ARTICLE IN PRESS

ISA Transactions ∎ (∎∎∎∎) ∎∎∎–∎∎∎

Contents lists available at ScienceDirect

ISA Transactions

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

Sensor fault detection and isolation system for a condensation process

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ARTICLE INFO

Article history:
Received 6 April 2016
Received in revised form
4 August 2016
Accepted 4 August 2016
This paper was recommended for publication by Prof. A.B. Rad

Keywords:
Fault detection and isolation
Nonlinear high-gain observers
Condenser

ABSTRACT

This article presents the design of a sensor Fault Detection and Isolation (FDI) system for a condensation process based on a nonlinear model. The condenser is modeled by dynamic and thermodynamic equations. For this work, the dynamic equations are described by three pairs of differential equations which represent the energy balance between the fluids. The thermodynamic equations consist in algebraic heat transfer equations and empirical equations, that allow for the estimation of heat transfer coefficients. The FDI system consists of a bank of two nonlinear high-gain observers, in order to detect, estimate and to isolate the fault in any of both outlet temperature sensors. The main contributions of this work were the experimental validation of the condenser nonlinear model and the FDI system.

1. Introduction

Historically, the industries have been looking for efficiency and quality in their processes or systems. Nowadays, industries are not only looking for these aspects, but also they need to provide security for human operators and for their equipments. Technological advances have made possible to implement different control techniques, this imply more dependence on the use of electronic and electromechanical instruments such as sensors and actuators. These instruments can be exposed to hard operating conditions for a long time and moreover to extreme environmental conditions. Therefore, they could experiment faults, and its behavior may not be optimal, these faults affect directly the overall system performance because most of the processes operate in close loop.

To solve the sensor and actuators damaged problem, several authors have developed model-based Fault Detection and Isolation (FDI) systems, in order to locate and identify faults in sensors and actuators [1,2]. The model-based fault diagnosis systems are characterized by the use of deterministic models. The objective of model-based fault detection system is to generate analytical redundancy through the design of a bank of *n*-observers. According to [3] the analytical redundancy is a better option than physical redundancy, because its implementation is less expensive. Since the observers design depends on the model, it is important to develop an accurate mathematical model capable of representing the system dynamics.

In this work, a condensation process was proposed in order to design a sensor FDI system. A condenser is a heat exchange device which is widely used in different kinds of industries like food, nuclear and energy industries. According to [4] approximately 60% of heat exchangers employed in industrial processes are used to condense or vaporize substances.

Different authors address their works to the study of condensation or evaporation processes [5,6], in these works, the authors proposed different mathematical models of distributed parameters to describe the condensation or evaporation processes in concentric-pipes heat exchangers, these models are based on mass, energy and momentum balances. In [7], the authors considered three regions during the condensation process which are: superheated steam region, biphase and saturated liquid. Therefore, it is of great importance to estimate the overall heat transfer coefficient according to each operating region of the condensation process. Besides, empirical correlations for helical pipes are evaluated for each operating region. However, the structure of

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http://dx.doi.org/10.1016/j.isatra.2016.08.004

Nomenclature

A	cross area section (m^2)
Cp	specific heat (J/kg °C)
Fv	volumetric flow (m^3/s)
Fm	mass flow (kg/s)
H	enthalpy (J/kg)
h	convective coefficient (W/m^2 °C)
p	pressure (Pa)
r	pipe radio (m)
T	temperature (°C)
t	time (s)
U	overall heat transfer coefficient (W/m^2 °C)
Vol	volume (m^3)
V_s	velocity (m/s)
Xg	steam quality
X_{tt}	Martinelli parameter

Dimensionless numbers

Dn	Dean number $\left(Dn = Re(d/a)^{1/2}\right)$
He	Helical number $\left(He = Dn/(1+(b/2\pi a)^2)^{1/2}\right)$
Nu	Nusselt number $(Nu = hd/\lambda)$
Re	Reynolds number $(Re = \rho dVs/\mu)$
Pr	Prandtl number $(Pr = Cp\mu/\lambda)$

Greek letter

ρ	density (kg/m^3)
μ	viscosity (kg/m s)
θ	observer gain
λ	thermal conductivity (W/m °C)

Subscripts

anu	annulus
bp	biphase
c	cold
ext	external
h	hot
i	input
int	internal
l	liquid
o	output
s	steam

mentioned models is complex, so, it is difficult to design and develop closed-loop control strategies, even more, to design and implement fault tolerant control systems.

The main problem to model the dynamics of the condensation process is when the change phase occurs, as a result to model the overall dynamic in a condensation process is a complex mathematical model [5], this is because the physical properties such as density (ρ), heat capacity (Cp) and heat variables as enthalpy (H), the convective heat transfer coefficients (h) have abrupt changes in their behaviour, which is similar to discrete dynamic in hybrid systems. The abrupt changes made the system not differentiable.

In the literature, there are works focused on control, fault diagnosis and fault tolerant control applied to heat exchangers, several works have been developed for heat exchanger with the presence of change phase (condensers or evaporators) [8,9], and others were developed to heat exchangers without the presence of change phase (coolers or heaters) [10,11]. In most cases to control an evaporator or condenser, different authors use artificial intelligent approaches [8,12,13], to be able to deal with the nonlinearities of the heat exchangers or others complex systems [12,13]. Also, in the literature, there are works focused on evaporators control, where a dynamic model is proposed, however, these works present complex models [9] and/or they are particular for each case study.

In order to propose a model-based FDI system for an experimental condenser, a heat transfer model for a particular experimental helical condenser and a bank of two nonlinear high-gain observers are developed. The condensers model was formulated by using three pairs of ordinary differential equations and heat transfer empirical equations, and the bank of nonlinear observers was design from the model equations. The main contribution of this work was the experimental validation of the condenser nonlinear model and the FDI system. The results showed the effectiveness of the proposed scheme.

The paper is structured as follows, in Section 2 we give the equipment description, in Section 3 we present the nonlinear model of the condensation process, in Section 4 we show the design of the fault detection and isolation system and its validation for the condenser. Finally, the conclusions are given in Section 5.

2. Equipment description

The condenser under study is a helical double pipe countercurrent heat exchanger. This configuration is widely used due to its high efficiency heat transfer, compact design, ease of manufacture and placement. The equipment is constructed by two concentric steel pipes and are well isolated with thermal isolation. In Fig. 1 the flows in the condenser pipes is shown. Into the inner section there enters superheated steam, which will be cooled and will change phase along the condenser. By the annular section there enters cooling water which absorbs the heat released.

Instrumentation is as follows: there are four thermocouples T-type with an accuracy of $\pm 1°$ C installed at the inlet and outlets flows (T_{hi}, T_{ci}, T_{ho} and T_{co}). Flows are measured by brass rotameters in both steams. A vacuum gauge Bourdon of 3" 316L-type is used to measure the absolute pressure in each of the pipes, annular section is operated near to atmospheric pressure (p_c) and the inner section has a vacuum pressure (p_h). It is assumed that the

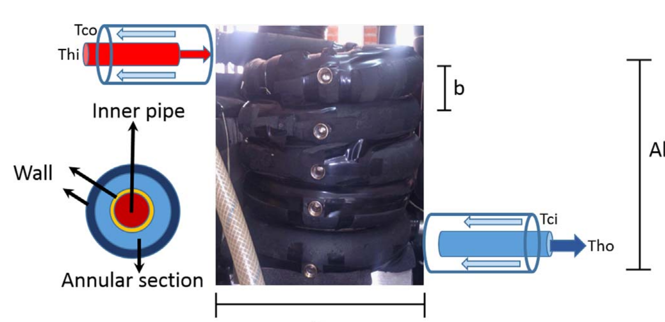

Fig. 1. Experimental helical condenser.

Please cite this article as: Castro MAL, et al. Sensor fault detection and isolation system for a condensation process. ISA Transactions (2016), http://dx.doi.org/10.1016/j.isatra.2016.08.004