METHOD TO DETECT FOULING IN HEAT EXCHANGERS

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ABSTRACT
Heat exchangers are frequently used in district heating systems, at power plants and public homes. Detecting fouling in district heating heat exchangers is of great importance. There are currently many different ways to detect fouling in heat exchangers that either rely on physical examination of the heat exchanger or modeling the heat exchanger and use measurements of the heat exchanger to predict fouling. The method describe in the paper can be used to detect fouling by using the inlet and outlet temperatures and either the hot or cold mass flow. Results of the method described on a simulated data are given.

INTRODUCTION
Heat exchangers are important devices that are widely used in industrial and domestic applications. Their purpose is to transport heat from one fluid to another by conduction through solid walls. Typical applications include chemical processes, air heating and cooling as well as use in district heating systems. Many different types and sizes of heat exchangers exist, but they are similar in principle and their classification is well defined (20). One side effect of using heat exchangers is the possibility that internal fouling will occur. Fouling typically occurs when the solid that is placed between the two fluids accumulates deposits from the fluids, builds up biofilm or corrodes. When fouling increases, the heat transfer between fluids decreases, which will increase the energy cost of the heat exchanger. It is therefore important to minimize or at least to monitor fouling in heat exchangers when possible, which is particularly important in district heating systems, where the amount of heat transfer is large.

Studies have shown that the total cost of fouling in heat exchangers in highly industrialized countries can be up to 0.25% of gross national production, (11) and (3). Fouling also has an effect on the environment since the increased resistance from fouling will increase power consumption of pumps. For instance in a 550 MW coal-fired power plant a fouling biofilm of 200µm lead to increase of about 12 tons of CO₂ per day, (9). Due to the cost and the environmental issues introduced with fouling, it is preferred to take steps to detect or reduce fouling if possible. Effective fouling mitigation techniques include, (4),

• Increasing the heat transfer area of the heat exchanger.
• Cleaning of the heat exchangers when they get fouled.
Research of fouling, both causes and detection, has been extensively studied. Studies that involve causes of fouling include (10) and (11) where modifications of the heat transfer surface was studied and ion implantation of fluorine and silicon ion into the heater alloys were also studied respectively. Other studies with a focus on detection of fouling include (12) and (13) where the thermal efficiency and temperature drop in the outlets were studied respectively.

The effect of fouling is often represented by a fouling factor, which measures the relative thermal resistance introduced by fouling. For a new heat exchanger the fouling factor is zero and it increases with time with increased fouling. The development of fouling depends on a number of things, (5) and (16). Major groups of fouling dependents are:

• Composition of the fluids.
• Operating conditions in the heat exchanger.
• Type and characteristics of the heat exchanger.
• Location of fouling.
• Presence of micro-organisms.

According to (5), (6) and (8) there is usually an induction time before a noticeable amount of mineral deposits has formed, which will change the overall heat transfer noticeably. Furthermore, research on fouling shows that the fouling may enhance the heat transfer for a short time in the beginning of fouling due to enhanced roughness on the heat transfer surface. It has also been shown that the fouling will grow with increased rate during the fouling period, (7).

Detection of fouling in heat exchangers have been studied extensively and the following list summarizes just few of the methods for fouling detection.

• In (17), a good overview of the use of ultrasonics, acoustic and optical techniques to detect fouling on-line is presented.
• In (18), heat exchangers are modeled with neural networks and in (1) the neural networks are used to detect fouling on-line.
• In (19), a measurements of electric resistance is used to detect fouling build up in the heat exchanger.

• In (2), an extended Kalman filter is used to detect fouling in counter-flow heat exchangers.

In this paper, changes in the overall heat transfer coefficient in heat exchangers is monitored by assuming that the heat exchanger is operating in a steady state condition over periods of time. Based on the model results, the Cumulative Sum control chart is used to detect if fouling occurs and estimate the starting time of fouling. The method is tested by using a dynamic finite volume model to generate data by simulation. This methodology results in a very controlled environment for generating data, where stochastic changes can be added to the data in order to generate realistic series.

FOULING DETECTION

The slope method

The following method is specially designed to monitor heat exchangers that operates in a condition close to a steady state. For instance the heat exchangers used in the district heating industry. According to the energy company Hitaveita Suurnesja the heat exchangers used there are usually close to a steady state operation their whole operating time. The heat exchangers get hot steam with almost constant pressure and flow. The cold side usually has almost constant temperature, but the cold mass flow can have some variations. The method uses the following assumptions:

• Steady operating conditions exist.

• Changes in the kinetic and potential energies of fluid streams are negligible.

• Fluid properties are constant.

The heat transfer rate for a parallel-flow and counter-flow heat exchanger in a steady state is

$$\dot{Q} = UA\Delta T_{LMTD} = \dot{m}_k c_p \Delta T_k$$  \hspace{1cm} (1)

where the subscript $k$ indicates either the hot or the cold side.

For a cross-flow heat exchanger it is necessary to add a correction factor $F$ for the log mean temperature difference, $\Delta T_{LMTD}$. The value of $F$ can be found in tables in (16). By looking at Eq. (1) the following relation can be derived for cross-flow heat exchangers

$$\dot{m} \Delta T_c \propto UAF \Delta T_{LMTD}.$$  

This method finds the fouling by calculating the slope $AUF$ over a sliding window of size $N$ from the plot $\dot{m} \Delta T$ against $\Delta T_{LMTD}$. A typical plot can be seen in Figure 1. By viewing the figure it can clearly be seen that there are strong correlations between observations. By monitoring the slope for changes from the slope of a reference operation it is possible to find out when the heat exchanger starts to build up fouling. As the slope decreases the more fouled the heat exchanger is. Because of the correlations it is necessary to have relatively long windows when estimating the slopes to minimize the effect of the correlations, especially when estimating the reference slope because the detection is done by comparing how the slope is changing with time to the reference slope.

Cumulative sum control chart

According to (15) the Cumulative sum control chart (CuSum) is very efficient when detecting small shift in mean of a process. Thus is the CuSum chart is used in this study.

A result of fouling in heat exchangers is a decrease in the overall heat transfer coefficient, $U$. Since the slope, $AUF$ that is calculated in the method include the overall heat transfer coefficient, $U$, and that the heat transfer area, $A$, and the correction factor, $F$, should change relatively small comparing to the changes in $U$ when fouling occurs it is possible to monitor the changes in the slope to detect fouling. The detection is made by using the CuSum chart.

When analyzing the parameters the average value of the parameters is calculated over a window of a specific length, which is chosen in accordance with the process being studied, and the CuSum chart is used to monitor the average value of the parameters for a shift from their reference value. If the average is not changing in time it is said to be under control, if on the other hand there is a shift in the average it is said to be out of control. If the process remains in control the cumulative sum should fluctuate around zero. If there is a shift in the value of the parameters, either upwards or downwards, the CuSum chart should pick it up quickly. If there is an upward shifting it is said to be a positive shift and conversely if there is a downward shift in the parameters, it is said to be a negative shift in the parameter. The CuSum control chart is calculated with Eq. (2) and Eq. (3), (15).
\[ S_H(i) = \max[0, x_i - (\mu_0 + K) + S_H(i - 1)] \] (2)
\[ S_L(i) = \max[0, (\mu_0 - K) - x_i + S_L(i - 1)] \] (3)

Where the starting values are \( S_H(0) = 0 \) and \( S_L(0) = 0 \). \( S_H(i) \) and \( S_L(i) \) accumulate deviations from the target value that is greater than the reference value \( K \), with both quantities reset to zero upon becoming negative. Care needs to be taken when choosing the value of \( K \) to minimize the chance of detecting fouling when none is, error of type 1, and not detecting fouling when fouling has occurred, error of type 2. If either \( S_H(i) \) or \( S_L(i) \) exceeds a constant \( H \), the process is out of control. This constant \( H \) is the decision interval.

There are many possible ways of choosing \( K \) and it is usually chosen to be about halfway between the target mean and the mean corresponding to an out of control state.

**THE SIMULATED DATA**

Since it was difficult to get access to data during this study from a cross-flow heat exchanger where fouling occurs the data used in the analysis was simulated with a Matlab program developed by Halldor Palsson. The program simulates time series from an unixed/unixed cross-flow heat exchanger. A cross-flow heat exchanger test rig is now under construction at the University of Valenciennes where fouling can be induced in a controlled environment. In the following sections an introduction will be given to the model used for simulation, the fouling factor and the data used in the analysis.

**Dynamic simulation model**

The mathematical model of a general heat exchanger specifies the fluid temperature as position dependent fields inside the heat exchanger, where energy travel in two ways:

- By pure convection from the hot fluid to the metal sheet.
- By conduction through the metal sheet. It is assumed that the conduction within each fluid is negligible.

In the program it is possible to model the heat exchanger either with a thin metal sheet between the fluids or without the metal sheet, that is, assume that the metal sheet has negligible heat capacity and infinit thermal conductivity. To compare the effect of the metal the output temperatures where calculated for with and without the metal sheet with the same input temperature and mass flow.

It is assumed that the cold and hot fluid flow only in \( x \) and \( y \) direction respectively. The width of the exchanger is \( W \), the height is \( H \) and the thickness of the hot and cold passages are \( d_h \) and \( d_c \) respectively. The energy balance for this system is described by two coupled partial differential equations where the field variables are the temperatures \( T_c \) and \( T_h \) for the cold and hot side respectively. The equations are

\[
\frac{\partial T_c}{\partial t} + \frac{m_c}{pcHd_c} \frac{\partial}{\partial x} (cT_c) = \frac{U}{pcd_c}(T_h - T_c) \] (4)
\[
\frac{\partial T_h}{\partial t} + \frac{m_h}{pcHd_h} \frac{\partial}{\partial y} (cT_h) = \frac{U}{pcd_h}(T_c - T_h) \] (5)

In this formulation \( \rho \) and \( c \) are dependent on the flow temperature and \( U \) is dependent on both \( T_h \) and \( T_c \) as well as position \( x \) and \( y \). Also the mass flow of the cold stream, \( m_c \), can depend on \( y \). The mass flow of the hot stream, \( m_h \), can depend on \( x \). Mass flow, heat transfer coefficient as well as the inflow temperatures can be time dependent.

**Simulation of fouling**

Resistance to heat transfer is the inverse of \( U \). The resistance to heat transfer corresponding to fouling, \( R_f \), is the increased resistance to heat transfer from the time that the heat exchanger is new.

\[
R_f(t) = \frac{1}{U(t)A} - \frac{1}{U(0)A} \] (6)

When the data used in this study was simulated the effect of fouling was introduced to the extent that the overall heat transfer coefficient, \( U \), dropped to half of what \( U \) would be for a clean heat exchanger. In Figure 2 the ratio \( \frac{U_{fouled}}{U_{clean}} \) is shown. In (7) it is shown that fouling increases with time, to simulate this effect the fouling used in this study was started slowly but increased with time. In Figure 2 it can clearly be seen that the accumulation of fouling starts slowly but increases with time.

The effect of fouling on \( U \) is calculated in the simulation with Eq. (7)

\[
U_{fouling} = U_{clean} \cos(at + b) \] (7)
The constant \( c_{f1} \) indicates the value of \( U_{\text{fouling}} \) as a percent of \( U_{\text{clean}} \) from a clean heat exchanger at the end of the time series. The constant \( c_{f2} \) indicates when the fouling will start. The values of \( c_{f1} \) and \( c_{f2} \) can be between \([0,1]\).

When a heat exchanger is designed a fouling factor is chosen, the fouling factor indicates how much fouling the heat exchanger can sustain before it needs to be cleaned. According to (1) a fouling factor for water is typically in the range \([0.0001, 0.0007]\). Typical values for the fouling factor can be found at (14). For the data used in this study the fouling factor on the previously mentioned interval corresponds to the interval \([0.395, 0.876]\) in dimensionless time. In Figure 3 the corresponding fouling factor is shown.

**Simulation data**

The simulated heat exchanger was 0.5 meters wide and height and had a depth of 0.002 meters for both the hot and the cold side. The reason for these dimensions was to insure turbulent flow in the simulated heat exchanger.

The inlet temperatures and the mass flows where chosen by randomly choosing base points over certain interval. The temperatures and the mass flows where then allowed to vary between the base points by interpolating randomly between the base points.

In all the data simulations the same fouling effect was used, in order to be able to compare the results for the methods and to do sensitivity analysis on their results. The fouling was allowed to decrease \( U \) to half of \( U \) from a clean heat exchanger, see Figure 2. To represent a heat exchanger in a district heating system only small variations in the inlets were allowed. Figure 4 shows one of the used data sets.

**RESULTS - SLOPE METHOD**

The slope method, described above, is derived to detect fouling in heat exchangers which usually have small variation in their inlets, as is the case for district heating heat exchangers. In district heating systems all the inlets have small variations except the cold mass flow. The cold mass flow varies with water demand. To simulate a case similar to a district heating system the inlet temperatures and the hot mass flow were only allowed small variations while the cold mass flow were allowed to vary considerably comparing to the hot mass flow.

The effect of fouling was allowed to decrease the overall heat transfer coefficient, \( U \), to half of the value of \( U \) for a clean heat exchanger, see Figure 2.

As has been mentioned previously, the method monitors changes in the slope \( AU F \) by comparing it to a reference slope, the reference slope is calculated with part of the data. In Figure 5 typical estimation of the reference slope is shown.

In Figure 6 the changes in the slope, \( AU F \), is monitored. The straight black line is the reference slope and the green line shows how the slope is changing in time. The above figure shows all the data points from all the windows the slope \( AU F \) is estimated from, in the lower figure the data points have been removed and the value of the x-axis have been changed to a dimensionless time to show how the slope is changing in time. If the slope is decreasing it may mean that the heat exchanger is accumulating fouling or that the inputs have changed.
The slope, \( UAF \), calculated with window size=400

\[ y = 1.96e+004 \times - 1.4e+006 \]

\( UAF = 1.96e+4 \)

Equation of the line:

**Reference slope**

Reference slope

**Clean** Gradually fouling

Fig. 5: Estimation of a reference slope.

**Fouled slope** The slope, \( UAF \), calculated with window size=400

\[ \Delta T_{LMTD} \]

\( m_{c} \)

\( p \)

\( \Delta T_{h} \)

**Reference slope**

Fig. 6: Figure a) shows all the data points from all the windows that the slope \( UAF \) is estimated from. Figure b) shows only the slopes, that is the data points have been removed, and the values of the x-axis represent a dimensionless time.

CuSum chart for the slope method

**Fouled heat exchanger** 1471 CuSum values

Shift detected in \( \Delta UAF \): 0.42

Fig. 7: Detection of shift in the slope.

To check statistically where the shift in the slope begins the CuSum chart was used. That is if there is a shift in \( \Delta UAF = UAF_{\text{reference}} - UAF_{\text{fouling}} \). Figure 7 shows only the CuSum values for the fouled part of the data. The CuSum charts detects shifts in the slope at 0.42 in dimensionless time.

If the detection is compared to the fouling factors in Figure 3 it can be seen that the detection corresponds to \( R_{f} = 0.00016 \) which can be considered a good result if compared to typical fouling factor values, which are in the range [0.0001, 0.0007].

**Sensitivity analysis on detection**

It can be shown that the mass flow has considerable effect on the heat transfer. This effect can influence the detection of fouling. The influence was studied by simulating 50 different time series and by going through the process of detection of fouling with the slope method. The result of this analysis is that the fouling is detected with 95% certainty between 0.33 and 0.92 in dimensionless time for the fouling factor used. This interval corresponds to a fouling factor on the interval [0.00007, 0.0008], see Figure 3.

It should be mentioned that in some cases the reference slope was either over- or underestimated, which resulted in the slope either overshooting, or undershooting the clean slope almost from the beginning. In the case where the slope was underestimated the fouling detection was made relatively late. In the case where the slope was overestimated the fouling detection was made relatively soon. These two cases explain the wide range of the detection interval. Solution to this problem might be to have a longer reference interval.

**CONCLUSIONS**

The aim of the present study was to detect fouling in cross-flow heat exchangers that are operating in a steady state condition. As mentioned above heat exchangers are designed to account for the effects of fouling by incorporating a fouling factor. The fouling factor indicates the maximum fouling the heat exchanger can sustain and still fulfill it operational requirements. The fouling factor is usually on the interval [0.00001, 0.0007]. It has been shown that the method derived can be used
to detect fouling in cross-flow heat exchangers. The detection analysis was only used on the fouled part of the data, that is the fouling begins in 0 in dimensionless time. The main results were the following:

- The slope method can detect fouling in a heat exchanger with a small variation of the inlet variables.
- The 95% detection interval for the slope method is [0.33, 0.92] in dimensionless time, which corresponds to the fouling factor interval [0.00007, 0.00008].

The slope method can be used to detect fouling in heat exchangers which have small variations in their inlet variables. The sensitivity analysis shows that the fouling detection is made when the fouling factor is in the interval [0.00007, 0.00008]. The wide range of the detection interval is due to the difficulties in estimating the reference slope. Typical fouling factor values are in the range [0.0001, 0.0007], as previously mentioned.

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References


