Applied Thermal Engineering 58 (2013) 605–614

Contents lists available at SciVerse ScienceDirect

Applied Thermal Engineering

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

Optimal allocation of cleanings in heat exchanger networks

Bruna C.G. Assis [a,1], Julia C. Lemos [a], Eduardo M. Queiroz [b], Fernando L.P. Pessoa [b], Fábio S. Liporace [c], Sérgio G. Oliveira [c], André L.H. Costa [a,*]

[a] Rio de Janeiro State University (UERJ), Rua São Francisco Xavier, 524, Maracanã, CEP 20550-900 Rio de Janeiro, RJ, Brazil
[b] Federal University of Rio de Janeiro (UFRJ), Avenida Athos da Silveira Ramos, 149, Cidade Universitária, CEP 21941-909 Rio de Janeiro, RJ, Brazil
[c] PETROBRAS/CENPES, Avenida Horácio Macedo, 950, Cidade Universitária, CEP 21949-900 Rio de Janeiro, RJ, Brazil

HIGHLIGHTS

- This paper addresses the optimization of cleanings in heat exchanger networks.
- The optimization problem corresponds to a mixed-integer linear programming.
- The solution allows a reduction in energy consumption during the network operation.

ARTICLE INFO

Article history:
Received 13 October 2012
Accepted 25 April 2013
Available online 6 May 2013

Keywords:
Fouling
Heat exchanger networks
Cleaning
Optimization

ABSTRACT

This paper addresses the identification of the optimal set of heat exchangers to be cleaned during a plant maintenance shutdown. The proposed methodology is based on the resolution of a mixed-integer linear programming problem which allows the identification of the cleaning requirements aiming to reduce costs during the interval between scheduled plant shutdowns. The linear structure of the proposed formulation avoids problems associated to multiple local optima, and the resultant problem dimension allows the analysis of large heat exchanger networks without excessive computational efforts. The application of the proposed approach is illustrated through the investigation of two heat exchanger networks. The first example explores some typical cleaning patterns and the other example demonstrates the utilization of the proposed approach applied to a real network.

1. Introduction

Heat exchanger fouling is the undesirable accumulation of deposits over the heat transfer surface of thermal equipment. This phenomenon reduces the overall heat transfer coefficient and hence decreases heat exchangers effectiveness. Therefore, fouling is associated with several economic penalties for process plants, affecting operational costs (e.g. increase in energy consumption) and capital costs (e.g. demand of larger thermal equipment).

In order to restore heat loads in heat exchangers affected by fouling, it is necessary to clean the thermal surfaces periodically. There are several available cleaning techniques, employing chemical and/or physical agents [1]. The performance monitoring of heat exchangers can supply valuable data for determination of the period between heat exchanger cleanings [2].

Considering the resources necessary for cleaning activities (manpower, cranes, chemicals, etc.) and the increased utility consumption due to an off-line heat exchanger (if the cleaning is conducted during the plant operation), the establishment of the best moment to clean a heat exchanger becomes a trade-off problem. This task may assume a considerable complexity in heat exchanger networks, which can have a large number of different units.

Several papers in the literature addressed this problem through the analysis of the cleaning schedule optimization of a heat exchanger network during plant operation. The mathematical techniques employed encompass mathematical programming [3–7] and stochastic methods [8,9], where the main system investigated was the fouling mitigation in crude preheat trains of petroleum refineries.

In the early 2000s, Georgiadis and Papageorgiou [3] used mathematical programming for solving the schedule optimization of heat exchanger network cleanings employing a mixed-integer linear programming (MILP) formulation. Avoiding linearizations which could cause inaccuracies, Smaïli et al. [4] proposed a mixed-

* Corresponding author. Tel.: +55 2181052084.
E-mail address: andrehc@uerj.br (A.L.H. Costa).
[1] Present address: Petróleo Brasileiro S.A. (PETROBRAS), Avenida Horácio Macedo, 950, Cidade Universitária, CEP 21949-900 Rio de Janeiro, RJ, Brazil.

1359-4311/$ – see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.applthermaleng.2013.04.043

Nomenclature

A	heat exchanger area (m^2)
c	linear model fouling rate (m^2 K/J)
C_C	cleaning costs ($)
Cop	utility costs ($/J)
Cp	stream heat capacity (J/(kg K))
CP	network inlet/outlet stream heat capacity (J/(kg K))
CR	ratio between heat capacity flow rates (dimensionless)
CSTR	subset of cold streams
D_e	outer tube diameter (m)
D_i	inner tube diameter (m)
DS	subset of desalters
fobj	objective function ($)
h	film coefficient (W/(m^2 K))
HE	subset of heat exchangers
HSTR	subset of hot streams
i	interest rate
k_w	thermal conductivity of the tube wall (W/(m K))
LT	lower bound on the stream temperatures (°C)
m	stream mass flow rate (kg/s)
MX	subset of mixers
n	network inlet/outlet mass flow rate (kg/s)
np	number of past periods
N_{max}	maximum allowable number of cleanings
NTU	number of transfer units (dimensionless)
p	weights of the numerical integration procedure
P	effectiveness (dimensionless)
PD	subset of demand units
PS	subset of supply units
Q	heat load (W)
R_f	fouling resistance (m^2 K/W)
R_f^∞	asymptotic fouling resistance (m^2 K/W)
$R_{f,0}$	fouling resistance at the plant shutdown (m^2 K/W)
s	present worth factor
S	subset of streams
SP	subset of splitters
STR	set of edges
t	time (s)
T	stream temperature (°C)
TI	set of time instants
U	overall heat transfer coefficient (W/(m^2 K))
UT	upper bound on the stream temperatures (°C)
V	network inlet/outlet temperature (°C)
VET	set of vertices
y	binary variable which indicates if a heat exchanger must be cleaned or not
yc	variable associated to a bilinear term of the cold streams
yh	variable associated to a bilinear term of the hot streams

Greek symbols

α	split fraction
Δ	temperature difference in the desalter (°C)
τ_f	asymptotic fouling rate model parameter (s)

Subscripts

c	cold stream
h	hot stream
i	inlet
o	outlet
in	edges into a vertex
out	edges from a vertex
ref	temperature reference
k	index of the edges (process streams)
k'	alias of index k
k''	alias of index k
t	index of the vertices (network elements)
tube	tube-side
shell	shell-side
τ	index of time instants

Superscripts

spe	specification
c	clean
d	dirty
yes	cleaning
no	no cleaning

integer nonlinear programming (MINLP) formulation for the identification of the optimal cleaning schedule. Later, Lavaja and Bagajewicz [5] showed that the same problem could be described using a MILP formulation, which could also be extended to include throughput loss considerations [6] and financial risks [7]. A comparison between the utilization of mathematical programming and a stochastic method was explored by Smaïli et al. [8]. A stochastic optimization method was also employed by Rodriguez and Smith [9] for exploring the manipulation of heat exchanger bypasses during the optimization of the cleaning schedule. More recently, further investigations included additional aspects of the problem, such as, the impact of the desalter unit [10] and the inclusion of the aging of the fouling deposits in the model [11].

However, fouling management based on cleaning schedules without entire network shutdown may not be feasible for several reasons: inexistence of bypasses, impossibility to keep the process variables within acceptable ranges with off-line heat exchangers, capacity limitations in final heaters and/or coolers, manpower limitations, etc. In these cases, the cleaning activities are limited to major maintenance shutdowns, where a large number of interventions are carried out simultaneously: catalyst inventory replacement, equipment inspections, etc. Expressive costs associated with the production interruption impose that maintenance shutdowns must be planned carefully and executed efficiently in order to reach the expected performance improvements without extra penalties due to delays [12]. Therefore, if the unique opportunity for heat exchanger cleanings is during a maintenance plant shutdown, the engineering staff must be able to select a proper set of heat exchangers to be cleaned.

Despite existent procedures for the optimization of heat exchanger cleaning schedules [3–9] could also be adapted for the selection of cleanings in maintenance shutdowns, the exploration of the particularities of this problem would allow the development of more efficient solution schemes.

In this context, the objective of this paper is to present a solution for the identification of the optimal set of units to be cleaned during a heat exchanger network shutdown. The optimization formulation consists of a mixed-integer linear programming problem, which avoids problems related to nonconvexities (e.g. selection of adequate initial estimates and existence of multiple local optima). The proposed formulation can be employed to networks with any pattern of interconnection among heat exchangers, such as, series or parallel alignments, presence of loops, etc. Additionally, there are no limitations in relation to heat exchanger configurations (countercurrent, crossflow, multipass, etc.), without using artificial linearizations of heat exchanger equations.