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# COMPARISON OF FOULING DETECTION BETWEEN A PHYSICAL METHOD AND A BLACK BOX MODEL

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## ABSTRACT

The paper presents two methods that are aimed at detecting fouling in cross-flow heat exchangers under normal operating conditions, using measurements that can easily be obtained, i.e. inlet and outlet temperatures and the mass flows of the hot and cold fluids. The methods are a) a physical method that is based on number of transfer units (NTU) relations and b) a black box model that is estimated using a clean heat exchanger.

In method a) the overall heat transfer coefficient is estimated from the NTU relations. It is known that the heat transfer coefficients is mass flow dependent and it is therefore convenient to use empirical relations to filter variations caused by mass flow changes from the estimated values.

In method b) a model of the heat exchanger is identified, based on past and present measurements from the heat exchanger. The model is then used to make one step predictions of the outputs of the heat exchanger.

Currently the methods have only been tested on simulated data from a Computational fluid dynamic (CFD) model. Although the CFD model has not been validated for a cross-flow heat exchanger it has been validated for a counter-flow heat exchanger with good results.

It is concluded that it is possible to detect fouling in cross-flow heat exchangers with the derived methods, within a reasonable accuracy and consistency.

## INTRODUCTION

Heat exchangers are commonly used in domestic and industrial applications involving transfer of energy from one fluid to another. General classifications of heat exchangers are parallel flow, counter-flow and cross-flow. Their operating conditions can be put into two main classes, steady state operation where mass flow and temperatures are relatively constant and dynamic operation where mass flow and temperatures can vary greatly with time. In most cases heat exchangers accumulate fouling on the heat transfer area during usage. As the fouling increases, the efficiency of the heat exchanger decreases. Because of decreasing efficiency it is important to have some knowledge of the condition of the heat exchange. Since fouling in heat exchangers is very common, heat exchangers are commonly designed to withstand mild fouling, see (Pope et al., 1978). It has also been shown that surface coating and heat transfer enhancements that intensify heat transfer can increase the fouling induction time, see (Nejim et al., 1999; Liu et al., 2009; Somerscales and Bergles, 1997). Fouling can be described as a process where the separating metal inside the heat exchanger gathers deposits from the fluids. As fouling accumulates on the heat transfer area the resistance to heat transfer increases and the effectiveness of the heat exchanger diminishes. The cost of fouling is a waste of energy and cost due to downtime because of cleaning procedures and additionally due to product faults. These costs can become significant, and also the waste of energy which is an environmental issue that should be taken seriously. If not only because of the high cost associated with fouling, it is important to have some knowledge of the condition of the heat exchanger. If the condition is known, fouling mitigation techniques may become more focused and cleaning of the heat exchanger can be scheduled at optimum intervals.

There are number of ways to detect fouling but many of the classical methods require the process to be operating in a steady state condition or to be stopped. These restrictions can be too strict or costly. If the steady condition can be met the detection has been proven to be relatively simple, since analytical and empirical relations can be derived for different heat exchanger types and used for all necessary calculations regarding time invariant conditions, see e.g. (Holman, 2002). In a dynamic operation, it becomes more complicated to monitor the condition of the heat exchanger and more complex models are used, see (Mishra et al., 2008) where finite difference method is used to model a cross flow heat exchanger.

It is important that a fouling detection method can follow the process in real time, for it to become useful. The detection can be done for example by monitoring possible drift in parameters or variables in a model. Then the discrepancies between the model predictions and what is actually measured will indicate fouling. Fouling detection has been an active field for the last years and many methods have been developed. Examples of methods that monitor parameters for drift using standard and extended Kalman filter are presented in (Gudmundsson et al., 2009a) and (Gudmundsson et al., 2009b) and also in (Delmotte et al., 2008) where Fuzzy models are used. An alternative example of a method monitoring drift in variables can be seen in (Andrjesdottir et al., 2011). Furthermore, examples of methods that detect fouling through discrepancies between model predictions and measured values are presented in (Lalot and Mercère, 2008) where a recursive subspace algorithm is used, in (Mercère et al., 2009) where linear parameter-varying models are used and in (Lalot and Palsson, 2010) where neural networks are used**.**

In this paper two methods are presented and compared. The first one is based on the classical number of transfer units (NTU) method and empirical relations for the mass flow rates. These empirical relations are added to make the NTU estimations valid for dynamic operating conditions. The second method uses known statistical methods to model the heat exchanger and detects fouling through discrepancies between prediction and actual measurements.

## FOULING DETECTION METHODS

The two methods presented here are fundamentally different. The first method is based on NTU relations, related to classical heat transfer, and fouling is detected by monitoring for a drift in the overall heat transfer coefficient. The second method is based on a black box model for the heat exchanger at hand where fouling is detected through change in prediction errors.

To detect the fouling, an one sided Cumulative Sum (CuSum) chart is used, see (NIST/SEMATECH, 2009). The CuSum chart was chosen since it is known to be effective to detect drift in mean values. When using CuSum charts, the moving average value, $\bar{x}$, of the process is calculated over a window of specific length and compared with a priori known average value of the process, $\mu_0$. For the drift detection it is necessary to define two CuSum parameters, a decision limit, *H*, to prevent false detection and a reference value for deviations, *K*. Detection is made when the cumulative sum of deviations crosses the decision limit. The test is defined as follows

a) Compute the cumulative sum:
$\mathrm{Cus}(i) = \max[0, \mu_0 - \bar{x}_i - K + \mathrm{Cus}(i-1)]$

b) If $\mathrm{Cus}(i) > H$ then a drift is detected.

For fouling detection it is convenient to monitor the overall heat transfer coefficient if possible. For a heat exchanger operating in a steady state condition it is fairly easy to detect fouling through a drift in *U*. However if the heat exchanger is operating under dynamic load it can be tricky to detect the drift in *U*, which can clearly be seen in Fig. 1 were *U* is estimated with NTU relations for heat exchanger operating under different dynamic load. Each plot is divided in two parts, a clean part and a fouled part. In the figure the mass flow interval is increased by 12% and the temperature intervals are increased by 3°C in each sequential figure. In all cases the first 25% is without fouling and then identical fouling evolution is used. Clearly, it is more difficult to observe the fouling in the right bottom figure than in the left top one.

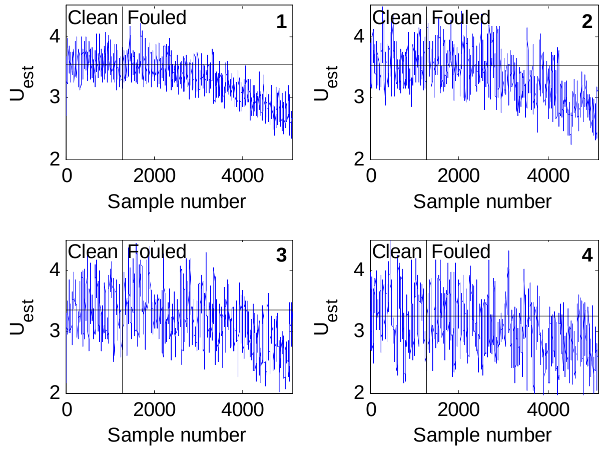


Fig. 1. Estimation of *U* from NTU relations on data with different excitement in the inlets.

### Physical method

In this method the fouling detection is performed by estimating the overall heat transfer coefficient, *U*, using NTU relations, as was done in making Fig. 1. Fouling detection is done by monitoring *U* for drift that can be related to diminishing efficiency because of accumulation of fouling. The NTU relations are commonly known and a description of them can be seen in (Holman, 2002).

The effectiveness of a heat exchanger can be calculated by

$$\varepsilon_1 = \frac{\Delta T_{\text{minimum fluid}}}{\Delta T_{\max}} \tag{1}$$

where the minimum fluid is the fluid that has the minimum value of the product of mass flow and specific heat. Effectiveness for an unmixed cross-flow heat exchanger can be obtained from the relation (Holman, 2002)

$$\varepsilon_2 = 1 - \exp\left( \frac{\exp\left( -\mathrm{NTU}^{0,78} \frac{C_{\min}}{C_{\max}} \right) - 1}{\frac{C_{\min}}{C_{\max}} \mathrm{NTU}^{-0,22}} \right) \tag{2}$$

In normal use, the overall heat transfer is usually unknown and it is therefore not possible to calculate NTU directly, but it can be found by solving Eq. (1) and (2) together.

The parameter NTU is defined by

$$\mathrm{NTU} = \frac{UA_{\text{heat transfer}}}{C_{\min}} \tag{3}$$

From Eq. (3) it is easy to derive the formula for *U*

$$U = \frac{\text{NTU } C_{\min}}{A_{\text{heat transfer}}} \quad (4)$$

At this point it is possible to estimate the value of $U$ as is done in Fig. 1, but it is apparent that the fouling detection would be quite hard if the heat exchanger is operating under dynamic conditions.

***Empirical relations.*** Since it is well known that heat transfer is largely dependent on the mass flow rates, it is convenient to use empirical relations between $U$ and the mass flow to filter variations because of mass flow changes from the estimation, see (Jonsson and Palsson, 1991). By using the empirical relations, changes in $U$ because of fouling can easily be seen.

The heat transfer coefficient can be written as

$$h = \underbrace{K}_{i}\underbrace{\mu^{(x-y)}k^{(1-x)}}_{ii}\underbrace{\dot{m}^{y}}_{iii} \quad (5)$$

Where $i$ is constant, $ii$ is temperature dependent and $iii$ is mass flow dependent. In this study only mass flow dependency was considered, since it has been shown previously by (Jonsson and Palsson, 1991) that the temperature dependency is much weaker and will therefore be neglected here. The relation in Eq. (5) can therefore be simplified as

$$h = C'\dot{m}^{y} \quad (6)$$

By assuming that Eq. (6) applies to both the hot and the cold side and neglecting the thermal resistance in the separating metal, the overall heat transfer coefficient, $U$, can be written as, see (Jonsson and Palsson, 1991),

$$U_{\text{mass dep.}}(t) = \frac{h_h(t)h_c(t)}{h_h(t)+h_c(t)} = \frac{C'\left(\dot{m}_h(t)\dot{m}_c(t)\right)^y}{\dot{m}_h^y(t)+\dot{m}_c^y(t)} \quad (7)$$

where $y$ is the exponent of the Reynolds number. In (Holman, 2002) it is recommended to use $y$ = 0.8 for turbulent flow, which is normally expected in a heat exchanger.

It can be practical to normalize $U$ with a reference mass flow to have indication of the actual values of $U$. The overall heat transfer coefficient according to the reference mass flow $\dot{m}_{h*}$ and $\dot{m}_{c*}$ then becomes

$$U_* = \frac{h_{h*}h_{c*}}{h_{h*}+h_{c*}} = \frac{C'\left(\dot{m}_{h*}\dot{m}_{c*}\right)^y}{\dot{m}_{h*}^y+\dot{m}_{c*}^y} \quad (8)$$

Equation (4) can now be multiplied by Eq. (7) to filter effects of the mass flow from the estimation, and further divided by Eq. (8) to normalize the estimations. The estimated overall heat transfer coefficient now becomes

$$U(t) = \frac{\text{NTU}(t)C_{\min}(t)}{A_{\text{heat transfer}}} * \frac{U_{\text{mass dep.}}(t)}{U_*} \quad (9)$$

The overall heat transfer coefficient in Eq. (9) is the variable that is used to detect the fouling in the heat exchanger.

**A black box model**

The second method proposed is to estimate a multi input single output nonlinear auto regression exogenous model (nlarx) of the heat exchanger, see (Tong, 1990) for description of nonlinear time series models. A black box model can be a good substitute to a physical method under right circumstances. When using a black box model it is necessary to have access to data that covers the whole operating range of the heat exchanger since extrapolating out of designed limits of the model can result in serious errors because of a erroneous model estimation.

The model was estimated on data that represents a clean heat exchanger. The model includes a linear block and nonlinear blocks, see Fig. 2. The model function can be described with

$$\begin{aligned}\hat{T}_{out}(t) &= F(u_n(t)) + L^T u_l(t) + d \\ &= \sum_{i=1}^{n} \alpha_i \kappa(\beta_i(u_n(t)-\gamma_i)) + L^T u_l(t) + d\end{aligned} \quad (10)$$

were $F$ is the nonlinear regression function, $u_n(t)$ are the nonlinear regressors, $n$ defines the number of sigmoids in the network, $\alpha_i$, and $\gamma_i$ are parameters of the estimator and $\beta_i$ is a row vector such that $\beta_i(u_n(t)-\gamma_i)$ is a scalar, $\kappa$ is the sigmoid function that is used to introduce nonlinearity in the model and is given by the following equation, where $z$ controls the behavior of the sigmoid curve.

$$\kappa(z) = \frac{1}{1+e^{-z}} \quad (11)$$

Furthermore, $u_l(t)$ are the linear regressors and $L$ is a parameter vector for the linear regressors and $d$ is a scalar offset. The regressors are measurements of the input temperatures and the mass flows.

In comparison on how well different model structures fitted the data, Eq. (12) showed that having 4 past values of the inlets, 2 past values of the outlets and a sigmoid network with 5 units as a nonlinearity block gave a reasonably good fit. Using more past values or more units in the sigmoid network did not add significantly to the prediction capabilities of the model. The model parameters were estimated with the focus on prediction using the System Identification toolbox in Matlab (MathWorks, 2010).

$$FIT = \left[1 - norm(T - \hat{T}) / norm(T - \overline{T})\right] \quad (12)$$

By comparing residuals between the model predictions and the actual outputs it is possible to detect effects of fouling through drift in the residuals.

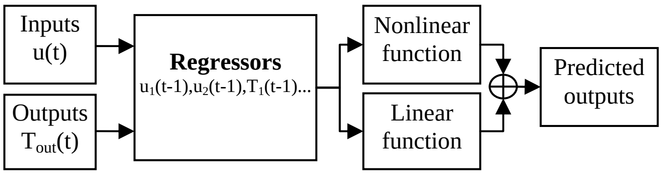


Fig. 2. Block diagram of nonlinear auto regressive model.

## SIMULATOR

The data used in this study was generated by using a simulator representing an unmixed cross-flow heat exchanger. Graphical layout of the model can be seen in Fig. 3.

The simulation model is based on a mathematical representation of two fluids flowing perpendicular to each other, separated with a fixed wall, as shown in Fig. 3. Various parameters in the model can be adjusted in order to represent different sizes of cross-flow heat exchangers. The state of the heat exchanger at a given point in time is represented by three field variables $T_c(x;y)$, $T_h(x;y)$ and $T_s(x;y)$, representing temperatures of cold fluid, hot fluid and the wall (the subscript $s$ denotes the separating material), where variables $x$ and $y$ indicate the location in the heat exchanger. Three coupled partial differential equations describe the temperature fields and how they are related to changes in time. A detailed description of the simulator can be found in (Gudmundsson et. al., 2009b) and (Mercère et. al. 2011).

Although the simulator has not been validated for a cross-flow heat exchanger it has been validated for a counter-flow heat exchanger, which is only different because of another direction of the flow, see (Andrjesdottir et al., 2011). The validation was based on measurements from a heat exchanger test rig.

## RESULTS

In the comparison of methods, the same data was applied for both and a CuSum chart was used to detect the fouling. To make the data more realistic, random measurement errors were added to the inlet and outlet temperatures as well as to the mass flows. Uniform random measurement errors on the interval [-0.2, 0.2]°C were added to the temperatures and [-2, 2]% of the average mass flow to the mass flows.

### Data

In this study the dimensions of the heat exchanger were $W = H = 0.5$ meters and $d_h = d_c = 2*10^{-4}$ meters. The advantage of using simulated data is that it is possible to control when and how much fouling will occur in addition to controlling the inlet temperatures and the mass flows.

The simulated data sets used in this study include 200 sets without fouling and 200 sets with fouling. The data sets are further divided equally between slow and fast fouling cases which are equal to long and short time series respectively. In the fouled cases the data set was without fouling for the first 25% and then the fouling factor was allowed to progress to a maximum of $R_f = 3.3*10^{-4}$ [m$^2$K/kW], which corresponds to a 25% decrease in the overall heat transfer coefficient. The temperatures for the hot side were in the interval [55, 70]°C and the cold side [10, 25]°C, the mass flow rates for the hot and cold side were in the interval [0.3, 1.5] kg/s.

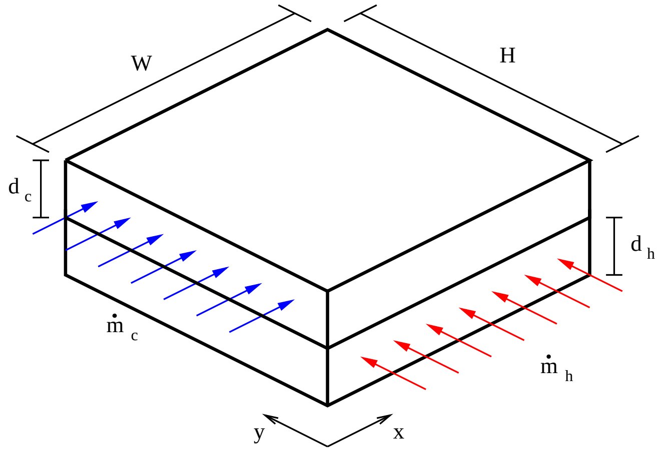


Fig. 3. Graphical layout of the simulated heat exchanger.

***Fouling characteristics.*** As mentioned above, heat exchangers are commonly designed to operate under mild fouling which is usually enforced by increasing the heat exchange area such that it can operate within the design specification up to a chosen fouling factor. Commonly the fouling factor is in the interval $1*10^{-4}$ to $7*10^{-4}$ [m$^2$K/kW]. According to (Bansal and Chen, 2005; Fahimina et al., 2005) there is usually an induction time before a noticeable amount of fouling has accumulated. In (Bohnet, 2005) it is shown that the fouling will grow with increased rate during the fouling period. Fig. 4 shows the evolution of the fouling factor used in this study from the time the heat exchanger starts to accumulate fouling until the simulation is stopped. A dimensionless time is used to make the comparison between different lengths of data series easy.

In this study the type or location of the fouling is not of a particular concern since the objective is to detect its existence before it starts to have harmful effects on the heat exchange process. This is well justified since it is known that the effect of fouling is the added resistance to heat transfer.

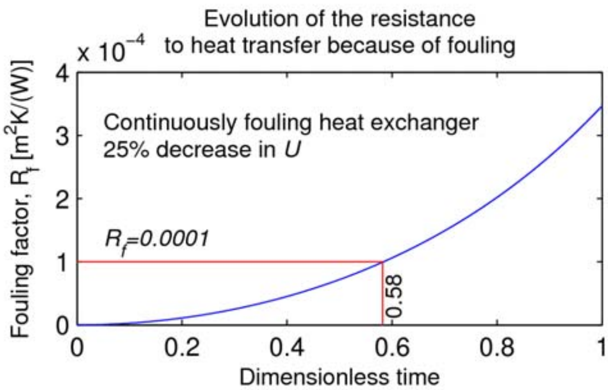


Fig. 4. Evolution of the fouling factor from the time the fouling is initiated.

It should be mentioned that a good fouling detection method should detect the fouling before the fouling factor reaches $1*10^{-4}$ [$m^2K/kW$] (which corresponds to a dimensionless time of 0.58 in Fig. 4) and preferably without a false detection.

**Results for the physical method**

In Fig. 5 the empirical relations have been applied to the estimation of $U$, the red color represent estimations using empirical relations while the blue color represents estimations without the use of empirical relations, as is done in Fig. 1. The drift in $U$ can now be clearly seen in all the figures. Each plot is, as before, divided in two parts, a clean part and a fouling part.

Comparisons of the drift detection that is shown in Fig. 6, where $U$ is estimated without empirical relations, and Fig. 7, where empirical relations are applied, show that it is possible to detect fouling in heat exchangers operating in dynamic condition with quite good accuracy by using NTU and empirical relations. In Fig. 7 and 8 the green line represents the decision limits of the CuSum chart. In Fig 8 the limits are very low compared to the CuSum values and can therefore hardly be seen.

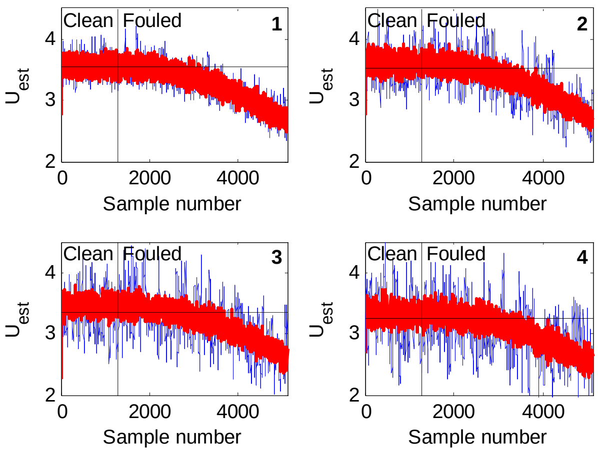


Fig. 5. Estimation of $U$ from NTU relations, with (red color) and without (blue color) empirical relations, on data with different excitement.

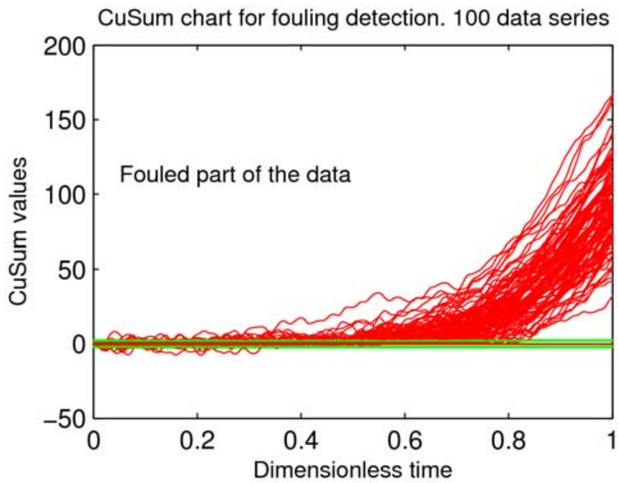


Fig. 6. Drift detection in $U$ estimated by NTU relations.

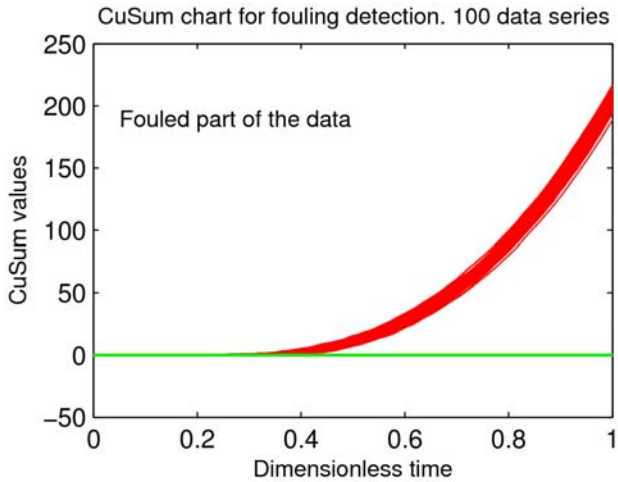


Fig. 7. Drift detection in $U$ estimated by NTU relations and filtered with empirical relations.

**Results for the black box model**

As with all black box models, there is always a possibility that the parameters of the model are over fitted, that is, the model will learn on the training dataset and consequently reduces its predictive abilities on a new and unknown dataset. This risk can be limited, for example by estimating the parameters using multiple datasets. In this study the model parameters were estimated by using 5 separate datasets that were generated without fouling. The prediction error drift can clearly be seen in Fig. 8 when applied to fouled dataset.

As mentioned above, it is known that the mass flow has a strong nonlinear influence on $U$ while the influence is much weaker for the temperatures. It was therefore tested if i) all regressors should be included in the nonlinear block or ii) if it would be sufficient to only include the mass flow regressors. Estimations showed that by using all regressors in the nonlinear block the model predicted a 93.5% fit to the data while using only the mass flow regressors in the nonlinear block the model fit was 92%. Although there is not much different between the fits, it can have considerable impact on the fouling detection as is shown in Table 1.

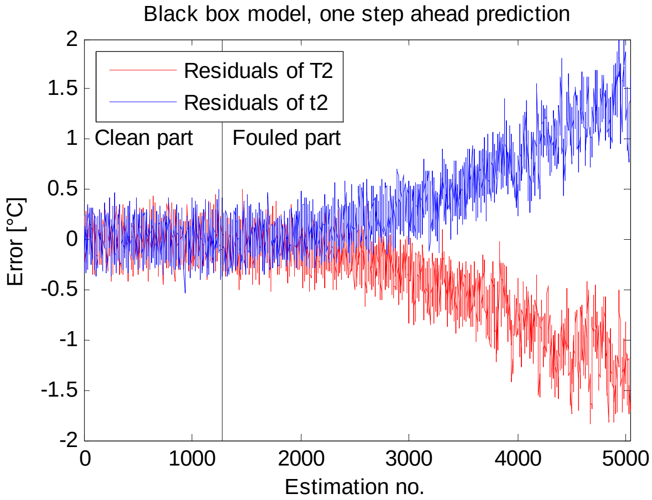


Fig. 8. Plot of the prediction errors for hot and cold output.

**Detection comparison**

In Table 1, a comparison is shown between the methods presented. For the black box model the two cases mentioned above are presented, i) uses all the regressors in the nonlinear block while ii) only uses the mass flow regressors. The CuSum chart is used to detect the fouling and a dimensionless detection time is used to compare the detection between the cases of fast fouling and a slow fouling.

From the table it can be seen that the physical method gives slightly worse results than the black box model when all regressors are used in the nonlinear block. This is an interesting result since the physical method is simpler and can be applied directly without the need to estimate any parameters.

Table 1. Comparison of dimensionless detection times between the two methods.

| | Physical method | Black box model | |
|---|---|---|---|
| | | i) | ii) |
| Percentiles | Fast fouling (short dataset) | | |
| 2.5% | 0.26 | 0.25 | 0.32 |
| 50% | 0.34 | 0.29 | 0.43 |
| 97.5% | 0.40 | 0.33 | 0.47 |
| Percentiles | Slow fouling (long dataset) | | |
| 2.5% | 0.23 | 0.20 | 0.29 |
| 50% | 0.30 | 0.25 | 0.44 |
| 97.5% | 0.35 | 0.30 | 0.48 |

As mentioned above, heat exchangers are commonly designed to operate with a fouling factor in the interval [1, 7] $*10^{-4}$ [$m^2K/kW$]. In the current data, a fouling factor of $1*10^{-4}$ [$m^2K/kW$] corresponds to the dimensionless time 0.58. The results therefore indicate that both methods can be used to detect fouling in cross-flow heat exchangers that are operating in a non-steady state condition, before a typical lower limit of fouling factor is reached. The methods seem to be stable in detecting the fouling, which can be seen from the narrow detection interval.

**DISCUSSION**

The results indicate that the methods proposed can be used to detect fouling in cross-flow heat exchangers operating under dynamic conditions by using measurements that can be obtained under normal operation. The physical method is based on the well known method of Number of Transfer Units, with addition of empirical relations to make the method valid over a wide range of mass flow rates.

By monitoring the calculated overall heat transfer coefficient, it is possible to detect changes that are due to fouling. The fouling detection is performed prior to the designed fouling factor interval. Since it is based on physics, it is possible not only to get an early fouling detection but also to estimate the effects of the fouling on the overall heat transfer coefficient. As can be seen in Fig. 5 the estimation of $U$ drops approximately 25%, which is the same percentage as $U$ in the simulated data is allowed to drop.

The black box model proposed here is used to find a nonlinear auto regressive exogenous model (nlarx) for the heat exchanger and to monitor the difference between model predictions and actual measurements. The results indicate that the black box model with all regressors included in the nonlinear block is slightly better in fouling detection than the physical method.

**CONCLUSIONS**

1. Both the physical method and the black box model can detect fouling before a typical lower design limit of fouling factor is reached, in dynamical conditions. The results indicate that there is a small difference between the black box model i) and the physical method. If the fact that the physical method gives indication of the value of the overall heat transfer coefficient is taken into account, it can be more appealing to implement the physical method even though there may be a slight delay in the fouling detection.
2. By including all regressors in the nonlinear block in the black box model, the fouling detection performs better than when only the mass flow regressors are included into the nonlinear block.
3. As for which method is preferable, it depends on how important it is to get an early detection. If a slightly later detection time is acceptable, the physical method may be a better choice because of the information it gives on the overall heat transfer coefficient. However it may also be preferable to take advantage of both methods simultaneously.
4. Further work will include validating the simulator using data from a real cross-flow heat exchanger that is being built at the University of Iceland.

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## NOMENCLATURE

$A$ surface area, $m^2$
$C'$ constant, dimensionless
$C$ heat capacity rate, kW/s °C
$d$ offset parameter, °C
$F$ Nonlinear regression function
$h$ convection heat transfer coefficient, $kW/m^2$ °C
$K$ constant, dimensionless
$k$ thermal conductivity, kW/m °C
$L$ regressors parameter vector, dimensionless
$\dot{m}$ mass flow rate, kg/s
NTU number of transfer units, dimensionless
$n$ constant, dimensionless
$R_f$ fouling factor, $m^2$ K/kW
$T$ temperature, °C
$t$ time, s
$U$ overall heat transfer coefficient, $kW/m^2$ °C
$u$ regressors vector
$x$ exponent of the Prandt number, dimensionless
$y$ exponent of the Reynolds number, dimensionless
z exponent in the sigmoid function, dimensionless
$\alpha$ regressors parameter, dimensionless
$\beta$ regressors parameter, dimensionless
$\Delta$ difference, dimensionless
$\varepsilon$ effectiveness, dimensionless
$\gamma$ regressors parameter, dimensionless
$\kappa$ nonlinear function
$\mu$ dynamic viscosity, kg/m s

### Subscript

c cold side
h hot side
i index indicator
l linear
max maximum
min minimum
n nonlinear
s separating material
* reference

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