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Heat exchanger fouling model and preventive maintenance scheduling tool

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Abstract

The crude preheat train (CPT) in a petroleum refinery consists of a set of large heat exchangers which recovers the waste heat from product streams to preheat the crude oil. In these exchangers the overall heat transfer coefficient reduces significantly during operation due to fouling. The rate of fouling is highly dependent on the properties of the crude blends being processed as well as the operating temperature and flow conditions. The objective of this paper is to develop a predictive model using statistical methods which can *a priori* predict the rate of the fouling and the decrease in heat transfer efficiency in a heat exchanger. A neural network based fouling model has been developed using historical plant operating data. Root mean square error (RMSE) of the predictions in tube- and shell-side outlet temperatures of 1.83% and 0.93%, respectively, with a correlation coefficient, R^2, of 0.98 and correct directional change (CDC) values of more than 92% show that the model is adequately accurate. A case study illustrates the methodology by which the predictive model can be used to develop a preventive maintenance scheduling tool.

Keywords: Heat exchanger fouling; Crude preheat train; Prediction model; Neural network; PCA; PLS

1. Introduction

Reduction of energy consumption is a major objective in all manufacturing processes. Refinery operations involve heating of large quantities of crude oil prior to their physical and chemical processing. For improved energy efficiency of the refining process, it is imperative to recover as much heat as possible from the product stream back into the input crude stream, to minimise the use of fresh energy, which is achieved by a battery of heat exchangers called the crude preheat train (CPT). Generally, crude oil flows through the tube side while various other hot streams and pump-around streams flow through the shell side in the heat exchangers. These fluids are highly fouling and the heat transfer coefficient and energy recovery can go down as low as 30% compared to their clean values. The annual loss attributable to heat exchanger fouling in US and UK together is of the order of USD 16.5 billion [1,2]. Hence, heat exchanger performance is very important for the overall refinery economics.

Fouling in heat exchangers has been the subject of intensive research by several groups of investigators. Crittenden et al. in a series of papers [3–7] reported their research on the mass transfer and chemical kinetics in hydrocarbon fouling. Ebert and Panchal [8] were the first to introduce theoretical concepts to the phenomenon of fouling. They modeled the fouling process using a rate equation and introduced the concept of threshold temperature below which fouling is minimum. They also investigated the effect of tube inserts on the reduction of fouling. Watkinson [9,10] investigated the fouling of exchangers by organic fluids. Watkinson and Epstein [11] investigated the effect of

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Nomenclature

t	time, [day]	x	variable to be normalized in Eq. (1)
t_i	tube inlet temperature, [°C]	x_{norm}	normalized variable
t_o	tube outlet temperature, [°C]	x_{min}	minimum value of the variable x
T_i	shell inlet temperature, [°C]	x_{max}	maximum value of the variable x
T_o	shell outlet temperature, [°C]	y	variable under test for CDC in Eq. (2)
V_s	shell flow rate, [m^3/hr]		

particulates on fouling. Saleh et al. [12] studied the effect of blending on the rate of fouling of Australian crude oils. Several researchers [13–15] have published theoretical modeling of the fouling behavior in crude oil heat exchangers. Muller-Steinhagen [16] has given a complete review of the state of the art in the area of fouling mitigation by various techniques. Markowski and Urbaniec [17] have presented an optimal scheduling of cleaning interventions in a heat exchanger network based on a computational approach to minimize losses.

ESDU [18] report gives a comprehensive review of the effect of various properties of the crude oil such as asphaltene content on the rate of fouling. A new model has been proposed by Nasr and Givi [19] that includes terms for fouling formation and removal. They have also reported the fouling rate of Australian light crude oil and drawn threshold curves to identify fouling and no fouling formation zones. Negrao et al. [20] have shown prediction of heat exchanger effectiveness from classical literature relations as a function of NTU and heat capacity ratio.

The performance reduction due to fouling is mitigated by periodic cleaning of the heat exchangers. However, during cleaning, the heat exchanger is out of the heat recovery loop and hence the overall heat recovery goes down. If the rate of fouling can be predicted *a priori*, cleaning of heat exchangers can be prescheduled to minimize operational disruptions. Development of such a prediction model is the aim of the current research work. Artificial neural network (ANN) is an important class of empirical technique to model nonlinear, complex or little understood processes with large input–output data sets. ANNs have been successfully used for a number of chemical engineering applications such as inferential measurements and control [21–25], fault-diagnosis [26], process modeling, identification and control [27,28]. A step-by-step practical methodology for data processing and network training of an inferential measurement system have been presented by Bhartiya and Whiteley [21] and Warne et al. [24]. In the present paper, one of the heat exchangers in CPT from a refinery in Malaysia has been modelled. Principal component analysis (PCA), and projection to latent structures (PLS) were used as tools for outlier removal and input variable selection. The fouling model was developed using neural network (NN) techniques. The prediction model was used in a case study to develop a preventive maintenance scheduling tool.

2. Fouling behavior of a refinery heat exchanger

2.1. Equipment studied

In the CPT studied in this work, there are 11 heat exchangers with a total rating of 66.5 MW. The unit chosen for this study from the CPT is one of the principal heat exchangers for the recovery of heat. The important characteristics of the heat exchanger are shown in Table 1.

2.2. Heat exchanger historical performance

The heat exchanger underwent mechanical cleaning during a turnaround in May 2002 and the overall heat transfer coefficient was equal to the clean design value (U_{clean}). The performance of the chosen heat exchanger for a period of 3 years starting from the turnaround is shown in Fig. 1. The heat transfer coefficient under fouled condition (U_{dirty}) was calculated using the actual log mean temperature difference (LMTD). The heat transfer efficiency was calculated as U_{dirty}/U_{clean}. As seen in Fig. 1, by June 2003 the efficiency dropped to almost 20%. The exchanger was then cleaned by a process known as 'hot melting' in which hot diesel with other cleaning chemicals are circulated over the heat transfer surface for several hours till the deposits were dissolved and removed. The maximum efficiency restored after the hot melting or turnaround is called the

Table 1
Characteristics of the heat exchanger studied

Parameter	Value
Heat duty	2650 kW
Heat transfer area	186 m^2
Overall heat transfer coefficient – Design clean value	293 W/m^2 K
Overall heat transfer coefficient – Design fouled value	217 W/m^2 K
Number of shell passes	1
Number of tube passes	6, Counterflow
Number of tubes	548
Tube OD	19.05 mm
Tube pitch	25.4 mm square pitch
Shell side fluid	Crude oil
Tube side fluid	Low sulfur waxy residue (LSWR)
Shell-side design ΔT	9.2 °C
Tube-side design ΔT	42 °C