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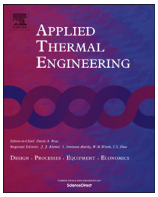

Heuristic optimization of the cleaning schedule of crude preheat trains

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HIGHLIGHTS

- A new optimization method for the cleaning schedule of crude preheat trains is discussed.
- The method is based on a heuristic algorithm using a greedy approach.
- The application of the method to examples from the literature showed competitive results.

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ABSTRACT

This paper addresses the optimization of cleaning schedules of heat exchangers in crude preheat trains in petroleum refineries. The optimization approach is based on a heuristic scheme composed of a set of movements according to a greedy rationale. Each evaluation of the objective function demands the simulation of the behavior of the crude preheat train during the investigated time horizon. The optimization scheme can be employed using two alternatives: a basic and a recursive heuristic algorithm, where the recursive option can obtain better solutions, but demanding higher computational efforts. The proposed optimization approach does not present nonconvergence problems and does not demand any special attention related to control parameters tuning. The proposed approach was applied to three examples of cleaning schedule optimization problems from the literature. The solutions obtained present values of objective function better or very near to the best solution previously reported.

1. Introduction

Crude preheat trains (CPTs) are heat exchanger networks in refineries which promote energy integration among the crude oil stream, the side-products and the pumparounds of atmospheric distillation columns. These petroleum refining columns are responsible for separating the crude oil in a set of hydrocarbon fractions according to their different boiling points [1]. The energy integration scheme provided by the CPTs supplies nearly 60–70% of the energy demand of the crude oil distillation process. The remaining energy demand is provided by heat released from fired heaters, which must heat the crude oil stream to about 380 °C [2].

During the operation of a CPT, the heat exchangers are affected by the accumulation of deposits over their thermal surface. The nature of these deposits depends on the position of the heat exchanger along the CPT. Heat exchangers located upstream of the desalter are more affected by particulate matter and salts, while heat exchangers located downstream of the desalter are more affected by chemical reaction fouling from the presence of asphaltenes. Corrosion products may be found along the entire train [3].

Independently of the origin of the deposit, the resultant fouling process continuously diminishes the heat transfer effectiveness, which decreases the inlet temperature in the fired heater. Consequently, a continuous increase of the fuel consumption and carbon emissions is observed. Because of the large throughput in petroleum refineries, even a loss of 1 °C in the fired heater inlet temperature involves considerable economic penalties [4].

Heat exchanger cleaning is a possible intervention which can be employed to reduce the deleterious effects from fouling. After the cleaning of a heat exchanger, its thermal effectiveness is restored. However, this activity has costs, e.g., cranes, chemicals, labor, etc. Additionally, if the cleaning is executed during the refinery operation, the energy consumption is increased because of the

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Nomenclature

A	heat exchanger area (m^2)
$\underline{\underline{A}}$	matrix of coefficients of the network flow model
$\underline{b}$	vector of the network flow model
c	fouling rate in the linear model (m^2 K/J)
C	heat capacity flow rate (W/K)
$\underline{\underline{C}}$	matrix of coefficients of the network energy model
C_C	cleaning costs (£)
C_{op}	utility costs (£/J)
C_P	heat capacity at the supply/demand vertices (J/kg K)
C_R	ratio between heat capacity flow rates (dimensionless)
$\underline{d}$	vector of the network energy model
D_e	outer tube diameter (m)
D_i	inner tube diameter (m)
DS	subset of desalters
fobj	objective function (£)
G	cost reduction gain (%)
h	convective heat transfer coefficient (W/(m^2 K))
HE	subset of heat exchangers
HEC$_j$	subset of heat exchangers associated to the cleaning constraint j
i	algorithm counter variable
J	set of cleaning action constraints
m	mass flow rate (kg/s)
MX	subset of mixers
n	network inlet/outlet mass flow rates (kg/s)
N_{HE}	number of heat exchangers
$N_{\min,j}$	minimum number of operating heat exchangers
N_P	number of periods
NTU	number of transfer units (dimensionless)
p_τ	weight of the numerical integration procedure
PD	subset of process demand vertices
PDC	subset of process demand vertices associated to operational constraints
PE	set of periods
PS	subset of process supply vertices
R_f	fouling resistance (m^2 K/W)
S	string
SP	subset of splitters
STR	set of edges
STRC	subset of edges associated to operational constraints
T_k	stream temperature (°C)
TI	set of time instants
U	overall heat transfer coefficient (W/(m^2 K))
V_t	network inlet/outlet temperature (°C)
VET	set of vertices
$\underline{x}$	variable vector of the network flow model
y	binary parameter related to heat capacity flow rates
$y_{t,p}$	binary optimization variable
$\underline{z}$	variable vector of the network energy model

Greek symbols

α	stream split fraction
Δ	temperature variation in the desalter (K)
ε	heat exchanger effectiveness (dimensionless)

Subscripts

base	base case
c	solution candidate index
c	cold stream
h	hot stream
i	inlet
o	outlet
j	index of the cleaning constraints
k	index of the edges (process streams)
min	minimum fluid
max	maximum fluid
p	index of the time periods
ref	temperature reference
shell	shell-side
tube	tube-side
t	index of the vertices (network element)
τ	index of time instants

Superscripts

cand	solution candidate
inc	incumbent
LB	lower bound
UB	upper bound

diminution of the total available heat transfer surface along the CPT. Therefore, because of this trade off, the identification of the optimal set of time instants for heat exchanger cleanings corresponds to an optimization problem. In fact, the optimization of the cleaning schedule in a CPT can assume a significant complexity, due to the presence of a large number of interconnected heat exchangers.

This problem has been addressed in the literature using different techniques. Because of the nature of the problem variables (cleaning decisions are binary variables and process variables are continuous ones), the utilization of mathematical programming was associated to mixed-integer programming formulations, encompassing mixed-integer linear programming (MILP) [5,6] and mixed-integer nonlinear programming (MINLP) [7–9]. Stochastic optimization techniques were also employed using different variants of simulated annealing algorithms [10,11]. More recently, some investigations aimed to extend the formulation of the cleaning schedule problem, including additional aspects, such as, manipulation of by-passes [11], hydraulic effects [12], and desalter behavior [13].

Despite the research effort devoted to the cleaning schedule problem, available solution schemes still present some limitations. Some drawbacks are related to MILP and MINLP approaches, e.g., rigorous MILP formulations may demand excessive computational efforts [6] and MINLP formulations suffer with non-convergence problems [7]. Additionally, stochastic optimization approaches may be very dependent on parameter tuning [14].

In this context, the current paper presents a simple heuristic optimization approach aiming to provide good solutions for the cleaning scheduling problem in CPTs. The proposed approach is based on three set of movements which, starting from a base case, generates a sequence of cleaning schedules with decreasing costs. Each movement set is based on a given pattern of insertion, deletion or dislocation of heat exchanger cleaning orders. The optimization scheme is coupled to a simulation algorithm which is employed to evaluate the performance of each solution candidate.

The proposed optimization algorithm is able to find good solutions for the scheduling problem through reasonable computational efforts. The straightforward structure of the solution scheme avoids non-convergence problems and the utilization of specialized optimization solvers.

The rest of this paper is organized as follows: Section 2 presents the modeling and simulation of CPTs, Section 3 describes the formulation of the cleaning schedule optimization problem, Section 4