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# DETECTION OF FOULING IN A HEAT EXCHANGER BY APPLICATION OF A LOCK-IN TECHNIQUE

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## ABSTRACT

In this study a very sensitive discrimination technique is applied for detection of drift in thermal systems. The method is based on the theory of lock-in amplifier channels as used for example in signal de-noising applications. In the first part of the paper, the theory behind the technique is briefly introduced combined with an application to a lumped system, enabling the determination of the minimum duration of the test. The second part is dedicated to the adjustment process of a numerical model of a heat exchanger, in steady state as well as in transient states. Results show that the computed outlet temperatures obtained by the numerical model are very close to measured temperatures obtained during experiments on a test rig at hand. Once all parameters are determined, validation of the dynamic behavior of the numerical model is carried out through new experiments. By using experimental data and computed results, it is shown that the detection technique can be applied using small levels of perturbations and that the new detection technique is very sensitive compared to known methods. Finally it is shown that it is possible to discriminate a mass flow decrease from the effect of fouling. It can therefore be concluded that the method is very useful for on-line fouling detection in systems under operation. It has to be noted that the operating conditions (i.e. the outlet temperatures) are only very slightly modified by the excitations.

## INTRODUCTION

Fouling detection in heat exchangers is still challenging (Wallhäußer et al., 2011) (Kim et al., 2011) (Mohanty and Singru, 2011), in particular when considering transient states. It is the subject of an international project sponsored by the French National Center for Scientific Research (CNRS). Many techniques have been developed in the project: neural networks, fuzzy observers, recursive subspaces method, extended Kalman filters and wavelets. All have been presented in international journals or conferences (Lalot and Pálsson, 2010) (Delmotte et al., 2008) (Lalot and Mercère, 2008) (Jonsson et al., 2007) (Ingimundardóttir and Lalot, 2011). A well known technique used in signal analysis (e.g. (Booton, 1964) (Libbrecht et al., 2003)) has been tested for detection of drifts in lumped systems and an electrical heater (Lalot et al., 2011). As it has been found that the lock-in technique is very sensitive in steady states as well as in transient states when well tuned, it has been decided to test it on fouling detection in a counter flow heat exchanger.

After the presentation of the experimental setup, a brief summary of the lock-in technique is given in the first part of the paper. The second part of the paper is dedicated to the adjustment of all parameters of the numerical. The third part shows that the model is accurate in transient state. Finally it is shown that the lock-in technique is much more sensitive than the study of the evolution of the effectiveness, and that it is possible to discriminate the fouling effect from the effect of a decrease in the flow rate of one fluid.

## EXPERIMENTAL SETUP

Experiments were performed (Fig. 1) on a heat exchanger from GEA of the type: VT04 CD-16. The heat exchanger (referred as $\boxed{1}$ in Fig. 1) is a plate and frame, counter flow heat exchanger and consist of 8 plates. Hence, there are 3 channels for the hot fluid and 4 channels for the cold fluid. To increase the heat transfer between the fluids the plates are corrugated, which contributes to making the flow turbulent. Oil is used as the hot fluid (heated by an electrical heater referred as $\boxed{2}$ in Fig. 1) and water as the cold fluid. Oil is further cooled by an air to oil finned tube heat exchanger referred as $\boxed{3}$ in Fig. 1. Flow rates are measured using Coriolis mass flowmeters, and temperatures are measured using Pt100 probes.

In addition, a numerical model was developed to simulate a counter flow heat exchanger in a realistic manner. The geometry of the numerical model is quite simple. It consists of two channels where the fluids flow, separated by a thin wall. The channels are of equal widths and equal lengths, but they can have different heights. These geometrical parameters (wall thickness and channel heights) were estimated during an adjustment process of the numerical model. It is worth mentioning here that among the advantages of the numerical model is that fouling effects can be enforced in a controlled manner.

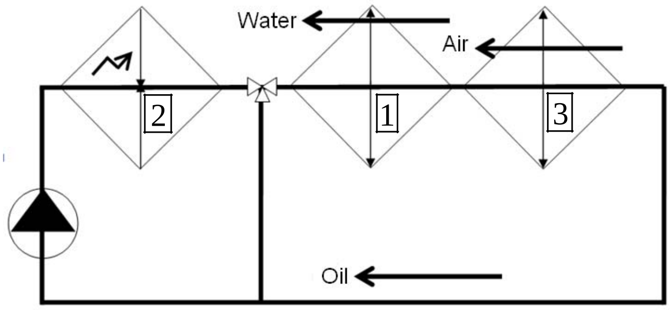

Fig. 1 The test rig

## LOCK-IN AMPLIFIER CHANNELS

Generally, a lock-in amplifier channel is composed of a multiplier and a low-pass filter. Using a two channel lock-in amplifier with a 90° phase shift, it is possible to retrieve the amplitude and the phase of the studied signal relative to a reference signal. Note that noise in the input signal does not influence the output of the low-pass filter. The application of the lock-in technique to a lumped system and an electrical heater was the subject of a previous study (Lalot et al., 2011a). The method is described in detail there but for convenience, the main concept is explained here.

When applying the technique to a thermal system, such as a heat exchanger, a reference signal is added to one of the normal inputs (e.g. the flow rate of one fluid oscillating around its mean value). The excitation must be periodic, either using square waves or sinusoidal waves. In the first case, the fundamental angular frequency is used in the final step of the computations. The amplitude of the oscillations is fixed so that the outlet temperature of either of the fluids is acceptable (i.e. does not disturb the process which the fluids are used in). The studied signal (e.g. the outlet temperature of the cold fluid) is then multiplied on one hand by a signal synchronized with the reference signal and on the other hand by a signal with a 90° phase shift. In order to get accurate values and to get rid of the measurement noise, it is necessary to carry out these multiplications over a long enough time window. Both signals are low pass filtered and termed $X$ and $Y$ respectively, which can be thought of as the real and imaginary parts of a complex number. It is then possible to compute the modulus $M$ and the argument of this complex number. Finally, the evolution of this modulus with respect to time (i.e. using sliding observation windows) is studied to detect any modification of the system under supervision. In this study this is accomplished by computing the absolute difference between the modulus obtained for a clean system and the modulus for a fouled one.

The application of the lock-in technique to a lumped system in the previous study showed that stable value for the module is obtained as long as the convection coefficient for the system is stable. As soon as there is a modification of the convection heat transfer coefficient, which is the case when fouling occurs, detectable variations occur. In the previous work it was shown that a very small drift can easily be detected for as low as a 25 hour test, corresponding to 6000 times the time response of the system. Furthermore it was shown that the technique is powerful in a transient state as well as in a steady state. This is illustrated in Fig. 2 where $\alpha$ corresponds to the degree of relative change of the convection coefficient: $\alpha = 1$ represents no fouling and $\alpha = 0.95$ corresponds to a decrease of 5% of the convection heat transfer coefficient. It can be seen that for a decrease of 1% of the convection coefficient ($\alpha = 0.99$), the difference is easily detected using a very simple test. If the differential is higher than a certain threshold, then fouling has occurred.

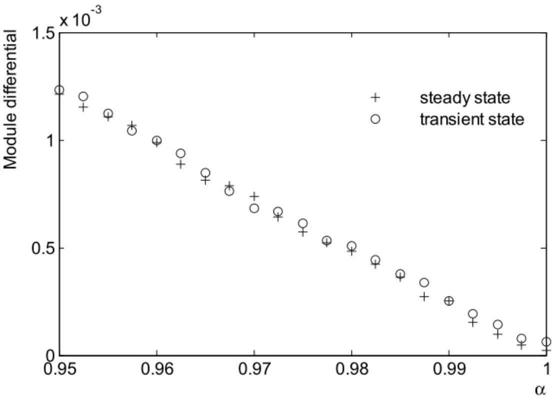

Fig. 2 Evolution of the modulus differential versus the degree of relative change of the convection coefficient for a lumped system

## ADJUSTMENT OF THE NUMERICAL MODEL

It is not yet possible to control the fouling rate in the test rig. So, a numerical model of a heat exchanger was developed. The model was adjusted to ensure that the results were comparable to the experimental values from the test rig at hand for a clean heat exchanger. The most common method used to design heat exchangers and/or assess their performance is the NTU-Effectiveness method (Lalot, 2011). The NTU or Number of Transfer Units is defined as:

$\mathrm{NTU}_h = \frac{UA}{\dot{m}_h c_h}$ for the hot fluid and $\mathrm{NTU}_c = \frac{UA}{\dot{m}_c c_c}$ for the cold fluid; where $U$ is the overall heat transfer coefficient that will vary with fouling and A is the total area of the heat exchanger.

The Number of Transfer Units represents the ratio of the heat that could be exchanged by convection/conduction between the fluids if they were at their inlet temperature all along the heat exchanger and what could be exchanged if the heat exchanger was perfect; for which the outlet temperature of the hot fluid is equal to the inlet temperature of the cold fluid and the outlet temperature of the cold fluid is equal to the inlet temperature of the hot fluid. The effectiveness E is defined as the ratio of the actually exchanged heat and what would have been exchanged by a perfect heat exchanger:

$$E_h = \frac{T_{h,in} - T_{h,out}}{T_{h,in} - T_{c,in}}, \quad E_c = \frac{T_{c,out} - T_{c,in}}{T_{h,in} - T_{c,in}}.$$

Another important parameter is the heat capacity rate ratio:

$$R_h = \frac{\dot{m}_h c_h}{\dot{m}_c c_c},\quad R_c = \frac{\dot{m}_c c_c}{\dot{m}_h c_h}.$$

From these definitions and from the energy balance in the heat exchanger it is possible to write: $E_c = E_h R_h$, showing that it is possible to determine one of the effectiveness values when the other one is known. Every type of heat exchanger is represented by an equation linking the effectiveness to the Number of Transfer Units. For a counter flow heat exchanger, this equation is:

$$NTU_h = \frac{\ln\left(\dfrac{1-E_h}{1-E_h R_h}\right)}{R_h - 1} \text{ if } R_h \neq 1 \text{ and } NTU_h = \frac{E_h}{1-E_h} \text{ if } R_h = 1.$$

The thermo-physical characteristics of water are well known. On the contrary, those of oil must be determined for the temperature range encountered during the experiment. Experiments on the test rig showed that if the mass flow rate on the hot side is kept constant while the mass flow rate on the cold side is varied, the steady state temperatures can be assumed to be constant. By knowing the temperatures in a steady state, the effectiveness for the cold fluid can be calculated. From the equations introduced above the Number of Transfer Units for the cold side can then be calculated, assuming that a first guess value of the specific heat of oil, $c_h$, is available. Furthermore, knowing the specific heat of water it is possible to compute the product $UA$. It is then possible to compute the Number of Transfer Units for oil as well as the effectiveness for oil, and to compare the result with the actual value obtained from experiments. The process is repeated until convergence is obtained for the specific heat $c_h$. Subsequently it is checked that the value obtained can be considered valid for other temperature levels.

The thickness of the channels in the test rig heat exchanger is small so that the flow regime is turbulent. Hence it is assumed that the convection heat transfer coefficient varies with the power 0.8 of the Reynolds number (which is directly proportional to the mass flow rate). Since one flow rate is kept constant, it is possible to write the overall heat transfer as:

$$U = \frac{1}{\dfrac{1}{h_{c,ref}}\left(\dfrac{\dot{m}_{c,ref}}{\dot{m}_c}\right)^{0.8} + \dfrac{1}{h_h}}$$

Through a number of measurements it is possible to determine the convection heat transfer coefficient for oil (the hot side) and the reference convection heat transfer coefficient for water (the cold fluid). Note that the actual convection surface area is determined by the geometry of the heat exchanger and the number of plates between the fluids. Also it is important here to note that the values obtained by this procedure are well within the usual range for the fluids considered.

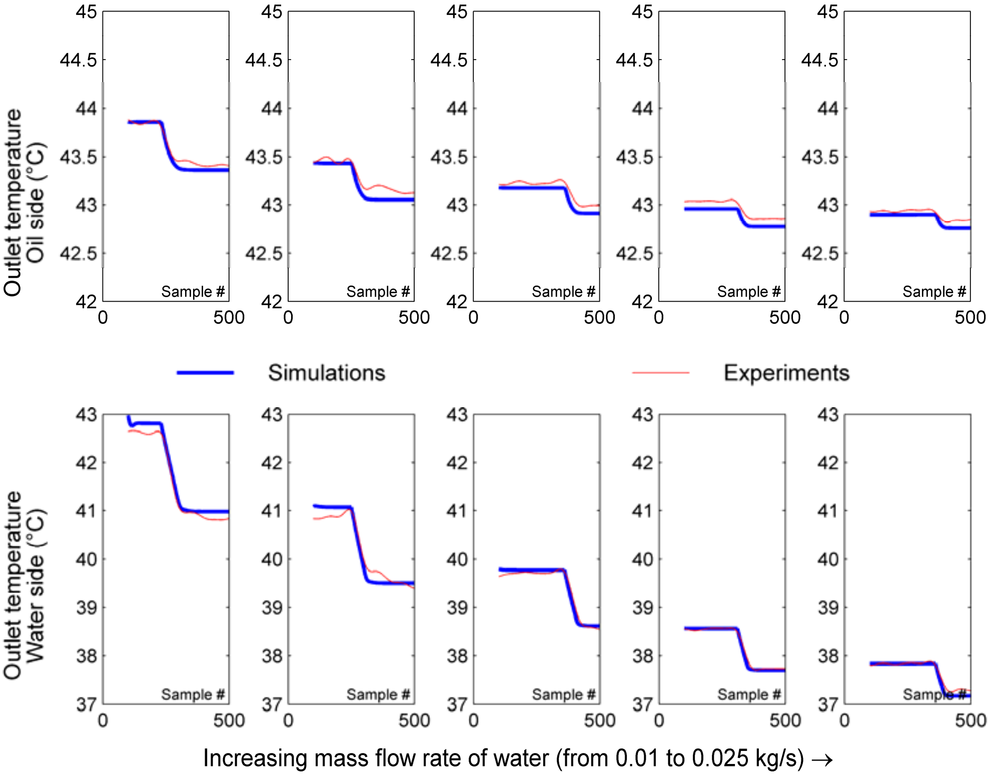

Fig. 3 Comparison of experimental values and simulated values in transient state

The last values to be determined are the thicknesses of the channels and the thickness of the separating wall in the numerical model, considering that the real width is fixed by the number of plates in the heat exchanger. These values were determined during transient state. A set of five experiments with varying mass flow rate of the cold fluid were carried out on the test rig and simulated in the numerical model. The thickness values for the channels are determined in a way that the correlation used in the program leads to the correct convection coefficient. The value of the wall thickness is then adjusted by trial and error method, so that the simulated outlet temperature during transient state is as close as possible to the actual temperature; the thicker the plate, the longer the time response. Figure 3 shows the evolution of the outlet temperature for the five steps of mass flow rate of the cold fluid. The results obtained using the numerical model are very close to the experimental values.

## VALIDATION

In order to validate the dynamic behavior of the numerical model number of experiments were performed. The application of the lock-in technique requires the flow rate of the cold fluid to oscillate around a mean value. So, a final validation was carried out. The outlet temperature of the cold fluid and of the hot fluid were recorded and simulated. This is used here as an example to validate the accuracy of the model and how well it represents a real heat exchanger. Figure 4 shows the outlet temperature of water for such an experiment. It can be seen that the simulated values are very close to the experimental values.

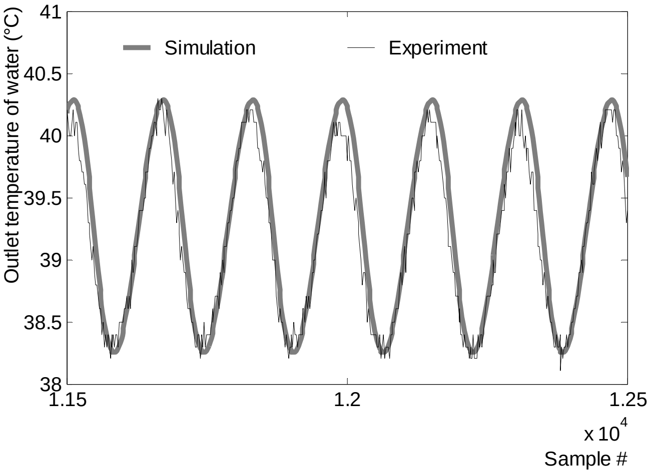

Fig. 4 Comparison of recorded values and simulated values for an oscillating water flow rate (water side)

Figure 5 shows the outlet temperature of oil for the same experiment. It can be seen that the simulated values are also very close to the experimental values and based on these two figures it can be concluded that the numerical model is reliable.

For all experiments the sampling period was 2 seconds. So, it can be seen in Figure 4, that even after more than 6 and 1/2 hour (11 700 samples), the simulated values are still very close to experimental values.

The whole process is described in full detail in (Lalot et al, 2011b).

It can also be noted that the measurement noise is about 0.1°C for both the cold side and the hot side and that the amplitude of the oscillations is much higher on the water side than on the oil side. The latter point is due to the fact that the water flow rate is varying and that the plates are similar to a thermal filter.

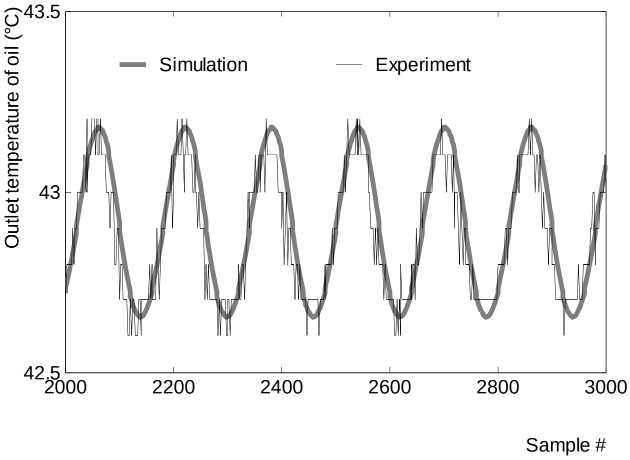

Fig. 5 Comparison of recorded values and simulated values for an oscillating water flow rate (oil side)

It must also be noted that the outlet temperatures should be relatively stable to ensure that they do not influence the process. So, it is important to know if the technique is efficient even for low values of the oscillations. Hence, from the experiments, the modulus of the complex number was computed, as explained before, for various amplitudes. Taking the reference values when the amplitude of the outlet temperature of water is about 2°C, as seen in Figure 4, the modulus ratios are plotted in Figure 6.

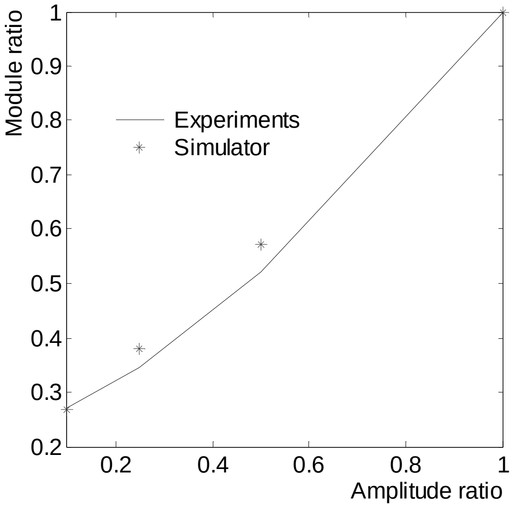

Fig. 6 Comparison of the modulus ratio computed using recorded values and simulated values for an oscillating water flow rate

This again shows that the simulations are reliable and that very small oscillations (close to 0.2°C) are sufficient to detect a variation of the modulus of the complex number. Provided that the length of the sliding observation window is large enough, the results are independent of the measurement noise (close here to 0.1°C); which is the most important characteristic of the method.

## RESULTS AND DISCUSSION

In order to assess the efficiency of the new technique, it has been decided to compare the results obtained by this technique to the results obtained by a very standard method: the analysis of the evolution of the effectiveness. As mentioned, it is not possible to control the fouling rate in the test rig. On the other hand, it is easy to get an evolution of the effectiveness which is comparable to what would be obtained when fouling occurs by varying one flow rate. To enable a comparison with another method, the choice here has been to vary the oil flow rate. It is important to note that in this case, the effectiveness of the water side is much more sensitive to the flow rate variation than the effectiveness on the oil side.

During the first half part of the experiment, the oil flow rate is stable and then it is progressively decreased. The water flow rate is kept constant during the whole experiment. The apparent decrease of the effectiveness is analyzed using the Cusum test, as it is known to be one of the most sensitive tests for drift detection (NIST website, 2011). Figure 7 shows that the detection time corresponds to a decrease of about 6.3% of the overall heat transfer coefficient and of the convection coefficient for the oil side.

As previously mentioned fouling effects can be included in the numerical model in a controlled manner. The numerical model was thus used to simulate fouling to test the applicability of the lock-in technique to detect drifts. The method can in principle be applied to both sides, i.e. the hot side or to the cold side. The results for the application of the method to the cold side will be shown here. The mass flow rate on the cold side was excited by a sinusoidal wave while the flow rate of the oil was kept constant. The outlet temperatures for a clean heat exchanger and a progressively fouled heat exchanger were then computed for various amplitudes of the sinusoidal function. The noise level added to the outlet temperatures to account for uncertainty in real systems was set to 0.1°C, according to what has been previously measured. The length of the sliding observation window was set to 30 exciting periods. The evolution of the differential of the module, for a clean and fouled heat exchanger, was then computed for the different amplitude levels.

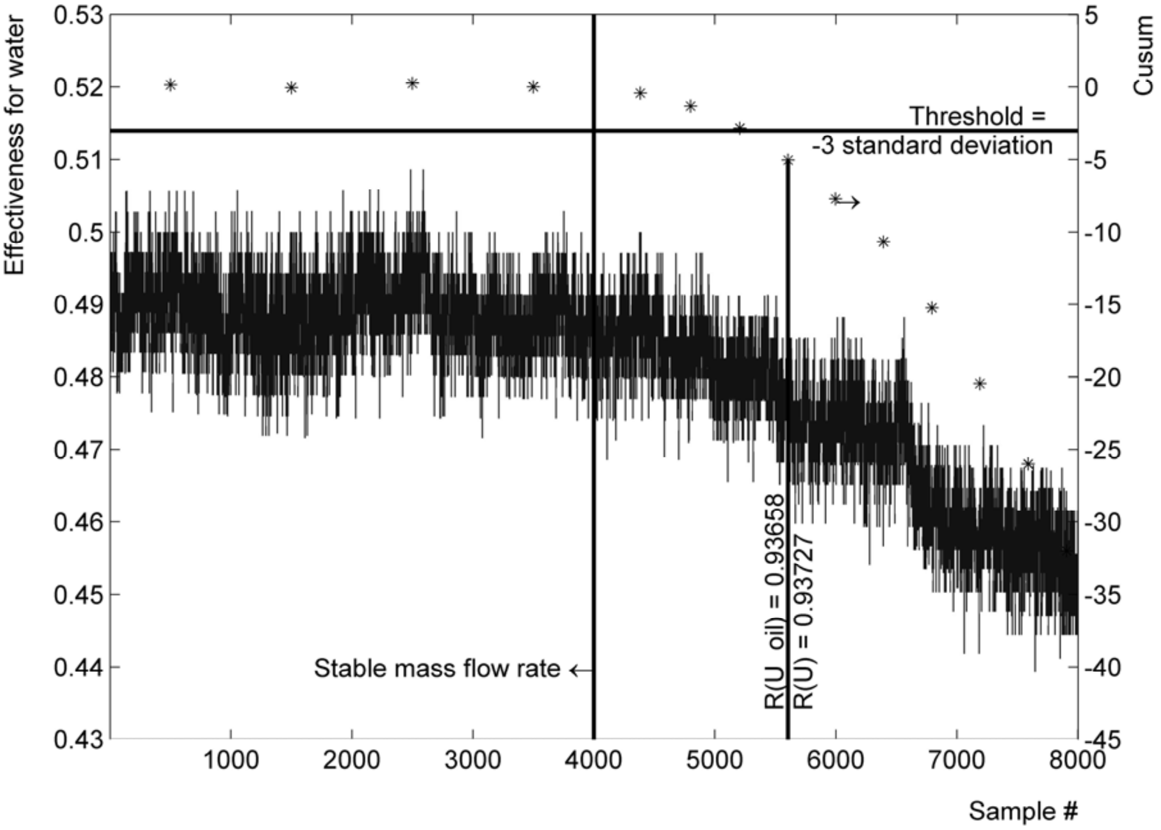

Fig. 7 Detection of a drift by analysing the evolution of the effectiveness

Figures 8 and 9 show such an evolution for two different amplitudes.

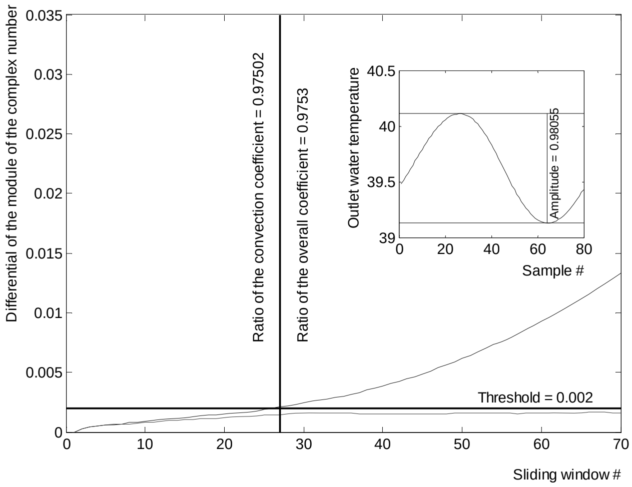

Fig. 8 Detection of fouling for a 1°C amplitude of the oscillations of the outlet water temperature

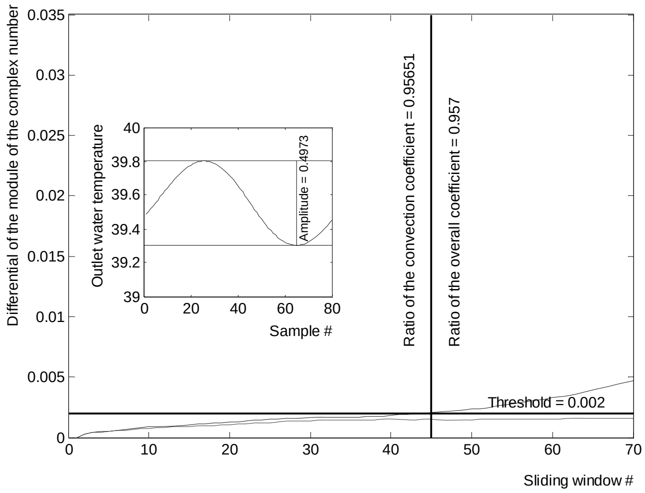

Fig. 9 Detection of fouling for a 0.5°C amplitude of the oscillations of the outlet water temperature

From the figures it is observed that a drift can easily be detected by a comparison to a threshold as low as 0.002 in both cases. Drift is detected sooner for higher amplitude levels but the response is still quite quick for the more desirable lower amplitude levels. In both figures, the curve that stays below the threshold is the evolution of the modulus differential as if the heat exchanger was kept clean. Note that if the amplitude is decreased to 0.2°C (not shown in the figures), fouling is detected when the overall heat transfer coefficient has decreased by 5.7%, which is still lower than what is obtained by the effectiveness analysis.

To summarize, it can be seen that fouling is detected when the overall heat transfer coefficient has decreased by about 4.3% as Figure 9 shows confirming that the present technique is more sensitive than the effectiveness analysis. It can be noted that this level is similar to what is obtained (4.4%) when studying the difference between actual values and values estimated by a neural network model of the heat exchanger (Gudmundsson and Lalot, 2011).

In a previous study (Lalot and Lecoeuche, 2003) dealing with electrical heaters, it has been shown that neural network models are able to discriminate the effect of fouling from the effect of the variation of the viscosity of the fluid. So, it is important to check that the lock-in technique is also able to discriminate two effects. To do so, the effect of the decrease of the flow rate has been studied and compared to the effect of fouling.

Figure 10 shows the results for both sides (water side and oil side). It can be seen that it is necessary to plot the current state point in the complex plane to be able to clearly discriminate the two effects, although this has been done in transient state (the water flow rate is oscillating). This is equivalent to what has been found when studying an electrical heater by the lock-in technique (Lalot et al., 2011a).

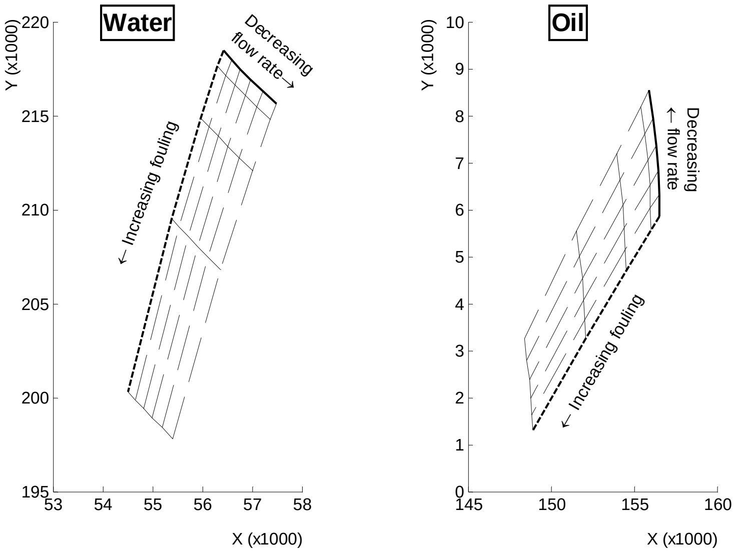

Fig. 10 Comparison of the effect of fouling and the effect of a flow rate decrease

## CONCLUSIONS

A very sensitive discrimination technique has been introduced for detection of drift in thermal systems. The method is based on the theory of lock-in amplifier channels. A numerical model of a heat exchanger was developed and validated trough experiments. Main findings are summarized in two parts:

1. Experimental data and computed results show that the new detection technique can be applied using small levels of perturbations and that the technique is very sensitive compared to other known techniques.
2. Results also show that the method is able to discriminate mass flow decrease from the effect of fouling. It can therefore be concluded that the method is very useful for on-line fouling detection in systems under operation, without significantly changing the operation conditions.

As further work, the technique will soon be implemented on a new test rig where actual fouling will occur. Its efficiency will be assessed and it will be verified that it is still efficient when the heat exchanger is not in a steady state.

## ACKNOLDEGEMENTS

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## NOMENCLATURE

| | |
|---|---|
| A | convection surface area, $m^2$ |
| E | effectiveness, dimensionless |
| c | specific heat capacity, J/kg.K |
| h | convection heat transfer coefficient, W/m².K |
| M | modulus of a complex number, K |
| $\dot{m}$ | mass flow rate, kg/s |
| NTU | Number of Transfer Units, dimensionless |
| R | heat capacity rate ratio, dimensionless |
| U | overall heat transfer coefficient, W/m².K |
| X | real part of a complex number, K |
| Y | imaginary part of a complex number, K |

### Subscript

| | |
|---|---|
| c | for the cold fluid |
| h | for the hot fluid |
| in | at the inlet |
| out | at the outlet |
| ref | taken as a reference |

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