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Sensor fault detection and isolation via high-gain observers: Application to a double-pipe heat exchanger

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ABSTRACT

This paper deals with fault detection and isolation (FDI) in sensors applied to a concentric-pipe counter-flow heat exchanger. The proposed FDI is based on the analytical redundancy implementing nonlinear high-gain observers which are used to generate residuals when a sensor fault is presented (as software sensors). By evaluating the generated residual, it is possible to switch between the sensor and the observer when a failure is detected. Experiments in a heat exchanger pilot validate the effectiveness of the approach. The FDI technique is easy to implement allowing the industries to have an excellent alternative tool to keep their heat transfer process under supervision. The main contribution of this work is based on a dynamic model with heat transfer coefficients which depend on temperature and flow used to estimate the output temperatures of a heat exchanger. This model provides a satisfactory approximation of the states of the heat exchanger in order to allow its implementation in a FDI system used to perform supervision tasks.

1. Introduction

Different fault detection and isolation (FDI) techniques have been proposed in the literature [1–3]. These techniques can be classified into physical and analytical redundancy. The analytical redundancy or model-based approach has the advantage of being low cost compared to the physical redundancy [4,5].

Model-based FDI techniques have been traditionally developed using linear and nonlinear models [6–9]. In these works the authors implement robust methods to perform FDI even under parametric uncertainties, modeling errors and noise. Usually, these diagnosis methods are based on the generation of residuals.

This paper deals with the subject of fault detection and isolation in a concentric-pipe counter-flow heat exchanger. Heat exchangers were chosen because they are widely used in industry, in exothermic processes or simply in processes where it is required to reduce the flow temperature [10]. The dynamics of these systems can be modeled by coupling a finite number of first order differential equations [11].

Steiner [12] presented simplified dynamical models to estimate states in heat exchangers. Other authors have designed control systems based on simplified models for heat exchangers [13,14]. However, these models have, a series of assumptions to describe the heat transfer phenomena. They consider the density (ρ) and the heat capacity (C_p) constant, as well as the heat transfer coefficient (U). These assumptions limit the operation range where the model is valid.

Some authors suggest that even if a sophisticated model is obtained, it could not be adequate to perform control tasks [15]. In this work, it is shown that finding a nonlinear model that describes the states dynamics with reduced approximation error makes it possible to design a model-based FDI system.

To obtain a model able to estimate states in the whole operation regions of the systems, it is necessary to calculate, on-line, the heat transfer coefficient using the convective coefficient (h_o, h_i) for different operating regions (laminar or turbulent flows). By estimating the heat transfer in the heat exchanger, it is possible to obtain a model with a reduced error in the temperature estimation, which can be used to develop nonlinear state observers. Thus, a FDI system based on state observers, in a concentric-pipe heat exchanger, can be developed. A problem with the observer-based approaches is the trade-off between the sensitivity of the residuals to a fault and the dynamics of the state reconstruction [16]. Furthermore, the trade-off between the speed of the state reconstruction and the stability of the observer has to be considered.

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Nomenclature and greek letters

Nomenclature

T	Temperature, (°C)
U	Heat transfer coefficient, (W/m^2 K)
A	Heat transfer area, (m^2)
C_p	Specific heat, (J/kg K)
V	Volume, (m^3)
W_v	Volumetric flow, (cm^3/min)
h	Convective coefficient, (W/m^2 K)
t	Time, (s)
Nu	Nusselt number
Pr	Prandtl number
Re	Reynolds number
D	Diameter, (m)
r_i	Inner radius, (m)
r_o	External radius, (m)
V_s	Fluid velocity, (m/s)

Greek letters

ρ	Density, (kg/m^3)
ζ	Error tolerance
θ	Observer gain
ΔT	Temperature increment
μ	Viscosity, (kg/ms)
μ_s	Viscosity on the wall surface, (kg/ms)
λ	Thermal conductivity, (J/ms K)

Subscripts

c	Cold
h	Hot
i	Input
o	Output

Fault diagnosis is based on the redundancy of nonlinear observers. Applying restrictions in the residual evaluation allows that if any output sensor fails, its signal is replaced by the observer and the system continues operating normally. The observers employed in this work are closely related to the high-gain observers developed in [17] and proposed in [18] for bioreactor processes.

An approach that has been used to detect faults in heat exchangers is based on detecting rapid changes in the heat transfer coefficient in the system by implementing recursive least square algorithms [19]. However, this approach has the objective of detecting fouling in the heat exchanger pipes. The advantage this work has over the work presented by Weyer in [19], is that not only the heat transfer coefficient is monitored but also faults in sensors are detected and isolated. This scheme provides a reliable supervision of the process by implementing a software sensor. So, the process engineers can continue monitoring the process variables until the faulty sensor is repaired.

The idea of the state observer approach is to reconstruct an unmeasured state; observers for nonlinear systems are used to detect failures via the residual evaluation [20]. The selection of this observer is due to the fact that the high-gain induces a time scale separation between the nonlinear process and the observer. Tornambè in [17], showed that when the error dynamics is faster than the process dynamics, then the observer has a fast convergence. This feature ensures not only a fast estimation, but also, in consequence, a fast detection of the faults. If a failure occurs, a selected observer should replace the sensor in the nonlinear systems.

Fig. 1. Double-pipe heat exchanger.

The main contribution of this work is based on a dynamic model with heat transfer coefficients which depend on temperature and flow used to estimate the temperatures of a heat exchanger. Fuzzy or neural networks are suited for process where the fundamental model is unknown, or the combination of process is difficult to describe. It is known that the accuracy of the model describing the behavior of the monitored system is essential in model-based fault detection [21]. This model provides a satisfactory approximation of the states of the heat exchanger in order to allow its implementation in a FDI system used to perform supervision tasks.

2. Heat exchanger simplified model

The double-pipe heat exchanger (Fig. 1) is formed by two concentric circular pipes with a liquid flowing in the internal pipe (hot fluid) and another fluid flowing in the external section or annular space between the pipes (cold fluid). This equipment is operated in counter-flow. In this work only the counter-flow configuration is considered.

The heat exchanger dynamics is obtained by one balance of energy for each side of the heat exchanger [22], given in Eq. (1) [19].

$$\begin{aligned} \dot{T}_{\mathrm{co}}(t) &= \frac{W_{vc}}{V_c}(T_{\mathrm{ci}}(t) - T_{\mathrm{co}}(t)) \\ &\quad + \left(\frac{U(T, W_{vc})A}{C_{p_c}\rho_c V_c}\right)(T_{\mathrm{ho}}(t) - T_{\mathrm{co}}(t)) \\ \dot{T}_{\mathrm{ho}}(t) &= \frac{W_{vh}}{V_h}(T_{\mathrm{hi}}(t) - T_{\mathrm{ho}}(t)) \\ &\quad + \left(\frac{U(T, W_{vh})A}{C_{p_h}\rho_h V_h}\right)(T_{\mathrm{co}}(t) - T_{\mathrm{ho}}(t)). \end{aligned} \tag{1}$$

The authors in [12,19,23] propose the use of the mathematical model described in Eq. (1), considering the heat transfer coefficient (U) constant, as well as the water physical proprieties (ρ, and C_p). However, by considering the heat transfer coefficient (U) constant, the valid range of the model to estimate the state variables is limited and the estimation error is bigger since the parameter U does not correspond to the flow rate conditions where the system operates. Thus, this model is valid only for the heat transfer coefficient values for which the model has been designed.

This work presents the experimental results obtained by implementing a two high-gain observer bank using the designed heat exchanger model. The dynamic model contains heat transfer equations, so the heat transfer coefficient is considered as dependent of the temperature and the flow $U(T, W)$. In the same