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Hybrid dynamic modeling for two phase flow condensers

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HIGHLIGHTS

- A hybrid modeling approach is proposed to describe the dynamic behavior of condensers.
- This modeling approach balances the trade-offs between complexity and accuracy.
- The model order is very low and all the state variables are available for measurement.
- The model validation studies show that the model predicts the system dynamic well.
- The model is suitable for dynamic analysis and model-based controller design.

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ABSTRACT

In this paper, a hybrid modeling approach is proposed to describe the dynamic behavior of the two phase flow condensers used in air-conditioning and refrigeration systems. The model is formulated based on fundamental energy and mass balance governing equations, and thermodynamic principles, while some constants and less important variables that change very little during normal operation, such as cross-sectional areas, mean void fraction, the derivative of the saturation enthalpy with respect to pressure, etc., are lumped into several unknown parameters. These parameters are then obtained by experimental data using least squares identification method. The proposed modeling method takes advantages of both physical and empirical modeling approaches, can accurately predict the transient behaviors in real-time and significantly reduce the computational burden. Other merits of the proposed approach are that the order of the model is very low and all the state variables can be easily measured. These advantages make it easy to be applied to model based control system design. The model validation studies on an experimental system show that the model predicts the system dynamic well.

1. Introduction

Due to the concern on energy consumption and environmental impacts, the performance of vapor compression refrigeration cycles has drawn a lot of research interests in recent years. However, the difficulty in modeling the complex thermofluid dynamics associated with phase changes which take place inside the evaporator or condenser has restricted the development of advanced control strategies for energy efficiency of these systems [1]. It is, therefore, a great challenge for the control engineers to develop an accurate yet simple dynamic model for two phase heat exchangers which can be applied to real-time control system.

A number of works in literature were dedicated to study the control-oriented dynamic modeling technologies of two phase heat exchangers. The existing modeling approaches can generally be classified into two categories: a data-based black-box approach and a physical-based first principles modeling approach.

The black-box modeling approach is to obtain the model using experimental measurements and identification techniques. Based on this principle, Machado et al. [2] present a 1st order linear model with time delay for the response of superheat when actuating expansion valve opening. Although this kind of model uses a simple and low-order form to describe the relationship between the input and output variables in the vicinity of a given set point, it is difficult to relate the identified model with the physical characteristics of the actual system and only works well in a small operating range.

The physical-based models can be further divided into two paradigms: finite difference models and lumped parameter models, as discussed in literature [1]. In the finite difference models [3,4], the conservation equations are approximated with a finite difference technique and applied to a number of elements in the heat exchangers. Although these models can be powerful tools for

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simulating the dynamic response of refrigerant properties and their spatial distribution with a high accuracy, they require iterations at each time step to solve the high-order, nonlinear simultaneous equations for all state variables, which are by far too complex to be applied for model based control system design [5].

Compared with the finite difference models, the lumped parameter models reduce the complexity by integrating partial differential equations for each zone over the total length of the heat exchanger. This is performed by taking into account the moving boundary zones, an average heat transfer coefficient and an average void fraction (the volumetric ratio of vapor to liquid) in each zone. Hence, several researchers used this approach to develop control-oriented models of vapor compression systems for controls and diagnostics purposes. He [6] firstly presents a lumped-parameter model of vapor compression cycle dynamics for the purpose of designing advanced controls. In this model, a moving-interface approach is introduced to predict the position of the two-phase/single-phase interface inside the one-dimensional heat exchanger and to model the dynamics associated with the two heat exchangers, i.e. the evaporator and the condenser. The relations between process outputs and actuating inputs are represented explicitly by a set of non-linear differential equations, which is readily applicable to control system design. Following this work, Eldredge et al. [7] expand the range of operating conditions of the models to present the first-principles models for heat exchangers with receivers and accumulators. Tilmann et al. [8] present a dynamic model of the exhaust gas heat exchanger for automotive waste heat recovery system, in which a new approaches for modeling wall temperature distribution and zone switching are developed to achieve high model accuracy in the broad range of operating conditions. McKinley et al. [9] present a switched modeling approach to develop the moving-boundary heat exchanger model for subcritical vapor compression cycles for the improvements to model accuracy and stability, yet still runs in real-time. Li et al. [10] extend their works to present the switched condenser model with five modes and the switched evaporator model with two modes. In order to develop a mathematical model which is low-dimensional, easy to parameterize and accurate enough to capture the essential dynamics and nonlinearities, Michel et al. [11] present a low-order dynamic model of a 1/1 pass compact plate heat exchanger, which is systematically simplified by exploiting the specific design and the typical operating conditions of compact plate heat exchangers. For the interest of studying the dynamic thermal characteristics of the heat exchangers and designing good-performance control system for the heat exchangers, Yao et al. [12] present the state-space form of the dynamic model for the air-to-water surface heat exchanger. Although these physical-based models which are highly nonlinear with high model-orders can describe the dynamic behavior of the systems, they have to be linearized at the specified operating point and reduce the model order in order to implement advanced control strategies. In addition, there are two limitations in the application of these types of models for control system design: 1) some state variables, such as the lengths of the superheat section, two phase section and subcooled section of the condenser, are not available for measurement; 2) the state variables lost their physical significance after model order reduction. Moreover, detailed system information, such as physical parameters of system component, coefficient of heat exchange and mean void fraction, etc., are required during the modeling exercise, which require that the control engineers must have a deep knowledge for the vapor compression systems.

In this paper, a hybrid dynamic modeling approach for condensers applied in a vapor compression system is proposed. The model is formulated based on mass continuity and energy conservation principles. By combining a move-boundary and lumped-parameter method, and lump its constant parameters and some of variables that vary insignificantly during operation into unknown parameters, two non-linear equations which describe the key relations between the system inputs and outputs are obtained. Its parameters are determined using the testing data on the experimental plant by the least square method. This modeling approach not only balances the trade-offs between complexity and accuracy, but also reduces the system order and retains the physical significance of the system variables. The model can be used as a tool for both dynamic analysis and model-based controller design. Experiment results show that the model can accurately predict the dynamic behaviors well.

2. Basic assumptions

Some assumptions, which were commonly used to simplify the derivation of physical models of condensers, are listed as follows:

1. The fluid flow is one-dimensional.
2. Pressure drops in the condenser and piping are negligible.
3. Axial conduction of the fluid flow and the tube wall is negligible.
4. The mean void fraction (the volumetric ratio of vapor to liquid) remains invariant in the two-phase region.
5. The compression of the fluid is assumed to be adiabatic with an isentropic efficiency.
6. Only the refrigerant-side dynamics is considered.
7. The inlet condition to the condenser is assumed to be superheated.
8. The outlet condition to the condenser is assumed to be subcooled.

Based on the above assumptions, the condenser can be partitioned into three regions: a superheat region, a two-phase region, and a subcool region, as shown in Fig. 1.

Since refrigerant pressure drop within the shell is negligible (assumption 2), the momentum-conservation equation is ignored and the model can be formulated based on energy balance and mass balance equations.

3. Energy balance

The dynamics for the energy conservation of refrigerant in any internal flow condition can be represented by the Navier–Stokes law [13]

$$\frac{\partial(\rho A h - AP)}{\partial t} + \frac{\partial \dot{m} h}{\partial x} = A_i \alpha_i (T_w - T_r) \tag{1}$$

In the subcooled region, the density, the enthalpy and the length of the subcooled section (L_{c3}), can be assumed to be a constant

$$\rho_{c3} = \rho_{cro} = \rho_{cf} \tag{2a}$$

an average of the inlet and the outlet enthalpies can be expressed as:

$$h_{c3} = \left(h_{cf} + h_{cro}\right)/2 \tag{2b}$$

and proportional to the enthalpy difference between saturation enthalpy, h_{cf}, and the outlet enthalpy, h_{cro},