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Research Paper

Area-based optimization approach for refinery heat exchanger networks

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ABSTRACT

This paper presents a new approach to optimize large-scale heat exchanger networks (HENs). The approach is particularly suitable for operational optimization and retrofit of industrial crude oil preheat trains, but it can be applied to HENs from other processes. Two main features distinguish this approach: first, an area-based simulation model that significantly simplifies the optimization, while capturing the details of the existing HEN. Second, a decomposition procedure to divide the large-scale HEN into two simpler HENs, which are optimized sequentially. This approach includes additional features that provide a more realistic representation of preheat trains, such as temperature-dependent heat capacities, the dependence of heat transfer coefficients on flow rate variations, and new types of stream splitters and mixers for the distillation products in the HEN. An industrial case study illustrates the application of the methodology, showing that the approach identifies opportunities to reduce energy consumption with minimal changes to the HEN structure.

1. Introduction

The optimization of heat exchanger networks (HENs) has been a topic of industrial and academic interest for more than three decades. From simple procedures based on thermodynamic principles to sophisticated computer algorithms, the optimization of heat exchanger networks continues to be a challenging area of process engineering. Early design approaches based on thermodynamic principles, such as pinch analysis introduced by Linnhoff [1], continue to provide useful insights to evaluate and target the energy consumption of existing HENs. However, the use of mathematical programming, as this paper shows, allows the consideration of more details and the evaluation of more design options.

Various approaches have been developed to perform retrofit of HENs; a comprehensive review of retrofit approaches can be found in [2]. These approaches can employ simple thermodynamic principles, optimization algorithms, or a combination of both. Graphical methods based on thermodynamic principles have been developed to retrofit HENs, such as methods based on pinch analysis [3], bridge analysis [4] or Retrofit Thermodynamic Diagrams [5]. Because of their ability to analyze complex heat exchanger networks in a simplistic manner, these methods tend to provide optimistic solutions that often prove impractical and less cost-effective once a more detailed assessment is carried out [6]. For this reason, thermodynamic principles are often employed along with optimization algorithms that can carry out more detailed economic calculations and can handle more practical constraints. Examples of these combined approaches are the works of Pan et al. [7] and Rohani et al. [8], who used the concepts of 'network pinch' [9] and 'bridges', respectively, to build HEN superstructures that are optimized using MINLP.

Even though optimization-based approaches for HEN retrofit facilitate the consideration of more practical constraints, these approaches still make simplifying assumptions that may produce impractical and inaccurate solutions. Regarding the retrofit of crude oil preheat trains, three aspects are typically simplified: a) the type of structural modifications considered in the optimization, b) the prediction of properties and, c) the representation of the heat exchanger network.

1.1. Approaches used to simplify the HEN optimization problem

Optimization approaches reported suitable for large-scale HENs can introduce structural inflexibilities that bias the search process for retrofit solutions. For example, the predefinition of the location and number of matches and splitters in a superstructure stage [10] and the failure to consider relevant retrofit modifications, such as stream splitting [7] and relocation of existing heat exchangers [11]. Other works, such as the approach of Bagajewicz et al. [6], consider retrofit modifications relevant to crude oil HENs, such as adding new matches, additional shells and heat transfer area,

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Nomenclature

Latin letters

A	vector of heat transfer areas
A	heat transfer area
b	vector of the indices of outlet streams related to the split fraction
C	vector of utility prices
CP	vector of heat capacity flow rates
$\overline{\mathbf{CP}}$	vector of average heat capacity flow rates
CP	heat capacity flow rate
Cp	vector of heat capacities
Cp	heat capacity
Cps	heat capacity at the supply temperature
Cpt	heat capacity at the target temperature
EMAT	vector of calculated exchanger minimum approach temperatures
EMAT	exchanger minimum approach temperature
F	volumetric flow rate
Ft	exchanger temperature correction factor
H	film heat transfer coefficient
LMTD	logarithmic average of the temperature difference
M	incidence matrix
m	vector of flow rates
N	number of HEN elements
NTU	number of transfer units
q	heat exchanger duty
QU	vector of utility energy requirements
sp	split fraction matrix for open-ended splitters
S	number of edges
T	vector of temperatures
T	temperature
TS	vector of specified supply temperatures
TS	supply temperature specification
TT	vector of specified target temperatures
TT	target temperature specification
U	overall heat transfer coefficient

Greek letters

$\boldsymbol{\alpha}$	vector of split fractions for conventional splitters
$\boldsymbol{\beta}$	vector of split fractions for open-ended splitters
$\mathbf{\Delta T}$	vector of temperature change specifications
ΔT	temperature difference
$\mathbf{\Delta H}$	vector of enthalpy change specifications
ψ	heat capacity ratio

Subscripts

+	matrix of positive elements
ADD	additional area
c	cold stream
CALC	calculated value
h	hot stream
HEN	indicates overall HEN
I	tube side
INST	installed area
min	minimum value
O	shell side
PH	exchangers in the primary HEN
PS	unbroken streams in the primary HEN
S	shell side
SH	exchangers in the secondary HEN
SS	streams in the secondary HEN
T	tube side
x	indicates stream break points

Superscripts

*	new specification
HE	heat exchangers
mx	open-ended mixers
PD	demand units
PDS	demand units in the secondary HEN
PRH	unit operations specified in terms of enthalpy
PRT	unit operations specified in terms of temperature
SP	conventional splitters
sp	open-ended splitters
T	transpose of an array
util	utility

Mathematical operators

diag	diagonal matrix operator
°	Hadamard product

stream splitting and relocation of existing exchangers. However, the approach of Bagajewicz et al. [6], based on the model of Nguyen et al. [12], assumes constant temperature-dependent properties (e.g. heat capacity). Considering the effect of temperature on heat capacity is important when streams undergo significant temperature changes; such is the case of crude oil and its products. It is reported [13] that assuming constant heat capacities in crude oil preheat trains can lead to prediction errors in the furnace inlet temperature of more than 25 °C.

Stochastic optimization approaches allow more details (e.g. non-linear cost functions, temperature-dependent heat capacities, non-isothermal mixing, maximum number of modifications) to be incorporated in the HEN retrofit problem, compared to deterministic optimization approaches. The reason for this is that stochastic optimization does not rely on the calculation of derivatives to find a solution. Details such as temperature-dependent heat capacities [14] and variable heat transfer coefficients [15] have been considered in HEN retrofit approaches that employ simulated annealing [14] and genetic algorithms [15]. However, the main drawback of these stochastic approaches is that they are computationally expensive [16].

Other simplifications typically made for the optimization of crude oil preheat trains relate to the modeling of the network. Most of the works in the literature specify the heat exchangers in terms of duty, instead of area. The advantage of using duty-based models is that exchangers are easier to simulate, compared to area-based models. However, with duty-based models, it is more difficult to capture the real-life area constraints of installed equipment during retrofit optimization. When heat exchangers are specified in terms of area, relevant variables (e.g. area installed in the network, per exchanger, additional area requirements) can be readily monitored and optimized.

This paper presents a methodology that overcomes some of the simplifications typically made when optimizing crude oil preheat trains. In particular, this paper considers retrofit modifications relevant to crude oil heat exchanger networks, temperature-dependent heat capacities, the variation of overall heat transfer coefficients with flow rate changes and exchangers specified in terms of area, and applies a more accurate model to represent the mixing and splitting of two or more crude oil products. The advantage of considering these details in the optimization problem is that more accurate and industrially-relevant solutions can be