Chemical Engineering Science 173 (2017) 537–559

Contents lists available at ScienceDirect

Chemical Engineering Science

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

New transshipment type MINLP model for heat exchanger network synthesis

Xiaodong Hong, Zuwei Liao *, Binbo Jiang, Jingdai Wang, Yongrong Yang

State Key Laboratory of Chemical Engineering, College of Chemical and Biological Engineering, Zhejiang University, Hangzhou, Zhejiang 310027, PR China

HIGHLIGHTS

- A novel MINLP model for simultaneous design of HEN is presented.
- Non-isothermal mixing, stream by-pass, and recycling flows are all included while keeping all constraints linear.
- A more accurate formulation for heat exchanger area is proposed by piecewise calculation.
- Better results are obtained for several literature examples.

ARTICLE INFO

Article history:
Received 5 December 2016
Received in revised form 5 June 2017
Accepted 8 August 2017
Available online 9 August 2017

Keywords:
MINLP
Transshipment model
Linear constraints
Heat exchanger networks
Multiple utilities

ABSTRACT

Heat exchanger network (HEN) is one of the most important parts in chemical process industry, owing to its significant advantages of energy recovery. However, models with plentiful HEN structures always result in complex mixed-integer nonlinear programming (MINLP) models with non-convexity of nonlinear constraints, which will cause heavy computational burdens. The computational time of MINLP models and even the feasibility of models without good initial points are still challenging researchers. This paper presents a novel transshipment type model for heat exchanger network synthesis (HENS), which is formulated as a MINLP problem with all linear constraints. Stream splitting, stream by-pass, isothermal and non-isothermal mixing, and recycling flows are all included, while multiple utilities are available in the model. Furthermore, new formulations are presented to calculate the temperature difference of heat exchangers, while a more precise heat exchanger area calculation method by piecewise calculation is developed in the new model. Six literature examples are presented to illustrate the effectiveness and applicability of the proposed model. It is shown that several better results are obtained by the proposed model.

1. Introduction

Process industry is an energy intensive industry. Owing to the rising prices of fossil fuels as well as more and more strict environmental regulations, process industry is looking for effective ways of improving their energy efficiency. Over the past four decades, heat integration which is related to heat exchanger network synthesis (HENS) is recognized as an effective way of energy recovery in both practice and research. Many methodologies have been developed for the optimal synthesis of heat exchanger network (HEN). Comprehensive reviews about HENS can be found in Gundersen and Naess (1988), Jezowski (1994a, b), and Furman and Sahinidis (2002).

The methodologies of HEN synthesis can be classified into two types: pinch technology and mathematical programming methodologies. Pinch technology is essentially a heuristic design approach derived from physical insights. Umeda et al. (1978) and Linnhoff and Flower (1978a, b) firstly identified the heat recovery pinch point. Linnhoff and Hindmarsh (1983) proposed the pinch design method (PDM). The design problem was divided into subproblems by pinch point. Subsequently, several work (Ahmad et al., 1990; Linnhoff and Ahmad, 1990; Townsend, 1984) based on pinch technology was presented to target the heat exchanger surface area, the energy, and the capital cost. Recently, a T-Q diagram method (Kang et al., 2016) based on the partition and merging of intervals was proposed for large-scale heat exchanger network synthesis.

Mathematical programming methods for HENS include sequential methods and simultaneous methods. Sequential synthesis methods divide the HENS problem into several subproblems, which generally include the minimum utility usage, the minimum number of exchanger units, and the minimum area cost of the network. Cerda and Westerburg (1983) formulated a linear programming (LP) problem to obtain the utility target using the transportation problem formulations. With the utility target, a

* Corresponding author.
E-mail address: liaozw@zju.edu.cn (Z. Liao).

http://dx.doi.org/10.1016/j.ces.2017.08.013
0009-2509/

Nomenclature

Subscript

e heat exchanger including heater and cooler
k, k' temperature interval
l, l' hot stream
ls, ls' hot stream substream
m, m' cold stream
ms, ms' cold stream substream
n, n' temperature level

Sets

C cold stream, H=CP∪CU, C=(m|m=1,2,3…M)
C_k cold stream in temperature interval k, $C_k \subset C$
CMS cold substream, CLS=((m,ms)|m∈C,ms∈MS,(m,ms)=(1,1),(2,1)…)
EX heat exchangers between a hot process substream and a cold process substream, EX=(e|e=1,2,3…,E)
H hot stream, H=HP∪HU, H=(l|l=1,2,3…L)
H_k hot stream in temperature interval k, $H_k \subset H$
HU hot utility, HU ⊂H
HP hot process stream, HP ⊂H
HLS hot substream, HLS=((l,ls)|l∈H,ls∈LS,(l,ls)=(1,1),(2,1)…)
LS substream of hot stream, LS=(ls|ls=1,2,3…)
MS substream of cold stream, MS=(ms|ms=1,2,3…)
TL temperature level, TL=(n|n=1,2,3…,N), N=K+1
TI temperature interval, TI=(k|k=1,2,3…,K)

Positive variables

cu_m cold utility m consumption, kW
CUC cold utility cost, $
$dt_{l,ls,m,ms,k}$ temperature difference of heat transfer match, K
$dthu_m$ temperature difference of heat transfer match for hot utility L, K
$dtcu_l$ temperature difference of heat transfer match for cold utility M, K
EXC exchanger cost, $
EXS sum of heat exchangers including heaters and coolers
$flr_{l,ls',n',ls,n}$ recycling mass flow from l,ls',n' to l,ls,n, kg/s
$flsk_{l,ls,k}$ flowrate of hot substream l,ls in temperature interval k, kg/s
$fmr_{m,ms',n',ms,n}$ recycling mass flow from m,ms',n' to m,ms,n, kg/s
$fmsk_{m,ms,k}$ flowrate of cold substream m,ms in temperature interval k, kg/s
hu_l hot utility l consumption, kW
HUC hot utility cost, $
$q_{l,ls,m,ms,k}$ heat load of heat exchanger between hot stream substream (l,ls) and cold stream substream (m,ms) in temperature interval k, kW
$qq_{l,ls,m,ms,k,e}$ heat load of heat exchanger e between hot stream substream (l,ls) and cold stream substream (m,ms) in temperature interval k, kW
$rqhs_{l,ls,n}$ residual energy of hot process substream l,ls in temperature level n, kW
$rqhs'_{l,ls,n}$ residual energy of hot process substream l,ls in temperature level n, kW
$rqcs_{m,ms,n}$ residual energy of cold process substream m,ms in temperature level n, kW
$rqcs'_{m,ms,n}$ residual energy of cold process substream m,ms in temperature level n, kW
TAC total annual cost, $
$til_{l,ls,k}$ inlet temperature of hot substream l,ls in temperature interval k, K
$tim_{m,ms,k}$ inlet temperature of cold substream m,ms in temperature interval k, K
$tol_{l,ls,k}$ outlet temperature of hot substream l,ls in temperature interval k, K
$tom_{m,ms,k}$ outlet temperature of cold substream m,ms in temperature interval k, K

Binary variable

$mlsk_{l,ls,n}$ existence of exporting mass flow from temperature level n of hot substream l,ls
$mmsk_{m,ms,n}$ existence of exporting mass flow from temperature level n of cold substream m,ms
zzc_l existence of a cooler for hot stream l in the last temperature interval K
zzh_m existence of a heater for cold stream m in the first temperature interval 1
$z_{l,ls,m,ms,k}$ existence of a heat transfer match between hot substream l,ls and cold substream m,ms in temperature interval k
$zlsk_{l,ls,n}$ existence of importing mass flow to temperature level n of hot substream l,ls
$zmsk_{m,ms,n}$ existence of importing mass flow to temperature level n of cold substream m,ms
$zz_{l,ls,m,ms,k}$ existence of the heat exchanger between hot substream l,ls and cold substream m,ms in temperature interval k
$zzs_{l,ls,m,ms,k}$ sum of $zz_{l,ls,m,ms,k}$ from k=1 to k
$x_{l,ls,m,ms,k,e}$ indicator to estimate whether $zzs_{l,ls,m,ms,k}$ is equal to e

Parameters

A annualized area cost coefficient for heat exchanger
B area cost exponent for heat exchanger
CCU per unit cost for cold utility, $/(kW yr)
CHU per unit cost for hot utility, $/(kW yr)
CL_m total heat load of cold process stream m, kW
$CLK_{m,k}$ available heat load of cold stream m in temperature interval k, kW
c_p heat capacity of water, kJ/(kg K)
E maximum number of heat exchangers between hot process substream l,ls and cold process substream m,ms
FC fixed charge for heat exchanger, $
fl_l flowrate of hot process stream l, kg/s
fm_m flowrate of cold process stream m, kg/s
HL_l total heat load of hot process stream l, kW
$HLK_{l,k}$ available heat load of hot stream l in temperature interval k, kW
$MRL_{l,n}$ maximum residual energy of hot stream l in temperature level n, kW
$MRM_{m,n}$ maximum residual energy of cold stream m in temperature level n, kW
ne_l ending temperature level of hot stream l, ne_l∈TL
ne_m starting temperature level of cold stream m, ne_m∈TL
ns_l starting temperature level of hot stream l, ns_l∈TL
ns_m starting temperature level of cold stream m, ns_m∈TL
tce_m ending temperature of cold stream m, K
tcs_m starting temperature of cold stream m, K
the_l ending temperature of hot stream l, K
ths_l starting temperature of hot stream l, K
tn_n temperature of temperature level n, K
$U_{l,m}$ heat transfer coefficient, kW/(m^2 K)
$\Omega_{l,m,k}$ upper bound for heat load of heat transfer matches between hot stream l and cold stream m in temperature interval k, kW