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Simultaneous synthesis of a heat exchanger network with multiple utilities using utility substages

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ABSTRACT

Heat exchanger network synthesis (HENS) has progressed by using mathematical programming-based simultaneous methodology. Although various considerations such as non-isothermal mixing and bypass streams are applied to consider real world alternatives in modeling phase, many challenges are faced because of its properties within non-convex mixed-integer nonlinear programming (MINLP). We propose a modified superstructure, which contains a utility substage for use in considering multiple utilities in a simultaneous MINLP model. To improve model size and convergence, fixed utility locations according to temperature and series connections between utilities are suggested. The numbers of constraints, discrete, and continuous variables show that overall model size decreases compared with previous research. Thus, it is possible to expand the feasible search area for reaching the nearest global solution. The model's effectiveness and applications are exemplified by several literature problems, where it is used to deduce a network superior to that of any other reported methodology.

1. Introduction

In the last half-century, optimization of process synthesis with process integration has been applied in most important fields of research and industry for increasing price competitiveness. In particular, there has been a focus on heat exchanger network synthesis (HENS) designed for energy integration of utilities and process streams. A significant portion of annualized cost, which includes capital cost and operating cost, can be minimized by HENS. One of the main approaches with HENS is the sequential method, which applies heuristics or physical intuitions for dividing a problem into subproblems; this method involves evolutionary design methodologies represented by the pinch technology (Linnhoff and Hindmarsh, 1983), dual temperature (Wood et al., 1991), and pseudo-pinch methods (Rev and Fonyo, 1986) and mathematical programming for solving several subproblems containing continuous and discrete problems (Floudas et al., 1986). The other is the simultaneous method, which solves the problem using mathematical programming techniques such as mixed-integer nonlinear programming (MINLP) without dividing a problem (Furman and Sahinidis, 2002). Recently, HENS has developed to the point of achieving optimal solutions not only mathematically but also in reality; for instance, addressing uncertainty, non-isothermal mixing, and bypass streams (Dipama et al., 2008; Huang et al., 2012). Thus, the research trend is focused on generalizing and expanding HENS models, which combine the optimization of simultaneous methods with the heuristics and realistic factors of sequential methods while reaching the optimum in a feasible amount of computing time.

In general processes, multiple utilities should be considered for generating optimal networks. To illustrate this, a steam cycle with a CO_2 post-combustion capture process can use various low-pressure, medium-pressure, and high-pressure (LP, MP, and HP) utilities as heat sources for stripping columns, decrease reboiler stream cost relative to using just a single utility. Furthermore, using various working fluids in an organic Rankine cycle can reduce irreversibilities, decreasing compressor operating costs. However, most conventional HENS models cannot synthesize networks with multiple utilities because they consider a single utility when composing the HEN (Yee and Grossmann, 1990).

HENS that consider multiple utilities were allegedly developed in several projects related to graphical techniques in the sequential method and mathematical techniques in the simultaneous method. In the sequential method field, Shenoy et al. (1998) proposed a multiple-utility model based on the pinch method. Total annual cost (TAC) is minimized by calculating the optimal minimum approach temperature and utility combination. Other graphical technique research considers stream temperature versus enthalpy plot supertargeting (STEPS) for optimizing the minimum approach temperature (Sun et al., 2013). For utility targeting in the

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Nomenclature

$A_{i,j,k}$	heat exchanger area of hot stream *i* and cold stream *j* at stage *k*
$Acu_{i,k,n}$	heat exchanger area of cold utility *n* and hot stream *i* at stage *k*
$Ahu_{j,k,m}$	heat exchanger area of hot utility *m* and cold stream *j* at stage *k*
$C_{i,j}$	area cost coefficient of heat exchanger
$CC_{i,n}$	area cost coefficient of cold utility
CCU_n	per unit cost of cold utility
$CF_{i,j}$	fixed cost of process stream heat exchanger
$CFC_{i,n}$	fixed cost of cold utility heat exchanger
$CFH_{j,m}$	fixed cost of hot utility heat exchanger
$CH_{j,m}$	area cost coefficient of hot utility
CHU_m	per unit cost of hot utility
CP	set of cold process stream
CU	set of cold utilities
CU'	expanded set of cold utilities
$dtcu_{i,k,n}$	temperature approach for matching hot stream *i* and cold utility at stage *k*
$dthu_{j,k,m}$	temperature approach for matching hot utility and cold stream *j* at stage *k*
$dtl_{i,j,k}$	left: temperature approach for matching stream *i* and *j* at stage *k*
$dtr_{i,j,k}$	right: temperature approach for matching stream *i* and *j* at stage *k*
EMAT	minimum approach temperature
F_i	heat capacity flow rate of hot stream
F_j	heat capacity flow rate of cold stream
h_i	heat transfer coefficient for hot stream *i*
h_j	heat transfer coefficient for cold stream *j*
h_m	heat transfer coefficient for hot utility *m*
h_n	heat transfer coefficient for cold utility *n*
HP	set of hot process stream
HU	set of hot utilities
HU′	expanded set of hot utilities
$LMTD_{i,j,k}$	Chen's log-mean temperature difference
$LMTDP_{i,j,k}$	Paterson's log-mean temperature difference
M	total heat contents of stream
NOK	number of stages
NOM	number of hot utilities
NON	number of cold utilities
$q_{i,j,k}$	heat exchanged between process stream *i* and *j* at stage *k*
$qcu_{i,k,n}$	heat exchanged between hot utility and cold stream *j* at stage *k*
$qhu_{j,k,m}$	heat exchanged between hot stream *i* and cold utility at stage *k*
ST	set of stages in the superstructure
ST′	expanded set of stages in the superstructure
$tc_{j,k,m}$	temperature of hot stream *j* at stage *k* and utility substage *m*
$th_{i,k,n}$	temperature of hot stream *i* at stage *k* and utility substage *n*
$TINcu_m$	inlet temperature of cold utility
$TINhu_n$	inlet temperature of hot utility
TIN_i	inlet temperature of hot stream
TIN_j	inlet temperature of cold stream
$TOUTcu_m$	outlet temperature of cold utility
$TOUThu_n$	outlet temperature of hot utility
$TOUT_i$	outlet temperature of hot stream
$TOUT_j$	outlet temperature of cold stream
$z_{i,j,k}$	binary variable denoting existence of heat exchanger between stream *i* and *j*
$zcu_{i,j,n}$	binary variable denoting existence of heat exchanger between stream *i* and cold utility *n*
$zhu_{j,k,m}$	binary variable denoting existence of heat exchanger between stream *j* and hot utility *m*

Greek symbols

β	exponent for heat exchanger area cost
βcu	exponent for heat exchanger area cost for cold utility
βhu	exponent for heat exchanger area cost for hot utility
γ	upper bound for temperature difference
θ	the maximum number of multiple utilities

Subscripts

i	hot stream
j	cold stream
m	hot utility
n	cold utility
k	subscripts for the stages

sequential method, a non-graphical procedure using rigorously calculated process stream thermodynamic properties was suggested (Castier, 2012) in order to consider realistic situations. These kinds of sequential models have the advantages of simple calculations, intuitive graphical visualization, and industrial feasibility. However, they contain the critical limitations inherent to sequential methods: inability to consider heat flows cross the pinch point and lack of a guarantee of a globally optimal network.

In the simultaneous methods field, Isafiade and Fraser (2008) suggested an interval-based MINLP model with multiple utilities, but the assumption of fixed utility end site superstructure could not be surmounted. Moreover, by expanding stagewise superstructure, the modified model could place utilities anywhere else (Ponce-Ortega et al., 2010). The proposed superstructure has new splitting streams, which involve multiple utilities in each conventional stage. Although modified HENS implements optimization with multiple utilities, it is hard to converge in many stages and analyzing a structure that contains subsequently arranged utilities is difficult because of inefficient superstructure geometry. Huang and Karimi (2013a,b) introduced generalized stagewise superstructure with cross flows and the model could calculate multiple utilities optimal network. However, even with the four utility simplification constraints, the problem had numerous discrete variables and constraints, which hampered calculations. Thus, in some examples, they set the time limitation on a solver related to global solver concepts such as BARON.

In this work, a new methodology is presented for solving HENS considering multiple utilities by using utility substages. The most important problems in previous methods, namely a search area too large to find an optimal solution in a feasible amount of computing time and inefficient superstructure network, can be solved by using a modified superstructure. Using the utility substage concept, series connection of multiple utilities can be taken into account in one stage. Also, fixing positions of utilities heuristically in order of temperature in the modified superstructure can decrease the number of discrete variables. A reduced model size results and can enhance solution quality in the same number of stages or less compared to previous models.