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Optimization of Velocity in Heat Exchanger Networks for Fouling Mitigation

Shihui Zhan, Yufei Wang*, Xiao Feng

State Key Laboratory of Heavy Oil Processing, China University of Petroleum (Beijing), 18 Fuxue Road, Changping, Beijing 102249, China.
wangyufei@cup.edu.cn

Fouling severely reduces energy recovery in heat exchanger network (HEN). Low velocity and high wall temperature are the reasons for a high fouling rate. Redistribution of velocity for the exchangers in the network is an efficient way to mitigate fouling. In this work, optimizing the velocity distribution through the network is considered to correlate heat transfer, pressure drop and fouling. Two ways are used to change the velocity in each heat exchanger. They are modifying detailed heat exchanger structure and redistributing flow rates in the two exchangers in parallel. Additionally, after redistributing flow rate in the two heat exchangers in parallel, the temperature of them is also changed due to the change in heat capacity flow rate. To describe the dynamic nature of fouling, the entire time zone is divided into several time intervals. Fouling resistance is used to link the two adjacent intervals. To optimize the heat exchanger network with comprehensive considerations of the above motioned factors, a methodology is proposed. A crude oil preheat train is used to verify the validity and efficiency of the proposed approach.

1. Introduction

Fouling is a serious problem in heat exchanger operation. It severely decreases the efficiency of heat exchanger, resulting that a great loss in energy recovery. How to mitigate fouling is a research focus. Even though some aspects of mechanism in fouling are still under research, models that quantify fouling rate have been proposed in the last twenty years and are applied to the design and retrofit of heat exchanger network, especially in crude oil preheat train, which is the largest fuel consumer in refinery. Many researchers have done a lot of work in this field.

Pressure drop is an important aspect to be considered, which is increasing with the deposition of fouling layer. In the work of Hassan Panjeshahi et al. (1991), they pointed out that pressure drop was usually the bottleneck of a HEN, the pump capacity should be considered as a constraint when design a HEN, or else the solution will be far from the optimum. The temperature field plot that first proposed by Wilson et al. (2002) can be used to described fouling behavior. On the basis of their work, Yeap et al.(2004) analyzed thermo-hydraulic effects of fouling, and Yeap et al., (2005) performed techno-economic analyze on the consideration of the exchanger and network levels. In their work, fouling is considered at both heat exchanger and HEN level, and heat transfer coefficients (HTC), fouling and pressure drop can be combined into the proposed method. However, the interactions with HTC, fouling and pressure drop are not addressed in their work. Ishiyama et al. (2011) considered fouling and ageing simultaneously, and optimal cleaning time between plant shutdowns can be obtained by the proposed methodology, but the work haven't been to be extended to HEN. Rodriguez and Smith (2007) investigated the operation variables that affect fouling rate and cleaning action management, a new method was proposed to retrofit a HEN. They divided the whole horizon into several intervals, and then the dynamic behavior of fouling can be described by steady state in each interval. However, pressure drop was not included in their work.

To mitigate fouling, heat-transfer enhancement is employed. Pan et al. (2013) applied tube inserts to HEN retrofit, to solve the computational difficulties due to nonlinear, an optimization procedures was proposed. Wang and Smith (2013) focused on the effect of topology on fouling rate. For different crude oils, the

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performance of HEN can be improved by using new design method after enhancement, which is proven to be effective.

In this paper, flow velocity and mass flow rate in each branch are the two manipulated variables, which relate fouling, heat transfer and pressure drop. To optimize the heat exchanger network with comprehensive considerations of the above motioned factors, a methodology is proposed. The investigated time horizon is divided into several intervals and all related parameters are recalculated at each interval by the link of fouling resistance. The performance of network is improved after optimization.

2. Exchanger performance models

2.1 Fouling model

In this work, Polley's model is used to predicted fouling rate, where α and γ are model parameters, usually obtained by data regression, E is activation energy, R_g is universal gas constant.

$$\frac{dRf}{dt} = \alpha Re^{-0.8} Pr^{-0.33} exp\left(\frac{-E}{R_g Tw}\right) - \gamma Re^{0.8} \tag{1}$$

2.2 Pressure drop model

For each heat exchanger, pressure drop can be comprised of three components: ΔPi indicates friction loss in straight pipe, ΔPr indicates local loss in cross section, ΔPn indicates entrance loss. They are calculated by Eq(2),Eq(3) and Eq(4).

$$\Delta Pi = \lambda \frac{L}{Di} \frac{\rho v^2}{2} N_{tube} = 4C_f \frac{L}{Di} \frac{\rho v^2}{2} N_{tube} \tag{2}$$

$$\Delta Pr = \zeta \frac{\rho v^2}{2} N_{tube} \tag{3}$$

$$\Delta Pn = 1.5 \times \frac{\rho v^2}{2} \tag{4}$$

$$\Delta Pf = \Delta Pi + \Delta Pr + \Delta Pn \tag{5}$$

2.3 Heat transfer correlation

Film coefficient in tube side can be calculated by Eq(6).

At each interval, the performance of every heat exchanger is obtained by evaluating the above three models repeatedly. Outlet temperatures of streams are achieved with NTU approach. Fouling resistance is used as the link between adjacent instants.

$$h = 0.023 \frac{\lambda}{Di} Re^{0.8} Pr^{0.4} \tag{6}$$

2.4 Constraints

The constraints include fluid velocity, flow rate of each branch, inlet and outlet temperatures bounds, which must be limited to the lower and upper bounds, and mass balances for splitters. To use the pump capacity available, the total pressure drop in crude oil stream can be larger than allowable pressure drop. In practice, fluid velocity can't be greater than 2.0 m/s, or vibration and abrasion of heat exchanger will be a big problem.

$$v^{LB} \le v \le v^{UB} \tag{7}$$

$$m^{LB} < m < m^{UB} \tag{8}$$

$$Th^{LB} \le Thi \le Th^{UB} \tag{9}$$

$$Th^{LB} \le Tho \le Th^{UB} \tag{10}$$

$$Tc^{LB} \le Tci \le Tc^{UB} \tag{11}$$

$$Tc^{LB} \le Tco \le Tc^{UB} \tag{12}$$

$$\sum m_{sp}^{in} = \sum m_{sp}^{out} \tag{13}$$

$$\sum_{ex} \Delta Pf \le \Delta P_{allowable} \tag{14}$$

2.5 Objective function

The objective is to minimize the summation of utility cost and power cost.

$$obj = \sum\left[huc \times Qh + cuc \times Qc\right] + \sum\left[pc \times \frac{V \times \Delta Pf}{\eta}\right] \tag{15}$$

2.6 Optimization algorithm

Simulated annealing (SA) is a stochastic algorithm for global problem. It is more effective when the search space is discrete. By accepting a move with a certain probability, a better solution is obtained, until a good approximation to the global optimum is found. In our work, SA is an appropriate method to solve the problem for fouling model is highly nonlinear. By changing velocity in heat exchanger and flow rate in branch, optimal fluid velocity distribution can be finally obtained when objective function is nearly the minimum. Moreover, the interaction of fouling, heat transfer and pressure drop is considered, and the sensitivity of heat exchangers' locations to fouling is analyzed.

3. A case study

The application of proposed model is illustrated by a simple crude oil pre-heat train, of which the network structure is shown in Figure1. Crude oil first comes through E1, and then is equally divided into two branches in parallel, E3 and E4 are on one branch, E2 is on another. After mixed, crude oil flows through E5, E6 and furnace. The furnace inlet temperature (FIT) is a key factor, which determines the fuel consumption of furnace. In the network, crude oil is the only cold stream and it flows in tube side in every heat exchanger. In most cases, fouling is dominated by crude oil in heat exchanger. In this paper, fouling of all heat exchanger is only considered in tube side. The stream data is listed in table1.

Table 1: Stream data

Streams	*MCP*(kW•℃)	T_{supply} (℃)	T_{target} (℃)
H1	59.8	180	30
H2	114.4	270	40
H3	33.8	350	30
H4	145.6	380	50
H5	657.8	150	100
H6	384.8	290	190
Crude oil	520	20	390

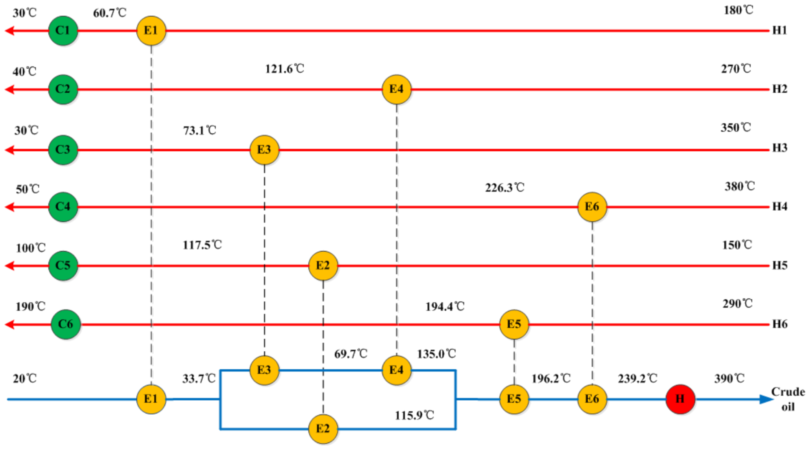

Figure 1: Heat exchanger network configuration in crude oil preheat train

4. Results and Discussions

Table 2: Optimization results

Exchanger	E1	E2	E3	E4	E5	E6
Velocity(m/s)	0.82	1.61	1.23	1.45	2.00	1.16
Mass flow(kg/s)	200	122	78	78	200	200

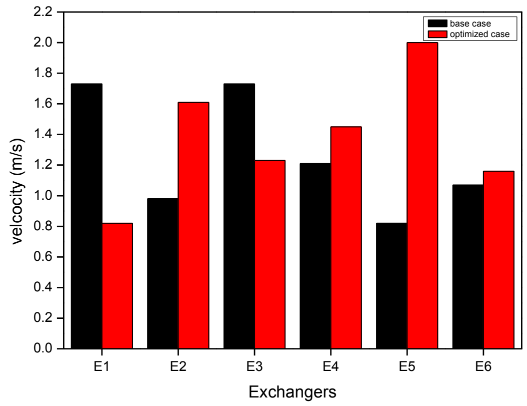

Figure 2: Comparison of velocity distribution in base and optimized cases

Table 2 summarizes the optimization results, including the velocity values and mass flow rates of two branches. The flow velocities of crude oil in each heat exchanger in base and optimized cases are shown in Figure 2. As estimated, it is needed to increase velocity when heat exchanger is close to hot end for mitigating fouling. However, velocity distribution may be different when consider pressure drop. In base case, velocity is no need to be so high in E1 for it is far from fouling region, it is going to not foul even reduced by half, and consequently velocity is decreased to avoid the unnecessary pump capacity consumption, and save pump capacity for increasing velocity in some other exchangers prone to fouling. E3 is same with the situation of E1. For E2, E4, E5 and E6, velocities are all increased. It is worth noting that the growth rate of velocity in E2 and E5 is higher than other heat exchangers. This can be explained from Figure 3.

Heat duty of heat exchanger determines the energy cost, of which is the major component of total cost. By comparing duty of each heat exchanger in base and optimized cases in Figure 3, it can be seen that duty of E1, E3, E4 and E6 reduce. For E1, as the first heat exchanger upstream, the reason for reduction in heat duty is because of the reduction in velocity. For E3 and E4, mainly because most flow rate of crude oil is assigned to E2, and duty of E2 is more highly sensitive to velocity than the two heat exchangers. As for

E6, even though heat transfer coefficient increases for flow velocity increases slightly, it is a downstream heat exchanger of E5, the inlet temperature rises sharply, wall temperature is higher and suffered severer fouling than before, resulting in duty reduction.

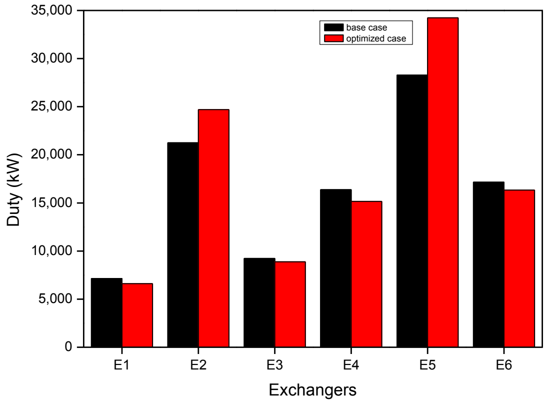

Figure 3: Comparison of duty in base and optimized cases

There are two reasons why the duties of E2 and E5 are sensitive to velocity. One is that their initial duties are large, with the same increase percentage of HTC, the increase of duties in E2 and E5 are larger than the others. The other is that the heat capacity flow rates of hot streams on another side are larger than the others, so that the increase in heat duty does not lead to a significant drop in the temperature of hot streams, which means the reduction in heat transfer driving force is low.

Another interesting thing is that the optimized flow rate of branch in E2 is slightly higher than the other branch, comparing with the equally distribution before optimization. It is because heat capacity of hot stream in E2 is far larger than that of E3 and E4, which means duty of E2 is more sensitive than the other two. As mentioned before, the initial duty of E2 is large, and the related energy cost is also very high. For reducing the total cost, it is more important to increase flow rate of branch in E2 to recover more heat from hot stream.

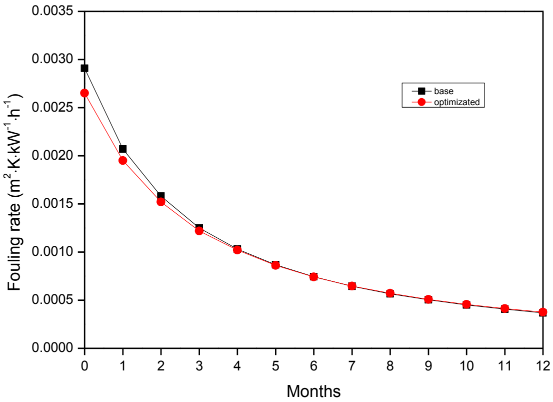

Figure 4: Fouling rates of E6 in base and optimized cases

Figure 4 presents the fouling rates vary with time before and after optimization in E6. It is different in the starting point of curves due to the redistribution of velocity. However, it is interesting that the two curves are tend to coincide after 6 months. Obviously, flow area in tube side decreases with the deposition of foulant. For the case of constant throughput, velocity must to be increasing to resume normal operation. The case with low velocity will have a faster deposition rate, resulting in a rapid velocity variation, while the case with high velocity is on the contrary. Finally they reach to the same fouling rate.

The variation tendency of FIT before and after optimization is shown in Figure 5. As can be seen, FIT have a big downward in two curves, especially in the first two months, then is slow to fall. However, the downward trend in optimized case much more gradual than that in base case. This indicates that the HEN's performance becomes better after optimization.

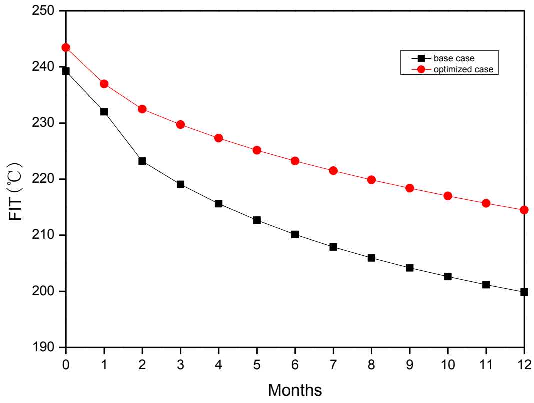

Figure 5: Comparison of FIT in base and optimized cases

5. Conclusion

A method for velocity optimization in a fixed HEN to mitigate fouling was proposed. In this work, flow velocity is used to correlate three critical parameters, namely heat transfer coefficient, pressure drop and fouling. To simulate the dynamic characteristic of fouling, time horizon is divided into several intervals, and all parameters are assumed to be steady at each interval. Fouling resistance can be used as a link between two adjacent intervals. Simulated annealing is employed as the optimization algorithm. By considering the effect of topology on fouling and pump capacity constraints, optimal velocity is redistributed. A crude oil preheat train is illustrated to verify the reliability of proposed method. The results show that energy is saving by velocity distribution and the network performance gets better.

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