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Simultaneous optimization of flow velocity and cleaning schedule for mitigating fouling in refinery heat exchanger networks

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ABSTRACT

Fouling is a crucial problem in refinery HEN (heat exchanger network) that reduces heat transfer and affects regular production. The conventional way to mitigate fouling is cleaning heat exchanger regularly or improving operation conditions, but simultaneous consideration of the two methods is rare. This paper presents a combined approach for mitigating fouling in HEN by optimizing operation condition and cleaning schedule simultaneously. For optimization of operation condition, flow velocity is selected as a key variable since it can correlate fouling, heat transfer and pressure drop. An overall optimization of network performance can be achieved through redistribution of velocity. In a refinery HEN, fouling cannot be completely prevented through optimization of operation conditions, so management of cleaning actions is optimized to deal with the remained fouling. SA (Simulated annealing) algorithm is used in this work to obtain a comprehensive strategy for mitigating fouling. The application of the proposed method is demonstrated using a case study. The results show higher energy saving and economic efficiency compared with existing methods.

1. Introduction

HEN (heat exchanger network) synthesis is a basic energy integration method in industry. Especially in refinery processes, HEN is an effective system to reduce energy consumption. However, a large number of heat exchangers in refinery have suffered from fouling problem in practical production. The main problems caused by fouling deposition are the negative effect on thermal and hydraulic performance of heat exchangers. Fouling deposition on heat transfer surfaces increases the heat transfer resistance, leading to a reduction in heat transfer efficiency. In addition, due to the reduction of channel duct dimension, flow velocity is increased so that the pressure drop is increased as well. Moreover, fouling also causes the corrosion of pipeline, reducing the service life of heat exchangers. Severe fouling can even plug the pipe and lead to shut down of the production process. Therefore, it is necessary to mitigate fouling to avoid the cost in extra energy input, pump load and cleaning of equipment.

The research of fouling requires appropriate models for predicting the fouling behaviors, which have been developed by many researchers in last three decades. Ebert and Panchal [1] first introduced the concept of fouling threshold in 1995. Since then, several modified models were proposed in order to improve the prediction accuracy of crude oil fouling behavior. Panchal et al. [2,3] introduced Prandtl number to take thermal properties into account. In Polley's model [4], wall temperature and Reynold number were used instead of film temperature and shear stress term. Compared with Ebert and Panchal's model, Polley's model is more accurate and shear stress term is eliminated so that the calculation is easier. Yeap et al. [5] carried out a large number of studies to evaluate different threshold fouling models using various laboratory and plant data sets, and proposed a more accurate and complex model compared with the other three models. Corresponding expressions for fouling threshold models are listed in Table 1. Recently, CFD (Computational Fluid Dynamics) simulations were used to predict fouling behaviors [6] and its effect on heat transfer condition [7]. In addition, fouling behaviors under different surface roughness were studied through a number of experiments [8].

Many researchers have focused on developing effective fouling mitigation techniques. For design stage, approaches of overdesign and design on bypass [9,10] are applied to deal with the fouling problem during operation. For existing HENs, one of the most common methods is to clean the fouled exchangers systematically.

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Table 1
Summary of fouling threshold models.

Model	Author
$Rf' = \alpha Re^{\beta} EXP\left(\frac{-E}{RT_f}\right) - \gamma^{\tau}$	Ebert & Panchal (1995)
$Rf' = \alpha Re^{\beta} Pr^{-0.33} EXP\left(\frac{-E}{RT_f}\right) - \gamma^{\tau}$	Panchal et al. (1997)
$Rf' = \alpha Re^{-0.8} Pr^{-0.33} EXP\left(\frac{-E}{RTw}\right) - \gamma Re^{0.8}$	Polley et al. (2002)
$Rf' = \frac{\alpha C_f u T_s^{2/3} \rho^{2/3} \mu^{-4/3}}{1+\beta u^3 C_f^2 \rho^{5/3} \mu^{-7/3} T_s^{2/3} EXP(E/RT_s)} - \gamma u^{0.8}$	Yeap et al. (2004)

It means that the fouled exchangers are taken out of service for cleaning while the others continue working online. At present, the optimization of the cleaning strategy for a single heat exchanger [11] is relatively mature, because the problem can be solved by simple deterministic method. For a HEN, heat exchangers are connected with each other through hot and cold streams. When a heat exchanger is off-line, heat load will be redistributed, which may cause deviation of HEN configuration from the optimal arrangement. The cleaning schedule optimization for a HEN is usually a MINLP (Mixed Integer Nonlinear Programming) model, because binary variables should be introduced to represent the cleaning condition of heat exchangers. Smaïli et al. [12] studied the cleaning sequence of the raw juice preheat train in a sugar refinery using linear fouling model, which was obtained by analyzing the operation data in the heat exchangers. A new modeling formulation was developed to solve MINLP problem and near-optimal results were provided. Georgiadis and Papageorgiou [13] presented a tight MILP (mixed integer linear programming) model to obtain global optimality. Ming Pan [14,15] proposed a MILP-based iterative approach for solving MINLP HEN problems, which converts the MINLP to a MILP, and significantly reduces the computational difficulties of nonlinear programming. Smaïli et al. [16] also proposed a method for optimizing cleaning schedule for large continuously operating HENs. In their work, the operation horizon was discretized into equally long periods in which the cleaning actions are located, all conditions in each interval were assumed constant and the equations representing outlet temperatures, heat transfer coefficients and fouling resistance were written in term of binary variables. Constraints set by pump around operation and pressure drop were considered. The MINLP problem was solved using two methods based on a multiple starting point strategy. One is the DICOPT++ solver in the mathematical programming software GAMS, the other is a simpler approach based on a greedy algorithm. In another paper of Smaïli et al. [17], the MINLP problem was solved using the OA (outer approximation) method in GAMS and the BTA (backtracking threshold accepting) algorithm, which is derived from the standard TA (threshold accepting) algorithm. Two cases were optimized, indicating that the BTA algorithm is relatively simple and stable, and it can be applied to solve large-scale problem.

The performance of HENS subjected to fouling can be significantly improved by applying an optimized cleaning schedule. The total operation cost can be also reduced through this way. Although the heat transfer surface can recover its original performance after fouling removal, this does not prevent it from fouling again [18]. According to fouling threshold model, it can be known that fouling rate can be slowed down or avoided in certain conditions. Some researchers tried to mitigate fouling by improving operation conditions. In some works [19–21], heat transfer enhancement was considered to increase heat recovery and decrease the fouling rate, as a result of their research, the heat exchanger operation time was prolonged. Several works [22,23] presented the optimization of flow rate distribution among parallel structure in HEN to mitigate fouling. Wang et al. [24] indicated that flow velocity is a critical variable correlated fouling rate, heat transfer coefficient and pressure drop. Operation condition optimization was simplified by changing flow velocity. They proposed a methodology to optimize the distributions of flow velocity in HEN to minimize the total cost. SA (Simulated annealing) algorithm was implemented to solve the optimization model based on a crude oil preheat train. Rodriguez and Smith [18] proposed a strategy for mitigating fouling in existing HEN by optimizing operation condition and cleaning schedule simultaneously. The operation condition was modified by bypassing hot stream to improve wall temperature profile inside the HEN. The proposed method leaded to higher energy saving compared with conventional cleaning schedule optimization.

Although a number of methods have been proposed to mitigate fouling in HEN, simultaneous optimization of cleaning strategy and operation conditions is still rare in the literature. In this paper, a new approach is proposed to mitigate fouling in HEN. In this approach, fouling problem is considered from two aspects: flow velocity is optimized to reduce fouling deposition rate in HENs, and optimization of cleaning schedule is used to deal with the consequence of fouling deposition. SA (Simulated annealing) algorithm is applied to solve the models, and to determine the optimal distribution of flow velocity and cleaning schedule in HENs. A case study of crude oil preheat train is researched to demonstrate the effectiveness of the proposed methodology.

2. Mitigation of fouling through changing operation conditions

The concept of fouling threshold proposed by Ebert and Panchal [1] suggests that chemical reaction fouling in crude oil preheat train follows two opposite mechanisms: fouling formation and removal. Fouling formation originates from chemical reaction, so formation rate is related to wall temperature. Correspondingly, fouling removal depends on flow velocity.

In this work, Polley's model [4] proposed in 2002 is used to calculate the fouling rate, in which Reynold number and Prandtl number are used to correlate flow velocity and fluid properties. The expression for this model is presented in Eq. (1).

$$Rf' = \alpha Re^{-0.8} Pr^{-0.33} EXP\left(\frac{-E}{RTw}\right) - \gamma Re^{0.8} \tag{1}$$

where Rf' is fouling rate, α and γ are model parameters, Re and Pr are Reynolds number and Prandtl number, R is gas constant, E is activation energy, and Tw is wall temperature. As shear stress term is expressed by Reynolds number in this model, calculation of fouling rate becomes much easier and it is easy to correlate with flow velocity.

In the case of $Rf' = 0$, gives Eq. (2).

$$\alpha Re^{-0.8} Pr^{-0.33} EXP\left(\frac{-E}{RTw}\right) - \gamma Re^{0.8} = 0 \tag{2}$$

If the property variables of crude oil are considered to be constant, rearranging Eq. (2) gives a formula in form of $Tw = f(u)$. In the formula, u is velocity. Simplified form of the model formulation is as follows.

$$Tw = \frac{a}{b - 1.6 \ln u} \tag{3}$$

The curve describing the relation between Tw and u based on Eq.