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Research Paper

Economic and system reliability optimization of heat exchanger networks using NSGA-II algorithm

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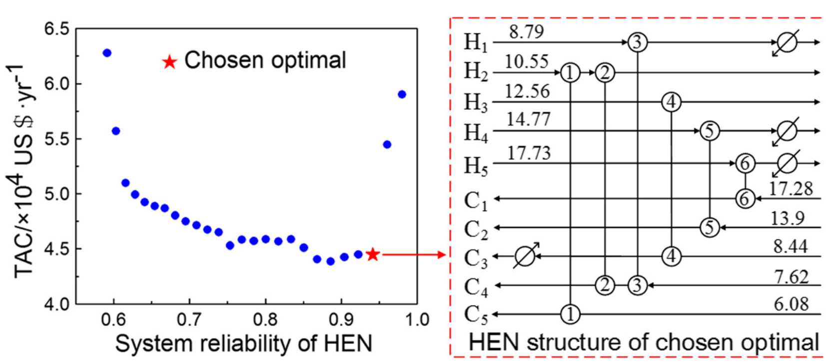
HIGHLIGHTS

- System reliability is incorporated as an objective function into the design of cost-effective HEN.
- NSGA-II is applied in multi-objective optimization of HEN.
- The results of three cases shows the tradeoff between economic and system reliability.

GRAPHICAL ABSTRACT



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ABSTRACT

Optimization of heat exchanger network (HEN) has traditionally been driven by economic objectives. Notwithstanding the importance of minimizing the total annual cost (TAC) of HEN, it is also important to ensure reliability. In order to obtain economical HEN considering system reliability simultaneously, a multi-objective optimization formulation of economic and system reliability is proposed in the design of HEN. A stage-wise superstructure is used to obtain feasible HEN, and the system reliability based on the number of heat exchangers in maximum irrelevant sub-network of HEN and the TAC are calculated as two objective functions. Then the non-dominated sorting genetic algorithm (NSGA-II) is applied to solve the multi-objective optimization mixed integer nonlinear programming model. Three case studies from literatures are used to assess the applicability and performance of the optimization formulation and solution algorithm. The system reliability is enhanced with TAC closes to the reported minimum, which is more meaningful than those obtained using single-objective optimization. The optimal solution set can aid in the selection of a safe and cost-effective network configuration for industrial plants and the proposed approach can easily be applied to include other objectives (e.g., sustainability and safety).

1. Introduction

Heat exchanger network synthesis (HENS) is an important area of research in process system engineering (PSE). Enhanced heat integration leads to conservation of energy resources and

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Nomenclature

Abbreviations

CSM	connection sequence matrix
GHGs	greenhouse gases
HEN	heat exchanger network
HENS	heat exchanger network synthesis (HENS)
HEs	heat exchangers
MISN	maximum irrelevant sub-network
MOO	multi-objective optimization
MOO-MINLP	multi-objective optimization mixed integer nonlinear programming
NSGA–II	non-dominated sorting genetic algorithm
PSE	process system engineering
SOO	single-objective optimization
TAC	total annual cost

Parameters

a	fixed cost of HEs ($\$\cdot a^{-1}$)
A	area of HEs (m^2)
b	heat-exchange area coefficient ($\$\cdot a^{-1}$)
c	heat-exchange area index
c_{cu}	unit cost of cold utility ($\$\cdot a^{-1}$)
c_{hu}	unit cost of hot utility ($\$\cdot a^{-1}$)
fh_i	heat capacity flow rate of hot stream i ($kW\cdot{}^{\circ}C^{-1}$)
$fh_{i,j,k}$	heat capacity flow rate of stage k from hot stream i ($kW\cdot{}^{\circ}C^{-1}$)
fc_j	heat capacity flow rate of cold stream j ($kW\cdot{}^{\circ}C^{-1}$)
$fc_{i,j,k}$	heat capacity flow rate of stage k from cold stream j ($kW\cdot{}^{\circ}C^{-1}$)
i	serial number of hot stream
j	serial number of cold stream
k	Index for stage
n	the number of HEs included by MISN
N_C	number of cold streams
N_H	number of hot streams
N_K	number of stages
TH_{in}, TH_{out}	inlet and outlet temperature of hot stream (K)
TC_{in}, TC_{out}	inlet and outlet temperature of cold stream (K)
$th_{i,k}$	temperature of stage k from hot stream i (K)
$tc_{j,k}$	temperature of stage k from cold stream i (K)
th_{ijk}	temperature of hot stream i in match k (K)
tc_{ijk}	temperature of cold stream i in match k (K)
th_{uj_in}	inlet temperature of hot unility j (K)
th_{uj_out}	outlet temperature of hot unility j (K)
tc_{ui_in}	inlet temperature of cold unility i (K)
tc_{ui_out}	outlet temperature of cold unility i (K)
$q_{i,j,k}$	heat load of match between hot stream i and cold stream j in stage k (kW)
$q_{cu,i}$	condensing heat load of hot stream i (kW)
$q_{hu,j}$	heat load of cold stream i (kW)
z_{ijk}	0–1 variable of whether the HE exists or not
z_{cui}	0–1 variable of whether the cooler exists or not
z_{huj}	0–1 variable of whether the heater exists or not

reduction in emissions especially greenhouse gases (GHGs) [1]. The design of heat exchanger network (HEN) has traditionally been driven by economic objective functions. With the growing interest in developing sustainable design strategies, other objectives (e.g., reliability, environmental impact, and flexibility) should be used in HENS [2].

Because of the high level of interaction among the heat exchangers (HEs) within a HEN and with the increasing complexity of industrial process, reliability is an important issue. Failure of one component within the network will cause temperature changes in associated sub-networks and may create infeasible or sub-optimal operations. Several researchers have considered the reliability of HEN [3–5]. Rad et al. [3] adopted the state-space method, which is suitable for analyzing repairable systems and for integrating the production cost and the utility reliability (increasing repair rate or decreasing failure rate of the system). Sikos and Klemeš [4] proposed a methodology that combines reliability software packages (RAMS) with specific HEN optimization to improve the reliability of HEN. Yi et al. [5] proposed a better method that can use mathematical expressions to estimate the system reliability of HEN by identifying the irrelevant sub-networks, which depend on the connection type of HEs. This computational method is useful but the method Yi et al. [5] adopted to optimize HEN has some drawbacks: (1) the system reliability of HEN is only treated as a constraint but not as an objective and (2) the system reliability is only improved by local HE decoupling method rather than directly generating HEN with higher system reliability. Therefore, such a computational algorithm cannot guarantee the optimality of the results and also requires greater computational efforts. Hence, it is necessary to treat both system reliability and TAC as objective functions and to coordinate the two objectives during HENS.

Mathematical programming approaches for HENS can be classified into single-objective optimization (SOO) and multi-objective optimization (MOO) depending on the number of objective functions. These MOO problems are typically handled either by aggregating the multiple objectives into one or by regarding TAC as an objective while treating the other objectives as constraints. Such approaches rely largely on SOO because the two objectives are only evaluated using quantitative weights or traded off by successively changing the bounds on the constraints for a SOO problem. Yi et al. [5] optimized the TAC of HEN while imposing constraints on system reliability (no less than 0.9). Francesconi et al. [6] applied a MOO ε-constraint algorithm developed in GAMS environment to HENS for ethanol processor, aiming at optimizing both hydrogen production efficiencies and HE area. Results show that a 50% reduction from the maximum area only decreases the efficiency value by 1% with the multi-objective methodology. Kang et al. also adopted ε-constraint algorithm in GAMS to optimize the MOO-HEN model for minimizing TAC and total CO_2 emission, and the model and solution strategy were implemented separately by considering the effect of ΔT_{min} on MOO problems [7], integrating a heat pump to HEN retrofit problems [8] and developing a systematic strategy for multi-period HEN retrofit [9]. Jin et al. [10] aggregated the environmental impact and TAC into a single-objective function using the weighted sum method, in which the annual waste release decreased by 68.07%. Sreepathi and Rangaiah [11] observed that SOO can obtain only theoretically optimal solutions within the various restrictions and requirements of practical operating environment because the multiple indexes of HEN are mutually associated, interactive and restrictive, and then concluded that MOO can optimize multiple objectives simultaneously and the Pareto solution set obtained by MOO can get a trade-off between multiple objectives.

Furthermore, global solution of MOO problems with high level of complexity using traditional methods (weighted sum method [10,12], ε-constraints [13,14], NIMBUS method [15,16], etc.) may be computationally challenging. These traditional MOO algorithms are simple to implement but not sufficient for solving complex