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Process Integration Accounting Fouling in Heat Exchanger Network: A Case Study of Crude Oil Distillation Retrofit

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This paper presents the approach to predict the future performance of a heat exchanger network based on Pinch retrofit design and detailed historical performance of the unit to improve the operation efficiency, save an energy and increase a throughput. The main input is a finding of a profitable solution of heat exchanger network based on Pinch Analysis, fouling predictive management and a start-up and shut-down time. The approach demonstrates the importance of a dynamic assessment of the retrofit design and operation modes. The case study was developed for crude oil distillation unit with annual capacity of 6 Mt. Dynamic fouling models were built to assist with designing and revamping of heat exchanger network, to reduce the fouling and increase the throughput. Rigorous modelling of refinery heat exchangers network and Pinch Analysis were executed to achieve increased throughput, reduce operation cost and harmful emissions. A new heat exchangers network with improved operation conditions predicting efficient exchanger cleaning schedules under various economic and operational constraints was obtained. The calculations use an HTRI shell-and-tube heat exchanger models, operation data, properties of crude oil and cleaning schedule. Process Integration steps were done by HILECT software and new operation schedule of efficient heat exchangers network was created by HTRI software. The strategy and recommendations for the optimal operation of the retrofitted network were proposed taking into account the economic and process constraints such as exchanger by-passes, operation budget, furnace duty and pumping limit.

1. Introduction

Last several decades a lot of Process Integration projects were implemented in different industries. However, the operation of retrofitted units usually faces the challenge of finding cost efficiencies to improve production while managing such issues as fouling and reduced throughput (Smith, 2017a). These issues lead to increased energy consumption and the efficiency of retrofit design is not as profitable as was calculated for heat exchangers network with the clean surface (Smith et al., 2017b). The impact on network performance of fouling in a particular exchanger may results from a given extent of fouling, in a manner similar to the “Sensitivity Table” analysis described by Kotjabasakis and Linnhoff (1986). This problem is usually takes place in refineries, petrochemical, coke-to chemical and other industry with raw material processing as reported by Polley et al. (2013). It is very important for industrial engineers to have a tool for monitoring and management of heat exchanger networks (Ishiyama et al., 2013).

HEX fouling is a widespread economic problem, accounting for 0.25% of gross national product in the highly industrialized countries; 10 % of losses in a crude oil processing is due to fouling, besides fouling generates 10% of refinery CO_2 emission (ESDU, 2000).

There are two main factors connected with fouling that influence operating performance of heat exchanger network. First, the thermal efficiency increases the thermal resistance, decreases the heat transfer coefficient and enlarges the utility consumption (Yeap et al., 2004). Second is a hydraulic effect that increases pressure drop, reduce the cross-sectional area of heat exchangers and blocks tubes with flow redistribution (Pan et al., 2016). Ebert and Panchal introduced the ‘threshold fouling’ approach for describing the initial rate of crude oil chemical reaction fouling in 1995. Wilson et al. (2017) summarises reviews of developments in the threshold modelling approach over the last ten years. Last time, there are a lot of practical applications of fouling mitigation.

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The solution to this problem is proposed, for example, by Ishiyama et al. (2013), in crude oil preheat train. It makes possible to reduce the CO_2 emissions and increase furnace inlet temperature minimizing total operation cost of crude oil unit. Pressure drop aspects were also considered by Mohd Navi et al. (2016). Pressure drop during CO_2 transportation in the pipeline system has been included to identify the implication of pressure drop in Total Site CO_2 Integration design and has resulted in about 29.01 MPa of the total pressure drop in the planning of CO_2 capture, utilisation and storage. Data reconciliation problem is a very important problem when analysing the fouling problem in crude oil preheat train (Ishiyama et al., 2011) as well as solving Process Integration problems on Total Site level (Yong et al., 2016). This aspect is very important for Process Integration techniques as it makes a big influence on overall design and operation of heat exchangers network. It contributes to the capital cost of network design as presented by Boldyryev et al. (2016). Besides the operating cost prediction is important for network design as well since it was analysed by many researchers. Boldyryev et al. (2017a) presented an approach for selection of appropriate temperature approach when designing and retrofitting network with energy price fluctuation and start-up of a retrofit.

This paper analysed the research gap of operation of retrofitted heat exchangers network and how the fouling of crude oil influences to the Process Integration measures. The authors proposed a methodology for the retrofit design of heat exchanger network of crude distillation unit accounting operation period. Based on previous research of referenced works (Ishiyama et al., 2013) the fouling model and approach for predictive maintenance was used to optimise the operation network cost. The case study of crude oil unit was analysed based on data presented by Tovazhnyanskii et al. (2009). The novelty of the present paper is a finding of a profitable solution of heat exchanger network based on Pinch approach, fouling management and a unit start-up and shut-down time. The approach demonstrates the importance of dynamic assessment of retrofit design and operation modes. It is shown that the operation conditions and fouling management is very important in the selection of the unit retrofit. The predictive scheduling of cleaning contributes to the unit OPEX and may influences to overall retrofit design, especially when high sulphuric crude is used with long operation period.

2. Methods

Method developed in this work deals with calculation of both operation cost and investment versus energy benefits for heat exchanger network retrofit. All integration options are estimated taking into account the influence of network fouling distribution and its influence to operation cost. Fouling management, at the same time, is based on detailed simulation of heat exchanger network and fouling propensity factor of raw material. The brief description of a methodology used in this paper is the next: an inspection of process system and a definition of hierarchy; an extraction of plant data including stream properties and conditions, equipment details, operation modes and type of crude slates; Pinch Analysis; finding of bottlenecks, disadvantages and pitfalls of existing heat exchanger network; selection of new retrofit design; fouling modelling of retrofit design; calculation of economic indicators, such as CAPEX, OPEX, payback period of retrofit design taking into account start-up, shutdown and operation time of unit; selection of another retrofit option and repetition of previous steps; the comparison and selection of most profitable solution.

2.1 Data extraction

The case study was calculated for crude oil distillation unit with nominal capacity of 6 Mt/y. The initial data presented by Tovazhnyanskii et al. (2009) was updated by hour-by-hour monitoring of process parameters, such as temperatures, pressures, flowrates for two-year period. The initial flowsheet of crude oil distillation was simulated by UniSim Design, preheat train operation was exported and detailed modeling was executed by HTRI software (see Figure 1). There are 22 shell-and-tube heat exchangers in a preheat train. A desalted oil is heated by 10 hot streams before entering the flash column. The operation cycle between overhauls is two years and heat exchangers are exploited without cleaning.

Operation mode for past 2 y was extracted. It includes temperatures, flowrates and pressures of process streams, besides the stream splitting of preheat train was included too. All economic calculations were done in Russian rubles (RUR) and the exchange rate for the date of research was 71 RUR for 1 EUR. Cost of hot utility is 0.47222 RUR/MJ, the cost of lost production is 2,844.9 RUR/t, the cost of CO_2 emissions is 762.04 RUR/t and plant operation time is 8,200 h.

A simulation of future operation mode was done for 2 y with time gap simulation of 1 d; it was done for both base case and retrofit designs. Cleaning cost of one heat exchanger is 1,500,000 RUR and the duration of cleaning procedure is 7 d.

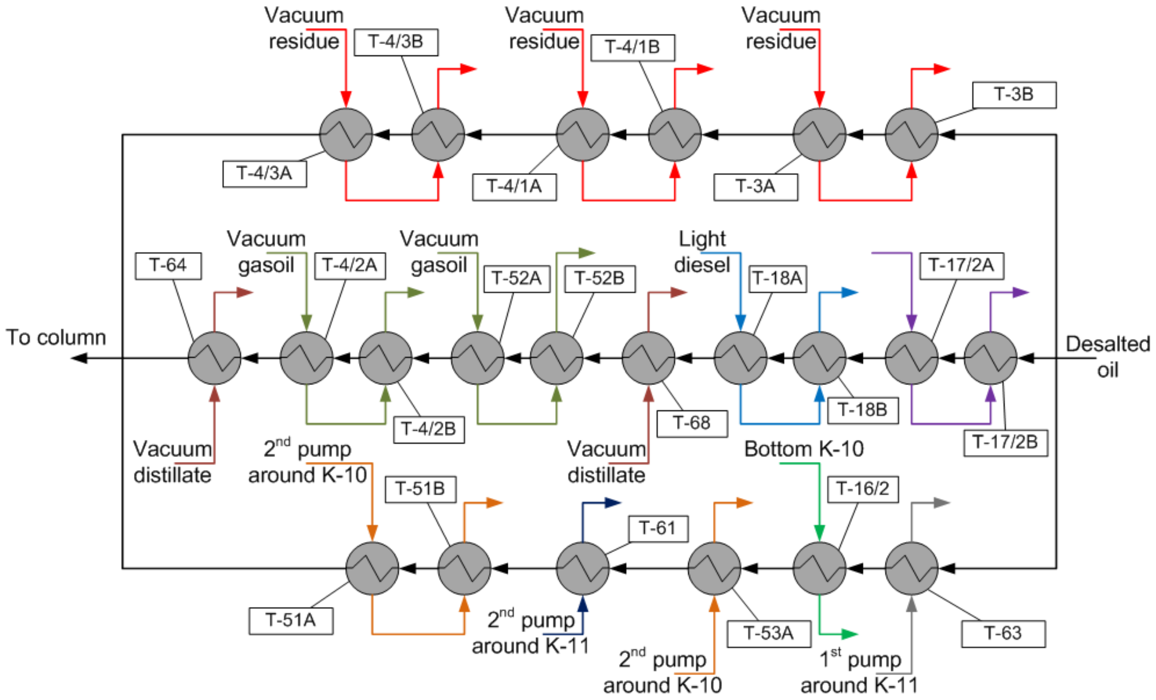

Figure 1: An initial preheat train of crude oil distillation unit.

2.2 Fouling modeling and network operation of retrofit design

The retrofit design of the crude oil distillation unit was built by Process Integration to improve the heat recovery and reduce both utility and CO_2 emissions. Retrofit has several options with different topological changes and different numbers of additional heat exchangers.

The operation of all retrofit design options was simulated for 2 y, as previously for the base case. The simulation was done with the use of asphaltene precipitation fouling model. All working conditions and parameters of heat exchangers were predicted and furnace inlet temperature of the crude oil is obtained. Besides, the operation modes with cleaning schedule of the retrofitted network were calculated. The optimal schedule of each retrofit option was obtained accounting the new working condition of heat exchangers and economic data that was defined at data extraction stage.

2.3 Selection of most profitable solution

The best retrofit design was selected in terms of investment (retrofit and cleaning), energy and CO_2 saving during 2 years. Investment of retrofit design was estimated taking into account the retrofit planning period as previously proposed by Boldyryev et al. (2017b). Retrofit cost includes new heat exchangers, revamp and design cost and a bank loan with 10 % rate. Cleaning schedule was optimised to get the minimum operation cost during 2 y accounting prices for energy and CO_2 from one side, and the prices of cleaning and lost benefits (capacity) from another one.

3. Results and discussions

3.1 Base case operation and cleaning schedule

The calculated furnace inlet temperature of the base case is presented in Fig. 2. In case of simulation without cleaning it is reduced by 24 °C and after 2 y operation it is 192 °C. When applying the cleaning schedule strategy, the furnace inlet temperature has a low bound 216 °C while the upper bound achieves 232 °C. Cleaning strategy saves 52,841 t of CO_2 and 444.7 M RUR in 2 y at the same time the cleaning cost is 34.5 M RUR.

3.2 Best retrofit design

The optimal retrofit design of heat exchangers network provides 3 new heat exchangers. The network operation and fouling model were simulated too. The changing of heat transfer coefficient of new heat exchangers during 2 y operation is presented in Fig. 3. It is seen that after 2 years operation the heat transfer coefficient in new heat exchangers is decreased 5 times less comparison to clean conditions. The main degradation of exchangers working condition is in the first year of an operation, it leads to low network efficiency.

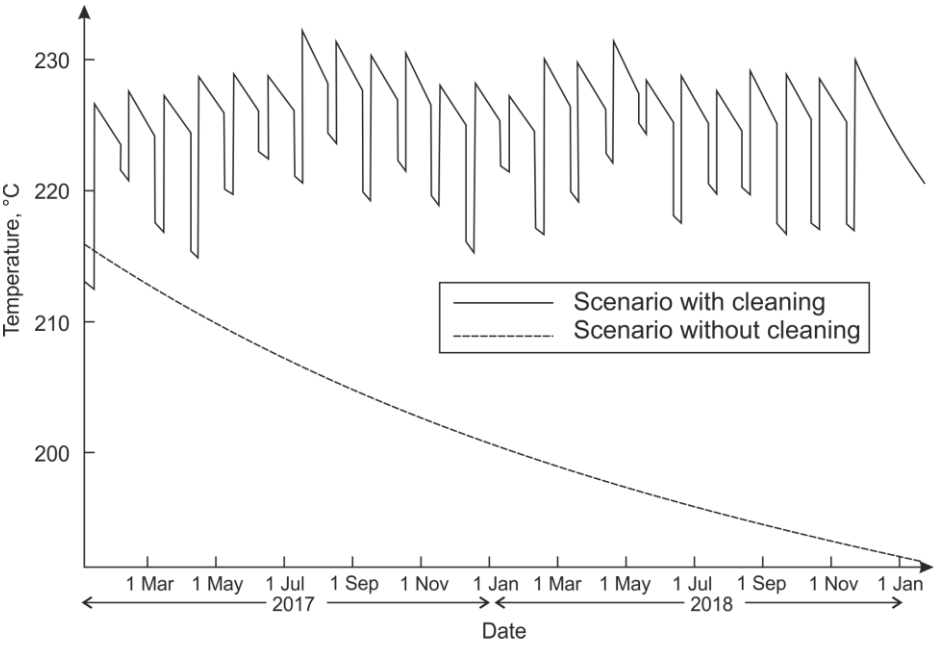

Figure 2: Furnace inlet temperature of base case.

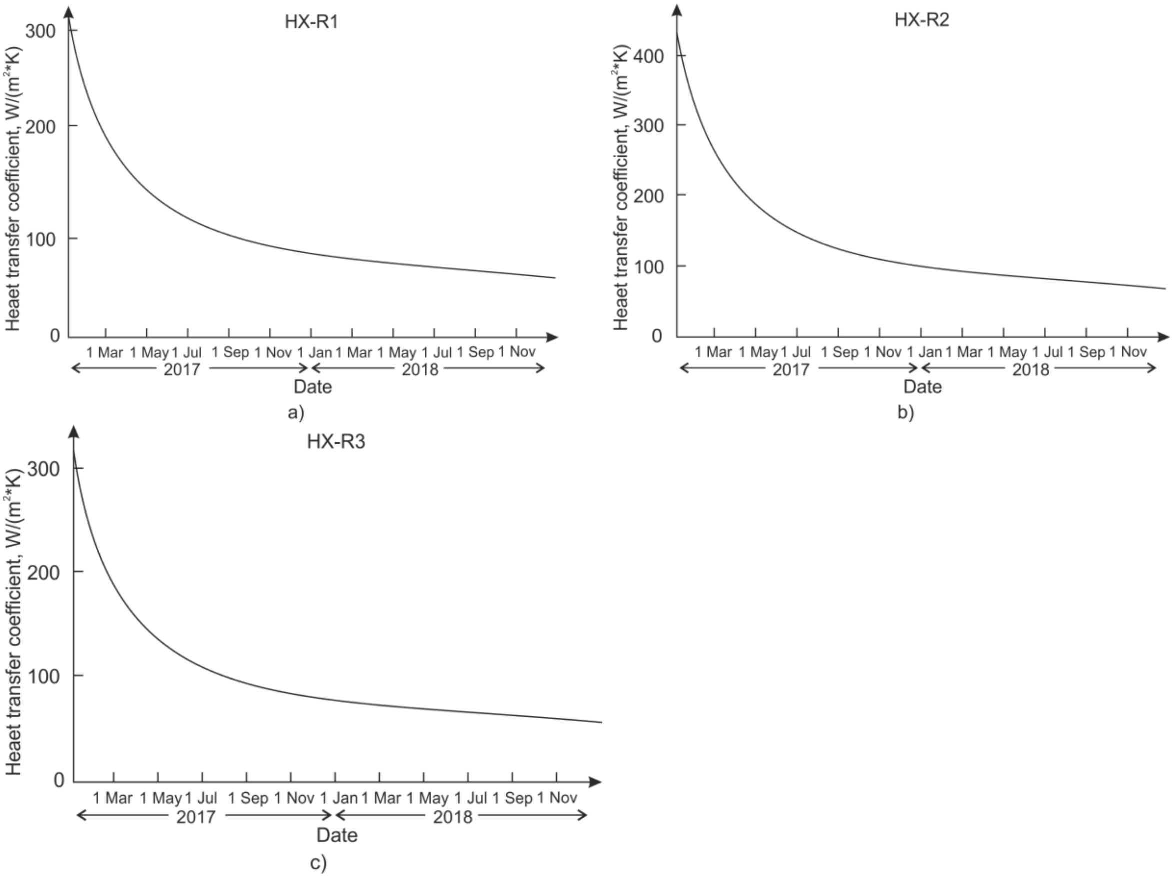

Figure 3: Heat transfer coefficient prediction of additional heat exchangers (R1-R3) of retrofit design.

The furnace inlet temperature indicates an overall network efficiency as shown in Fig. 4. This temperature is increased up to 230 °C when applying an improved integration design. Nevertheless, the furnace inlet temperature is dropped down to 203 °C after 2 years operation. This value is less than the base case temperature without integration option. The furnace inlet temperature without cleaning reaches 216 °C after the 1-year operation and it is the same as minimum inlet temperature of the base case with the cleaning schedule. In this case, the application of an integrated option without cleaning is less beneficial than the operation of the base case with cleaning schedule.

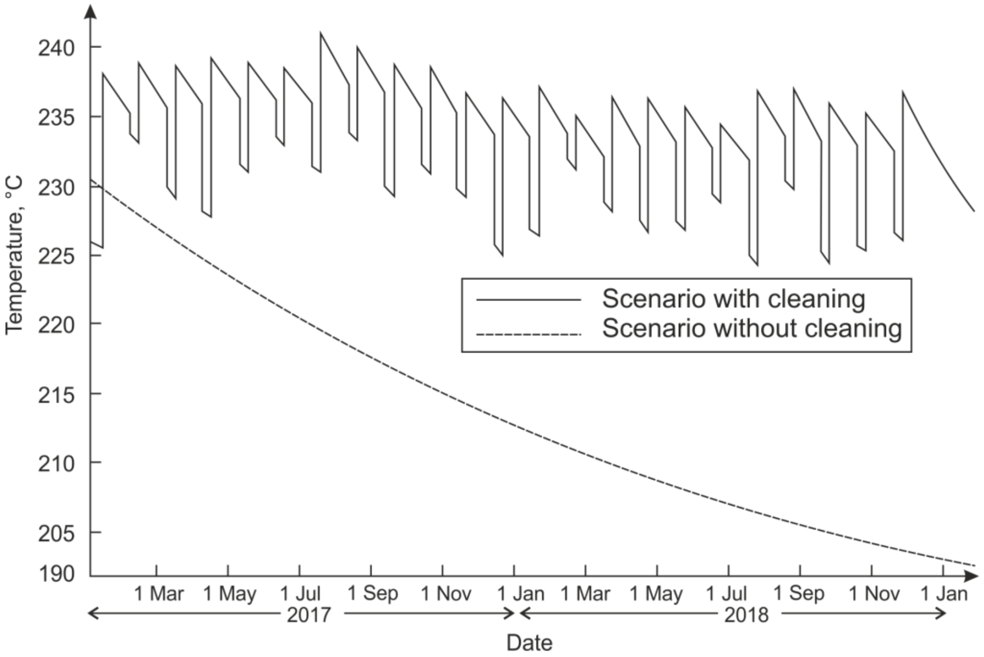

Figure 4: Furnace inlet temperature of retrofit design.

The optimisation of the operation mode of retrofit design in terms of fouling mitigation determines 2 years cleaning schedule with total cleaning budget 33 M RUR. It makes possible to save 46,200 t of CO_2 and 386 million RUR of operating cost in comparison to retrofit design without cleaning. A minimum furnace inlet temperature is 224.5 °C and maximum value achieves 241 °C.

3.3 Limitations and future works

One of the most important issues that have to be additionally discussed is an availability of historical data of plant operation. The historical data forms the base for fouling model determination and definition of fouling propensity factor. The lack of this data may lead to errors of fouling prediction and distribution within the heat exchangers network and, as result, increased operating cost. This issue is determinative for a retrofit design that could be performed but the return on investment and cash flow will be far from calculated values.

Another one important issue is an availability of experimental data of fouling propensity factors of different substances. There are some data for crude oil and different oil products but there are a lot of highly fouling substances and mixtures in different industries. Availability of these data could make possible to develop an integrated and energy saving solutions and improve process operation.

4. Conclusions

This paper updated a methodology of integrated network design accounting detailed heat exchanger and network conditions and fouling factor. The methodology shows the importance of fouling mitigation when applying Process Integration techniques for an operation performance of heat exchangers network, especially when exploiting highly fouling process streams. A representative case study of crude oil distillation was investigated; retrofit design and optimal cleaning schedule were developed. The optimal network design was selected accounting investment, utility and 2 y operation cost. The optimal integrated retrofit design increases the furnace inlet temperature at 15 °C and the optimal cleaning schedule additionally saves 46,200 t of CO_2 and 386 M RUR of operating cost. Results of this work may be exploited for viable retrofit of heat exchangers network, prediction of plant operation condition after the retrofit, operation cost and CO_2 reduction as well as a sustainable development of the industry.

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