Applied Thermal Engineering 128 (2018) 861–876

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Research Paper

An integrated random walk algorithm with compulsive evolution and fine-search strategy for heat exchanger network synthesis

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HIGHLIGHTS

- Fine-search strategy was proposed to improve the performance of RWCE.
- Fine-search strategy can enhance the global search ability of continuous variables.
- FS-RWCE could refine and enhance the evolution of integer variables in HENS.
- FS-RWCE was demonstrated reliable and applicable to large-sized HENS problems.

ARTICLE INFO

Article history:
Received 11 April 2017
Revised 8 August 2017
Accepted 15 September 2017
Available online 18 September 2017

Keywords:
Heat exchanger network synthesis
Integer variables optimization
Random Walk algorithm with Compulsive Evolution
Fine-search strategy

ABSTRACT

Heat exchanger network synthesis has been extensively studied in process system engineering for its complexity and difficulty resulting from stream matches and the nonlinearity of continuous variables. Stochastic methods have difficulties in finding the precise optimum solution on the near optimal regions and expanding the integer variables optimization in the late evolution. Therefore, a novel fine-search strategy was established on the basis of the evolutionary mechanism of random walk algorithm with compulsive evolution. The fine-search strategy was efficient in achieving the accuracy of solutions for a certain heat exchanger network structure. Then, the fine-search strategy and Random Walk algorithm with Compulsive Evolution were integrated to enhance and refine the optimization for continuous and integer variables in heat exchanger networks synthesis simultaneously. The integrated method could satisfy the needs of global and local search abilities for heat exchanger network synthesis. Finally, the proposed method was applied in three different-sized cases and more economical in contrast to the best results with no splits published thus far were obtained.

1. Introduction

The investigation of global optimization solutions for heat exchanger network synthesis (HENS) has a far-reaching theoretical and practical significance in the chemical engineering industry. Most of the contributions to HENS research can be classified as either sequential synthesis or simultaneous synthesis methods [1]. Sequential synthesis methods divided the HENS problem into a series of sub-problems to reduce the computational requirements for obtaining a network design. Sequential methods were further divided into two subcategories: thermodynamic methods and sequential mathematical programming methods. Pinch analysis [2,3] was probably the most widely accepted technology for HENS considering the laws of thermodynamics, which demonstrated excellent efficiency and has been further improved in many different process integration issues correlated to improving sustainability of chemical processes [4]. Sequential mathematical programming methods mainly contained linear programming (LP) based on a Transportation model [5] and mixed integer linear programming (MILP) formulations on basis of a transshipment model [6] respectively. These methods divided the problem into several sub-problems and then solved each sub-problem within different temperature intervals. Subsequently, Floudas et al. [7] developed nonlinear programming (NLP) based on a model derived from the previous two sub-problems and other researchers proposed more sequential methods [8]. Kim and Bagajewicz [9] presented an extension of the superstructure exchanger network grassroots design [10] to include several matching of two streams, activate splitting control, and allow mixing temperature control. However, the limitation of sequential methods was often leading to a suboptimal network design.

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http://dx.doi.org/10.1016/j.applthermaleng.2017.09.075

Nomenclature

Superscripts

in	inlet of streams
out	outlet of streams

Subscripts

CU	cold utility
HU	hot utility
i	index for hot streams
it	iteration
it1	iteration in fine-search strategy
j	index for cold streams
k	index for stages
n	index for individuals
p	index for heat exchangers

Variables

$A_{i,j,k}$	areas of heat exchangers, m^2
$A_{\mathrm{CU},i}$	areas of cold utilities in hot stream *i*, m^2
$A_{\mathrm{CU},j}$	areas of cold utilities in cold stream *j*, m^2
$A_{\mathrm{HU},i}$	areas of hot utilities in hot stream *i*, m^2
$A_{\mathrm{HU},j}$	areas of hot utilities in cold stream *j*, m^2
C_{AC}	area cost coefficient of cold utility, \$/y
C_{AE}	area cost coefficient of heat exchangers, \$/y
C_{AH}	area cost coefficient of hot utility, \$/y
C_{CU}	utility cost coefficient of cold utility, \$/y
C_{HU}	utility cost coefficient of hot utility, \$/y
C_{FC}	fixed charge of cold utility, \$/y
C_{FE}	fixed charge of heat exchangers, \$/y
C_{FH}	fixed charge of hot utility, \$/y
GCp	heat capacity flow rate, kW/K
N_{C}	number of cold streams
N_{H}	number of hot streams
N_{E}	total number of process heat exchangers
N_{S}	number of stages
NF	the number of fine-search processes
$Q_{i,j,k}$	heat exchanged between stream *i* and *j* in level *k*, kW
$Q_{\mathrm{CU},i}$	heat exchanged between stream *i* and cold utility, kW
$Q_{\mathrm{CU},j}$	heat exchanged between stream *j* and cold utility, kW
$Q_{\mathrm{HU},i}$	heat exchanged between stream *i* and hot utility, kW
$Q_{\mathrm{HU},j}$	heat exchanged between stream *j* and hot utility, kW
$T_{\mathrm{h},i,k}^{\mathrm{in}}$	inlet temperatures of a single heat exchanger at hot stream *i*, °C
$T_{\mathrm{h},i,k}^{\mathrm{out}}$	outlet temperatures of a single heat exchanger at hot stream *i*, °C
$T_{\mathrm{h},i,N_{\mathrm{S}}}^{\mathrm{out}}$	terminal outlet temperatures of hot stream *i*, °C
$T_{\mathrm{c},j,k}^{\mathrm{in}}$	inlet temperatures of a single heat exchanger at cold stream *j*, °C
$T_{\mathrm{c},j,k}^{\mathrm{out}}$	outlet temperatures of a single heat exchanger at cold stream *j*, °C
$T_{\mathrm{c},j,1}^{\mathrm{out}}$	terminal outlet temperatures of cold stream *j*, °C
T_i^{in}	the inlet temperatures of hot streams, °C
T_i^{out}	the target temperatures of hot streams, °C
T_j^{in}	the inlet temperatures of cold streams, °C
T_j^{out}	the target temperatures of cold streams, °C
$T_{\mathrm{HU}}^{\mathrm{in}}$	the inlet temperatures of hot utilities, °C
$T_{\mathrm{HU}}^{\mathrm{out}}$	the outlet temperatures of hot utilities, °C
$T_{\mathrm{CU}}^{\mathrm{in}}$	the inlet temperatures of cold utilities, °C
$T_{\mathrm{CU}}^{\mathrm{out}}$	the outlet temperatures of cold utilities, °C
$dT_{i,j,k}$	temperature approach for match (*i*, *j*) at temperature location *k*, °C
$dT_{\mathrm{CU},i}$	temperature approach for match *i* and cold utility, °C
$dT_{\mathrm{CU},j}$	temperature approach for match *j* and cold utility, °C
$dT_{\mathrm{HU},i}$	temperature approach for match *i* and hot utility, °C
$dT_{\mathrm{HU},j}$	temperature approach for match *j* and hot utility, °C
ΔT_{min}	minimum temperature approach, °C
U	overall heat transfer coefficient, kW/m^2/K
Z	0–1 binary variables representing the fine-search operation
h	individual heat transfer coefficient for streams, kW/m^2/K
$z_{i,j,k}$	0–1 binary variables representing the existence of heat exchangers
$z_{\mathrm{CU},i}$	0–1 binary variables representing the existence of coolers
$z_{\mathrm{HU},j}$	0–1 binary variables representing the existence of heaters
β	exponent for area cost
θ	heat exchange temperature difference of inlet and outlet, °C
ϕ	the probability for fine-search
$\boldsymbol{M}$	heat load matrix of population, kW
$\boldsymbol{Q}$	heat load matrix of each individual, kW

Simultaneous synthesis methods could achieve the optimal solution without problem division and yield better heat exchanger network structures than sequential methods [11]. Simultaneous methods were primarily mixed integer nonlinear programming (MINLP) formulations subject to various simplifying assumptions used to facilitate the solution of the complex models, including the hyper-structure model [12] and stage-wise superstructure (SWS) model [13,14]. The SWS model could accomplish the simultaneous synthesis of match selection, utility and area cost, which could reduce the size of the problem. Therefore, it is still popular nowadays as any potential match can occur among streams at each stage. Furthermore, some improvements have been made on the SWS model in recent years: Björk and Westerlund [15] followed the SWS model, but did not assume isothermal mixing. Huang and Karimi [16] proposed two new superstructures and the corresponding MINLP models, allowing some different configurations. Peng and Cui [17] modified the presentation of SWS model, proposed a flexible utility placement, and allowed substitute infeasible matches with utilities to deal with the infeasibility of heat exchange temperature difference. Short et al. [18] modified the objective function in the MINLP model to consider diverse correction factors such as overall heat transfer coefficients, area correction factors, pressure drops for hot and cold process streams, and the number of shell passes to make the model more closely mirror the designed exchangers. In conclusion, the HEN simultaneous synthesis problem is basically a combinatorial optimization problem containing numerous integer variables, with the objective to reveal a specified structure and heat distribution with an optimal total annual cost (TAC). It was proved to be actually non-deterministic polynomial-time hard (NP-hard) in the strong sense by Furman and Sahinidis [19], therefore it was unknown if there existed a computationally efficient (polynomial) exact solution algorithm for this problem.

Therefore, more stochastic methods without being limited by the non-linearity, non-convexity and discontinuity of the models [20] have been introduced to tackle HENS problems including Tabu Search [21], genetic algorithm (GA) [22,23], differential evolution (DE) algorithm [24], particle swarm optimization (PSO) [25],