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Improved threshold fouling models for crude oils

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A B S T R A C T

The existing threshold fouling models always predict an increase in initial fouling rates with an increase in bulk temperature which may not hold good for some crude oils. In this study, an improved threshold fouling model is proposed which uses an effective film temperature in the Arrhenius expression. Experiments were conducted in a high pressure, high temperature recirculation flow pilot-scale fouling test rig with three test crude oils with differing properties under the operating conditions of surface and bulk temperatures ranging from 243 to 334 °C and 82–180 °C, respectively, and velocities at 0.35 and 0.5 m/s. The proposed model has been shown to predict initial fouling rates very closely with the experimental data with R^2 values above 0.98 for the three test crude oils used in this study.

1. Introduction

Sustainable and cleaner production model has been embraced as a policy and practice by the governments and industries, respectively, as an effort to counter the deterioration of environment. Cleaner production has become a primary part of planning, design, operation and management in all industrial sectors today [1]. Models and methods are developed to support sustainable planning and supervision [2]. Heat exchanger fouling has been a challenging problem in process industries, especially, in crude preheat trains of petroleum refineries. Fouling is associated with severe energy, environmental and economic repercussions. The thermal efficiency of heat exchangers decreases with time due to fouling which results in reduced heat recovery [3]. In the case of crude preheat trains, additional fuel is required to heat the crude oil to the required temperature, and the use of additional fuel leads to associated environmental impacts due to the production of more CO_2 [4]. The additional pumping cost due to increased pressure drop may also be significant as fouling decreases the flow area and results in higher frictional pressure drops [5]. Frequent cleaning of heat exchangers, thus, becomes necessary [6] to restore the heat transfer efficiency and as a result the heat exchangers are periodically taken out of service for cleaning [7]. Taking into account all the costs associated with fouling, it was reported in 2009 that the cost of fouling is USD 15 billion and USD 2.5 billion in USA and UK, respectively [8].

A number of techniques are employed to mitigate the effects of fouling in crude preheat trains. The chemical methods involve the use of anti-foulants as chemical additives [9] and the physical methods include the use of inside- and outside-tube mitigation devices such as tube inserts, twisted tubes, helical baffles, etc. [10]. Since the cost associated with chemical and physical methods of fouling mitigation are quite significant, other alternative mitigation strategies such as operation below the threshold fouling conditions is gaining interest in the industry and academia, e.g., the use of threshold fouling models in the shell and tube heat exchanger design software such as EXPRESSplus by ESDU and HTRI Edgeview™. These commercial software packages use the threshold fouling models which are discussed further in this paper for predicting threshold fouling conditions during the design of heat exchangers.

Even though there is a lack of crude oil fouling characterization standards, extensive experimental works have been carried out to understand the hydrocarbon fouling and a number of factors influencing fouling have been identified and studied [11]. Several

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types of fouling experimental units are used to study crude oil fouling which are broadly categorized as laboratory and field units. The detailed construction and application of different fouling test rigs are discussed by Ref. [12]. Advantages/disadvantages of studies conducted using different types of experimental units on crude oil fouling are summarized by Ref. [13]. Laboratory units such as stirred batch cells [14] [15], and recycle flow loop with tubular [16] or annular cross-section [17] [18] are widely used for fouling studies. Theories describing asphlatenes adhesion inside the tubes of heat exchangers were proposed [19] and computational fluid dynamics based fouling prediction approaches were also used by a few researchers to predict precursor/asphaltenes deposition on heat transfer surfaces [20]. Crude oil composition, flow velocities, surface and bulk temperatures are some of the important factors that affect the rate of fouling.

Mathematical models were developed to predict the rate of fouling with varying complexities which include theoretical, semi-empirical and empirical models [21]. Ebert and Panchal [22] introduced the concept of threshold fouling conditions below which the net rate of fouling is nil or very low. This is a realistic approach to model the rate of fouling in crude preheat trains. The semi-empirical threshold fouling model proposed by Ref. [22] is

$$\frac{dR_f}{dt} = \alpha Re^{-\beta} \exp\left(\frac{-E}{RT_f}\right) - \gamma\tau_w \quad (1)$$

The first term in the RHS of (1) represents the rate of deposition of foulants on the heat transfer surface while the second term represents the rate of removal due to wall shear stress and the net rate of fouling is the rate of deposition minus the rate of removal.

Panchal and coworkers [23] later modified the Ebert and Panchal model by including the Prandtl number to take into account the thermal properties of the crude oil as:

$$\frac{dR_f}{dt} = \alpha Re^{\beta} Pr^{-0.33} \exp\left(\frac{-E}{RT_f}\right) - \gamma\tau_w \quad (2)$$

Polley et al. [24] assumed that the reaction is taking place at the heat transfer surface and used surface temperature, T_s, instead of film temperature, T_f, in the Arrhenius term. They also assumed that the rate of foulant removal is mass transfer related rather than due to wall shear stress. The model proposed by Ref. [24] is

$$\frac{dR_f}{dt} = \alpha Re^{\beta} Pr^{-0.33} \exp\left(\frac{-E}{RT_s}\right) - \gamma Re^{0.8} \quad (3)$$

This model is found to be more appropriate when the surface temperatures are very high, nearly at coking conditions where the effect of bulk temperature becomes negligible. In the real plant situations, the surface temperatures are relatively low and hence this model cannot be used for modeling fouling in crude preheat trains.

The value of β, the exponent of Re in the generation term, was assumed to be −0.66 by Panchal et al., and −0.8 by Polley et al. while the other model parameters are fitted to the experimental data. Nasr and Givi [25] proposed a new threshold fouling model which includes β as one of the parameters to be estimated from the experimental data as:

$$\frac{dR_f}{dt} = \alpha Re^{\beta} \exp\left(\frac{-E}{RT_f}\right) - \gamma Re^{0.4} \quad (4)$$

The value of β for Australian light crude oil was reported to be −1.547.

These threshold fouling models express fouling rate as a function of fluid velocity, film or surface temperature and thermophysical properties of crude oil. Generally, the rate of fouling is directly proportional to the rate of chemical reaction given by the Arrhenius-type expression as [26]:

$$\frac{dR_f}{dt} \propto exp\left(\frac{-E}{RT}\right) \quad (5)$$

The temperature, T, used in expression (5) depends on the assumption as to where the reaction is taking place. Some researchers consider the film temperature, T_f, emphasizing that the chemical reaction takes place in the film to form the fouling precursors [22], [23], [25] while Polley et al. used the surface temperature, T_s, assuming that the reaction to take place at the heat transfer surface [24]. Conventionally, the film temperature, T_f, is calculated as the arithmetic mean of surface and bulk temperatures. But, the commonly used expression for T_f in the existing threshold fouling models is:

$$T_f = T_b + 0.55(T_s - T_b) \quad (6)$$

In accordance with the expression (5), the rate of fouling increases with an increase in the film temperature, T_f, or surface temperature, T_s. This has been very effectively supported by many experimental studies [27]. Quite the contrary, it has been observed from the data published in the literature that the fouling rates do decrease with an increase in film temperature, T_f, caused by an increase in bulk temperature, T_b [28].

The threshold fouling models that use film temperature, as defined in Eq. (6), in the Arrhenius term do not describe the phenomenon of decreasing fouling rates at higher bulk temperatures. Since the characteristics of precipitation and dissolution of fouling precursors/asphaltenes in each crude oil differ and it is difficult to predict the foulant forming reaction zone, the restrictions given by the existing models to the definition of film temperature do not hold good for all the crude oils. Srinivasan and Watkinson (2005) correlated fouling rates for some Canadian crude oils using a modified film temperature, T_f', which weighed more heavily on surface temperature as [29]:

$$T_f' = 0.3T_b + 0.7T_s \quad (7)$$

A modification to the definition of the film temperature, T_f, which is flexible enough to take into account the varying characteristics of precipitation/dissolution of fouling precursors of different crude oils at different bulk temperature conditions is required. The present research attempts to develop an improved threshold fouling model with a flexible definition for the film temperature which is crude oil dependent and by including the parameter β as one of the model parameters to be estimated. The present research is aimed at investigating the effects of bulk temperature on crude oil fouling characteristics for the chosen test crude oils experimentally in a recirculation flow fouling test rig; and to develop and validate the improved threshold fouling model for the crude oils.

The rest of the paper is organized as follows. A brief description of the fouling test rig, experimental procedure for the thermal fouling experiments and the results of experiments are provided in Section 2. The limitation of the existing threshold fouling models for the effect of bulk temperature variations is analyzed and discussed in Section 3. Section 4 deals with the improved threshold fouling model to overcome the limitation of the existing models. The model is further validated for different test crude oils with the experimental data. A special case of the improved threshold fouling model is also introduced and discussed in Section 5. The possible reasons for the limitations of the existing