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Research Paper

Simultaneous integrated design for heat exchanger network and cooling water system

Fuyu Liu [a], Jiaze Ma [a], Xiao Feng [b,*], Yufei Wang [a]

[a] State Key Laboratory of Heavy Oil Processing, China University of Petroleum, Beijing 102249, China
[b] School of Chemical Engineering and Technology, Xi'an Jiaotong University, Xi'an 710049, China

HIGHLIGHTS

- A simultaneous methodology to integrate heat exchanger network and cooling water system.
- A novel stage-wise superstructure for the integrated design.
- A MINLP model based on economic performance for the integrated design.
- Better design obtained through the simultaneous methodology compared with the conventional one.

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ABSTRACT

Heat exchanger network and cooling water system are two major elements of energy systems in processing plants. Such two subjects have a very close interaction with each other. However, most of current researches firstly synthesize heat exchanger network and then design cooling water system. This sequential methodology probably misses the optimum solutions, and results in some suboptimal designs from an overall perspective. To overcome this limitation of traditional methods, in present paper a simultaneous methodology is introduced to integrate heat exchanger network and cooling water system as a whole system. Unlike conventional approaches, the methodology treats cooling water as a special cold stream whose mass flow rate, initial and final temperatures are all unknown variables and require to be optimized. The methodology mainly makes use of a modified stage-wise superstructure that covers most possible configurations for integrating heat exchanger network and cooling water system. The mathematical optimization model corresponding to the superstructure is a mixed integer nonlinear programming (MINLP) problem. The total annual cost (TAC) is set as the objective function composed by utility cost, pumping cost, and capital cost of cooling tower and heat exchanger. An industrial case study is used to demonstrate the capabilities of the proposed methodology.

1. Introduction

Nowadays the growing prices of fossil fuel and strict environment regulations seriously force industrial clusters to improve processing plants' energy efficiency as much as possible. Therefore, industrial energy systems, like heat exchanger networks, cooling water systems, rankine cycles and so on, have attracted high attentions from both academic and industrial practices [1]. Among these energy systems in a processing plant, a heat exchanger network and a cooling water system are two major elements which have very close relationships to energy consumption [2]. Such two subjects have been widely and deeply studied in the past few years and various kinds of design approaches have been proposed with extensive application to industrial cases.

1.1. Synthesis of heat exchanger network

The concept of heat exchanger network synthesis is initially proposed by Masso and Rudd [3] in 1970s. According to Núñez-Serna and Zamora [4], the methodologies for heat exchanger network synthesis could be classified into two categories, sequential and simultaneous approaches. In principle, the sequential methodology decomposes heat exchanger network synthesis into several sub-problems. One well-known sequential methodology for heat exchanger network synthesis is Pinch Technology (PT) proposed by Linnhoff and Hindmarsh [5]. They utilized a minimum temperature difference to find the bottlenecks for energy savings which

* Corresponding author.
E-mail address: xfeng@xjtu.edu.cn (X. Feng).

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Nomenclature

Sets

NH	set of hot streams, $NH = \{i \mid i = 1, 2 \ldots I\}$
NC	set of cold streams, $NC = \{j \mid j = 1, 2 \ldots J\}$
NK	set of stages, $NK = \{k \mid k = 1, 2 \ldots K\}$

Parameters

F	heat capacity flow rate, kW/°C
Tin_i	inlet temperature of hot streams i, °C
$Tout_i$	outlet temperature of hot streams i, °C
Tin_j	inlet temperature of cold streams j, °C
$Tout_j$	outlet temperature of cold streams j, °C
ρ	density, kg/m^3
cp	specific heat capacity, kJ/°C kg
μ	viscosity, pa s
κ	thermal conductivity, W
$\Delta Tmin$	minimum temperature difference, °C
Ω	upper bound for heat load, °C
Γ	upper bound for temperature difference, °C
Lt	tube pitch of heat exchanger, mm
$Dtin$	internal diameter of the tube, mm
$Dtout$	external diameter of the tube, mm
De	equivalent diameter of the tube, mm
CU	hot utility cost, $/kW y
Af	annual factor for capital cost.
Pe	price of electricity, $/kW h
Hy	annual operation time, h

Variables

t	stream temperature at the end of stage, °C
q	heat load of a heat exchanger, kW
dt	temperature difference of a heat exchanger, °C
qu	heat load of a heater, kW
dtu	temperature difference of a heater,°C
A	area of a heat changer or cooler, m^2
Au	area of a heater, m^2
ΔP	pressure drop, Pa
Q	pump power, W
M	mass flow rate of stream, kg/s
Mu	mass flow rate of blow-down water, kg/s
Md	mass flow rate of make-up water, kg/s
tmu	temperature of make-up water, °C
R	temperature range, °C
tin^w	supply temperature of cooling water, °C
$tout^w$	target temperature of cooling water, °C
$Pumping$	annualized pumping cost, $/y

Binary variable

z	existence of a heat exchanger or cooler
zu	existence of a heater

was also called as pinch point. Heat exchanger network synthesis is thereby divided into designing two sub-networks above and below the pinch points. Papoulias and Grossmann [6] and Cerda et al. [7] respectively developed a transshipment and a transportation model, in which heat exchanger network synthesis was implemented as a sequentially mathematical programming problem. Energy saving target, number and area of heat exchanger are sequentially optimized step by step. However, these sequential methods may not find the optimum solution, since energy saving and capital investments are not trade off simultaneously.

The other methodology for heat exchanger network synthesis is simultaneous approach that considers various factors holistically like utility expenses, pumping cost and capital investments of heat exchangers. Such methodology normally makes use of mathematical programming models to optimize an objective function subject to several heat and mass constraints. For example, Yee and Grossmann [8] studied heat exchanger network and established a stage-wise superstructure for it. The corresponding mathematical model named Synheat Model is a mixed integer nonlinear programming (MINLP) model. Since Synheat Model can cover most possible configurations for heat exchanger networks, it has been deeply studied in several previous literatures, such as Short et al. [9] and Zhang et al. [10]. Nevertheless, the aforementioned studies were mostly performed ignoring pressure drop which directly affects the capital and operation cost of driving pump. So Souza et al. [11] considered this key factor for simultaneous synthesis of heat exchanger networks. The cost statistic in their researches shows that pumping cost possesses a considerable percentage of the total costs. Some good reviews on simultaneous heat exchanger network synthesis can be found in recent works like Zhang et al. [12] and Lv et al. [13].

1.2. Synthesis of cooling water system

Cooling water system is another important element of energy systems in processing plants. It removes most waste heat rejected from hot process streams, thus the flow rate of cooling water is particularly large as well as its capital investments and operation costs. Early attempts to cooling water system synthesis were carried out through graphic targeting methods. For instance, Kim and smith [14] initially developed a PT method for cooling water system synthesis by focusing on the systems' components from an overall aspect. Due to the highly close interactions between cooling water networks and cooling tower performance, it is particularly necessary to take account into all components as a whole. Continuously, Kim et al. [15] extended their approach to cooling water system synthesis for effluent flow-rate reduction. Their method can rearrange some coolers from parallel to series configurations, rather than increasing the mass flow-rate of cooling water. However, their researches were mostly based on graphic targeting tools that cannot addressed capital investments and operation cost simultaneously. Thus the optimum solutions may be missed and suboptimal designs may be obtained accordingly.

Actually, there exist various costs in the synthesis of cooling water systems, such as pumping costs, capital costs of cooling towers and heat exchangers. Unlike graphic methods, mathematical programming methods consider these costs simultaneously and holistically. Because of this point, many researchers suggested mathematical programming methodology for the synthesis of cooling water system. Kim and Smith [16] presented a mathematical optimization model for the retrofit of cooling water systems. An automated method based on mathematical programming was explored to find guidelines for the debottlenecking of cooling water systems. But the cooling towers and cooling water networks in their research were studied separately and this may result in suboptimal solutions. Thereby, Majozi and Moodley [17] treated cooling towers and cooling water network as a whole. A new MINLP model was presented for synthesizing cooling water systems wherein multiple towers were used to remove the waste heat on process streams to the environment. More reviews on cooling water system synthesis can be found in several papers like Sun et al. [18] and Ma et al. [19].