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Fouling in Heat Exchanger Networks

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Fouling in heat exchangers has major cost implications; especially in applications such as crude oil pre-heating. In principle, fouling can be mitigated through changes in the way a heat exchanger network is designed and operated. In crude oil fouling, the rate of fouling is dominated by the wall temperatures of the heat exchanger tubes and the shear rate at the tube wall. Prior studies have demonstrated that under certain sets of wall temperatures and tube shear rates, a threshold for fouling deposition exists, which can be used for mitigation purposes. In principle, fouling can be alleviated or stopped by adjusting conditions within individual heat exchangers. Previous research has shown that heat exchanger networks can be designed and operated to mitigate fouling by accounting for the effects of wall temperature and shear rate. Various fouling models have been suggested previously to predict fouling rate as a function of temperature and shear rate. However, all of these models have adjustable parameters that need to be fitted to experimental data. The previous approach to this has been to carry out laboratory tests in shear cells. Unfortunately, this is impractical for most applications. Each crude oil (which might be subjected to frequent changes in a given pre-heat train) needs the appropriate parameters to be fitted. Also, the relationship between the fouling in laboratory shear cells and fouling in actual heat exchangers has yet to be established. This presentation will develop an alternative approach to fitting parameters to fouling models based on actual operating equipment. The approach presented allows for data reconciliation and model fitting from operational data that allows different fouling models to be fitted simultaneously for each side of a heat exchanger. Once such parameters have been fitted, they can be used for operational optimisation for fouling mitigation, including the optimisation of cleaning schedules. In design and retrofit, dynamic fouling characteristics can be included in the procedure to design and retrofit so that fouling can be mitigated simultaneously through operating cycles by the systematic manipulation of operating conditions and optimisation of cleaning schedules.

1. Introduction

In crude oil refineries, fouling in heat exchanger networks represents one of the major operational issues, since its occurrence carries out with it significant complications in terms of capital and operational costs. Thermal and hydraulic performance of heat transfer equipment is seriously affected by fouling deposition, increasing energy requirements such as fuel consumption in furnaces and additional pumping across the distillation column. Cost penalties derived from maintenance and cleaning also contribute to the total cost of fouling, in some cases rising up to magnitudes of millions of dollars per year (Coletti and Macchietto, 2011).

Different strategies have been developed in order to avoid the over accumulation of unwanted material on the equipment surface. Most commonly, periodic cleaning of the fouled surface is applied; the cleaning process can be applied by means of on-line or off-line procedures, including the use of chemical additives and installation of additional equipment during the design stage. The main issues regarding such strategies are the amount of time it takes to get the equipment out of service and the cost associated with the cleaning process. For this reason, the scheduling of every cleaning process must be systematically planned in such a way that the minimum loss of production is achieved.

Cleaning processes aim to restore the equipment to its original effectiveness (or at least as close as possible), because of this, cleaning is limited to mitigate the consequences of fouling, rather than its cause. At the moment, several studies have clarified the relation between the rate at which fouling is developed, and certain operational conditions such as temperature and wall shear stress, as Ebert and Panchal (1995) reported.

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Other studies have been proposed, in order to account for the contribution of thermal physical properties (Panchal et al., 1999) and wall temperature (Polley et al., 2002). The concept behind these models is the fouling threshold concept, which defines the maximum wall temperature (for a given flow velocity) at which no fouling occurs. The concept also defines the fouling rate as the difference between a formation and a removal rate, each one depending on certain operational conditions as it was mentioned above.

The threshold concept allows industries to design heat transfer equipment and locate this equipment into the non-fouling region, mitigating the potential existence of material depositing onto the surface. The same approach has been applied to operational fouling mitigation; where wall temperature and flow velocity are manipulated to finally move the operating conditions into a zone below the threshold curve (Rodriguez and Smith, 2007). The successful mitigation of fouling through optimisation of operational conditions is based on the knowledge of the fouling mechanism that lies on a particular heat exchanger. Each fouling rate model presents a set of parameters that needs to be determined in order to predict and optimise output conditions within the network. One of the most common methods for calculating these parameters is fitting the model itself to a series of experimental data. The model is regressed against the data and the parameters are determined using a least square approach. Several laboratory equipment has been to use to accomplish this task, some examples are the batch stirred cell (Young et al., 2011) and the recycle flow loop with tubular section (Crittenden et al., 2011).

Experimental work presents the disadvantage of being impractical for some cases, since there is an unclear certainty regarding the relation between the test conditions and what actually happens in the refinery (Wang et al., 2015). Crude oil changes are not considered in these studies and the amount of time needed for each test is for most of the cases, significantly long. So far, it is possible to optimise operating conditions to mitigate fouling, and through this procedure optimise cleaning schedules for design and retrofit purposes is possible. However, there is a significant gap between the current context and the potential mitigation solutions, represented by the fouling model. The proposed methodology uses on-line measurements to fit different fouling models for both sides of a heat exchanger, in contrast with previous works such as Yeap et al. (2004) and more recently Arsenyeva et al. (2013), where experimental data is used and no data treatment is applied in order to account for the impact of measurement errors. As a first step, the measurements are reconciled by minimising the measurement errors using operational constraints. Once a fouling model is selected (depending on the conditions and location of the heat exchanger in the network), the operational fouling resistance is regressed against the fouling data, determining the set of model parameters for the specific fouling model and crude oil, unlike similar approaches where some of the parameters are set based on previous experiments at different conditions (Arsenyeva et al., 2013). The fitted model can be used for optimisation of cleaning schedules and operational mitigation, as well as in design and retrofit for future network applications.

2. Fouling threshold models

Ebert and Panchal (1995) defined the fouling rate as the difference between formation and removal mechanisms. The first one depends mostly on the surface temperature and fluid viscosity, among other factors. The removal mechanism depends on flow velocity and is physically represented by the transport of material away from the surface, and back to the fluid. Based on this interaction, fouling occurs when the formation rate is higher than the removal rate, on the other hand; fouling might be negligible if the removal rate surpasses the formation rate.

Different fouling models can be used for calculating fouling rates and determining optimal cleaning conditions. Since formation and removal rates depend on thermal properties, the location of a heat exchanger within a heat exchanger network might play an important role regarding the fouling mechanism dominating the overall rate. The most common fouling rate models are summarised in Table 1.

Table 1: Fouling threshold models

Model	Equation
Ebert and Panchal (1995)	$\frac{dR_f}{dt} = \alpha Re^{\beta} \exp\left(\frac{-E_A}{RT_f}\right) - \gamma\tau$
Panchal et al. (1999)	$\frac{dR_f}{dt} = \alpha Re^{-0.8} Pr^{-0.33} \exp\left(\frac{-E_A}{RT_f}\right) - \gamma\tau$
Polley et al. (2002)	$\frac{dR_f}{dt} = \alpha Re^{-0.8} Pr^{-0.33} \exp\left(\frac{-E_A}{RT_W}\right) - \gamma R$

The set of parameters (α, β, E_A, γ) is the set that needs to be fitted for a specific crude oil. By choosing the proper fouling rate model, the set of parameters can be determined and used later on for optimisation and prediction purposes.

3. Optimisation of cleaning schedules

For crude oil refineries, cleaning of heat exchangers can be significantly complex, since most of the operational variables involved in the process are highly interconnected; a small change in any stream can affect greatly on the remain variables (Gonçalves et al., 2014). To clean a heat exchanger, chemical or mechanical procedures can be applied, depending on the equipment specific characteristics. In most cases, a heat exchanger is dismantled and taken out of service, increasing the overall cost, since more energy is consumed and extra personnel is needed.

Due to this high complexity, the decision process and identification of the optimal set of time intervals for heat exchanger cleaning is paramount, if economic and energetic savings are to be achieved. Therefore, the problem for finding the optimal set of cleaning operations involves binary variables (cleaning decisions) and continuous variables (temperature, flow rate, pressure, etc.). This formulation can be solved using a minimisation problem by searching for the best distribution of cleaning tasks, which optimises the operation cost.

Several methodologies have been developed, considering the nature of each variable and accounting for single heat exchangers and an entire heat exchanger network. Mixed integer linear programming has been used in milk industry (Georgiadis and Papageorgiou, 2000), where utility and cleaning costs are minimised by accounting for operational, time-related and fouling constraints. A different approach was proposed by Markowski and Urbaniec (2005), where the avoided loss of energy (defined as the difference among the energy recovered by cleaning, recovery without cleaning and the cost of cleaning) was maximized. In this case, fouling in a given heat exchanger was considered as a deposit build-up, driven by the influence of the previous heat exchangers in the network.

An alternative method is to address the optimisation problem by solving the cleaning schedule calculation using stochastic algorithms. Rodriguez and Smith (2007) proposed a case study where an optimal set of cleaning tasks was found by solving the optimisation problem using simulated annealing. The solver is based on the application of random moves and evaluating the objective function and comparing it with certain criteria; each move is accepted or neglected depending on the value of the objective function.

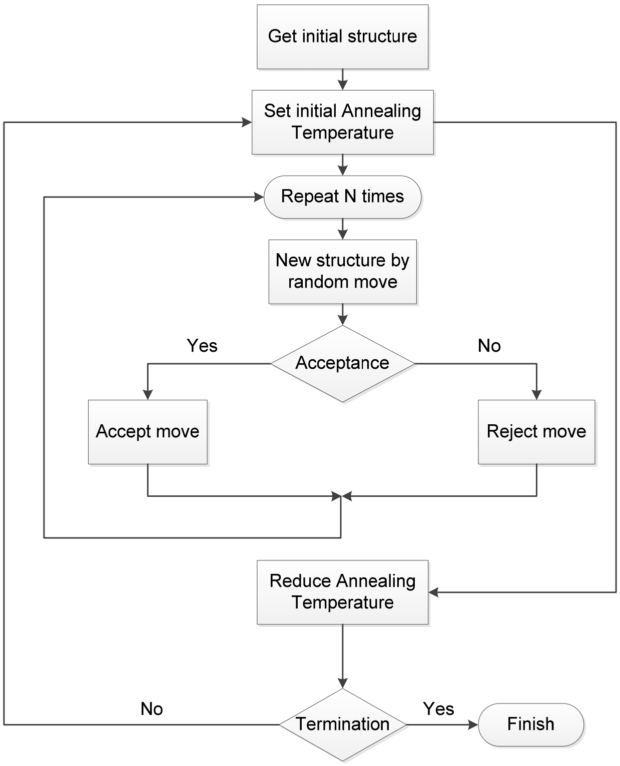

Figure 1: Simulating Annealing diagram.

This methodology has the advantage of finding global optima and several different scenarios can be tested in order to find the minimum value of objective function. A description of the algorithm is depicted in Figure 1. Fouling resistances were updated dynamically to account for the change in the fouling rate when the accumulation of deposits varies compared to its initial value.

Most recent works focus their attention into include more rigorous physical phenomena as constraints for the simulation and optimisation problem. One of these examples is the methodology developed by Diaby et al. (2016), where a two-layer model for accounting the fouling deposit layer was applied. Including the change and development of material into the fouling layer may increase the accuracy of the optimal solution; but at the moment, finding a realistic predictive model for the fouling layer is still part of the current research challenges.

4. Design and retrofit of networks for fouling mitigation

4.1 Fouling considerations for network design and retrofit

Given that fouling has such a significant impact on the performance of a heat exchanger network, great deal of attention has been put onto the optimal design and retrofit of a network structure and operation. Traditional approaches consider the fouling resistance as a constant value through time, not accounting for the dynamic behaviour that comes with fouling occurrence. Since fouling is a non-steady state process, its effect on the overall network energy consumption must be considered in the same modelling scheme.

When designing a network, there are some aspects that need to be considered. According to Fryer (1988), depending on the topology of a certain network (design for a certain heat load), fouling can affect such network at a different extent, compared to a different network structure for the same heat load. This sensitivity can define a base for designing networks that present a low degree of fouling dependency, maximizing the heat recovery. However, the capital cost for manufacturing such network can reach significantly high magnitudes, depending on the operating costs and profits.

Wall temperature also presents an important role when it comes to design and retrofit a network. Since chemical reaction fouling depends on the surface temperature, if its value is decreased (for a given velocity), fouling can be mitigated by moving the operation conditions across the fouling threshold curve (Rodriguez and Smith, 2007). Wall temperature can be modified by arranging the stream matches in such a way the wall temperature can reach a minimum value, for a given set of target temperatures in the network.

By modifying operational conditions, it is possible to avoid fouling occurrence, since the location within the threshold curve indicates that no fouling is expected. However, this can also limit the amount of heat recovered, due to the changes in the overall heat transfer coefficient of every heat exchanger that has been modified to operate below the threshold. In order to obtain an optimal level of heat recovery, a trade-off between the fouling acceptance limit and the cost penalties for operating under certain conditions such as temperatures and velocity must be analysed.

4.2 Dynamic simulation of fouling for design and retrofit

The interactions among each variable involved in a heat exchanger network are complex physical relations that can be expressed as thermodynamic modelling. The optimisation of design and retrofit of a network includes the optimisation of decision variables as well, represented by re-piping, removing or adding splitters and heat exchangers, etc. These process variables need to be related with economic constraints, since every move carries out its own cost, increasing the complexity of the optimisation method.

The cost for fouling is related to the consumption of utilities, which provide the enough amount of energy the cold streams need for reaching their target temperatures. If the total cost is to be minimised, the variable cost for fouling deposition has to be included, along with the capital cost for equipment, modifications and energy cost.

The use of fouling models is paramount to consider the transient change in fouling resistance over time. Depending on the location of a heat exchanger within the network, different fouling rate models can be properly applied. Fouling rate can be used to dynamically update the fouling resistance for each time step, establishing a link among the constant changes in fouling resistance.

The updating process is detailed in Figure 2. If the heat exchanger is clean at the initial time, its fouling resistance is initialized as a null value; on the other hand, if the fluid is changed or the heat exchanger was not clean after a different cleaning process, the resistance is initialized as the resistance on the previous time step. Eq(1) defines the updating procedure, based on an Euler forward numerical integration.

$$R_f|_{n+1} = R_f|_n + \Delta t \left.\frac{dR_f}{dt}\right|_n \qquad (1)$$

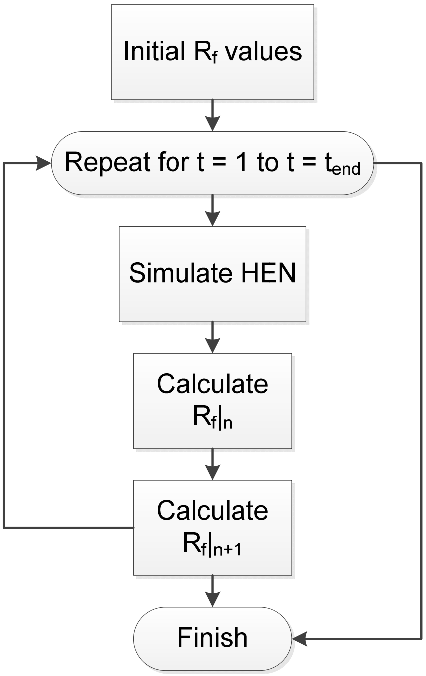

Figure 2: Fouling resistance dynamic simulation.

5. Development of fouling models for crude oil refinery

The current state of the art covers the optimisation of operational conditions for fouling mitigation, as well as the minimisation of cleaning tasks to optimise cleaning costs. Based on these approaches it is possible to find the best set of movements to optimise the design and retrofit of new and existing networks.

In order to apply all the above calculations, it is necessary to have a certain notion about the fouling mechanism and its fouling rate model. As it is shown in Table 1, each fouling model presents a set of parameters that needs to be determined for each type of crude oil. Different methods have been applied for calculating these sets, varying from experimental procedures and development of empirical correlations.

Unfortunately, in most cases, the relation between experimental and field data is unclear, since the controlled conditions in the laboratory are unfeasible whilst operating a pre-heat train. Besides, the amount of time necessary to run each test, for each crude oil sample might take too long, if instant results are needed for selecting further process decisions.

In order to account for the constant changes and real conditions into the problem, on-line data can be used as an input, and the fouling model can be estimated and fitted for any variations within a certain time range. Since field data is to be used, measurement errors must be considered, and the data needs to be reconciled before fitting the model. It is important to note that data reconciliation minimises the measurement error when only random error is contained in the data. However, in some cases the measurement instruments might present null or partial calibration, leading to biased data, compromising the reliability of each reconciled value (Romagnoli and Sanchez, 1999). Because of this, any data reconciliation problem has to be solved simultaneously with a gross error identification and estimation problem.

The reconciled data can be used to fit the measurements to determine the set of parameters for a specific fouling model. Fouling resistances are calculated by means of a heat exchanger network simulation model and updated using the dynamic approach depicted in Figure 2. Using the fitted parameters, a fouling model is obtained, which allows performing prediction of outlet conditions, optimisation of cleaning schedules and optimal design and retrofit of heat exchanger networks.

A limitation of this approach is the trade-off between the available and needed instrumentation for calculating the fouling resistances for each heat exchanger in the network. Within this set of variables that needs to be measured, there must be a different set of measurements that needs to be free from gross error, since the accuracy of reconciled data decreased significantly when simultaneous gross errors are contained (Narasimhan and Jordache, 1999). The amount of available data from measurement instruments is then critical, since it sets the input for the reconciliation and fitting strategies.

6. Conclusions

Fouling deposition represents one of the most complex issues for crude oil refinery. Its impact is not just in terms of economics, but thermal and hydraulic performance of any equipment is decreased by its development. A great number of fouling mitigation techniques has been proposed, considering the dependency fouling presents with operational conditions such as wall shear stress and surface temperature. Based on this knowledge, it is possible to mitigate the effect of fouling deposits by manipulating operational conditions and moving the current state to a new state where fouling occurrence is minimised.

Optimisation of cleaning schedules allows for finding the best set of cleaning operations, which can result in significant savings in terms of total cost and energy consumption. Mitigation by manipulation of operational conditions can also be applied for the design and retrofit of heat exchanger networks. By changing an existing network structure, fouling can be mitigated and the total cost for energy consumption and adjustments is minimised.

In order to successfully optimise a network in terms of fouling mitigation and cleaning schedules, the fouling model must be identified. By using on-line reconciled data, a specific fouling model can be fitted and used for predictions and optimisation considering several time horizons. For this methodology to work, the results from its implementation need to be tested with actual plant data, and the issues regarding available instrumentation must be addressed.

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