Fouling Detection in Heat Exchangers using Extended Kalman Filter

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Abstract. Heat exchangers are important equipment widely used in industries for heat transfer. However, after a long operation, the efficiency of heat transfer may be reduced due to the deposition of impurities on the heat transfer surface, called, fouling. In practice, detection of fouling in heat exchangers is needed for diagnostic, monitoring, and maintenance purposes. This research proposes a fouling detection method using Extended Kalman Filter. Heat exchangers are simulated using cell-based model. Asymptotic fouling model is considered. In detection of fouling in heat exchangers, overall heat transfer coefficient will be estimated using Extended Kalman Filter. The required information in Extended Kalman Filter includes measurement of outlet temperatures on hot and cold sides and low-order cell-based model of heat exchangers.

1. Introduction
Heat exchangers are important equipment widely used in industries for heat transfer. However, after a long operation, the efficiency of heat transfer may be reduced due to the deposition of impurities on the heat transfer surface, called, fouling. In practice, detection of fouling in heat exchangers is needed for diagnostic, monitoring, and maintenance purposes. Many researches [1,2,3] have devoted to methods for fouling detection.

This research proposes a fouling detection method using Extended Kalman Filter. Heat exchangers are simulated using high order cell-based model of [4]. In detection of fouling in heat exchangers, overall heat transfer coefficient will be estimated using Extended Kalman Filter. The required information in Extended Kalman Filter includes measurement of outlet temperatures on hot and cold sides and low-order cell-based model of heat exchangers.

2. Model of Heat Exchangers
In this research, cell-based dynamic heat exchanger models [4] is used for the simulation of heat exchangers. The cell-based models combine a number of perfectly mixed model tanks, called cells, which makes the simulation results equivalent to those from a distributed model. A concept of cell-based model can be illustrated in Figure 1.
Under assumptions including perfectly mixed tanks, constant fluid density and heat capacity, neglected wall resistance, cell-based models of a heat exchanger can be written,

\[
\frac{dT_{H,\text{out}}}{dt} = \frac{v_H}{V_H} (T_{H,\text{in}} - T_{H,\text{out}}) - \frac{U \cdot A}{\rho_H \cdot C_{p,H}} \left( T_{H,\text{out}} - T_{C,\text{out}} \right)
\]

(1)

\[
\frac{dT_{C,\text{out}}}{dt} = \frac{v_C}{V_C} (T_{C,\text{in}} - T_{C,\text{out}}) - \frac{U \cdot A}{\rho_C \cdot C_{p,C}} \left( T_{H,\text{out}} - T_{C,\text{out}} \right)
\]

(2)

For asymptotic fouling behavior, the fouling resistance \( R_f \) can be expressed by

\[
R_f = R_f^* \left( 1 - e^{-\frac{t}{t_c}} \right)
\]

(3)

This can affect overall heat transfer coefficient \( U \) as,

\[
U = \frac{U_c}{1 + R_f U_c}
\]

(4)

### Table 1. List of nomenclature

| Nomenclatures | Descriptions |
|---------------|--------------|
| \( T_{H,\text{out}}, T_{C,\text{out}} \) | Outlet temperature on hot and cold sides of cells |
| \( T_{H,\text{in}}, T_{C,\text{in}} \) | Inlet temperature on hot and cold sides of cells |
| \( \dot{V}_{H}, \dot{V}_{C} \) | Fluid volumetric flow rates on hot and cold sides |
| \( V_H, V_C \) | Volume on hot and cold sides |
| \( A \) | Heat transfer area |
| \( \rho_H, \rho_C \) | Fluid density on hot and cold sides |
| \( C_{p,H}, C_{p,C} \) | Fluid heat capacity on hot and cold sides |
| \( U, U_c \) | Current and clean overall heat transfer coefficients |
| \( R_f^* \) | Asymptotic fouling resistance |
| \( t_c \) | Residence time |

### 3. Extended Kalman Filter

Kalman filter is a linear quadratic estimator that can be used to estimate unknown states and parameters of processes. When nonlinear model is used in the algorithm, it will be called “Extended Kalman Filter or EKF”. EKF algorithms consists of two major parts including model prediction and measurement update as follows,
Model prediction

\[
\frac{d \hat{x}_{k+1|k}}{dt} = f(\hat{x}_{k|k}, \hat{\mu}_{k|k}) \quad (5)
\]

\[
P_{k+1|k} = A_R P_{k|k} A_R^T + Q_k \quad (6)
\]

Measurement update

\[
K_{k+1} = P_{k+1|k} C_{k+1}^T (C_{k+1} P_{k+1|k} C_{k+1}^T + R_{k+1})^{-1} \quad (7)
\]

\[
\hat{x}_{k+1|k+1} = \hat{x}_{k+1|k} + K_{k+1} (y_{k+1} - C_{k+1} \hat{x}_{k+1|k}) \quad (8)
\]

\[
P_{k+1|k+1} = (I - K_{k+1} C_{k+1}) P_{k+1|k} \quad (9)
\]

where the matrices P, Q, and R are Kalman tuning parameters, K is Kalman gain matrix.

In detection of fouling in heat exchangers, overall heat transfer efficient will be estimated. In model prediction part, equation (5) will include model of heat exchangers and overall heat transfer coefficient. To reduce model complexity, low-order cell-based model should be used in the EKF. Furthermore, because fouling usually has slow dynamic, constant overall heat transfer efficient will be assumed and this is equivalent to \(\frac{dU}{dt} = 0\).

In heat exchangers, available measurements are usually flowrates, inlet and outlet temperatures. Measured flowrates and inlet temperatures are required in the model prediction equation (5) while in measurement update, the output measurements \(y_k\) in equation (8) are outlet temperatures on hot and cold sides of heat exchangers for observability. The incorporation of the proposed EKF in estimation of overall heat transfer coefficient can be illustrated in Figure 2.

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**Figure 2.** Incorporation of EKF in estimation of overall heat transfer coefficient
4. Results and Discussions
Parameters used in simulation of heat exchangers are shown in Table 2. Using cell-based model, the number of cells need to be determined. More number of cells improves model accuracy but with expense of computational effort. In this paper, fifty cells are chosen because only little improvement of temperature results can be expected for more number of cells.

| Parameters                                      | Values  |
|-------------------------------------------------|---------|
| Inlet temperature on hot side (°C)              | 80      |
| Inlet temperature on cold side (°C)             | 25      |
| Volumetric flow rate of fluid on hot and cold sides (m³/min) | 0.003   |
| Volume on hot and cold sides (m³)               | 0.0023  |
| Heat transfer area (m²)                         | 0.5     |
| Fluid density on hot and cold sides (kg/m³)     | 1,000   |
| Specific heat capacity of fluid on hot and cold sides (J/kg.°C) | 4,184   |
| Clean overall heat transfer coefficient (J/min.m².°C) | 8,000   |
| Asymptotic fouling factor (min.m².°C/J)         | 2x10^{-4} |
| Residence time (fouling) (min)                  | 16,000  |

Figure 3 shows simulation result of heat exchangers without and with fouling effects. Fouling reduces heat transfer efficiency as noted by higher value of outlet temperature on hot side and lower value of outlet temperature on cold side of heat exchangers. Fouling decreases overall heat transfer coefficient and increases fouling resistance as shown in Figure 4.

**Figure 3.** Dynamic responses of heat exchangers (a) without fouling effect and (b) with fouling effect

**Figure 4.** Effect of fouling to (a) overall heat transfer coefficient and (b) fouling resistance
In detection of fouling, this paper will estimate overall heat transfer coefficient of heat exchangers using EKF. To see the performance of the estimation, the results will be divided into two cases including perfect model case, i.e., using same models in simulated heat exchangers and EKF, and mismatch model case, i.e., using high-order cell-based model in simulated heat exchangers and low-order cell-based model in EKF.

4.1 Perfect model case
In the perfect model case, two-cell model is used in both simulated heat exchangers and EKF. Figure 5 shows estimation of overall heat transfer coefficient without and with fouling.

![Figure 5](image1.png)

Figure 5. Estimation of overall heat transfer coefficient (a) without fouling effect and (b) with fouling effects for perfect model case (solid line – actual value, dashed line – estimated value)

The guess initial estimate is at 5,500 J/min.m². However, after some times, the estimates can track the actual value for both cases without and with fouling effects. In conclusion, EKF with perfect model can estimate overall heat transfer coefficient very well.

4.2 Model mismatch case
In the model mismatch case, fifty-cell model is used in the simulated heat exchanger while two-cell model is used in EKF. The estimation results without and with fouling effects are shown in Figure 6.

![Figure 6](image2.png)

Figure 6. Estimation of overall heat transfer coefficient (a) without fouling effect and (b) with fouling effects for model mismatch case (solid line – actual value, dashed line – estimated value)

Although there is an existence of offset in estimation for EKF with model mismatch, the proposed EKF can track the change of overall heat transfer coefficient properly as shown in Figure 6b.
5. Conclusions
This research proposes a fouling detection method using Extended Kalman Filter (EKF). Heat exchangers are simulated using cell-based model of [4] plus asymptotic fouling model. In detection of fouling in heat exchangers, overall heat transfer coefficient is estimated using EKF. The required information in EKF includes measurement of outlet temperatures on hot and cold sides and low-order cell-based model plus simple constant overall heat transfer coefficient model. The results show that for perfect model case, i.e., using same model in simulated heat exchanger and EKF, overall heat transfer coefficient can be properly estimated. However, for model mismatch case, i.e., using high-order cell-based model in simulated heat exchangers and low-order cell-based in EKF, an offset in estimation can be observed. Although there is an existence of offset in estimation, the proposed EKF can predict the trend of change in overall heat transfer coefficient quite well.

6. References
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