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FOULING MONITORING IN THERMOSIPHON REBOILER

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ABSTRACT

A method to monitor the fouling resistance, R_f, of heat exchanger, especially thermosiphon reboiler, is presented. The historical hourly data of reboiler and distillation column are used to analyze R_f. The initial value of overall heat transfer coefficient, U_0, and the current overall heat transfer coefficient, U, are needed to calculate fouling resistance. Since U_0 is not constant but is affected by operating conditions such as shell/tube flow rate and temperature, a relationship between U_0 and these operating conditions has to be developed to calculate R_f. However, sometimes important data such as tube-side flow, inlet/outlet temperature of hot/cold fluid, liquid level in shell/tube, that are needed to bring out the fouling condition of equipment, are missing. With such insufficient information, the fouling behavior can be analyzed by building a new equation based on measurable data. Dimensional analysis determines the structure of the function; parameters of each term are obtainable using short term plant data after cleaning, assuming that there is no fouling during this period. As it is not easy to measure actual R_f temporal change in the heat exchanger tube, the calculated fouling resistance is compared with the relative amount of solid material removed from the equipment during cleaning, and it is evaluated qualitatively. The comparison shows good agreement. In addition, the evolution of the fouling resistance of some thermosiphon reboilers over a period of a few months or even years can be matched using this model.

INTRODUCTION

In studying the fouling process in a heat exchanger, a lot of information can be acquired by understanding the fouling behavior. For example, just by monitoring the fouling rate, it is possible to determine the precise operating conditions (flow rate and inlet/outlet temperature of hot/cold fluid) at which fouling would increase, as well as to establish a correlation between the distillation column efficiency and the fouling buildup in the reboiler. The current method of heat exchanger fouling management involves monitoring indirect parameters such as temperature difference (ΔT), pressure drop, overall heat transfer coefficient, and so on. But these parameters are also influenced by the change of operational conditions such as loading. Monitoring of fouling may be difficult when these parameters are affected complicated influence. Therefore, although this method is effective for a process in which the operating conditions are nearly constant, it is hard to say whether the predicted fouling rate is applicable when the operating conditions change significantly. To solve this problem, Sahin et al. calculated U_0 using fluid velocity data and monitored fouling by R_f [1]. Markowski et al. also implemented more detailed U_0 estimation using flow and temperature data [2]. However, it may be difficult to use these methods if there are not sufficient instrumental to measure necessary data.

In this study, fouling rate is monitored by a direct index: the actual fouling resistance, R_f. In particular, a method is proposed for computing R_f in the case of insufficient process data. Moreover, prediction and controlling of fouling is performed by computing R_f.

CALCULATE FOULING RESISTANCE

Assuming that the thermal conductivity and deposit structure (porous deposit and compact deposit) of the fouling material is constant, there is a linear relationship between average fouling heat resistance, defined by equation (1), and fouling thickness, so that the amount fouling can be monitored by calculating the fouling heat resistance.

$$R_f = \frac{1}{U_{dirty}} - \frac{1}{U_{clean}} \tag{1}$$

The dirty overall heat transfer coefficient, U_{dirty}, is calculated by equations (2) and (3), using the measured values of one flow rate (F_{shell}) and four temperatures ($T_{shell,\ in}$, $T_{shell,\ out}$, $T_{tube,\ in}$, $T_{tube,\ out}$).

$$Q = F_{shell} C_p \left(T_{shell,out} - T_{shell,in}\right) \tag{2}$$

$$U_{dirty} = \frac{Q}{Af\Delta T_{lm}} \tag{3}$$

U_{clean}, the overall heat transfer coefficient without the effect of fouling, is determined by equation (4). $h_{i,clean}$ and $h_{o,clean}$ are film heat transfer coefficients of the tube side and shell side, respectively.

$$U_{clean} = \left(\frac{1}{h_{i,clean}} + \frac{1}{h_{o,clean}} + \frac{\delta}{\lambda}\right) \tag{4}$$

If there is no fouling, U_{clean} is equal to U_{dirty}.

$$U_{clean} = U_{dirty} \tag{5}$$

Ideally, $h_{i,clean}$ and $h_{o,clean}$ are estimated from correlations based on the heat exchanger configuration and the applicable process conditions. However, sometimes the necessary data needed to calculate those heat transfer coefficients are not measured in the actual equipment.

In this study, the fouling behavior can be analyzed by building a new equation based on measurable data using dimensional analysis. Assuming that the heat exchanger is completely clean (no fouling) for a certain period of time, the parameters of such equation is determined to satisfy equation (5).

METHODOLOGY

An actual thermosiphon reboiler of a distillation column in an aromatics plant is used as a model system. Fig.1 shows the flowsheet of the process around the column. CL is the distillation column. A part of its bottoms product is sent to the thermosiphon reboiler, TR. U_{dirty} is computed by (2) and (3) from measurable values shown in fig.1. To calculate U_{clean}, the steam-side heat transfer coefficient, $h_{o,clean}$, is obtained by condensing flow equation (6).

$$h_{o,clean} = 1.47\left(\frac{4F}{\mu_f}\right)^{-0.33}\left(\frac{\mu_f^2}{k_f^3\rho_f^2 g}\right)^{-0.33} \tag{6}$$

For the tube side, as the process flow temperature increases, the liquid feed vaporizes, resulting in a multiphase flow going back to the column. With such a complicated heat transfer phenomena, a different correlation has to be used for each individual mechanism.

The Sieder-Tate equation can be used to calculate the heat transfer coefficient in the liquid phase zone.

$$h_l = 0.023\frac{k}{D}\mathrm{Re}^{0.8}\,\mathrm{Pr}^{0.33} \tag{7}$$

In the multiphase zone, contributions from multiphase convection and nucleation boiling, in their respective proportions, need to be accounted for.

－Convection [3]

$$h_{tp} = 3.5h_l\left(\frac{1}{X_{tt}}\right)^{0.5} \tag{8}$$

$$X_{tt} = \left(\frac{F_l}{F_g}\right)^{0.9}\left(\frac{\rho_l}{\rho_g}\right)^{0.5}\left(\frac{\mu_l}{\mu_g}\right)^{0.1} \tag{9}$$

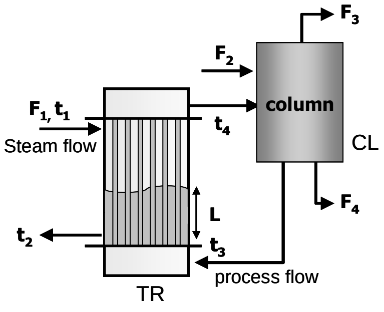

Fig.1 Process flowsheet

－Nucleation boiling

$$h_b = m\left(t_w - t_b\right)^{n-1} \tag{10}$$

－Combination

$$h_v = \alpha h_{tp} + \beta h_b \tag{11}$$

The overall heat transfer coefficient is computed from (7) and (11) considering the heat transfer area of each phase.

$$h_{i,clean} = \frac{h_l\Delta L_l + h_v\Delta L_v}{L} \tag{12}$$

The problem with this method is that the equations contain variables that cannot be measured in an actual heat exchanger, such as m, α, β, and ΔL. Furthermore, since the reboiler is driven by the thermosiphon principle, the process flow rate is normally not measured.

To solve this problem, an alternative method using dimensional analysis is proposed to calculate $h_{i,clean}$. Considering that the unknown variables (ΔL, process flow rate, and so on) are related to other variables, $h_{i,clean}$ is expressed as a function of measurable variables and physical properties, as shown in equation (13). This equation is then rearranged into equation (14) by dimensional analysis.

$$h_{i,clean} = f\left(F_1, F_2, F_3, F_4, t_1, t_2, L, C_p, \rho, \mu, \lambda\right) \tag{13}$$

$$h_{i,clean} = k\phi_2^a\phi_3^b\phi_4^c\phi_5^d\phi_6^e\phi_7^f\phi_{nd} \tag{14}$$

Here, ϕ_i are dimensionless variables representing the operating conditions. The unknown coefficients k and a~f are determined from operation data (hourly average of data by a second) in the first two- week period during which the heat exchanger can be assumed to be completely clean (eq.5 is applicable). Thus, minimizing the error sum of squares J in equation (15) gives the coefficients in model (14).

$$J = \sum_{i=1}^{n}\left(U_{dirty} - U_{clean}\right)^2 \tag{15}$$

This model can be used to calculate the value of $h_{i,clean}$ (and U_{clean}) at arbitrary process conditions. R_f can then be calculated by comparing U_{clean} and U_{dirty}.

Furthermore, the fouling rate is also related to operating conditions. This relationship which contains operating conditions and current fouling make it possible to simulate unsteady behavior of fouling increasing or decreasing. The modified Ebert-Panchal equation (16) [4] is used as the basic fouling model.

$$\frac{dR_f}{dt} = a_1\mathrm{Re}^{-0.8}\,\mathrm{Pr}^{-0.33}\exp\left[-\frac{E}{RT_f}\right] - \gamma u^{0.8} \tag{16}$$

Assuming constant physical properties over the temperature range of each heat exchanger, this equation can be rewritten as (17).

$$\frac{dR_f}{dt} = C\cdot u_{dirty}^{-0.8}\exp\left[-\frac{E}{RT_f}\right] - \gamma' u_{dirty}^{0.8} \tag{17}$$

The film temperature, T_f, can be obtained by the following equation.[4]

$$T_f = T_{bulk} + 0.55(T_w - T_{bulk}) \tag{18}$$

To account for fouling inside the tubes, the linear velocity in the tube is adjusted based on equation of continuity.

$$u_{dirty} = \frac{1}{\rho A_{clean}} \frac{F}{\varphi} \tag{19}$$

where $\varphi = \frac{A_{dirty}}{A_{clean}} = \left(1 - \frac{k_f}{r_i} R_f\right)^2$

Parameters C, γ', and k_f/r_i need to be adjusted based on operational data, so as to allow the calculation of fouling rate.

RESULTS & DISCUSSION

Monitoring

The comparison between the values of calculated U_{clean} (from eq.3) and U_{dirty} (from eq.4) during the exchanger's clean period is shown in fig.2. In this case, 1008 data points (24 hours × 2 weeks × 3 clean periods) were used to determine the parameters of eq.14. A good agreement between U_{clean} and U_{dirty} suggests that this correlation is suitable for describing $h_{i,clean}$.

Using eq.14, the value of U_{clean} for various plant conditions can be estimated. Fig.3 shows the time profiles of U_{clean} and U_{dirty} for over 3 years of plant operation. During each term of operation, the value of U_{dirty} calculated by eqs.2 and 3 initially agrees with the calculated value of U_{clean} from eq.4. However, after some time, U_{dirty} begins to gradually deviate from U_{clean}, as fouling occurs and inhibits heat transfer in the exchanger. As described by eq.1, the difference between the reciprocals of these two values is the fouling resistance, R_f.

The R_f profile is shown in fig.4. The clean period, fouling starting point, fouling growth, asymptotic behavior, and desorption by cleaning can be identified in this plot. The long induction period during term A (from 2009/7) was caused by certain operation changes. The decrease in R_f indicates desorption of fouling.

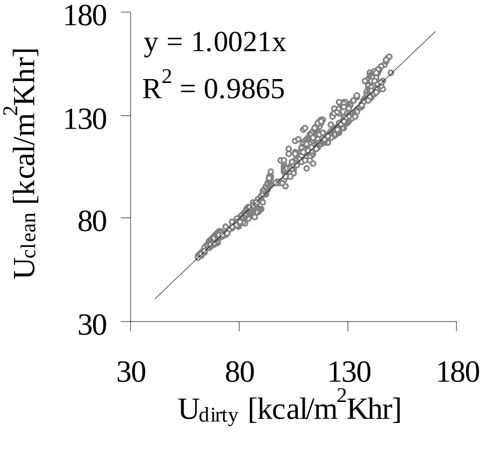

Figure 2. Comparison between U_{dirty} and U_{clean} during the exchanger's clean period

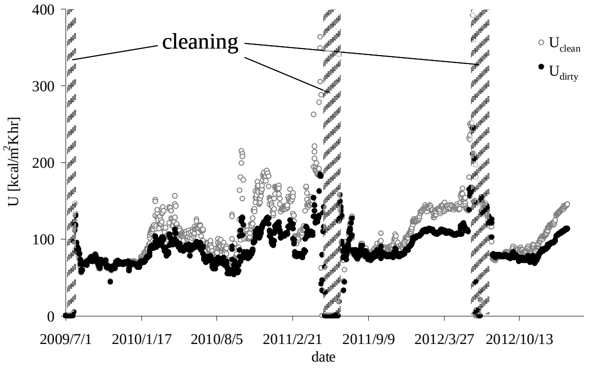

Figure 3. Comparison between U_{dirty} and U_{clean} profiles

Prediction

Based on the calculated values of R_f during terms A and B, the parameters C, E and γ of the fouling model (eq.17) were obtained, and used to predict the fouling behavior during term C. Fig.5 shows the comparison between monitored and modeled values of R_f during term C. A good agreement can be found, as characterized by an initial increase in fouling followed by an asymptotic behavior.

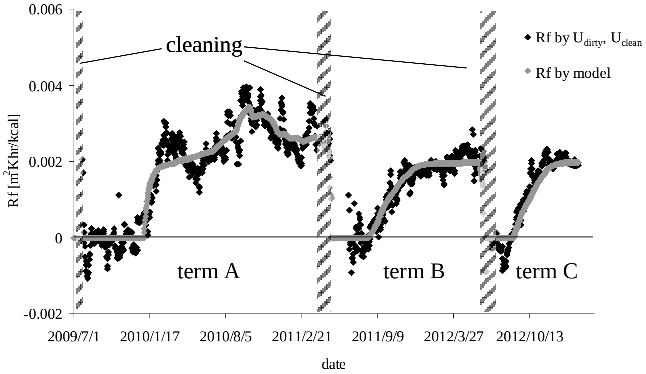

Figure 4. Profiles of fouling resistance

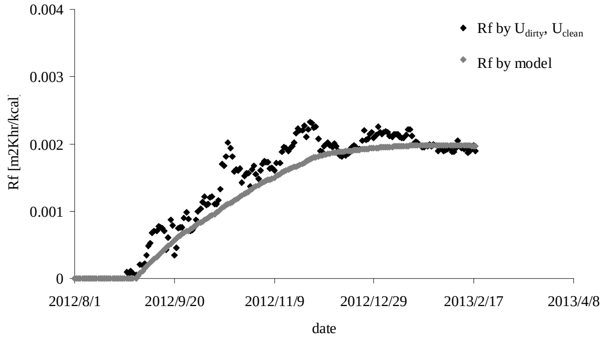

Figure 5. Comparison between monitored and predicted R_f during term C

Control index

Fig.6 shows the time profiles of steam flow rate F1 and film temperature inside the tube T_f, which are the key variables of the fouling model. It can be seen that while F1 varies significantly during operation, T_f practically stays constant at all times. Therefore, the fouling model (eq.17) can be simplified by only considering F1. To account for the effect of fouling, the correction factor φ according to eq.19 is introduced. Fig.7 shows the relationship of F1/φ and fouling rate, which exhibits an excellent correlation. As F1/φ increases, fouling rate dR_f/dt decreases and reaches negative value finally. φ contains factor of current fouling. Therefore, dR_f/dt can be controlled solely by adjusting F1. If the steam flow rate is kept above the threshold value (corresponding to $dR_f/dt = 0$), fouling will decrease or does not occur at all.

CONCLUSIONS

A method to analyze the fouling behavior in a heat exchanger, particularly a thermosiphon reboiler, using plant operation data is provided.

1. In a situation that some data are not measurable, fouling rate is monitored from only measurable data using a correlation obtained by dimensional analysis.
2. The monitored fouling behavior is used to estimate the parameters of a simplified Ebert-Panchal model, which can then be used to predict future fouling behavior under specified operating conditions.
3. A fouling threshold index is given by restructuring the model. In this case, fouling rate can be controlled by steam flow rate.
4.

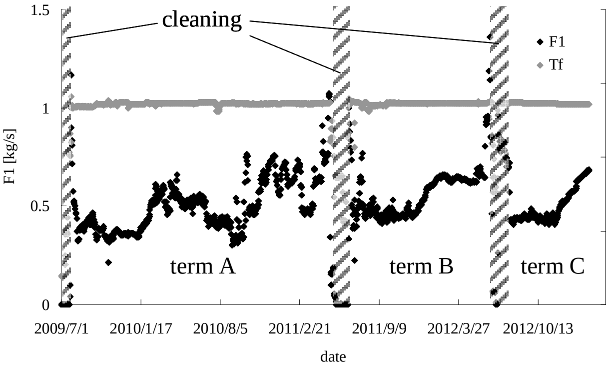

Figure 6. Time profiles of steam flow rate and tube film temperature

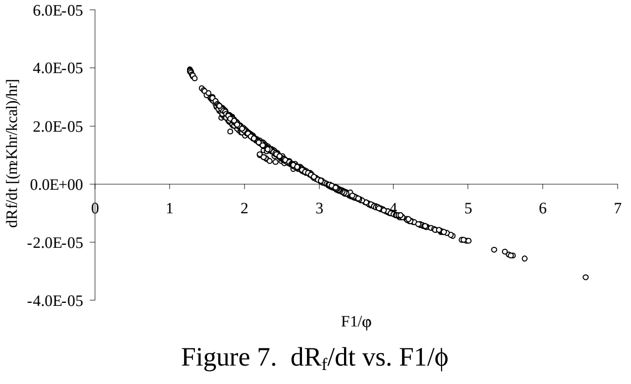

Figure 7. dR_f/dt vs. F1/ϕ

NOMENCLATURE

A	heat transfer area of exchanger, m^2
C	parameter
C_p	specific heat at contant pressure, kcal/kg.K
D	tube diameter, m
F	mass flow rate, kg/hr
f	correction factor, dimensionless
g	gravity, m/s^2
h	film heat transfer coefficient, kcal/m^2.K.hr
L	liquid phase level in shellside, m
m	parameter
n	parameter
Q	heat transfer rate, kcal/hr
t	temperature, K
U	heat transfer coefficient, kcal/m^2.K.hr
u	tubeside velocity
ΔT_{lm}	log mean temperature difference, K
X	Lockhart-Martinelli parameter

Greek letters

α	parameter
β	parameter
δ	tube thickness, m
ϕ_i	dimensionless term from dimensional analysis
φ	ratio of A_{fouled} / A_{clean}
λ	thermal conductivity, kcal/m.K.hr
μ	viscosity, kg/m.s
ρ	density, kg/m^3

Subscript

b	boiling
bulk	bulk of fluid
clean	clean condition
dirty	dirty condition
f	fluid
g	gas
i	inside of tube
l	liquid
o	outside of tube
tp	heat transfer
tt	turbulent flow
v	vapor
w	wall

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