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Research Paper

A specific strategy for determination of feasible domain of heat exchanger networks with no stream splitting and its assessment by application of ACO_R Algorithm

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HIGHLIGHTS

- Theory of feasible domain for HENs with no stream splitting is developed.
- ACO_R are used for HEN synthesis.
- Exchangers are allowed to have any ΔT_{min} greater than a specified value.
- Comparisons are done with other solutions from the literature.
- Application of ACO_R algorithm in the feasible domain provides very good results.

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ABSTRACT

Two of the main obstacles in the procedures for searching of the global optimum answer of an optimization problem are the vast number of local optimums and the complexity of the constraints in the search space of the problem. Most meta-heuristic methods by increasing the exploration of the problem space try to encounter these obstacles. But, by increasing the diversification of the search, the number of infeasible solutions resulting from violation of the constraints increases which leads to enhancement of computational effort. Heat exchanger network optimization problem is known as a problem with complex constraints. In the present work the real feasible domain of the heat exchanger networks with no stream splitting is found while not decreasing the feasible region in order to decrease the computational effort, improve the quality of the final result and to establish a way to compare various results of different algorithms in a fair way. Here, for a specified configuration, after the calculation of feasible domain by the proposed algorithm, the region is sampled by Ant colony optimization in the real number domains to find new exchanger area for a network with specified matches of the streams. Note that, the networks with stream splits will be optimized by removing splits. The examples presented in this work show that the introduced search space is very effective and reduces the computational effort of the optimization algorithm.

1. Introduction

In the last few decades, several methods for heat exchanger network (HEN) synthesis and optimization have been developed which can be categorized into three main groups, pinch design methods or thermodynamic approaches [21,23] mathematical programming methods [9,10,29,38,40] and stochastic methods such as differential evolution [39], genetic algorithms (GAs) [17,18] and Tabu Search (TS) [19].

HEN synthesis problem has been regarded as complex due to the number of structural network alternatives usually available, each being subject to continuous parametric optimization. HENs are usually cast as mixed-integer nonlinear programming (MINLP) models, formulated in terms of continuous variables (i.e. heat-exchanger duties and streams split fractions) and discrete decision variables (i.e. stream matches) [17]. It should be noticed that in HEN synthesis problem the number of variables and equations substantially increases with the number of process streams.

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Nomenclature

A	heat transfer area of heat exchanger (m^2)
C_{CU}	cost of cold utility
C_{HU}	cost of hot utility
dt_{iijj}	temperature approach for match ii and jj
$dt_{ii,CU}$	temperature approach for match ii and cold utility
$dt_{jj,HU}$	temperature approach for match jj and hot utility
FCp	heat capacity flow rate
g	Gaussian function
h	heat transfer coefficient
J	objective function
k	dimension or size of the archive $\|\boldsymbol{T}\| = k$
m	number of (artificial ants) new solution constructed from existing archive
n	number of decision variables in a solution
NC	number of cold streams
NE	number of process heat exchangers
NEHii	number of process heat exchangers on the hot stream ii
NEHjj	number of process heat exchangers on the cold stream jj
NH	number of hot streams
NITA	number of iterations used in the algorithm by ACO_R
P	probability density function
P_j	probability of choosing solution j
Q	heat exchanged between two stream
q	parameter of ACO_R specifying of Locality of the search process
$Q_{ii,CU}$	heat exchanged between stream ii and cold utility
$Q_{jj,HU}$	heat exchanged between stream jj and hot utility
s_j^i	the value of the ith variable of the jth solution
T	temperature
$\boldsymbol{T}$	solution archive
t_{oil}^{finite}	amount of oil temperature that can be cooled to that temperature finitely
U	overall heat transfer coefficient
ΔT_{min}	minimum temperature approach
μ	mean of the Gaussian function
ξ	speed of convergence
σ	standard deviation of the Gaussian function
ω_j	weight associated with solution j.

Superscripts

a	power index in heat exchanger area formula
In	inlet
out	outlet

Subscripts

CU	cold utility
ck	index for heat exchangers on cold stream jj
hk	index for heat exchangers on hot stream ii
HU	hot utility
i	index of problem or solution variables
ii	index for hot process streams
j	index for solution of a problem
jj	index for cold process streams
kk	index for heat exchangers
R	real number domain

Abbreviations

ACO	ant colony optimization
ACO_R	ACO in the real number domain
GA	genetic algorithm
HEN	heat exchanger network
MER	maximum energy recovery
PDF	probability density function
RND	Random Number Distribution
TS	Tabu Search

Although HEN synthesis problem has been one of the most studied problems in process synthesis, until now finding the feasible domains or at least reducing the number of infeasibilities even for small scale HEN problems has not received much attention.

In the design of HENs the infeasibilities may occur in two major steps, firstly in the population of random produced structures and secondly in the random distribution of HEN continuous parameters with positive real numbers.

For example in a random produced structure, matching of a cold stream with higher inlet temperature than its coupled hot stream outlet temperature results in the non-feasibilities at each cross sectional cutting of the rigid structure (two streams are called coupled when they belong to the same exchanger). On the other hand in a feasible random produced structure sampling of random real numbers accounting for all HEN continuous parameters constraints is the major second task in HEN design. This subject has not ever been (apart from some methods with their own disabilities) discussed fundamentally from the start of the HEN synthesis problem.

Lewin et al. [18] suggested a strategy of excessive use of utilities to eliminate the exit temperature constraints and claimed that with this method the randomly generated HENs (individuals) are always feasible because structures with lower heat recovery (namely low fitness) will have a low probability of being selected in the next generation, and vice versa. Also they stated that: (a sufficiently large population size is required in order to guarantee adequate diversity in the feasible set. It is difficult to quantify what is a sufficiently large population size. Fortunately, GA methods are not usually sensitive to the population size provided that the population size is not very small. However, relatively large population sizes have been used [18]. The strategy of excessive use of utilities is also used by Chen et al. [4], Luo et al. [25] and Fieg et al. [8] in order to heat or cool the streams to their target temperatures. But it is very important to note that the strategy of excessive use of utilities do not really prevent producing infeasible random solutions but instead it conducts the population of networks toward the real feasible solution accounted for HEN constraints with a high probability. Because in this method, the structures with lower heat recovery will not be lucky to exist in the next generation, and vice versa. So it seems that Lewin et al.'s method for obtaining feasible solutions is a penalizing strategy which does not provide complete assurance for producing feasible random solutions.

Recently Escobar and Trierweiler [7] developed a new strategy for the initialization of the variables for the synthesis of HENs. Their strategy was developed to converge the nonlinear problems, which was based on the superstructure proposed by Floudas et al. [9]. This approach was applied successfully in order to find an initial feasible solution. This feasible solution provides a good starting point and allows the algorithm to evolve toward the optimum. It should be noticed, as pointed out by the authors, it is possible that sometimes this approach fails to produce complete feasible solution, but all the mass and heat balances will be satisfied by their procedure. And at least this approach will reduce the number of infeasibilities.

Thus, till now, a systematic reliable method has not been proposed which can stand all situations in producing of feasible solutions in HEN design procedure. Researchers in the present work focus on the heart of the HEN design problem in order to find the real feasible domain and thus real bounds for the variables