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Optimization of scheduled cleaning of fouled heat exchanger network under ageing using genetic algorithm

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ABSTRACT

The problem of heat exchanger network (HEN) fouling and ageing has been a costly feature of chemical and petrochemical industries, particularly, the oil refineries. In this paper, a strategy to determine the optimal cleaning schedule of the crude oil refinery's preheat train (PHT) under fouling and different ageing scenarios (i.e., slow and fast ageing) is addressed by a specialized Genetic Algorithm (GA) which uses an array of discrete and positive integers as chromosome representation. Specifically, the effect of key cleaning decision factors (i.e., which, when and how to clean), dictated by the GA, on optimal cleaning schedules based on both thermal and economic behavior of the PHT was studied. The results highlight the efficacy of the GA and a novel chromosome application to the optimization of complex cleaning scheduling. Considerable savings are achieved by the implementation of optimum cleaning schedules for all the ageing scenarios compared with un-optimized cleaning or no cleaning performed in a case study involving a 14-unit crude oil refinery HEN. Fast ageing led to significant reduction in energy losses, and hence, improved heat recovery and fewer number of cleanings due to the higher formation rate of a more thermally conductive coke, compared with slow ageing.

1. Introduction

The growing need for energy savings and operating cost minimization make the subject of efficient energy management important. In the chemical and petrochemical industries, specifically oil refineries, the crude distillation unit is equipped with a network of *heat exchangers* (HEXs) called *preheat train* (PHT) for the purpose of heat recovery and energy minimization. Thus, operational requirements demand that the PHT provides a specified heat transfer, while maintaining an acceptable pressure drop in the heat exchangers. Realization of this requirement is hampered by fouling; hereafter the term fouling refers to the fresh build-up of gel-like, crude oil deposits on the heat transfer surfaces of HEXs. The negative impact of fouling represents the most significant contribution to a refinery's operating costs (Bott, 1995; Garrett-Price et al., 1985; Somerscales and Knudsen, 1981; Thackery, 1980). This necessitates regular cleaning of both individual HEXs and

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Nomenclature and units

A	heat transfer surface area (m^2)
A_c, $A_{c,m}$	pre-exponential factor of ageing, modified factor (m/day)
c_p^c, c_p^h	specific heat of cold/hot stream (kJ/kg K)
C_E	energy cost ($/kW/day)
C_{chem}, C_{mech}	Cleaning costs: chemical, mechanical ($/clean)1
CIT	coil inlet temperature (°C)
E_f, E_c	activation energy of fouling (gel formation), ageing (kJ/mol)
K_0	kinetic parameter, zeroth-order ageing (m/day)
$\dot{m}^c$, $\dot{m}^h$	mass flow rate of cold stream, hot stream (kg/s)
n	heat exchanger
n_d	heat exchangers downstream to the desalter
n_u	heat exchangers upstream to the desalter
N_{chem}	number of chemical cleanings
N_{mech}	number of mechanical cleanings
N_E	number of heat exchangers in the PHT
N_{Ed}, N_{Eu}	number of downstream unit cleaned, upstream units cleaned
N_p	number of periods
N_{pop}	population of candidate solutions
N_{tour}	tournament size
OPC	operating cost ($)
P_c	crossover probability
P_m	mutation probability
pop	population size
Pr	Prandtl number
Q, Q_c, Q_t,	heat duties, when average, clean, fouled (kW)
R	gas constant in Eqs. (3) and (5) (J/mol/K)
Re	Reynolds number
r_c	rate of coke formation (m/day)
r_d	net rate of deposition (m/day)
$R_{f,g}$, $R_{f,c}$, R_{fT}	gel layer resistance, coke layer resistance, overall deposit resistance (m^2K/kW)
$\dot{R}_{f,g}$, $\dot{R}_{f,c}$, $\dot{R}_{fT}$	fouling rate: gel, coke, overall deposit rates ($m^2K\,kW^{-1}\,day^{-1}$)
t	time (days)
Tc^{in}, Th^{in}	Inlet temperatures of cold stream, hot stream (K)
Tc^{out}, Th^{out}	outlet temperatures of cold stream, hot stream (K)
T_{in}	gel-coke interface temperatures (K)
T_S,	gel-crude oil interface temperatures (K)
t_F	heat exchanger network operating time span (1 year)
U, U_c	overall heat transfer coefficient: typical, clean condition (kW/m^2K)
z	binary variable

Greek symbols

α, γ	parameters in fouling model Eq. (3) ($m^2K\,kW^{-1}\,day^{-1}$)
δ_g, δ_c, δ_T	gel deposit thickness, coke layer thickness, overall deposit thickness (m)
$\dot{\delta}_g$, $\dot{\delta}_c$, $\dot{\delta}_T$	gel deposit growth rates, coke layer growth rate, overall deposit growth rate (m/day)
λ_g, λ_c	thermal conductivity of gel, coke (kW/m/K)
Δt	discretised time step (day)
φ	objective function (US $)

Subscripts

c	coke layer, cold stream, clean state
fT	overall deposit rate/resistance
g	gel layer
h	hot stream
in	gel-coke interface
a	slow and fast ageing
n	heat exchanger unit
n_d	downstream unit relative to the desalter
n_u	upstream unit relative to the desalter
S	gel-crude oil interface

Superscripts

*	optimal
chem	chemical cleaning
j	cleaning method
mech	mechanical cleaning
–	average

heat exchanger network (HEN), giving rise to a coupled process between fouling and cleaning (Wilson, 2005).

The dynamics of the "fouling-cleaning" coupling is influenced by the extent of exposure of a fouling deposit to intense heating by the heat exchanger tube walls, as arises in crude oil downstream PHT fouling, resulting in an aged deposit. Fouling and deposit ageing are thus intertwined due to their related temperature sensitivities (Ishiyama et al., 2010), both being a major unresolved problem. It is well recognized that ageing of fouling deposits complicates the effect of fouling (Ishiyama et al., 2010). In the PHT, given the interactions between several interconnected units, fouling and ageing impact not only on the thermo-hydraulic responses of affected individual HEXs but also the entire network, itself. To mitigate these effects, HEXs are cleaned in between shutdowns of operations.

The effect of ageing on fouling dynamics in heat exchanger operation (Coletti et al., 2010; Ishiyama et al., 2010) and cleaning (Ishiyama et al., 2014; Pogiatzis et al., 2012b) has not been infrequently researched. In the past four decades, several cleaning scheduling methodologies developed for single heat transfer device (Caputo et al., 2011; Casado, 1990; Ma and Epstein, 1981; Sheikh et al., 1996) and HEN (Georgiadis and Papageorgiou, 2000; Georgiadis et al., 2000; Ishiyama et al., 2008; Lavaja and Bagajewicz, 2004, 2005a, 2005b; Markowski and Urbaniec, 2005; Rodriguez and Smith, 2007; Sanaye and Niroomand, 2007; Smaïli et al., 1999; Smaïli et al., 2001, 2002; Wilson et al., 2001; Xiao et al., 2010) omit to feature ageing effects on operation and cleaning dynamics. As a consequence, these studies assume that the use of a single cleaning method suffices to completely restore to their original state, the decayed performances of HEXs in a network. However, contrary to this assumption, physical/chemical properties of foulants do not remain constant over time. Their prolong exposure to process conditions lead to structural changes as well as changes in thermal conductivity (Diaby et al., 2016; Ishiyama et al., 2010; Ishiyama et al., 2011a). Thus, the effect of fouling in HEXs is complicated by ageing of the fouling deposits which interferes with the operation as well as the cleaning dynamics of HEXs.

For a HEN, the schedule-determining method, which is mainly based on traditional Mathematical Programming (MP) methods, involve the decomposition of a complex