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Use of extended Kalman filtering in detecting fouling in heat exchangers

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Abstract

This paper is concerned with how non-linear physical state space models can be applied to on-line detection of fouling in heat exchangers. The model parameters are estimated by using an extended Kalman filter and measurements of inlet and outlet temperatures and mass flow rates. In contrast to most conventional methods, fouling can be detected when the heat exchanger operates in transient states. Measurements from a clean counterflow heat exchanger are first used to optimize the Kalman filter. Then fouling is considered. The results show that the proposed method is very sensitive, hence well suited for fouling detection.

Keywords: Heat exchangers; Fouling; Extended Kalman filter; Parameter estimation; On-line detection

1. Introduction

The heat transfer between two fluids will inevitably result in fouling. For a district heating system, where the heat transfer is great, it is important to minimise fouling in the heat exchangers. The expense for achieving a desired heat transfer is increased with the decrease of the heat transfer coefficient. For example, at the Vestegnens Kraftvarmeselskab in Denmark (VEKS), it is said, that for every 5° temperature increase for which the hot water flowing into the heat exchangers must be heated because of fouling, is an added 800–940 k€/year cost for the consumers, see Jakobsen and Stampe [1]. The installed power at VEKS is 770 MW which is similar to that of the District Heating Company of Reykjavik, Iceland. From the environmental point of view, fouling is also harmful. For example, Casanueva-Robles and Bott [2] report that a fouling biofilm thickness of 200 μm in a 550 MW coal-fired power station leads to about an increase by 12 tons of CO_2 per day.

Causes for fouling, common methods to avoid it, or at least to mitigate it, have long been studied, see for example Poulsen [3], Thonon et al. [4], Ramachandra et al. [5], and Abd-Elhady et al. [6]. The detection of the presence of fouling is also an active research area, see for example Jerónimo et al. [7], Bott [8], Riverol and Napolitano [9,10], Chen et al. [11], Nema and Datta [12] and is still a challenge and conferences are regularly organized (see for example http://www.engconfintl.org/).

The classical detection methods are based on e.g.

1. Examination of the heat transfer coefficient (or the effectiveness),
2. simultaneous observations of pressure drops and mass flow rates,
3. temperature measurements, e.g. $(T_{\mathrm{h,in}} - T_{\mathrm{h,out}})/(T_{\mathrm{h,in}} - T_{\mathrm{h,out}})_{\mathrm{design}}$,
4. ultrasonic or electrical measurements,
5. weighing of heat exchanger plates.

To be very accurate, these methods require either that the system presents successive steady states (1–3), i.e. the

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Nomenclature

A	state matrix or surface area for heat transfer when used with a subscript
B	state matrix
Cus	cumulative sum function
c	constant or specific heat when used with a subscript
$\frac{d}{dt}$	derivative with respect to time
$\frac{\partial}{\partial v}$	partial derivative with respect to variable v
$E[v]$	mean value of variable v
F	state matrix
$\underline{f}$	state space function
g	threshold coefficient
H	measurement matrix
h	threshold coefficient or convection coefficient when used with a subscript
I	identity matrix
K	Kalman gain matrix or constant when used with subscripts c or h
k	discrete time index
M	mass of fluid in one section
$\dot{m}$	mass flow rate
$\underline{\dot{m}}$	mass flow rate state vector
N	normal (Gaussian) distribution
ns	number of sections in the heat exchanger
P	covariance error matrix
Q	covariance matrix
R_f	fouling factor
R_{th}	thermal resistance of the tube between the two fluids
T	temperature
$\underline{T}$	temperature state vector
t	time
U	overall heat transfer coefficient
v	dummy variable
w	white Gaussian noise sequence with zero mean and covariance matrix Q
$\underline{w}$	noise state vector
$\underline{x}$	overall state vector
y	exponent of the Reynolds number in a convection correlation
$\underline{z}$	measurements vector
$0(m \times n)$	null matrix having m lines and n columns
$\underline{0}$	null state vector

Greek symbols

α	model parameter
β	model parameter
Δt	time step
$\underline{\theta}$	parameter state vector
σ	standard deviation
τ	model parameter

Subscripts

c	cold side
design	as should be obtained according to the design computations
f	relative to the state space function
h	hot side
i	in section #i
in	inlet
k	at discrete time index k
out	outlet
ref	reference
z	relative to the measurements
α	relative to the model parameter α
β	relative to the model parameter β
θ	relative to the parameter state vector

Superscripts

*	relative to the reference state
T	transpose

inlet temperatures and flows must be stable for a period long enough to be able to compute or measure the values of interest, or are local (4), or require to stop the process (5). This is far too restrictive or costly.

Another approach is based on modelling the heat exchanger and then looking for any discrepancy between what is predicted by the model and what actually occurs. The method proposed by Prieto et al. [13,14] is based on an adaptation of the model when necessary (after the detection of the discrepancy), and on the analysis of the differences between two consecutive models. To pursue this approach, the aim of the present study is to show how non-linear physical state space models, recursively determined, can be applied to detect fouling in heat exchangers. In Jonsson and Holst [15] and Jonsson [16] heat exchanger models and the statistical estimation of their parameters are discussed. The models are based on the physical properties of the heat exchanger. An improvement has been brought so that the estimation is continuous, and the main focus here is to determine how sensitive the proposed method is to changes in the parameters of the model due to fouling.

Being based on the measurements of the mass flow rates and on the inlet/outlet temperatures, the estimation could be done while the heat exchanger is in use, even in a non steady state.

In the first part, the heat exchanger model is developed. Then the estimation algorithm is presented. This estimation is carried out using the extended Kalman filter. The last section is split into two subsections. The first subsection