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Lifetime Estimation of Heat Exchangers with Consideration of On-line Cleaning

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Abstract: In the presented paper two quality parameters are used to represent the state of a heat exchanger. The remaining lifetime can be estimated by trend regression. Also of interest is the uncertainty of the predicted lifetime which is determined by the confidence interval of the parameter estimation. These algorithms developed are used in this paper in an off-line evaluation of the measurements on a heat exchanger in a refinery. It is shown that the time point of the heat exchanger cleaning can be predicted. So the presented method can be used for planning the cleaning time point in advance and saving money in maintenance.

1. INTRODUCTION

In practice there is always a risk that the pipes of a heat exchanger become clogged with solid particles due to strong temperature differences. During the operation it is not possible to look into the interior of the heat exchanger. So the state of heat exchanger has to be monitored based on measurable quantities. Such measurements are temperature, flow and pressure drop. These measures allow not only the description of the current state but the planning of maintenance in due time. Most methods, which are known in the literature, are based on models. The models can be separated into two groups. In the first case, the models are based on multivariate regression, PCA, neural networks and so on. An advantage of all these methods is that they can be used without detail knowledge about the inner states and chemical reactions in the heat exchanger. All these models commonly need fault free training data to generate e.g. the regression model. Also there are disadvantages. If the heat exchanger leaves the normal working point, probably a neural network becomes bad, or a fault with no effect on the used principal components will be not detected, because not all possible conditions can be realized with a real plant. In the other case physical models based on inlet and outlet are used. There are several methods, which try to observe the inner state of the heat exchanger. Using complex physical models can cause problems with the generalization far from the working point. However, if there is only one question: “Is the heat exchanger in a normal condition?” a simple model can be used. In this paper, two quality parameters both based on an easy physical model are compared. The first one is ε the degree of efficiency and the second one is UAF a combination of the heat transmission coefficient with the inner surface and the flow. Big advantages of these methods are that they can be used without any training data and the observation can start from any state of the heat exchanger. A great and important target of the conditioning monitoring is to predict the time interval until a detected disturbance reaches a tolerance level and becomes a fault. The dwell time of the fluids in the heat exchanger is very small against a normal observation period. In addition, if there are complex chemical and physical reactions it is probably not possible to predict the future with an exact model. As explained before the two quality parameters ε and UAF are observed and the remaining lifetime is estimated by trend regression. The quality of the regression can be observed by using statistical tests like a *t*-test. Also of interest is the uncertainty of the predicted lifetime which is determined by the confidence interval of the parameter estimation. The presented method is used with real measurements from an oil refinery. The target is to predict the time points of the cleaning on-line. Thereby the measurements are evaluated in on-line mode. Also it is shown that the quality parameter UAF allows a better prediction than with the classical degree of efficiency ε.

2. METHODS AND THEORY

In the following a counter current heat exchanger will be dealt with. In the actual application the inlet and the outlet flow are coupled on thermal side, see Fig. 1. The cold reactant with temperature T_{1E} enters the heat exchanger on the cold side. It is preheated by the product flow and it leaves the heat exchanger with temperature T_{2E} on the hot side. The hot product enters the heat exchange with temperature T_{2P} on the hot side. The fluent is cooled down by the reactants and it leaves the heat exchanger with temperature T_{1P} on the cold side. In the following chapters both quality parameters for the monitoring of the heat exchanger are presented. After that the method for rest live time prediction is shown.

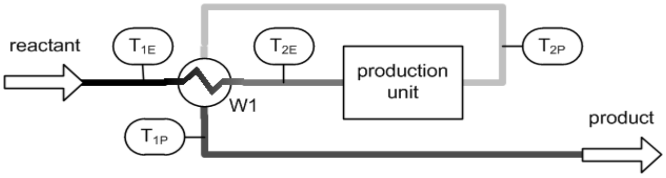

Fig. 1. Simplified flow diagram of the plant

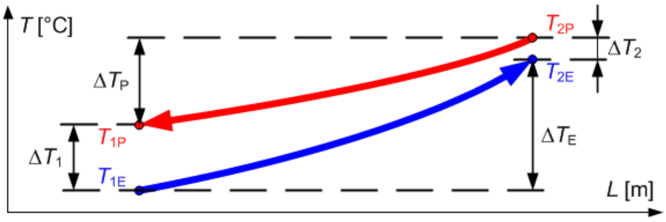

Fig. 2. Temperature profile of a current flow heat exchanger with tube length L

2.1 Quality parameter – degree of efficiency

Fig. 2 shows a typical temperature profile over a counter current heat exchanger. The state of the heat exchanger can be described by the ratio of the actually transferred energy and the maximum transferable energy. The actual amount of transferred energy is proportional to the temperature difference between inlet and outlet of the reactant, $\Delta T_E = T_{2E} - T_{1E}$. The maximum transferable energy is proportional to the temperature difference between the fluid inlet temperatures, $T_{2P} - T_{1E}$. For this definition the assumptions $\Delta T_E > \Delta T_P$ and $\Delta T_1 > \Delta T_2$ are used. The ratio of actual and maximal energy transfer is given by (1), where ε is the degree of efficiency see Wagner (2005).

$$\varepsilon = \frac{T_{2E} - T_{1E}}{T_{2P} - T_{1E}} \tag{1}$$

The efficiency depends on the set point and the inner state of a heat exchanger. The set point is defined by the inlet temperatures and the rate of fluid flow. The inner state depends on the fouling. Therefore in the present paper nearly steady-state conditions are assumed for the inlet temperatures and the amount of fluid flow. In this case a change in the degree of efficiency is caused by fouling.

2.2 Quality parameter – heat transfer coefficient

As discussed above the quality parameter (degree of efficiency) depends on the set point and the inner state of the heat exchanger. Therefore an additional formulation will be used. The model equation for heat transfer can be written as (2) see Wagner (2005).

$$Q = U \cdot A \cdot \Delta T_{\log} \tag{2}$$

In (2) Q stands for the heat flow, U for the coefficient of heat transmission, A for the surface of the heat exchanger and $\Delta T_{\log}$ for the logarithmic mean temperature difference. The logarithmic mean temperature difference is defined in (3). Increasing fouling leads to a decreasing coefficient of heat transfer due to additional heat resistance; see (4).

$$\Delta T_{\log} = \frac{\Delta T_1 - \Delta T_2}{\ln\left(\dfrac{\Delta T_1}{\Delta T_2}\right)} \tag{3}$$

$$U = \frac{1}{\dfrac{1}{\alpha_i} + \dfrac{s_{wall}}{\lambda} + \dfrac{s_{dep}}{\lambda_{dep}} + \dfrac{1}{\alpha_a}} \tag{4}$$

In (4) α denotes the heat transfer coefficient, s the coat thickness and λ the heat conductance coefficient. The index i stands for the inner and a for the outer side of the pipe and dep denotes biomass coat or solid deposition. The heat flow Q can be calculated from the measured process parameters by (5) see Friebel et al. (2009) and Wagner (2005).

$$Q = F_E \cdot c_{pE} \cdot \Delta T_E \tag{5}$$

In (5) F_E stands for mass flow of the reactant, c_{pE} for the heat capacity of the reactant and ΔT_E for the temperature difference from outlet to inlet of the reactant, see Fig. 2. By combining (2) and (5) the quality parameter UA can be defined as shown in (6) see Friebel et al. (2009).

$$UA = F_E \cdot c_{pE} \cdot \frac{\Delta T_E}{\Delta T_{\log}} \tag{6}$$

Simulations presented in Friebel et al. (2009) show that the quality parameter UA is sensitive for fouling. This is a big advantage against the degree of efficiency because fouling can be distinguished from model input drift. This means the degree of efficiency is sensitive for

- a drift in one or both of the inlet temperature,
- a drift in one or both of the fluid flows and
- a drift in the model parameter UA i.e. in the heat transfer.

By analyzing the above listing it is clear that it is nearly impossible to differ among all possible combinations of drifts. Therefore, it is more practical to estimate the model parameter UA at every steady-state sampling point k according to (6). In the special case where the flow of the reactant F_E cannot be measured the flow and c_{pE} are assumed constant. Then (6) can be transformed to (7)

$$UAF = \frac{\Delta T_E}{\Delta T_{\log}} \tag{7}$$

It is important to see that the parameter UAF is sensitive to fouling and disturbances in the flow.

2.3 *Extrapolation of a regression model*

Above a proper quality parameter for the heat exchanger is defined. The last question is: how long is the rest lifetime until a critical level is reached. Therefore a linear discrete-time regression model is used, see (8). Here u_k is the independent variable and y_k the dependent variable, see Montgomery et al. (2001). In the following application the actual measurement is the best representation of the inner state of the heat exchanger. Therefore the point of origin is equal to the actual measurement. The regression model contains only the unknown parameter $\hat{c}_1$.

$$y_k = c_1 u_k = \hat{y}_k + e_k = \hat{c}_1 u_k + e_k \quad (8)$$

With a simple extrapolation the rest lifetime u_{pred} can be calculated, while the regression model $\hat{y}_{\text{pred}}$ is equal to the tolerance limit y_{tol}. As it was shown in Friebel et al. (2009) the quality of the regression can be proven by a statistical *t*-test. The uncertainty of a regression can be shown by his confidential intervals. With the assumption, that the uncertainty at the actual measurement is equal to zero the confidential limits for future measurements can be calculated by (9) see Montgomery et al. (2001)

$$\hat{y}_k \pm s_{\text{reg}} = \hat{y}_k \pm u_k \cdot t_{\frac{\alpha}{2};N-1} \cdot \sqrt{\frac{\sigma^2}{\sum_{k=0}^{N-1} u_k^2}} \quad (9)$$

Here σ is the residual error, N the amount of used data with the regression and t the value of a *t*-distribution for a given significance level α and $N-1$ degrees of freedom. By setting the left term in (9) equal to y_{tol} and solving the equation the predicted rest lifetime $u_k = u_{\text{pred}}$ can be calculated with its uncertainty s_{reg}.

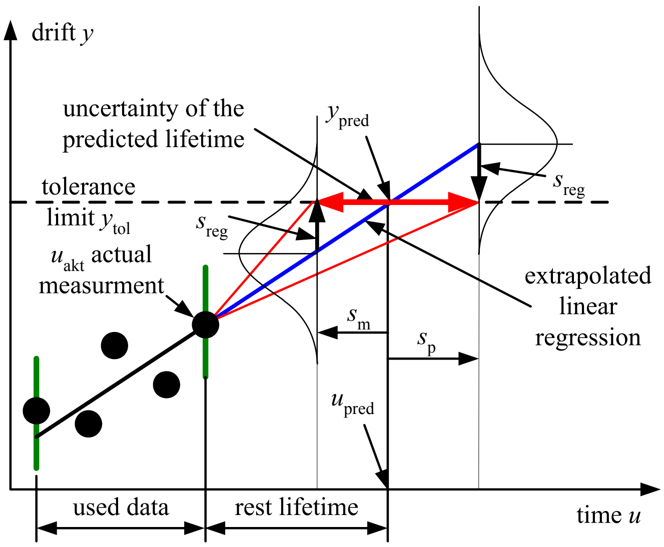

Fig. 3. Estimation of the rest lifetime

The principle of the calculation is shown in Fig. 3. The calculated uncertainties in time s_{m} and s_{p} have different values. For an easier interpretation in the practical use a middle uncertainty $\bar{s}$ is defined in (10)

$$\bar{s} = \frac{s_{\text{m}} + s_{\text{p}}}{2} \quad \text{with} \quad s_{\text{m}} < s_{\text{p}} \quad (10)$$

3. APPLICATION

3.1 *Problem description*

As it is seen in Fig. 1 the reactant is preheated by the product and the product is cooled by the reactant. In Fig. 4a the tubes of a cleaned heat exchanger are shown. In Fig. 4b the problem with fouling, adhesion on the surface inside and outside the tubes is shown. On the right side in Fig. 4c the totally blocked tubes can be seen. Blocked tubes cause the following problems:

- pressure drop over the heat exchanger increase
- the maximal cooling power of the heat exchanger decreases
- product have to be cooled additional before entering the storage
- reactant have to be heated additional before entering the production unit

Fouling costs some money. Normally a heat exchanger is observed by the degree of efficiency ε. To prevent the above listed problems the quality parameters UA and UAF are used.

3.2 *Problem solution*

Typical measurements (temperature) are shown exemplary in Fig. 5. In this analysis, several years are taken into account, but only some examples are shown in this paper. Therefore, the discrete time *k* does not start at one. The period starts and ends with a cleaning of the heat exchanger, all temperatures are low. The cleaning was performed if the degree of efficiency reached a value of e.g. 90%. Now the target is to predict these cleaning time point in order to plan a cleaning in advance. The temperatures of the production process are in a range between 350 and 450 °C see Friebel et al. (2010). The reactant is drawn with solid lines and the product in dashed lines.

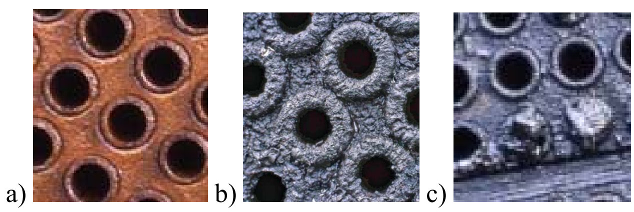

Fig. 4. Problems with fouling in a tube bundle heat exchanger a) clean surface and tubes, b) surface with fouling and c) blocked tubes after fouling see Friebel et al. (2010)

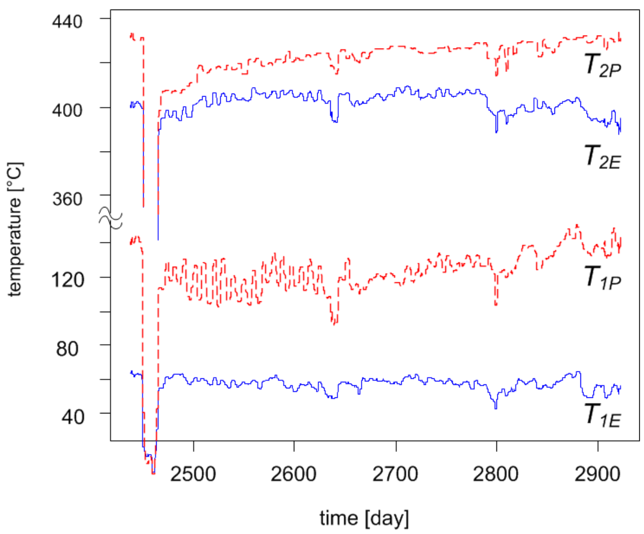

Fig. 5. Temperature measurements of the heat exchanger for a time period between the plant revisions

It can be seen, that the product temperatures (dashed lines) increase over the time. Also the temperatures are noisy especially the product outlet T_{1P} and the reactant outlet T_{3E}. The reason is a periodical sinusoidal disturbance with a period of approximately 11 days, which is caused by the plant management. The problem is that the amplitude is not constant and also there are some stepwise phase shifts in the periodical signal. In Fig. 6 the degree of efficiency ε and the model parameter UAF calculated by (1) and (7) are shown for an interesting part of this time period.

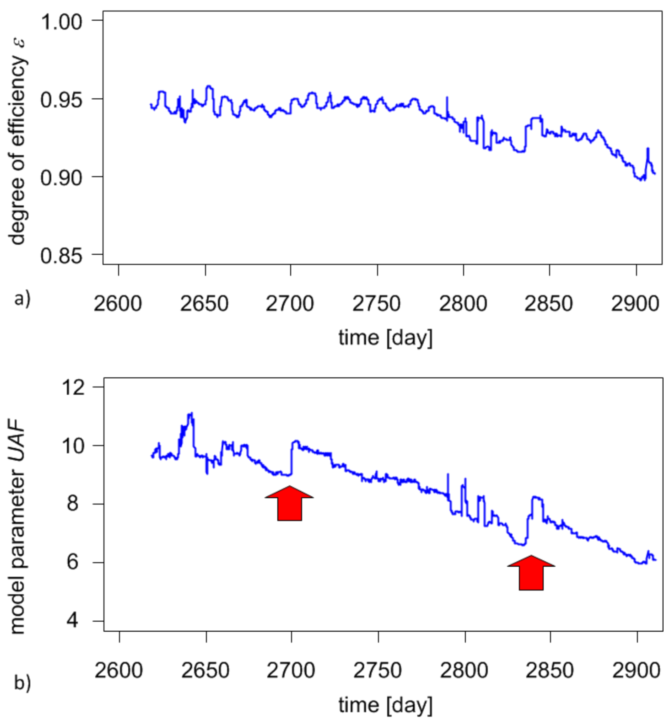

Fig. 6. Example for calculated a) degree of efficiency ε and b) model parameter UAF

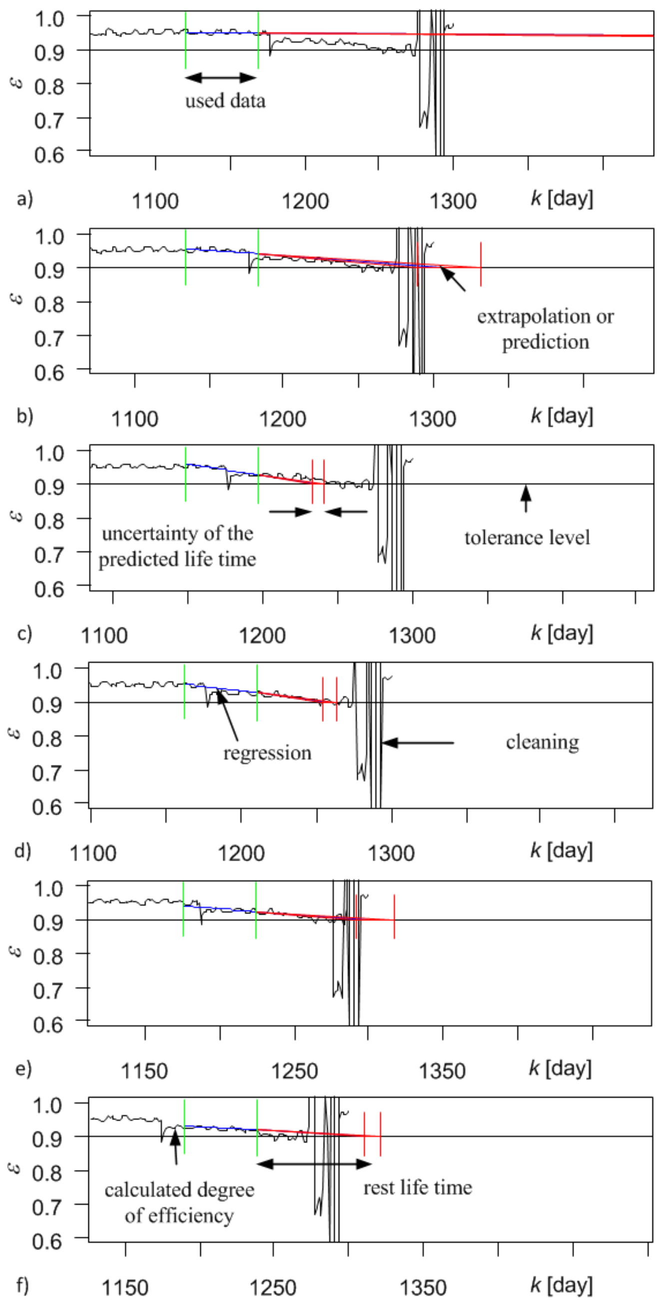

Fig. 7. Regression based lifetime estimation a) 19, b) 17, c) 15, d) 13 e) 11 and f) 9 weeks before shutdown.

It can be seen, that the calculated degree of efficiency ε is very noisy. The sinusoidal disturbance is clearly visible. But by observing the model parameter UAF these disturbances are eliminated. In the model parameter some additional information can be detected. There are two steps which are marked with arrows. These steps are caused by not recorded technological handlings. It is not possible to detect both steps in the degree of efficiency. Because this signal is caused by periodical disturbances and the parameter is not so sensitive for this case. Therefore it is a good idea to use the model parameter UAF instead the degree of efficiency ε.

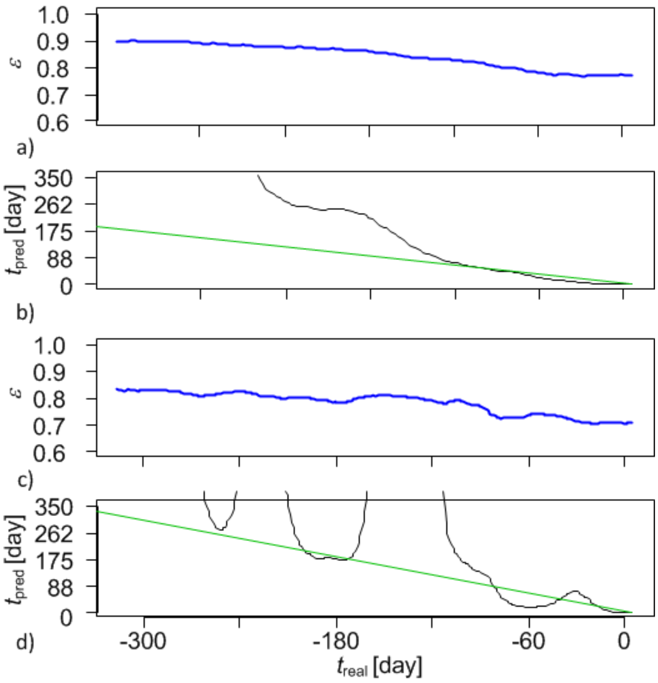

Fig. 8. Two observation periods; a) and c) degree of efficiency (solid line) and filtered signal (dashed line), b) and d) predicted rest lifetime t_{pred} versus real time t_{real} until shutdown

In Fig. 7 the calculated efficiency for another example is presented. The regression was carried out with 50 measurements in the on-line mode. Fig. 7a shows the regression 19 weeks before the shutdown. The following figures show in turn the regression always two weeks later. The rest lifetime is predicted with a small uncertainty, because the interval limits on the tolerance level are close together. As a conclusion of Fig. 7 the following points can be marked out, see also Friebel et al. (2010).

- The rest lifetime t_{pred} could be predicted nearly exact several weeks before the shutdown.
- With a *t*-test it could be shown, that the used regression model is always significant.
- The corresponding significance values α are nearly 0 %.
- The confidence limits lie near to the predicted rest lifetime t_{pred}.

In Fig. 8 two additional periods are analysed. The time until the next realized shutdown t_{real} is shown on the horizontal axis. In Fig. 8a the filtered and calculated heat exchanger efficiency is shown for a further period between two cleaning cycles. It can be seen, that the signal is not very noisy. In Fig. 8b the predicted rest lifetime t_{pred} is plotted on the vertical axis. In the ideal case the times t_{pred} and t_{real} are equal, which is marked by the diagonal line. Two month before the shutdown an acceptable prediction is possible. In the second period in Fig. 8c it can be seen that calculated degree of efficiency temporally increases because of a not recorded technological handling. This has a direct impact on the

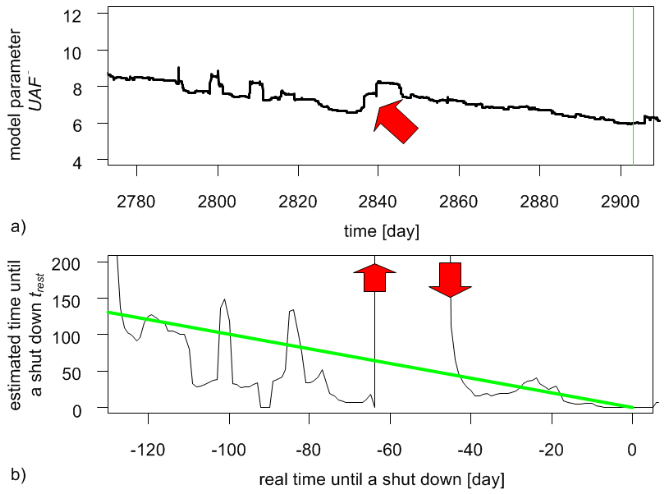

Fig. 9. Model parameter UAF with a step caused by online cleaning in a) and the corresponding rest lifetime estimation in b)

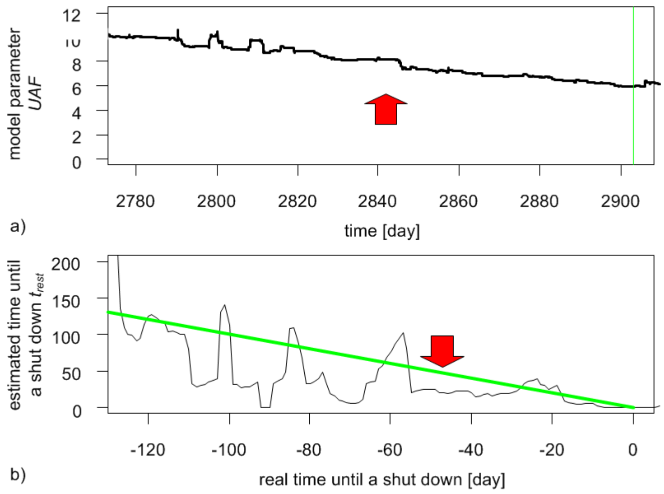

Fig. 10. Model parameter UAF for the time period from Fig. 9 with considered step in a) and the corresponding rest lifetime estimation in b)

prediction of rest lifetime in Fig. 8d. The trend is clearly visible along the diagonal line. Because of the noisy signal and the technological handling there are changes in sign of the slope.

The calculated model parameter UAF is sensitive for any not recorded technological handlings. During such a procedure some cleaning solution is added to the reactant. The result is a shortly better heat exchanger condition (higher value for the model parameter), because the amount of solid depositions decreases and the heat transfer increases.

Fig. 9a shows the last section of the data form Fig. 6b. Around day 2840 a step in the model parameter UAF was detected, see the arrow. The estimated rest lifetime is shown in Fig. 9b. It is easy to see that around the step in the model parameter the estimated rest lifetime becomes infinite large. In the period marked by the arrows no practical prediction is possible. 100 and 80 days before the shut down the prediction were disturbed by additional changes in the inlet temperatures.

In the new approach all regressions before the stepwise disturbance are calculated with the data from Fig. 9a. For all regressions after the stepwise regression the values before the disturbance are shifted upwards that the step in the model parameter disappeared. The new course of the model parameter is shown in Fig. 10a and the corresponding estimation of the rest lifetime is shown in Fig. 10b. It is easy to see that in this case in every time point a practical prediction is possible. It is important to know that Fig. 10a shows the model parameter for the view after day 2840. Fig. 11 shows all data from Fig. 6b and also at the first step at day 2720 a proper prediction is possible. The values in Fig. 11d are not infinite high; they are smaller than 1900 days.

4. CONCLUSION

In Friebel et al. (2009 and 2010) a simple method for lifetime estimation was presented and analyzed in some case studies. In the presented paper an additional representative parameter for the state of the heat exchanger is used with the explained method. The assumptions and simulations were tested by analyzing measurements of a real plant. By comparing the results and simulations the following results can be summarized.

- The classical parameter for the observation of the state of the heat exchanger is the degree of efficiency ε. This quality parameter is sensitive for drifts in the inlet temperatures, the fluid flows and the heat transfer coefficient.
- The model parameter UA, a combination of the heat transfer coefficient and the inner surface of the heat exchanger, is not sensitive for a drift in inlet temperature and fluid flows.
- If the flow cannot be measured then only the observed parameter UAF can be calculated. Hereby a constant flow is assumed, otherwise a drift in flow and in the heat transfer cannot be differed.
- Using the model parameter UAF is better than using the degree of efficiency ε.
- It would be better to use a quality parameter which is independent of the working point. Therefore the universal model parameter UA should be preferred if possible.
- The prediction of the rest lifetime can be made by a simple linear regression. The quality of the regression can be proven with a statistical t-test. Also a statistical based uncertainty of the predicted rest lifetime can be formulated.
- It is easier to detect and compensate the on-line cleaning in the model parameter UAF than in the degree of efficiency ε.
- By considering the steps caused by the on-line cleaning, the predicted rest lifetime becomes more practical with realistic predictions.

Further research work is planned in order to detect and to consider the change in flow during the data recording.

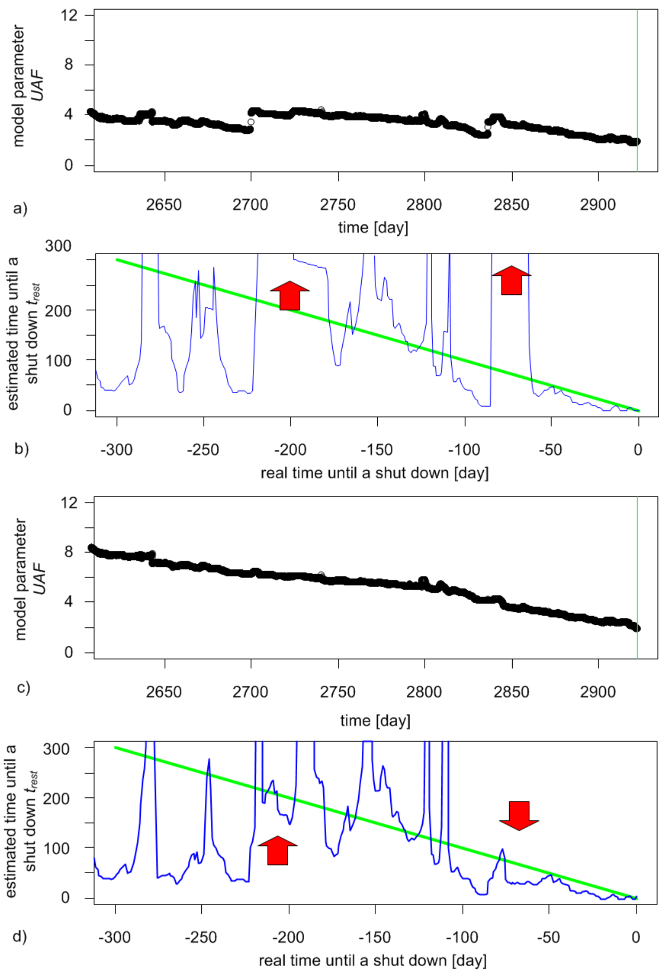

Fig. 11. Model parameter UAF for the time period from Fig. 6b with considered step in a) and the corresponding rest lifetime estimation in b)

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