Development of a Semi-Empirical Fouling Model to Accommodate Characteristics Linear, Exponential and Sigmoid on Heat Exchanger

Widita Trisniani 1*, Totok Ruki Biyanto 1*

1 Engineering Physics Departemen, Institut Teknologi Sepuluh Nopember (ITS)
*Corresponding author: dita.widi@yahoo.com, mainan.engineering@gmail.com

Abstract— Fouling is the formation of a layer of deposits on heat transfer surfaces of undesirable materials or compounds. It is influenced by fluid property that is the presence of flow rate and fluid temperature. Fouling on heat exchanger is a very complex phenomenon in such a way that difficult to analyze analytically. So it takes a mathematical fouling model to predict fouling rate in order to increase the efficiency of the heat exchanger caused by the existence of fouling. The model was developed based on the first principal model with the advantage that the model has more detailed potential phenomena regarding the occurrence of fouling, nonetheless the data that this research used is difficult to find. As broadly known, the advantages of an empirical model was able to get fouling rate with ease and it agree with the form of fouling that occurs in the plant, but it could not describe the phenomenon that occurs. Therefore it takes a developed fouling model by combining the first principal models and empirical equations to become a semi-empirical model on heat exchanger which could describe the phenomenon and also follow the pattern to accommodate the linear, exponential and sigmoid characteristics. The Boltzmann-sigmoidal function captures the fouling initiation period which is the major advantage of this model over the other type of models used by previous researchers. This paper presents the development of empirical models for an industrial HEN (Heat Exchanger Network) using the plant operating data. The fouling models are developed and shown to describe the fouling resistance over time in a crude preheat train with reasonable accuracy.

Keywords— fouling model, heat exchangers, semi-empirical models, the linear, exponential and sigmoid characteristics

I. INTRODUCTION

Fouling in heat exchanger is a serious refineries problem (Aminian, 2007). This is caused by the highly complex phenomenon that consist simultaneous activity on the general mechanism of physics and chemistry. Some of the mechanisms that experienced by the heat exchanger is the formation of deposits, corrosion, chemical reaction fouling, sedimentation and bio-fouling (Bayat, 2012). The formation of deposits layer will continue to grow while the heat exchanger is operated. The accumulation deposit on the surface of the heat exchanger raises the reduced surface area, and lead to increase of the pressure drop and decrease heat transfer efficiency (Bott, 1995).

The occurrence of fouling characteristics is difficult to analyze analytically. Therefore, in order to know the characteristics of the process of physical phenomena, a comprehensive method of mathematical modeling will be needed (Kovov, 2006). The mathematical equation using computer simulations is utilized to produce a solution to the problem or behavior of a system (Meyer, 1992). Basic laws of physics and chemistry are utilized to describe the process of fouling phenomena mathematically. The developed mathematical model generally consists of a derivative equation that is too complicated, so that it becomes impossible to be solved by analytical methods. But the solution of mathematical model that derived can be achieved with an analog or digital computer model simulation. The success of the approach is set not only by the completeness and reliability of the mathematical model but also by the amount and accuracy of the data experiment (Perry and Green 1997).

Because the existence of fouling which has a negative impact, the consequence is a mathematical fouling model need to be constructed to predict fouling rate to increase the efficiency of heat exchangers. The fouling rate model was first described based on the concept of Kern and Seaton (1959) where the model is developed based on the first principal model that is fouling rate. Fouling rate is the difference between the current rate of deposition and removal. The flow rate of deposition is described by the reaction transport models, while the rate of removal is described by the mass transfer. In addition, Epstein (1994) considers the occurrence of fouling at the initial time where it is difficult to justify the limited time at the onset of fouling phenomena. The advantages of a model based on first principal models are it has more details about potential phenomena regarding fouling however the data used is hard to obtain (Biyanto, 2013).

Model fouling is also developed by empirical model based on artificial neural network (ANN) because of the superior capabilities in handling complex and nonlinear systems. Artificial neural network models have been developed for preheat exchangers based on historical data (Radhakharishnan, 2007) and artificial neural
network models have also been developed based on data from a laboratory scale ring test (Aminian, 2008). The advantages of the empirical model are able to get fouling rate with ease and fit with the form of fouling that occurs in the plant, but it could not describe the phenomenon that occurs.

Furthermore, some research conducted an assessment of the fouling concept when threshold fouling conditions using semi-empirical models such as the linear, exponential and sigmoid characteristics (Deshannavar, 2010). Ebert and Panchal (1995) proposed a semi-empirical model to predict a linear rate of fouling as a function of temperature film and fluid velocity. This model ignores the thermal conductivity and specific heat and only considers the effect of the density and viscosity through the Reynolds number. Polley (2002) made a simple modification of Ebert and Panchal models by observing the turbulent flow rate passing through the circular tube and got exponential Reynolds number at -0.8 based on the Arrhenius equation. Therefore, in this paper, a model will be developed which is capable to describing fouling phenomena and also follow a pattern based on semi-empirical models to accommodate the linear, exponential and sigmoid characteristics. Models which include the initiation period may lead to a better estimate of optimal cleaning periods. An attempt has been made in this paper to develop empirical fouling models which include the initiation period where necessary and thereby more accurate fouling models.

II. METHOD

Fouling is a phenomenon that occurs during the initial time \( t_0 \) until the time is infinite \( t_\infty \). In order to know the phenomenon that occurs, it will require the mathematical model which is able to describe the behavior characteristics of fouling in the heat exchanger. In general, a mathematical model that describes crude oil fouling on proposed heat exchangers is still being developed that consists of theoretical model, semi-empirical and empirical (Ramasamy & Deshannavar, 2014). The theoretical and semi empirical models consider the first principal model which is different to the empirical model that exclude the phenomenon of fouling that occurs (Deshannavar et al., 2010).

The fouling model is first described based on the empirical concept (Kern and Seaton, 1959) where the fouling rate is the difference between the deposition rate \( (md) \) and the removal rate \( (mr) \), which is shown in the following equation 1:

\[
\frac{dR_f}{dt} = m_d - m_r \tag{1}
\]

Fouling principles and working methods are affected by heat exchanger design, operating conditions and crude oil content. So on different fouling characteristics cause the different design of heat exchanger.

In general, linear, falling rate and asymptotic fouling models are used as characteristics related to fouling behavior in the heat exchanger industry (Sanaye & Niroomand, 2007) as shown in figure 1.

\[
R_f(t) = at \tag{2}
\]

In addition, assuming the fouling rate is proportional for a driving force such as heat flux, Epstein (1998) showed a mathematical analysis of falling rate on curve B. Where this mathematical model ignores the induction period that is shown in equation 3:

\[
R_f(t) = a. \ln(t) - b \tag{3}
\]

One model that used to describe fouling behavior in general, as Kern and Seaton (1959) suggest, is a model that interprets mathematics in the asymptotic model as shown in curve C, so this model also ignores the induction period. So the mathematical equations of this model is equation 4.

\[
R_f(t) = a(1 - e^{-bt}) \tag{4}
\]

Differences in the fouling model are used to describe the behavior of fouling in different heat exchanger conditions. It is observed from the characteristic of fouling in heat exchanger which has a change of fouling trend after cleaning. Therefore, the selection of fouling model type for heat exchanger cannot describe the fouling behavior at all time. It is also not possible to precisely verify the type of model each time in the heat exchanger after the clean condition.
To observe the characteristics of fouling heat exchanger, (Biyanto, 2013) used a fouling model that is able to explain the phenomenon characteristic of fouling with sigmoidal curve, so that Boltzmann-sigmoidal function is a type that capable of fulfilling the previous fouling model deficiency. The graph describing the Boltzmann-sigmoidal function is shown in Fig. 2.

The Boltzmann-sigmoidal function has four parameters: $A_1$ is the left horizon asymptote in the form of the initial value, $A_2$ is the right horizon asymptote in the form of the final value, $\omega$ is the center point of inflection and $b$ is the width of the slope. This function can be a model of fouling characteristics by changing the values of the four parameters. The value of the parameter adjusts to the fitting curve such as the deviation between the fouling data and the minimum prediction value with the convergence standard 0.0001 with 100 iterations. The minimum standard adjusts the deviation value of the variable you want to search using Newton’s algorithm. So the sigmoid equation is shown in the following equation:

$$\frac{dR_f}{dt} = A_2 + \frac{A_1 - A_2}{1 + e^{-\omega(t-t_0)}}$$

(5)

Decreasing the value of $t_0$ will remove the initial period (into the asymptotic curve) and increase the value of $b$ which will make the curve to be linear. This description yields equation 6 and in fact $t_0$ is very small and $e^{\omega b} >> 1$, that is:

When $b = \text{rise time} = X \rightarrow b \gg$, so

$$\frac{dR_f}{dt} = at + c$$

(6)

with

$$a = \frac{(A_1-A_2)}{2\frac{t_0}{b}}$$

$$c = A_2 + \frac{(A_1-A_2)}{2\frac{t_0}{b}}$$

In addition, when initial fouling is very low $A_2=0$ and $t_0 = \text{center} = t_0 \ll$, the sigmoid boltzmann becomes an exponential function as in equation 2.8.

$$R_f(t) = A_2 - A_2e^{-\frac{t}{b}} = A_2(1 - e^{-\frac{t}{b}})$$

(7)

The Boltzmann-sigmoidal function is able to combine three types of previous empirical models, that is linear, falling rate and asymptotic, by selecting the appropriate parameters. For example, for very low values of $\omega$, indicating none or low induction periods, the magnitude of $b$ and $A_2$ indicates the type of the linear fouling model, while for $b$ and $A_2$ indicating the asymptotic fouling model type. Where the values of $\omega$ and $b$ are time constants that cannot be calculated, it affects how fast the fouling occurs. Therefore, the values of $\omega$ and $b$ are obtained from the fitting process.

The biggest reason when developing the fouling model becomes very difficult to analyze analytically is the development of asymptotic model, as true value of $a$, cannot be determined with operational data for short periods during cleaning conditions. However, one advantage of this study is the availability of operational data for a long enough period to determine the asymptotic value of the fouling resistance on the operational data of the heat exchanger.

The rate and mechanism of fouling varies with heat exchanger design, operating conditions, and crude oil properties. Therefore, different heat exchangers experience different fouling characteristics. Generally, linear, falling rate and asymptotic fouling models are used to characterize the fouling growth behavior in industrial heat exchangers (Sanaye, 2007).

Generally, different fouling model types were used to describe the fouling behavior in different heat exchangers in a given HEN. Moreover, the above empirical models do not include the fouling initiation or induction period. These shortcomings motivate to search for a single model which can describe the fouling characteristics of different types and that include the induction period as well.

III. RESULT AND DISCUSSION

Refineries are generally operated with varying crude oils which varies in their properties very much. Ignoring the physical and chemical properties of the crude oils, the fouling characteristics are modeled through simple semi-empirical models such as linear, exponential and sigmoid (Kuppan, 2000). In this research, sigmoidal equation is proposed and utilized to characterize the fouling growth behavior as observed from the characteristics curves for certain heat exchanger, as seen in figure 5.
Figure 3 Fouling characteristics of heat exchanger HE 1

Figure 4 Fouling characteristics of heat exchanger HE 2

Figure 5 Fouling characteristics of heat exchanger HE 3
Fouling characteristics of the individual heat exchangers differs very much from each other. Heat exchanger HE 1 follow exponential fouling growth behavior. In this paper is observed that heat exchanger HE 2 follow linier fouling characteristics. The sigmoid in heat exchanger HE 3. The other heat exchanger follow sigmoideal fouling growth behavior. The sigmoid fouling growth behavior indicates that there is an initiation period for fouling. Different fouling behavior among the heat exchanger processing the same crude oil indicates that the operating conditions, namely, the velocity and the bulk and surface temperatures play a major role in the fouling behavior.

From Table 1, it is observed that the chosen model forms closely describe the actual fouling characteristics which are indicated by the R² values of 0.9 to 0.99. It may be noted that fluctuations in industrial data are quite normal and value of R² of 0.8 and above can be considered to be very good fits.

| Heat Exchanger No. | Model type | Model Parameters | R²  |
|--------------------|------------|-----------------|-----|
| HE 1               | Exp.       | 1.04E-02, 1.65E-02, --- | 0.942 |
| HE 2               | Linear     | 2.89E-05, ---, --- | 0.973 |
| HE 3               | Sig.       | 1.04E-02, 37.26, 112 | 0.965 |

IV. CONCLUSION

The fouling characteristics for each heat exchanger has been investigated and extracted from the operating plant data. Appropriate semi-empirical fouling models were chosen and the model parameters are estimated and reported. High values of coefficients of regression, R², indicated that the developed models closely follow the actual fouling behavior in the plant.

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