Energy Conversion and Management 74 (2013) 60–69

Contents lists available at SciVerse ScienceDirect

Energy Conversion and Management

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

Mathematical programming model for heat exchanger design through optimization of partial objectives

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ARTICLE INFO

Article history:
Received 20 March 2013
Accepted 1 May 2013
Available online 31 May 2013

Keywords:
Mathematical programming
Mixed integer non-linear programming (MINLP)
Heat exchanger design
Shell-and-tube heat exchanger (STHE)
Sequential optimization

ABSTRACT

Mathematical programming can be used for the optimal design of shell-and-tube heat exchangers (STHEs). This paper proposes a mixed integer non-linear programming (MINLP) model for the design of STHEs, following rigorously the standards of the Tubular Exchanger Manufacturers Association (TEMA). Bell–Delaware Method is used for the shell-side calculations. This approach produces a large and non-convex model that cannot be solved to global optimality with the current state of the art solvers. Notwithstanding, it is proposed to perform a sequential optimization approach of partial objective targets through the division of the problem into sets of related equations that are easier to solve. For each one of these problems a heuristic objective function is selected based on the physical behavior of the problem. The global optimal solution of the original problem cannot be ensured even in the case in which each of the sub-problems is solved to global optimality, but at least a very good solution is always guaranteed. Three cases extracted from the literature were studied. The results showed that in all cases the values obtained using the proposed MINLP model containing multiple objective functions improved the values presented in the literature.

1. Introduction

Optimal heat recuperation is fundamental in solving the problem of efficient energy usage and consequently to promote the reduction of gas emissions and fuel consumption. Since nearly 80% of the total energy consumption is related to heat transfer, improvement on heat transfer performance is of great significance to the reduction of the energy consumption [1–4]. In this perspective, heat exchangers are one of the most efficient types of heat transfer equipment used to recover heat between two process fluids [5,6]. Shell-and-tube heat exchangers (STHEs) are widely used in industrial chemical processes, plants, power and process industries because of their great adaptability to different operational conditions, strength characteristic and design flexibility. However, the design of STHEs, including thermodynamic and fluid dynamic design, cost estimation and optimization, is a complex process involving the integration of design rules and empirical knowledge from several areas, especially for the shell-side that presents complex characteristics of heat transfers and pressure drop [7].

The design of STHEs involves the determination of a large number of thermal–hydraulic and operative variables for obtaining the optimum geometry, satisfying the required amount of heat and the set of constraints imposed by the process [6,7]. In the last decade, due to the important role developed by the STHEs within the industrial context, a considerable research effort has been devoted to solving the optimization problem of this type of equipment. Thus, several researchers used different optimization techniques: i.e. genetic algorithms [8–11], particle swarm optimization [6], and mathematical programming [7,12–14], to improve the design of this type of heat exchangers by optimizing different objectives like the annual cost, including area expenses and/or pumping costs [6,7,9,12–14] or entropy generation [11,15,16]. Other studies have been dedicated to the optimization of a single geometric parameter, such as the spacing of baffles [17,18], or a variety of geometric and operational parameters of STHEs [19].

Different design methods have also been proposed. The first method for determining the thermal–hydraulic parameters, heat exchange area, heat transfer coefficients and pressure drop was published by Kern [20]. The method of Kern was developed for designing heat exchangers or to evaluate existing equipment with regard to pressure drop and fouling. In this method, correlations were obtained based on equivalent diameter, overestimating the design parameters for the shell-side [7]. According to Taborek [21], the method of Bell–Delaware provides more realistic and

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http://dx.doi.org/10.1016/j.enconman.2013.05.011

Nomenclature

A	heat exchange area
a_c	cost constant
arr	tube arrangement
b_c	cost constant
c_c	pumping cost constant
Cp	heat capacity
dex	tube external diameter
din	tube internal diameter
$Dotl$	tube bundle diameter
Ds	shell external diameter
Fc	fraction of total tubes in cross-flow
fl	Fanning's factor
$Fsbp$	fraction of cross-flow area available for bypass
Ft	correction factor of LMTD
h_0i	shell-side heat transfer coefficient for an ideal tube bank
h^s	shell-side film coefficient
h^t	tube-side film coefficient
Jb	correction factor for bundle-bypassing effects
Jc	correction factor for baffle configuration effects
ji	Colburn's factor
Jl	correction factor for baffle-leakage effects
L	tube length
lc	baffles cut
$LMTD$	log mean temperature difference
ls	baffle spacing
m	mass flowrate
Nb	number of baffles
Nc	number of tube rows crossed in one cross-flow section
Ncw	number of tube columns effectively crossed in each window
N_S	number of shells
Nt	number of tubes
Ntp	number of tube passes
Nu	number of Nusselt
C_{area}	area cost
C_{pump}	pumping cost
C_{total}	total cost
Pr	number of Prandtl
pn	tube pitch normal to flow
pp	tube pitch parallel to flow
pt	tube pitch
Q	heat duty

Rb	pressure drop correction factor for bundle-bypassing effects
Re	Reynolds number
rd	fouling factor
Rl	pressure drop correction factor for baffle-leakage effects
Sm	reference normal area for shell-side flow
Ssb	shell-to-baffle leakage
Stb	area tube-to-baffle leakage
Sw	area for one baffle area flow thought the window
T	temperature
Uc	clean overall heat transfer coefficient
Ud	dirty overall heat transfer coefficient
v	fluid velocity
y^f	binary variable which defines the fluid allocation
y^L	binary variable which defines the tube length
y^{arr}	binary variable which defines tube pattern arrangement
y^{nt}	binary variable which defines the variables of Table 1
ε	roughness
ΔP	pressure drop
ΔP_{bi}	pressure drop for ideal cross-flow
ΔP_{wi}	pressure drop for the window
k	thermal conductivity
μ	viscosity
ρ	density

Acronyms

GAMS	general algebraic modeling system
GDP	generalized disjunctive programming
MILP	mixed integer linear programming
MINLP	mixed integer non-linear programming
NLP	non-linear programming
STHE	shell-and-tube heat exchanger
TEMA	tubular exchanger manufacturers association

Subscript

c	cold fluid
h	hot fluid
s	shell-side
t	tube-side
in	inlet
out	outlet

accurate results for the shell-side concerning the heat transfer coefficients and pressure drop, due to the consideration of five different streams (i.e. leakages between tubes and baffles, bypass of the tube bundle without cross flow, leakages between shell and baffles, leakages due to more than one tube pass and the main stream and tube bundle cross flow), that were not taken into account in the method of Kern [20]. These streams do not occur in well-defined regions, but interact between them, needing a complex mathematical treatment to represent the real shell-side flow.

In a previous study, Mizutani et al. [12] presented an optimization procedure for the design of STHEs using the Bell–Delaware Method for calculating the heat transfer coefficients and pressure drop to the shell-side. The authors used generalized disjunctive programming (GDP) for problem formulation and a MINLP reformulation for its solution. The model did not follow the TEMA standards [22], thus some characteristics as number of tubes and tube bundle diameter, which are calculated and optimized, may not conform to the standards. In Ravagnani and Caballero [7], the Bell–Delaware Method is used to formulate a mathematical model involving continuous and discrete variables for selection of an optimal configuration of a shell-and-tube heat exchanger. Just as in Mizutani et al. [12], the model is based on GDP and is optimized with a MINLP formulation, but in this case rigorously following all the TEMA standards, it was possible to find all the mechanical characteristics such as shell diameter, tube bundle diameter, tube external diameter, tube pitch, arrangement of tubes, number of tube passes and number of tubes.

The use of a detailed process model results in a highly non-convex MINLP problem. It is important to remark that even the best state of the art deterministic solvers cannot guarantee the global optimal solution. As the probability of the solution to become trapped in a local optimum is large, it is of interest to study other optimization strategies avoiding such a situation. This paper presents a computer-aided approach for STHEs thermal and hydraulic design, based on the Bell–Delaware Method to formulate a MINLP model for the selection of the optimum equipment configuration. The proposed model follows rigorously the TEMA standards [22], has been optimized using mathematical programming and solved with the software GAMS. A new approach of sequential optimization was developed through the use of diverse objective targets.