturbance rejection. Lersbamrungsuk et al. [27] used linear programming (LP) problem formulation to find the control scheme for optimal operation of HENs. A degree of freedom analysis was performed to identify structural feasibility and optimum utility cost. Sun et al. [28] suggested a method to design controllable HENs by finding optimal bypass location using non-square relative gain array (ns-RGA). Escobar and Trierweiler [29] considered simultaneous cost optimization, bypass selection, and control of an existing HEN. More recently, Escobar et al. [30] developed a computational framework for synthesizing controllable HENs. The framework was based on a two-stage strategy. The first stage involved selection of design variables. In the second stage, the control variables were adjusted based on uncertain process parameters. The HEN synthesized was not only optimal in terms of cost but also exhibited good controllability features.

In short, in the design and synthesis of HENs, the classical objectives of minimizing the total capital cost and maximizing the heat recovery must be considered in conjunction with controllability aspects of the network. In addition, the trade-off between economics, heat recovery, and controllability must be taken into account. This paper presents a methodological framework for heat exchanger networks, which takes into account both cost and controllability. The framework consists of quick and easy hierarchical steps that can be used to design HENs complying with the heat recovery targets while taking into account the economics, steady-state, and dynamic aspects of control. The proposed framework has been applied to a case study. Steady-state simulations have been performed using Aspen Energy Analyzer and HYSYS. In addition, the dynamic behavior of the designed HEN has been studied using Aspen-HYSYS dynamic process simulator. In addition, the effect of bypass fractions on the total annualized cost and controllability of the designed HEN has been investigated. At the end, the trade-off between the cost, heat recovery, and controllability has been optimized and the optimum values of bypass fractions have been presented.

2. Methodology

In this section, a simple three-step methodological framework is proposed in order to design HENs with optimal heat recovery, economics, and controllability. First, a heat integration analysis is performed. In this step, Pinch and superstructure heat integration methods are compared in terms of economics, heat recovery, and steady state control parameters. Second, to allow for robust controllability, bypass placement analysis is performed in order to identify the location of bypass streams. Third, the dynamic behavior of the HEN is studied in terms of its disturbance rejection.

2.1. Stage 1: Selection of the most suitable heat integration method

In the first stage of the proposed framework, the most suitable heat integration method for HEN synthesis is selected. The choice lies between the two well-known classical synthesis algorithms: heuristic-based Pinch design by Linnhoff et al. [31] and computer-based superstructure design [32]. The same synthesis techniques have been suggested in previous investigations on HENs [33,34]. Details of these two heat integration methods are presented elsewhere in the literature [32,35,36]. Criteria of heat recovery, total annualized cost, and controllability can be used to select between the two heat integration methods. For any type of design, the first criteria of heat recovery can be analyzed using Aspen Energy Analyzer.

For the case study considered in this work, the total annualized cost (AC, $/yr) of the two designs can be evaluated based on the following equation reported by Konukman et al. [34]:

$$AC = \gamma\sum_{j=1}^{NE}(C_E + \alpha A_j^{\beta}) + \sum_{k=1}^{NC} C_c Q_{c,k}^0 + \sum_{l=1}^{NH} C_H Q_{H,l}^0 \tag{1}$$

where A_j is the area of the jth heat exchanger, NE is the number of heat exchangers in the network, $Q_{c,k}^0$ is the heat load of the kth cooler for zero-disturbance case, NC is the number of coolers, $Q_{H,l}^0$ is the heat load of the lth heater for zero-disturbance case, NH is the number of heaters, C_C and C_H are cost coefficients for cooling and heating, respectively, C_E, α, and β are the investment cost