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Monitoring of Important Variables Affecting the Formation of Fouling in Crude Oil Heat Exchangers

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Conventional methods for determination and monitoring of the total thermal resistance of fouling are based on computing the overall heat transfer coefficient U over time. Heat exchanger cleaning schedules are developed using historical process data on the periods when the thermal resistance of fouling has become too high. There are many different variables of the preheating process that determine the actual rate of fouling build-up in crude oil heat exchangers, namely: flow velocities of the fluids in both shell- and tube-side of exchanger; wall temperatures of the exchanger tubes and the shear rates at the tube surfaces. In this paper, using data records acquired during 5 y of operation of a heat exchanger network coupled with a Crude Distillation Unit, the monitoring of those variables is discussed and their influence on fouling growth is estimated.

1. Introduction

In process plants incorporating heat exchanger networks (HENs) for heat recovery, deposits (fouling layers) building up on heat transfer surfaces hinder correct operation and lead to economic losses (Smith et al., 2017). The immediate reasons for these losses are increased energy consumption and, in certain cases, also undesirable plant stoppages for heat exchanger cleaning. The detrimental effects of fouling can be reduced by on-line cleaning of heat exchangers; this makes it also possible to avoid plant stoppages. In the procedure of on-line cleaning, a selected heat exchanger is disconnected from network and subjected to cleaning. Upon completion of the procedure, the heat exchanger is reconnected to the HEN. The key issues of on-line cleaning of heat exchangers are: diagnostics of deposit build-up in the exchangers (Liporace et al., 2007) and scheduling of cleaning interventions on the individual exchangers in network (Pogiatzis et al., 2012). The scheduling of cleaning interventions, that is, planning the sequence of cleaning of the specified heat exchangers, could be based on the a-priori knowledge of the time behaviour of the thermal resistance of deposits $R_f(t)$ in individual exchangers (Markowski et al., 2005). It was also demonstrated that the values of thermal resistance of fouling can be determined if operating parameters of the heat exchangers have been measured and recorded during previous production periods (Markowski et al., 2013a).
When it comes to fouling in crude-oil heaters operated in Crude Distillation Units (CDUs), there are many different variables of the preheating process that determine the actual rate of fouling build-up. The most important variables are (Deshannavar et al., 2010): temperature of the heating surface, bulk temperature, bulk velocity (Zhan et al., 2015), shear stress and crude type. In tubular crude-oil heat exchangers, it is generally found that a lower crude inlet velocity and high temperature of the tube wall will accelerate the rate of fouling. For this reason, the scheduling of on-line cleaning interventions in heat exchangers, if based on the characteristics of the build-up of thermal resistance of fouling from previous production periods, may be problematic. This issue can be resolved by adaptive decision making on the cleaning interventions supported by the monitoring of deposit build-up, that is, by on-line measurements and processing of the operating parameters including variables that affect fouling growth. The on-line monitoring makes it possible to adjust $R_f(t)$ characteristics in case of deviations of the operating conditions from those recorded during previous production periods. In this work, a case study on the monitoring of fouling and the variables of selected heat exchangers of the CDU processing 220 kg/s of Russian export blend crude oil (REBCO) is presented.

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2. Monitoring of fouling in crude oil heat exchangers

2.1 Determination of the thermal resistance of fouling in shell and tube heat exchangers

Plant data, collected from the industrial shell-and-tube heat exchangers, located at the pre-heat trains of a CDU in Polish oil refinery, were employed to determine the total thermal resistance of fouling. In order to make the determination of fouling effects possible, it is necessary to acquire the geometric data of the heat exchanger along with the values of process data measured over a sufficiently long period of plant operation. The required process data include mass flow, temperature and parameters of chemical composition of the relevant process streams; this enables one to determine physicochemical properties of process media flowing through the heat exchanger. However, raw process data may reflect malfunctioning of measuring instruments, disturbances in data transmission and recording, as well as transient states of the exchanger and therefore cannot be directly used for the determination of heat transfer coefficients. To overcome this problem, the data should be pre-processed by: filtering aimed at the elimination of gross errors; averaging over time intervals long enough to make the application of steady-state models of heat exchange phenomena possible; reconciliation to minimize the uncertainty induced by the limited accuracy of measurements and the bias due to the application of steady-state modelling.

For modelling and calculation purposes, the fouling layer is represented by the total thermal resistance of deposits attached to both sides of the heat transfer surface R_f. After retrieving the geometric data of the exchanger and the relevant part of the averaged and reconciled measurement data, R_f can be calculated as the difference between the thermal resistances of fouled and clean heat exchanger surfaces. The mathematical model includes three main components: well known relationships which describe the heat exchange phenomena and energy balance of the exchanger, multicell representation of shell-and-tube heat exchanger, and algorithm for the determination of the value of heat transfer coefficient – see Figure 1.

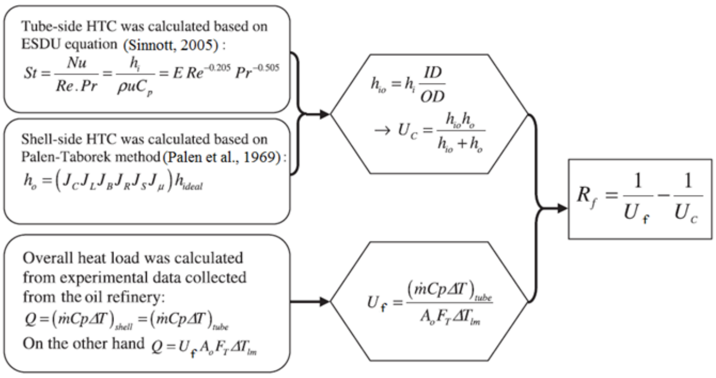

Figure 1: Equation-based procedure for calculation of fouling resistance (Bayat et al., 2012, and references indicated in the figure)

Nomenclature for Figure 1:

A_o - overall heat transfer area, m^2,
Cp - specific heat capacity, $Jkg^{-1}K^{-1}$,
ESDU - Engineering Sciences Data Unit,
E - coefficient calculated as:
 $E=0.0225\exp(-0.0225\mathrm{Ln}(Pr)^2)$,
F_t - dimensionless multipass temperature correction factor,
HTC - Heat Transfer Coefficient,
h_o - shell-side HTC, $Wm^{-2}K^{-1}$,
h_i - tube-side HTC,$Wm^{-2}K^{-1}$,
h_{io} - tube-side HTC based on tube outside diameter, $Wm^{-2}K^{-1}$,
h_{ideal} - ideal tube-side HTC,W $m^{-2}K^{-1}$,
ID - tube inside diameter, m,
J_B - bundle bypass correction factor,
J_C - baffle cut correction factor,
J_L - baffle leakage correction factor,
J_R - laminar flow correction factor,
J_S - unequal baffle spacing correction factor,
J_μ - wall viscosity correction factor,
$\dot{m}$ - mass flow rate, kgs^{-1},
Nu - Nusselt number,
OD - tube outside diameter, m,
Pr - Prandtl number,
Q - total heat load WK^{-1},
Re - Reynolds number,
R_f - fouling resistance, m^2KW^{-1},
St - Stanton number,
u - inlet velocity, ms^{-1},
U_C - clean overall HTC, $Wm^{-2}K^{-1}$,
U_f - dirty overall HTC, $Wm^{-2}K^{-1}$,
ΔT - temperature difference, ^0C,
ΔT_{lm} - LMTD temperature difference, ^0C,
ρ - density, kgm^{-3}.

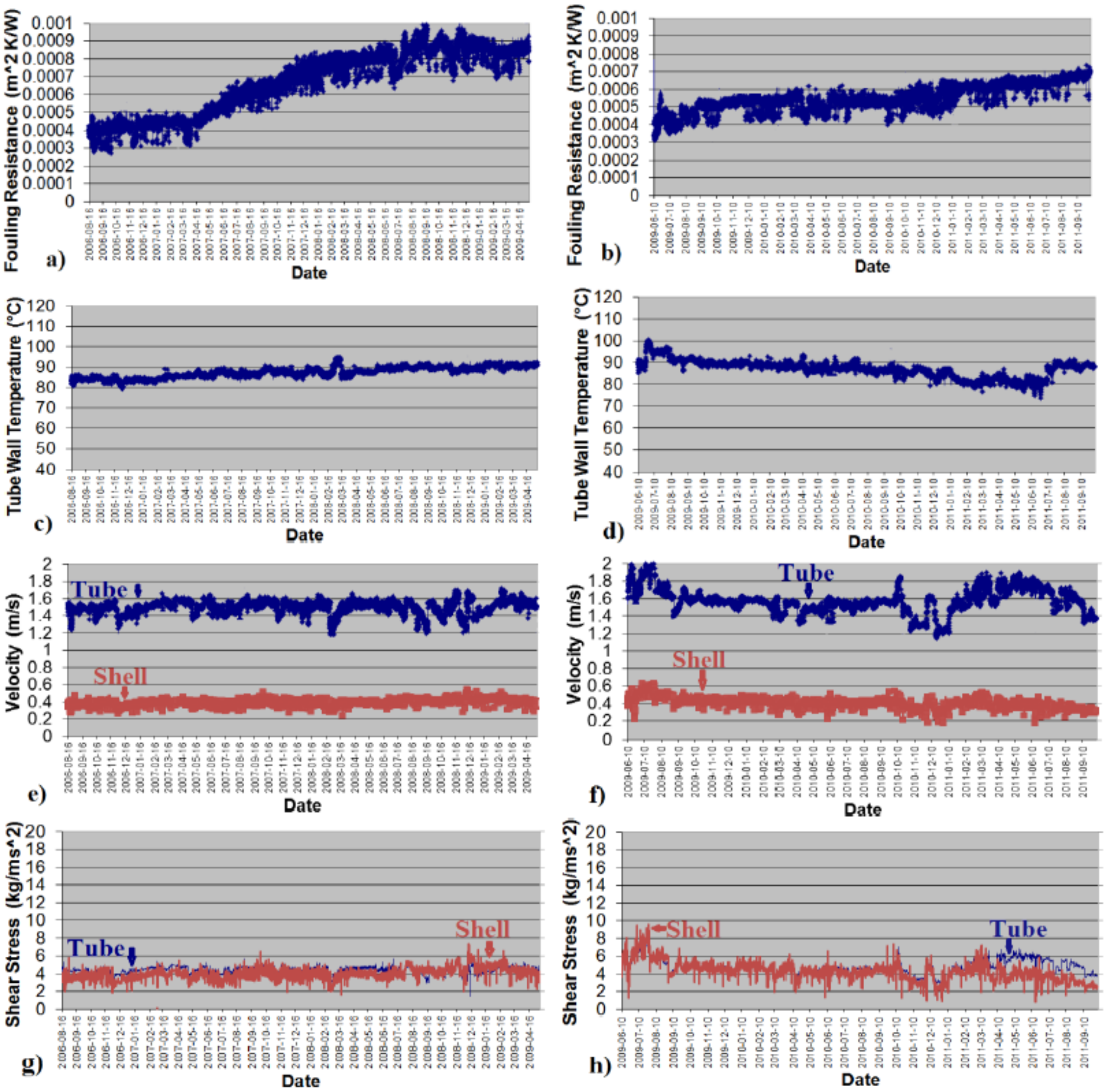

Figure 2: Heat exchanger E25 parameter trends vs. operational time: a, b – fouling resistance, c, d – tube wall temperature, e, f – velocity, g, h – shear stress

2.2 Variables affecting the formation of fouling in crude oil heat exchangers

Many correlations have been recommended for the prediction of individual fouling mechanisms (Deshannavar et al., 2010). However, these correlations are generally not applicable to industrial conditions where a combination of fouling mechanisms and foulants occurs. Upon comparison of fouling data from a range of industries, the qualitative effects of process parameters on the fouling have been identified as follows:

- Fouling rate usually increases linearly with increasing foulant concentration in the fluid bulk;
- The fouling resistance usually decreases with increasing flow velocity and wall shear stress due to increased removal forces;
- For almost all fouling mechanisms, the fouling resistance increases exponentially with increasing tube wall temperature.

In this paper, the following key variables that influence fouling are calculated and monitored:

- **Wall temperature**

The bulk temperature, theoretical heat transfer coefficient across the exchanger, effective mean temperature difference, and heat transfer coefficient of the fluid are used to calculate the cold side and hot side wall temperature:

$$T_{wall} = T_{bulk} + (U_f \Delta T_M)/h_{cold}, \qquad T_{wall} = T_{bulk} - (U_f \Delta T_M)/h_{hot} \qquad (1), (2)$$

where: $T_{bulk}=(T_{in}+T_{out})/2$ - the bulk temperature for each side is the average of its inlet and outlet temperature, $\Delta T_M = F_t \cdot \Delta T_{lm}$ - effective mean temperature difference.

- **Tube-side and shell-side flow velocity**

The tube-side and shell-side velocities of the fluids are calculated as:

$$u_t = G/\rho_t, \quad u_s = G_x/\rho_s \tag{3), (4}$$

where: ρ_t - density of tube-side fluid, ρ_s - density of shell-side fluid, G, G_x - mass velocity and average crossflow mass velocity.

- **Tube-side and shell-side shear stress**

The tube-side and shell-side shear stresses are calculated by:

$$\tau_t = (\rho_t f_{t,is} u_t^2)/2, \quad \tau_s = (\rho_s f_{s,is} u_s^2)/2 \tag{5), (6}$$

where: $f_{t,is}$, $f_{s,is}$ – isothermal friction factors for tube-side and shell-side.

Using the isothermal friction factor instead of the corrected friction factor is not expected to cause significant error. The isothermal friction factor for tube-side and shell-side is calculated based on the Reynolds number.

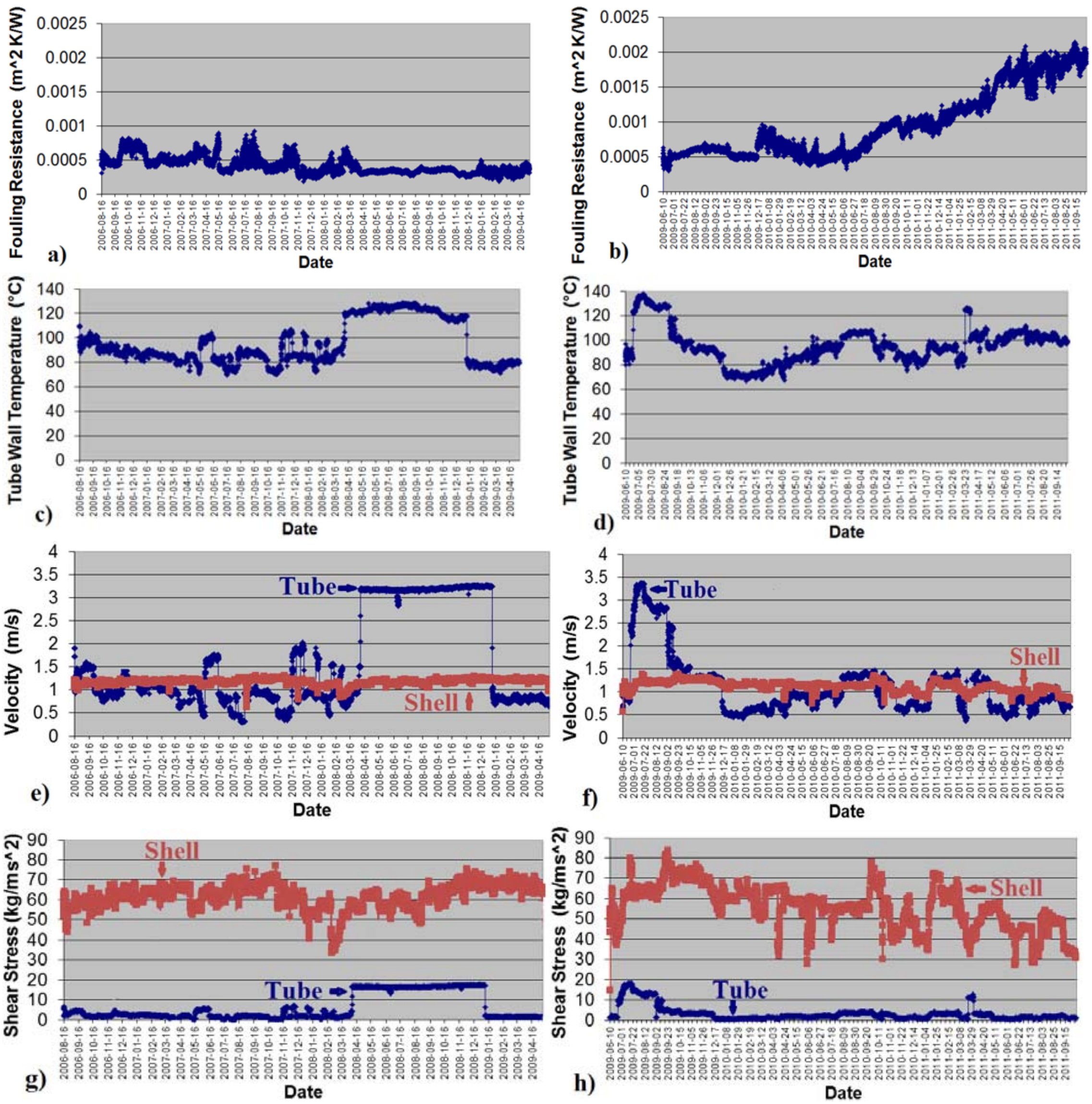

Figure 3: Heat exchanger E09 parameter trends vs. operational time: a, b – fouling resistance, c, d – tube wall temperature, e, f – velocity, g, h – shear stress

3. Case study and discussion

The approach outlined above was tested on real-life shell-and-tube heat exchangers, with straight tubes and floating heads, installed before the desalting unit of the CDU rated 220 kg/s of crude oil. According to the procedure described in section 2, the thermal resistance of fouling and the variables affecting fouling growth in three of the selected crude oil pre-heaters named: E25, E09 and E05 (see a process flow diagram in Markowski et al., 2013b), were obtained and their time characteristics are illustrated in Figures 2, 3, and 4. In these Figures the designations “a”, “c”, “e” and “g” refer to the process data recorded during first production period (dates 2006.08.15-2009.05.07) and the designations “b”, “d”, “f” and “h” refer to the second production period (dates 2009.06.10-2011.10.04). The selected heat exchangers were cleaned during the time interval between the two production periods.

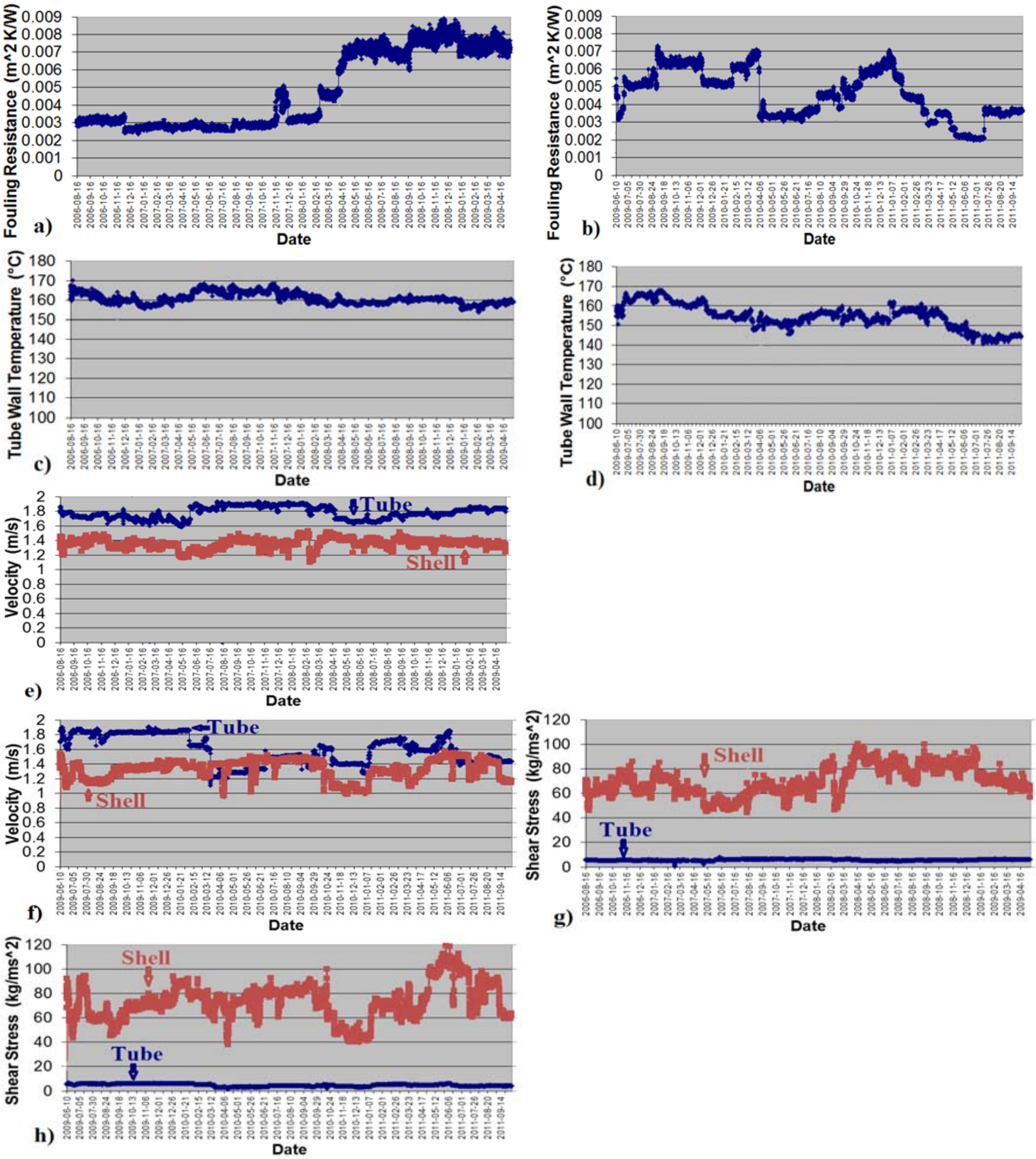

Figure 4: Heat exchanger E05 parameter trends vs. operational time: a, b – fouling resistance, c, d – tube wall temperature, e, f – velocity, g, h – shear stress

Regarding exchanger E25, the time characteristics of thermal resistance of fouling in both operating periods are typically shaped and geometrically similar (Figures 2a, 2b) but the maximum resistance values are different: R_f = 0.00100 m^2KW^{-1} and R_f = 0.00075 m^2KW^{-1} in the first and second period. The lower rate of the increase in thermal resistance in the second period can be attributed to the recorded changes in tube wall temperature (Figures 2c, 2d). While parameter R_f has been increasing with the increasing wall temperature during the first period, temperature drop from 100 ºC to 80 ºC resulted in a slower R_f increase during the second period. The concurrent changes in the time characteristics of shear stress and flow velocity in the studied exchanger (Figures 2e, 2f, 2g, 2h) appear not to have influenced R_f values.

Regarding exchanger E09, the time characteristics of thermal resistance of fouling in the first operating period is flat (Figure 3a) with the resistance value close to R_f = 0.0005 m^2KW^{-1}. In this case, it can be inferred that the values of tube wall temperature, flow velocity and shear stress (Figures 3c, 3e, 3g) did not reach threshold values at which R_f growth would be initiated. R_f starts growing in the middle of the second operating period. The time characteristics of all the important variables are chaotic in both operating periods (Figures 3c, 3d, 3e, 3f, 3g, 3h); however, it seems that the shell-side shear stress value (Figure 3h) dropping below 50 $kgm^{-1}s^{-2}$ has been decisive in initiating R_f growth.

During the first operating period, the thermal resistance of fouling in the exchanger E05 has been increasing steadily in a typical manner up to R_f=0.009 m^2KW^{-1} (Figure 4a). However, the second period is characterized by several intervals of R_f growth followed by reduction, accompanied by growth and reduction of all the measured quantities (Figures 4d, 4f and 4h).

4. Conclusions

The analysis of calculated time characteristics of heat exchanger fouling in three selected exchangers indicated that historical data may not constitute a reliable basis for quantitative predictions of fouling growth. It was shown that in two consecutive operating periods of a heat exchanger, time characteristics of the thermal resistance of fouling $R_f(t)$ may be different. The scheduling of on-line cleaning interventions in heat exchangers, if performed by the CDU Operator on the basis of $R_f(t)$ characteristics from previous production periods, may lead to the overestimation of fouling effects and consequently, to non-optimal cleaning schedules. This confirms the importance of on-line monitoring of heat exchanger fouling and simultaneous monitoring of the process variables that may affect fouling growth. The issue of uncertainties in the determination of cleaning schedule for a heat exchanger can be resolved by adaptive scheduling, that is, scheduling based on $R_f(t)$ characteristics adjusted depending on the detected deviations of the operating conditions from those recorded during previous production periods.

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