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Research paper

Heat exchanger network synthesis incorporating enhanced heat transfer techniques

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HIGHLIGHTS

- Enhanced heat transfer techniques are incorporated into grassroot HEN design.
- Tube and shell side EHT techniques are simultaneously incorporated.
- Performance and economic trade-off determine suitability of EHT techniques.
- The new approach achieves capital investment and improved energy savings.

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ABSTRACT

Appropriate integration of tube- and shell-side enhanced heat transfer (EHT) techniques is essential for better thermal performance, lower heat transfer area requirement and reduced utility consumption in a heat exchanger network (HEN). In this study, EHT techniques have been integrated into grassroot HEN design to improve heat transfer rates and energy recovery. Based on performance and cost indices, an optimization model is proposed that identifies suitable tube-side and shell-side EHT techniques for implementation in grassroot HEN. The tube-side enhancement techniques considered include twisted-tape inserts, coiled-wire inserts, internal fins, the combination of coiled-wire inserts and internal fins, and the combination of twisted-tape and internal fins; external fins, helical baffles, and the combination of external fins and helical baffles are considered for the shell-side. Two examples are presented to demonstrate the capabilities of the models. The results obtained show that the proposed model ensures optimum selection of enhancement techniques, and savings in capital investment and utility costs. The study concludes that integration of enhancement devices into grassroot heat exchanger networks achieves capital investment and utility cost savings.

1. Introduction

Improving energy efficiency is becoming a topical issue in the process industries in recent times due to ever increasing demand for fast-diminishing conventional fossil energy sources, environmental emission concerns as well as heightened global business competitiveness. Process integration, a major thermodynamic tool for process heat recovery, is hereby receiving greater global attention by researchers and industrialists alike [1]. Of particular importance to process energy integration are the Heat Exchanger Networks (HENs) due to their role in process heat recovery. The HEN represents an interconnected system of heat exchanger units that effect exchange of heat energy between hot and cold process streams, in order to attain the target temperatures specified for the process stream, without or with minimal use of external hot and/or cold utilities. It is therefore essential that these prime tools of process energy recovery – the heat exchanger networks – be synthesised, retrofitted where necessary, and operated as efficiently and optimally as possible.

Extensive research has been carried out in the synthesis of optimal HEN using both mathematical programming and the pinch technology. Gundersen and Naess [2] and Furman and Sahinidis [3] provided exhaustive reviews on the evolution of synthesis methods for optimal HEN. Mathematical programming has however been in

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the vanguard as a result of its capability to simultaneously optimize all the cost elements of HEN design. Mathematical programming approaches to optimal HEN have been extended to incorporate various aspects of process operation that improve thermal performance of HEN. Isafiade et al. [4] extended the stage-wise superstructure of Yee and Grossmann (the SYNHEAT model) to synthesize HEN for multiperiod operations involving single and multiple utilities. Escobar et al. [5] developed an approach that accounts for uncertainties in plant operations and carried out synthesis of flexible HEN using heuristic algorithms predicated upon Lagrangean decomposition. The approach presented by these authors effectively incorporated flexibility and controllability into HEN synthesis.

Peng and Cui [6] adopted a stochastic solution algorithm in place of the common deterministic global optimization methods in a bid to overcoming the combinatorial and non-convex nature of HEN synthesis models. These authors employed simulated annealing algorithm involving a two-level procedure for optimal HEN synthesis. In their approach, viable heat exchanger network structures are evaluated at the first level, while the second level optimizes the heat distribution of each network structure obtained at the first level for minimum total annual cost. Comparison of different mathematical approaches for optimal HEN synthesis was made by Escobar et al. [7], and it was concluded upon implementation of these models using the General Algebraic Modelling System (GAMS) that the SYNHEAT model of Yee and Grossmann provided the best performance due to its simplifying assumptions and linear constrained formulation.

Enhanced heat transfer (EHT) involves techniques that are employed to improve heat fluxes within heat transfer devices. Employing these techniques in heat exchangers can therefore improve heat transfer rates without directly increasing the heat exchanger area requirement. Furthermore, EHT techniques offer higher heat fluxes irrespective of the fluids involved in heat transfer. Tube-side enhancements, principally tube inserts, increase shear stress at the tube wall thereby reducing fouling [8]. Increase in pressure drop resulting from implementing shell-side and tube-side EHT techniques can be compensated for by reducing the fluid velocity, via reduction in the number of exchanger tube passes and shell number. This is because EHT techniques enable heat exchange to occur at higher heat fluxes in heat exchangers with reduced fluid velocity [9]. Enhancement devices are broadly classified into active, passive and compound techniques. Active techniques are commonplace as they function by impeding or altering the normal flow pattern of fluid to achieve higher values of the product of heat transfer coefficient and heat transfer surface area in the process. The passive enhancement devices require external energy to effect secondary flow required to increase heat fluxes, while the compound techniques are an integration of devices in either or both of active and passive classes.

Mathematical methods that systematically implement EHT techniques in HEN retrofit have been proposed by researchers. Wang et al. [9] adopted simultaneous annealing optimization algorithm to locate heat exchangers suitable for enhancement and determine their appropriate level of enhancement. Pan et al. [10] presented a novel MILP approach applicable to large scale networks that systematically identifies suitable heat exchangers for enhancement and the degree of enhancement required to achieve cost-effective retrofit without any structural modification to network configuration. Different tube-side and shell-side EHT techniques are then simultaneously implemented in the identified heat exchangers to improve thermal performance of HEN.

Despite the benefits afforded by heat transfer enhancements, no approach has been developed to integrate grassroot HEN design with the systematic implementation of EHT techniques. This study therefore presents an optimization model, based on the SYNHEAT model of Yee and Grossmann [11], which systematically selects different EHT techniques for implementation in grassroot HEN. Based on a trade-off between the cost and enhancement performance, suitable tube-side and shell-side EHT techniques are simultaneously identified for implementation in grassroot HEN. The objective of the new approach is to identify appropriate EHT techniques that offer improved thermal performance of HEN at minimal total annual cost. Two examples from literature are presented and optimized to demonstrate the capabilities of the developed model.

2. Model formulation

The proposed optimization model is based on the MINLP formulation of Yee and Grossmann [11]. The strategy adopted involves development of a stage-wise superstructure that consists of all possible matches between hot and cold streams, and is subdivided into a predetermined number of stages as shown in Fig. 1. The objective is to simultaneously optimize all costs associated with HEN synthesis: capital costs resulting from heat exchanger area requirement and associated heat exchanger fixed charges, as well as energy costs resulting from consumption of hot and/or cold utility. The selection of matches and number of exchanger units are optimized alongside due to the elaborate formulation of the model. Binary variables declared with the appropriate model indices represent the network configuration in terms of selected matches and ensure proper calculation of exchanger fixed charges. Non-linearity is introduced into the formulation by Chen's approximation for expressing logarithmic mean temperature difference (LMTD) [12].

Eqs. (1)–(6) present the heat balances on the process streams, process stages defined by the process stream temperature intervals, and process utility load required to take the process streams to their target temperatures. The logical constraints that show the existence of heat exchangers matches are presented in Eqs. (7)–(9), while the logarithm temperature difference for the process and utility matches are presented in Eqs. (10)–(12). Eqs. (13)–(20) present the constraints and modified objective function that integrate EHT techniques into the HEN.

2.1. Base-model equations

The equations presented in this section are same as in Yee and Grossmann (1990):

Stream heat balance

$$(Ta_i - Tb_i)FCp_i = \sum_k \sum_j q_{i,j,k} + q_{i,cu}, \quad i \in HP \tag{1}$$

$$(Tb_j - Ta_j)FCp_j = \sum_k \sum_i q_{i,j,k} + q_{hu,j}, \quad j \in CP \tag{2}$$

Stage heat balance

$$(t_{i,k} - t_{i,k+1})FCp_i = \sum_j q_{i,j,k}, \quad i \in HP \tag{3}$$

$$\left(t_{j,k} - t_{j,k+1}\right)FCp_j = \sum_i q_{i,j,k}, \quad j \in CP \tag{4}$$