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Modeling of crude oil fouling in preheat exchangers of refinery distillation units

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Abstract

The aim of this paper is to propose a new model for crude oil fouling in preheat exchangers of crude distillation units. The experimental results of Australian light crude oil with the tube side surface temperature between 200 and 260 °C and fluid velocity ranged 0.25–0.4 m/s were used [Z. Saleh, R. Sheikholeslami, A.P. Watkinson, Heat exchanger fouling by a light australian crude oil, in: Heat Exchanger Fouling and Cleaning Fundamentals and Applications, Santa Fe, 2003]. The amount of activation energy depends on the surface temperature has been calculated. A new model including a term for fouling formation and a term for fouling removal due to chemical and tube wall shear stress was proposed, respectively. The main superiority of the model are independent to *Pr* number, thermal fouling removal and determination of β based on experimental tests. Finally using the proposed model the fouling rate of Australian light crude oil has been calculated and the threshold curves to identify fouling and no fouling formation zones have been drawn.

Keywords: Heat exchanger; Fouling; Modeling; Crude oil; Distillation unit

1. Introduction

Fouling formation in preheat exchangers of a crude distillation unit (CDU) is identified as a main energy consuming unit in petroleum refineries. Almost half of the overall operational cost of the refineries is due to the energy loses resulted from fouling formation in the preheat exchangers [2]. As a matter of fact, it is recognized that the main parameter in fouling of CDU is the wall temperature so that for example by increasing the tube wall temperature, chance for asphaltene deposition increases. Furthermore, the present of some impurities in crude oil such as metals and metal oxides also accelerates the fouling rate [3]. To predict the fouling rate it is necessary to relate the fouling rate to the wall temperature. Therefore, in proposed models the Arrhenius relation is commonly used.

2. Crude oil fouling models

A large number of models for crude oil fouling have been presented [4]. However they are not able to predict the fouling formation by changing of the operating conditions and differing crude types. Some models can only able to predict fouling without considering the effect of fluid velocity on the fouling removal. For example, Saleh et al. proposed a model as follows [1]:

$$\frac{dR_f}{dt} = \alpha P^{\beta} u^{\gamma} \exp\left(\frac{-E}{RT_f}\right) \tag{1}$$

They used portable fouling research unit (PFRU) fitted with an annular HTRI heat transfer prob, which was operated at constant heat flux with time and all runs were conducted in the transition region. All other reported models were in the turbulent region and applied to data collected from a refinery or coking stream.

And in 1995, Ebert and Panchal [5] proposed threshold model for crude oil fouling formation as follows:

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Nomenclature

E	activation energy	T_f	film temperature
f	friction factor	T_s, T_w	wall temperature
P	pressure	u	velocity
R	gas constant	ρ	density
Re	dimensionless Reynolds number	τ	shear stress
t	time	$R_{f,exp}$	fouling rate due to experimental results
T_b	bulk temperature	$R_{f,Th}$	fouling rate due to model results

$$\frac{dR_f}{dt} = \alpha Re^{\beta} \exp\left(\frac{-E}{RT_f}\right) - \gamma\tau_w \quad (2)$$

where

$$\beta = -0.88$$
$$E = 68 \text{ kJ/mol}$$
$$\alpha = 8.39 \text{ m}^2 \text{ K/J}$$
$$\gamma = 4.03 \times 10^{-11}(\text{m}^2/\text{N})(\text{m}^2 \text{ K/J})$$

and

$$\tau_w = \frac{f}{2}\rho u^2 \quad (3)$$

In Eq. (2) the first statement shows that the fouling formation depends on chemical reaction and film temperature. The second statement also shows that the fouling removal depends on tube wall shear stress or tube side fluid velocity. This means that as the velocity increases the rate of fouling formation decreases. Typical relationships can be given by the following equations according to flow regimes. For example, for laminar flow regime [6]:

$$f = \frac{16}{Re} \quad (4)$$

and in turbulent flow [6]:

$$f = 0.0035 + \frac{0.264}{Re^{0.42}} \quad (5)$$

Ebert and Panchal threshold model was improved by Polley et al. Their model is required the tube wall temperature in the fouling formation statement as follows:

$$\frac{dR_f}{dt} = \alpha Re^{-0.8} Pr^{-0.33} \exp\left(\frac{-E}{RT_w}\right) - \gamma Re^{0.8} \quad (6)$$

where

$$\alpha = 1{,}000{,}000 \ (\text{m}^2 \text{ K W}^{-1} \text{ h}^{-1})$$
$$\gamma = 1.5 \times 10^9(\text{m}^2 \text{ K W}^{-1} \text{ h}^{-1})$$
$$E = 48(\text{kJ mol}^{-1})$$

The model is developed and justified based on Knudsen's experimental results [7]. It should be mentioned that to extend the model for the other type of crude oil the constant values have to be recalculated correspondingly.

3. The proposed model

To propose a new model the experimental results reported by Saleh et al. were used [1]. The properties of crude oil that they used are mentioned in Table 1.

Table 2 shows the conditions of the experimental tests and also the fouling rate which has been calculated in their report curves [1].

The new model can be proposed by the following equation:

$$\frac{dR_f}{dt} = \alpha Re^{\beta} \exp\left(\frac{-E}{RT_f}\right) - \gamma Re^{0.4} \quad (7)$$

In Eq. (7), E(J/mol) is the activation energy. By drawing the fouling rate versus $1/T_f$, the amount of the activation

Table 1
Physical properties of Australian light crude oil [1]

Density (g/ml)	0.792
Viscosity (Mpa s)	1.969
Asphaltenes (wt.%)	0.05

Table 2
Experimental condition and the fouling rate based on Australian light crude oil

Inlet bulk temperature (°C)	Surface temperature (°C)	Velocity (m/s)	Pressure (kPa)	Fouling rate (m^2 K/kJ) $\times 10^6$	Run no.
80	180	0.2500	379	0.2003	1
80	200	0.2500	379	0.2872	2
80	220	0.2500	379	0.3989	3
80	240	0.2500	379	0.4797	4
80	260	0.2500	379	0.4795	5
80	245	0.2500	379	0.4806	6
80	245	0.2500	510	0.4592	7
80	245	0.2500	655	0.5361	8
80	245	0.3500	379	0.2847	9
100	245	0.3500	379	0.2911	10
120	245	0.3500	379	0.5199	11
80	245	0.2500	379	0.5004	12
80	245	0.3000	379	0.3496	13
80	245	0.3500	379	0.2661	14
80	245	0.4000	379	0.2351	15