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Switched linear control for refrigerant superheat recovery in vapor compression systems

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ABSTRACT

Extended durations of liquid refrigerant ingestion by the compressor of a vapor compression system (VCS) can lead to damage or failure of this component. While this can be prevented by inserting an accumulator between the evaporator and compressor, this addition of hardware may be undesirable for applications in which the weight or size of the thermal management system is critical. As an alternative, this paper proposes a switched Linear Quadratic Gaussian (LQG) design to quickly recover the presence of a superheated phase at the exit of the evaporator using feedback control. Stability analysis of the closed-loop switched system is presented, and application of the control approach in both simulation and on an experimental VCS testbed demonstrate the success of the control design.

1. Introduction

A basic vapor compression system (VCS) consists of four components: 1) an evaporator, 2) a compressor, 3) a condenser, and 4) an expansion valve, connected as shown in Fig. 1. In this thermodynamic system, refrigerant cycles through the four components, undergoing phase changes as a result of heat transfer and changes in pressure, transporting thermal energy from the evaporator secondary side to the condenser secondary side.

Operational objectives for a VCS can be characterized by three criteria. First, the system should achieve a given performance metric. For example, this metric might be to provide a desired cooling or heating capacity, or to regulate a conditioned space within temperature constraints. Second, the system should operate efficiently. This may be evaluated by the coefficient of performance (the ratio of cooling or heating provided to the electrical energy consumed), by the electrical power consumption itself, or by the monetary cost of operation.

The third operational objective, and most pertinent to this work, is for the system to operate safely, in particular so as to minimize component wear. In many systems, the inclusion of an accumulator between the evaporator and compressor performs an important safety function by preventing liquid from being ingested by the compressor, which if unchecked can lead to compressor damage or failure (Rasmussen, 2005). However, in some applications the system configuration of Fig. 1 may be preferred in order to reduce the weight and/or size of the VCS by not including an accumulator. Such applications include next-generation aircraft, for which VCSs have been investigated as a lighter, less expensive, and more efficient alternative to air-cycle systems for thermal energy management (Emo, Ervin, Michalak, & Tsao, 2014).

In absence of an accumulator, minimizing compressor liquid ingestion must be achieved by feedback control—using measurements of system temperatures, pressures, etc. to ensure that the refrigerant exiting the evaporator is of superheated phase. Such control traditionally involves set-point regulation of evaporator superheat, T_{SH}, defined as:

$$T_{SH} = T_{evap,ref,out} - T_{sat}(P_{evap,ref,out}) \quad (1)$$

where $T_{sat}(P_{evap,ref,out})$ is the saturation temperature of the refrigerant as a function of evaporator pressure. While increasing the superheat set-point does improve robustness against the complete loss of the superheated phase, this comes at the expense of reduced efficiency. For example, in (He, Liu, Asada, & Itoh, 1998), it is reported that an increase in superheat set point from 5 °C to 10 °C resulted in a 10% increase in energy consumption of a VCS. In this light, selection of the superheat set point is seen as a tradeoff between safety and efficiency. As discussed in Section 2, this selection is made even more critical by the fact that many VCS control designs are not functional at low values of superheat, nor are they designed to be capable of recovering a superheated phase at the exit of the evaporator in the event of its loss (Schurt, Hermes, & Trofino Neto, 2010). Such control is especially difficult because the superheat response in the transitional region between zero and low (typically under 5 °C) values of superheat is known to exhibit highly nonlinear behavior (Elliott & Rasmussen, 2010).

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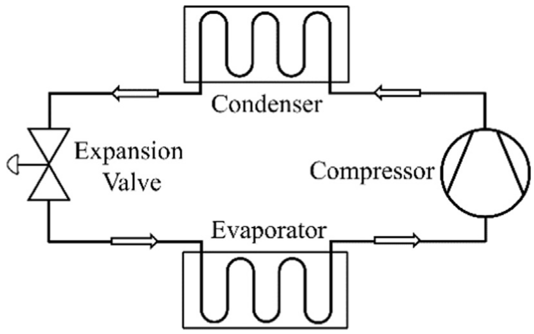

Fig. 1. Schematic of a basic vapor compression system.

This paper presents a switched linear control approach that is able to rapidly recover a superheated phase when it is lost in the evaporator in systems without an accumulator, demonstrating that the need for additional hardware to prevent extended durations of compressor liquid ingestion can be avoided by instead applying a more intelligent control design to the system. This switched approach allows powerful and reliable linear tools to be applied to an inherently highly nonlinear system. Stability analysis of the closed-loop system is presented, and application of the control approach in both simulation and on an experimental VCS testbed demonstrate the success of the control design.

The rest of this paper is organized as follows. Section 2 briefly reviews the relevant literature on VCS control design. Section 3 motivates the need for switched control and discusses the linear models used in control. Section 4 presents the control architecture and formulation, as well as stability results. Section 5 provides simulation and experimental results demonstrating the proposed approach. Lastly, Section 6 presents conclusions and future work. Portions of the work presented in this paper have been previously included in the thesis of (Pangborn, 2015), and in an abbreviated form without experimental results and detailed stability analysis in (Pangborn & Alleyne, 2016).

2. Relevant VCS control in the literature

The literature includes many control designs for VCSs, including decentralized single-input-single-output (SISO) loops (Jain, Li, Keir, Hencey, & Alleyne, 2010), multi-input-multi-output (MIMO) control (He et al., 1998), and gain-scheduled MIMO control (Rasmussen & Alleyne, 2010). While the minimum superheat set point at which various control designs are found to robustly regulate a given system is not often reported, the high nonlinearity in superheat response at low values limits the performance of many designs, as discussed with regard to PID controllers in (Rasmussen & Larsen, 2009). The work in (Elliott & Rasmussen, 2010) presents a nonlinear cascaded control architecture to produce a more linear input-to-output relationship between actuator commands and superheat response at low values, while (Rasmussen & Larsen, 2009) proposes a backstepping method, however controlled superheat recovery is not considered.

The authors in (Schurt et al., 2010) demonstrate that for a particular experimental system and MIMO linear quadratic Gaussian (LQG) controller, superheat regulation is possible between 9.5 °C and 22 °C of superheat, but becomes unstable below 8.5 °C of superheat due to changing input-to-output gains. This use of a linear plant model and controller allows well known results on optimal control of linear systems to be employed, but linearization about a single operating condition limits the range over which the control is valid. The operational range of linear controllers is extended in (Li, Jain, & Alleyne, 2012) and (Li, 2013), in which a control design that switches among multiple linear matrix inequality (LMI) representations of linear quadratic regulation (LQR) is applied to switch among cooling capacity set points by driving the system between operating conditions which include different phase flow conditions in both the condenser and the evaporator.

This paper builds upon previous efforts in switched linear control by presenting an alternative formulation that includes feedforward control, zero-offset tracking, and other beneficial features, by focusing specifically on the case of superheat recovery (which was not previously treated), by experimentally validating the proposed control approach, and by providing further results on the stability of the switched system.

3. System modeling

3.1. Nonlinear models

The nonlinear VCS models used in this work are taken from the Thermosys™ toolbox for MATLAB/Simulink® developed at the University of Illinois at Urbana-Champaign (Rasmussen, 2005). The heat exchangers of the system (the evaporator and condenser) are modeled using a lumped-parameter approach known as the moving boundary (MB) method (Rasmussen, 2005). In this method, the heat exchanger is partitioned into control volumes (CVs) that track each refrigerant phase flow zone (subcooled, two-phase, or superheated). Conservation equations of refrigerant energy, refrigerant mass, and tube wall energy are applied to each CV to develop a dynamic model of the heat exchanger. As given in (Rasmussen & Shenoy, 2012), the nonlinear heat exchanger models take the descriptor form:

$$Z(x)\dot{x} = f(x, u)$$
$$y = g(x, u) \tag{2}$$

where x, u, and y are the states, inputs, and outputs, respectively.

In a "switched" MB (SMB) model, the governing equations are derived separately for each possible combination of fluid phase zones in the heat exchanger, which are treated as modes of the plant (Pangborn, Alleyne, & Wu, 2015). The model then switches between the set of equations for each mode in order to accurately capture the component behavior across multiple phase flow combinations. Fig. 2 shows the two evaporator modes used in this work. These consist of the "nominal" mode, for which both two-phase and superheated refrigerant flow are present in the evaporator, and the "off-nominal" mode, for which the refrigerant is two-phase for its entire flow through the evaporator. These "nominal" and "off-nominal" labels follow from the assumption in this work that the control objectives include maintaining the

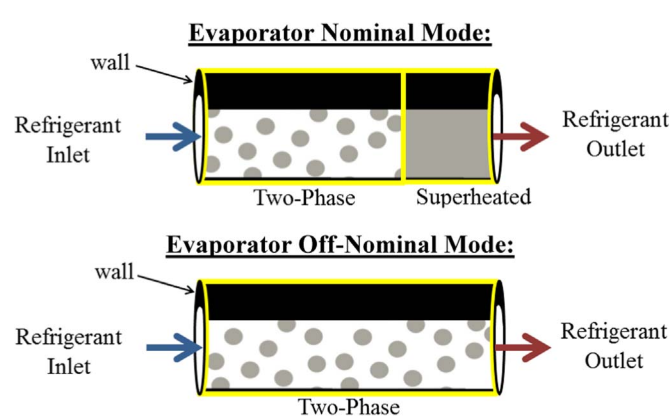

Fig. 2. Evaporator modes.