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IFAC-PapersOnLine 49-7 (2016) 019–024

Energy-based visualisation of a counter-flow heat exchanger for the purpose of fault identification

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Abstract: The need for fault detection and diagnosis (FDD) is becoming increasingly important for industrial processes as the complexity of processes increases. A state space model of a counter-flow heat exchanger is used as a case study to illustrate the usefulness of energy-based FDD. Energy is regarded as a unifying parameter to uniquely describe the state of the heat exchanger under fault conditions of fouling and heat leakage. Both steady state and transient energy-based residuals are proposed for the purpose of FDD. The results indicate that the use of energy-based residuals seems viable and warrant further investigation.

Keywords: Energy-based visualisation, fault identification, counter-flow heat exchanger, state-space model.

1. INTRODUCTION

Fault detection and diagnosis (FDD) methods can mainly be classified into two groups: Model-free methods and Model-based methods according to Gertler (1998). Model-free methods do not use a mathematical model of the plant. It is focused on physical redundancy through special sensor topologies or limit checking. Signal processing based fault diagnosis is also a form of model-free FDD that extracts fault information from the process signals.

Model-based fault detection and diagnosis methods use an explicit mathematical model of the plant under consideration. Model-based FDD can again be classified into observer-based, parity-space and parameter identification approaches. Observer-based approaches have received considerable attention due to the advantage of early fault detection and ease of on-line implementation as described by Ding (2008), Chen and Patton (2012). In the case of non-linear model-based approaches difficulties in terms of stability and convergence arise and is still a very active research field. The interested reader is directed to Marzat et al. (2010); Chen and Patton (2012); Witczak (2003).

Typical faults in heat exchangers are leaks (mostly caused by corrosion) and contamination by means of dirt and dissolved or suspended matter as described by Isermann (2011). According to Dawoud et al. (2007) heat leakage due to insulation failure is another fault that degrades the heat exchanger efficiency.

In this paper an energy-based visualisation approach to FDD of a counterflow heat exchanger is proposed. Energy is seen as a unifying parameter across physical domains as discussed in the paper of Van Schoor et al. (2014) and proves to be particularly useful in control systems as basis for stability. Investigating the use of energy or energy distributions as a basis for FDD is therefore seen as a logical step. Since energy patterns are composed in a structured manner with due cognisance of the basic law of conservation of energy and prior knowledge i.t.o. heat exchanger operation, the approach followed in this paper is regarded as model-based.

The paper is structured as follows: A state space model for a simple counter flow heat exchanger is derived in section 2 after which the model simulation is discussed in section 3. In section 4 a frame work for energy characterisation of the heat exchanger is proposed. Section 5 proposes and evaluates energy-based residuals for FDD.

2. STATE SPACE MODEL

A double-pipe, counter-flow heat exchanger consists of 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). For the purposes of modelling the counterflow heat exchanger is represented by two separate flow channels separated by a heat conducting wall (See Fig. 1). The equations that govern fluid flow and heat transfer in a heat exchanger are the continuity, momentum and energy equations. Since heat exchangers are generally considered as distributed parameter systems, such systems are modelled using partial differential equations. For the purpose of this paper the heat exchanger will be considered as a lumped parameter system. This allows the use of finite volume discretisation of the system. Two types of control volumes (CVs) will be considered; a node centred control volume, i and an element centred control volume,

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10.1016/j.ifacol.2016.07.210

j. The balance equations may then be derived in terms of ordinary differential equations for each control volume. In each control volume the average values of the velocity, density, pressure and temperature will be used. The fluid flow inside the pipes is assumed to be one-dimensional. This means that only the flow velocity component normal to the cross-sectional area of the pipe is taken into account.

2.1 Fluid domain

Consider the fluid domain representation of the heat exchanger in Fig. 1, based on a single node centred control volume per side. The mass conservation equation for the

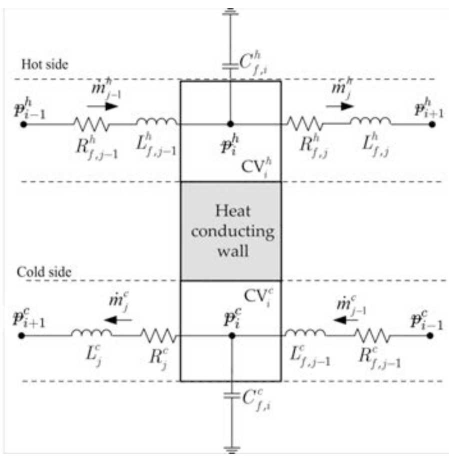

Fig. 1. Fluid domain representation of heat exchanger

i-th node-centred CV may be given by

$$\frac{dM_i}{dt} = \dot{m}_{j-1} - \dot{m}_j, \tag{1}$$

where M_i is the mass in the i-th CV (let $i = 1, \ldots, N$, with N the total number of node centred control volumes) and $\dot{m}_{j-1}$ and $\dot{m}_j$ represent the mass flow entering and leaving the control volume respectively. Let the superscripts h and c represent the hot and cold fluids respectively. By introducing the pressure p_i, as the pressure in the i-th CV, (1) may be written as

$$\frac{dM_i}{dp_i}\frac{dp_i}{dt} = \dot{m}_{j-1} - \dot{m}_j. \tag{2}$$

It then follows that

$$\frac{dp_i}{dt} = \frac{1}{C_{f,i}}(\dot{m}_{j-1} - \dot{m}_j), \tag{3}$$

$$C_{f,i} = \frac{dM_i}{dp_i} = V_i\left(\frac{d\rho_i}{dp_i}\right). \tag{4}$$

$C_{f,i}$ represents the fluid capacitance element, describing the compressibility of the fluid. V_i and ρ_i; represent the volume and density in the i-th CV. The fluid capacitance may also be written in terms of the bulk modulus, B,

$$C_{f,i} = \rho_i V_i / B. \tag{5}$$

The momentum equation for a single j-th component-centred control volume may then also be given by

$$\frac{d\dot{m}_j}{dt} = \frac{A_j}{\ell_j}p_i - \frac{A_j}{\ell_j}p_{i+1} - \left(\frac{A_j}{\ell_j}\right)\left(\frac{\xi\ell_j}{2\rho_j D_j A_j^2}\right) \mid \dot{m}_j \mid \dot{m}_j, \tag{6}$$

with A_j the cross-sectional area, ℓ_j the length of the CV, ξ the friction factor and D_j the diameter of the pipe section. With the fluid inductance given by

$$L_{f,j} = \ell_j / A_j, \tag{7}$$

and the fluid resistance by

$$R_{f,j} = \frac{\xi\rho_j\ell_j}{2D_jA_j^2} \mid \dot{m}_j \mid, \tag{8}$$

(6) can be rewritten as

$$\frac{d\dot{m}_j}{dt} = \frac{1}{L_{f,j}}(p_i - p_{i+1}) - \frac{R_{f,j}}{L_{f,j}}\dot{m}_j. \tag{9}$$

Let the state vector of the fluid domain for a single CV on each side be given by

$$\mathbf{X}_f = \left[\, \dot{m}_{j-1}^h,\, p_i^h,\, \dot{m}_j^h,\, \dot{m}_{j-1}^c,\, p_i^c,\, \dot{m}_j^c \,\right]^T, \tag{10}$$

and the input vector of the fluid domain be given by

$$\mathbf{U}_f = \left[\, p_{i-1}^h,\, p_{i+1}^h,\, p_{i-1}^c,\, p_{i+1}^c \,\right]^T. \tag{11}$$

The state equations for the hot side may be written as follows:

$$\dot{x}_1 = -\frac{R_{f,j-1}^h}{L_{f,j-1}^h}x_1 - \frac{1}{L_{f,j-1}^h}x_2 + \frac{1}{L_{f,j-1}^h}u_1, \tag{12}$$

$$\dot{x}_2 = \frac{1}{C_{f,i}^h}(x_1 - x_3), \tag{13}$$

$$\dot{x}_3 = -\frac{R_{f,j}^h}{L_{f,j}^h}x_3 + \frac{1}{L_{f,j}^h}x_2 - \frac{1}{L_{f,j}^h}u_2. \tag{14}$$

Similarly for the cold side:

$$\dot{x}_4 = -\frac{R_{f,j-1}^c}{L_{f,j-1}^c}x_4 - \frac{1}{L_{f,j-1}^c}x_5 + \frac{1}{L_{f,j-1}^c}u_3, \tag{15}$$

$$\dot{x}_5 = \frac{1}{C_{f,i}^c}(x_4 - x_6), \tag{16}$$

$$\dot{x}_6 = -\frac{R_{f,j}^c}{L_{f,j}^h}x_6 + \frac{1}{L_{f,j}^h}x_5 - \frac{1}{L_{f,j}^h}u_4. \tag{17}$$

2.2 Thermal domain

Consider the thermal domain representation of the heat exchanger in Fig. 2, based on a single node centred control volume per side. The energy equation for the control

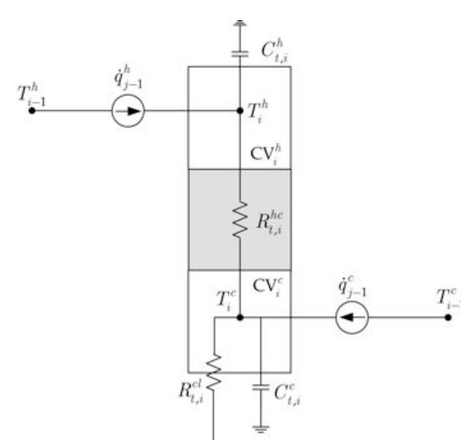

Fig. 2. Thermal domain representation of heat exchanger