CHEMICAL ENGINEERING RESEARCH AND DESIGN 93 (2015) 473–482

Contents lists available at ScienceDirect

Chemical Engineering Research and Design

journal homepage: www.elsevier.com/locate/cherd

Sensor fault compensation via software sensors: Application in a heat pump's helical evaporator

R.F. Escobar[a],*, *C.M. Astorga-Zaragoza*[a], *J.A. Hernández*[b], *D. Juárez-Romero*[b], *C.D. García-Beltrán*[a]

[a] *Centro Nacional de Investigación y Desarrollo Tecnológico, Int. Internado Palmira S/N, Palmira, C.P. 62490 Cuernavaca, Morelos, Mexico*

[b] *Centro de Investigación en Ingeniería y Ciencias Aplicadas-Universidad Autónoma del Estado de Morelos, Av. Universidad 1001, Col. Chamilpa, C.P. 62209 Cuernavaca, Morelos, Mexico*

ABSTRACT

This work presents a sensor fault compensation system, applied to a heat pump's helical evaporator. The mathematical model of the evaporator is given by algebraic and differential equations. These equations were selected according to the phases and regime of the fluid to be evaporated. The sensor fault compensation is based on fault detection and isolation system and a MPC (model predictive control) strategy. The fault detection isolation system is based on a bank of two high-gain observers which have two main purposes. The first one is to generate adequate residuals when a sensor fault occurs. The second purpose is to act as a software sensor, meaning, the measure estimated by the observer replaces the measure given by physical sensor when a sensor fault occurs. The high-gain observers were selected because they are easy to implement and tune. Furthermore, they provide an adequate estimation of the process outputs (when a sensor fault occurs) to a model predictive control (MPC) strategy. The MPC has been implemented to regulate the steam outlet temperature. Several experiments were carried out to show that the MPC regulates the process output even if a fault occurs. The experiments in the evaporator of the absorption heat pump have shown reliability of the method presented in this work to detect a sensor failure, isolate the sensor failure and regulate the steam temperature when a total or partial failure occurs.

Keywords: Fault tolerant control; Fault diagnosis and isolation; High-gain observers; Heat exchangers; Heat pump; Evaporator

1. Introduction

Control theory and its application in industrial processes arises from the need to provide regulated operating conditions to ensure repeatability of the results in processes and to provide security for the operators of industrial equipment. The heat exchangers are an important part of industrial processes (food, textiles, chemicals, etc.) (Kakac and Liu, 2002). Some heat exchangers are designed for cooling or heating substances; while other applications of this equipment are evaporation or crystallization. In this kind of processes (evaporation and crystallization) to keep temperature conditions under control is not an easy task, because of the close interaction with the pressure.

The heat exchange systems have been the subject of study in order to propose strategies that will maintain the systems under controlled conditions and/or under supervision (Astorga-Zaragoza et al., 2007; Jonsson et al., 2007; Karsten and Ballé, 2000; Hangos et al., 2004; Weyer et al., 2000). Zavala-Río and Hernández-González (2007) presented a bounded positive adaptive control for counter-flow heat exchangers. The advantage of this control law is that it does not depend on a model of the system and its implementation is easy. The authors in (Zavala-Río and Hernández-González, 2007; Maidi et al., 2008)

---

* *Corresponding author*. Tel.: +52 777 3627770; fax: +52 7773627795.
E-mail address: esjiri@cenidet.edu.mx (R.F. Escobar).

http://dx.doi.org/10.1016/j.cherd.2014.06.017

proposed techniques of control in heat exchangers without change of phase in fluids. Qu et al. (2006) consider necessary an exact model of the heat exchanger in order to realize an accurate control of its temperatures. In Maidi et al. (2008) it is presented an optimal linear PI fuzzy controller. The design of the controller is based on the use of a finite-dimensional approximation model of high order. Another application of the fuzzy controllers in thermodynamics process is presented in Hua and Fei (2011), where the authors present a fuzzy control with feedforward compensator to save energy and improve COP (coefficient of performance) of the system. Maidi et al. (2009) presented a model by partial differential equations to design a boundary geometric control law with an application in a counter-current heat exchanger.

Works by Cardona et al. (2007), Aguado (2006), Giraldo et al. (2006), Pérez et al. (2004) present researches about control applications in evaporators. In Aguado (2006), Giraldo et al. (2006), it is presented a model predictive control using ARX models. In these works it is mentioned that employing this kind of models is a good choice to control multivariable systems with delays. Some authors (Pérez et al., 2004) suggest that the evaporators are complex systems that are required to be linearized in the equilibrium point to control the process. Another work in the control of heat exchangers is presented in Rasmussen and Larsen (2011), in this work a low order nonlinear model of the evaporator is developed and used in a backstepping design of a nonlinear adaptive controller. The proposed method allows work in a wide range of operating points.

In large systems, as it is the case of heat pumps, each component is designed to provide a specific service to its operation. The overall system works satisfactorily if, and only if, all components provide the adequate service for which they were designed. A faulty component such as the evaporator usually changes the overall behavior of the system. Generally, a failure is an event that changes the behavior of a system such that the system does not suit its purpose. The failures are the leading cause of changes in the behavior of the system or parameters, and they will eventually lead to a degraded system performance or even loss of control of the system (Blanke et al., 2006). Accordingly, several researches had been published, addressing fault detection and isolation (FDI) schemes. For instance Du and Mhaskar (2012) propose a fault detection isolation (FDI) scheme focused on sensor faults. This approach is based on analytical redundancy by using of a bank of high-gain observers. The authors have shown the effectiveness of FDI system in a chemical process.

The absorption heat pumps present several interactions and nonlinearities in their behavior, so it is difficult to design a controller for this system (Ohgata et al., 1997). The nature of this process makes it difficult to control it manually. In the work presented by Escobar et al. (2008), it is shown a strategy to estimate the COP (coefficient of performance) of the absorption heat pump, however the authors did not present a control strategy to ensure the steady state of the heat pump, but they indicate that it is possible to implement a control strategy from the estimation of the COP. Experimental results (Olarte-Cortés, 2010; Escobar et al., 2009; Rodriguez, 2008; Bonilla, 2007) show that it is difficult to maintain steady state conditions in the process due to the lack of a suitable automatic control system. In addition, due to equipment failure caused by sensors or actuators, it cannot work for long periods.

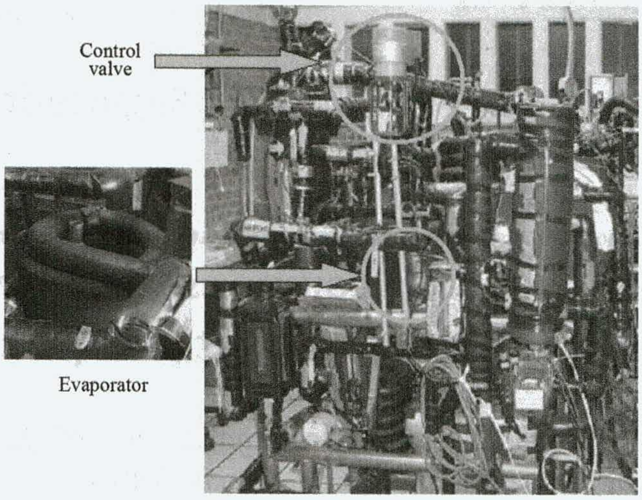

Fig. 1 – Absorption heat pump.

Therefore, the main goal of this research is the implementation of a sensor fault compensation via high-gain observers, which is applied in the outlet sensors of the absorption heat pump's evaporator (Fig. 1). The high-gain observers were designed from an energy model commutated by the states, the commutations allow the estimation of the temperatures in the three operating regions of the evaporation process, subcooled liquid, biphase and superheated steam. The high-gain observer was selected because it is easy to implement and tune. Furthermore, this kind of observer provides an adequate estimation of the process outputs. The estimation time can be decreased by increasing the value of the tuning parameter of the observer. The main idea to use high-gain observer to develop a FDI scheme is to reconstruct the full system states. Also use the properties of the observer as precision and speed to the convergence, in order to isolate faster the faulty sensor, allowing a trade-off between precision and speed. This feature ensures a fast estimation in consequence, a fast detection of the failure. A fault detection system (FDI) based on physical redundancy implies an increment in the cost (in the majority of cases). The proposed method in this research, offers an alternative to implement a FDI system based on a virtual sensor (software solution) that will keep the continuous operation of the process. In addition, a model predictive control (MPC) was implemented, in order to regulate the heat supplied to the absorber. The MPC allows the continuous regulated operation of the heat pump even in faults presence of output sensors.

1.1. *Evaporator model*

A double-pipe heat exchanger is formed by two concentric circular pipes with a fluid flowing in the internal pipe and another fluid flowing in the external section or annular space between the pipes. The dynamics of these systems can be modeled by coupling a finite number of first order differential equations (Khalil, 2002).

The heat exchanger dynamics is obtained by a balance of energy for each side of the heat exchanger (Fazlur-Rahman and Devanathan, 1994) as shown in Eq. (1). This model has been used in different works (Escobar et al., 2010; Zavala-Río and Hernández-González, 2007; Weyer et al., 2000; Varga et al., 1995) to represent the heat exchange in systems which do not have change of phase in any fluid.

In this work the model presented in Eq. (1) was used to represent the dynamic of an evaporator. The heat exchanger model describes the temperature profile in the evaporation process. To realize this task it was used a thermodynamic