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Vapor compression refrigeration cycle for electronics cooling – Part II: gain-scheduling control for critical heat flux avoidance

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ABSTRACT

This paper addresses the feedback control of a vapor compression cycle for electronics cooling at different operating conditions including near the critical heat flux (CHF) condition. The control objective is to maintain the temperature of the heated wall below a safe threshold during large transient heat loads. The lumped-parameter model developed for this system is used to design the control strategy. Our experimental testbed is used for evaluation and validation. Linear controller design is applied based on the linearization about specific operating points. The controllers are tuned to achieve good robustness margins to guard against nonlinearity and other modeling errors. When the system traverses through multiple operating points, a gain-scheduling approach is used to switch between the controllers. For heat load changes which would lead to CHF, a dual-input gain-scheduling controller, using both expansion valve and compressor speed, is designed using the evaluator wall temperature as the feedback variable as well as the scheduling variable. Comparison between open-loop and closed-loop experiments for the same operating conditions shows that a 80 °C rise in the wall temperature is avoided with the gain-scheduling controller.

1. Introduction

Vapor compression cycles (VCC) are a promising solution for cooling high-heat-flux electronic systems [1–5]. Among their attractions are high heat transfer coefficients achieved through two-phase boiling, low temperatures of the cooling fluid, and the possibility to cool multiple heat sources using a single refrigeration loop. There are also concerns, however, including increased cost, condensate build-up, and the need for systems level control to balance efficiency and performance [6]. Control of the flow conditions at the exit of the evaporator is considered a requirement for VCC to be a practical solution to electronic cooling [7–9]. Most of the research for high-heat-flux electronics cooling focuses on enhancing the heat transfer coefficient at the device level. Less attention has been given to maintaining high heat transfer coefficients during transient operation and the efficient removal of heat at the systems level. Some control-theoretic analysis of VCCs for traditional cooling systems, e.g., air conditioning and chillers, has emerged over the past decade [10–14], but application to high transient heat flux situation is still lacking.

In contrast to traditional VCCs, VCC for electronics cooling faces imposed heat flux as the boundary condition at the evaporator as opposed to an imposed inlet temperature difference. For the former reaching the critical heat flux (CHF) condition could cause large and sudden rise in temperature leading to device burnout. The boiling process in the evaporator achieves high heat transfer coefficient, however, when the imposed heat flux reaches the CHF, liquid is replaced by vapor at the heated interface resulting in a sudden and severe drop in heat transfer coefficient [15]. To avoid such catastrophic situation, the exit of the evaporator must be maintained in the two-phase (liquid–vapor) regime. Therefore, the addition of a heated accumulator or other type of system modification is needed to protect the compressor.

The control objective for traditional VCCs involves increasing efficiency by controlling the degree of superheat or maintaining the temperature of the secondary fluid in the evaporator within specified limits [16,14,12]. For electronic cooling, the control objective involves regulating the temperature of the electronic device [17,4] while satisfying constraints such as the CHF avoidance in the evaporators. This paper presents a gain-scheduling approach

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to control a VCC operating near the CHF condition. Gain-scheduling control is a popular nonlinear control strategy which uses a family of linear models to represent a nonlinear system over its entire operating range [18,19]. These linear models are obtained from linearizations of the nonlinear plant at different equilibrium points. Linear controllers are designed for these linear systems and are combined by using a "scheduling" variable [20]. These controllers are tuned to ensure good robustness margins (gain and phase margins) for nonlinearity and other model errors. We choose gain-scheduling control for CHF avoidance under varying heat loads due to its simplicity and ability to deal with nonlinearity. More complex methods such as model predictive control [21,22] are also viable candidates, but tuning such controllers for robustness is generally much more challenging. In our context, we consider two operating regimes: away from CHF where the control objective may be systems efficiency or temperature regulation as described in [23], and near CHF where the control objective should be CHF avoidance through reduction of evaporator exit quality, possibly at the sacrifice of efficiency. As the evaporator wall temperature will rise when the system approaches the CHF condition, we will use this variable as the scheduling variable. We apply both single-input (electronic valve opening and compressor speed individually) and dual-input (valve opening and compressor speed simultaneously) control design for each of the operating regimes. In both simulation and experiments, we demonstrate that the gain scheduled controller can avoid or significantly delay the onset of the CHF condition.

2. Experimental setup

Fig. 1(a) shows our experimental VCC testbed. It consists of three cartridge heaters immersed in the refrigeration loop that act as evaporators, an electronic expansion valve for each evaporator, a heated accumulator, two compressors with a variable frequency drive (VFD) (only one compressor is active at a time), a condenser, and a subcooler connected to a chiller (not shown in the figure). The testbed is instrumented with three absolute pressure transducers, five differential pressure transducers, 20 type-T thermocouples (15 immersed in the flow and five attached to the cartridge heaters), and four Coriolis mass flow sensors (Fig. 1(b)). The sensors allow measurements of absolute pressure

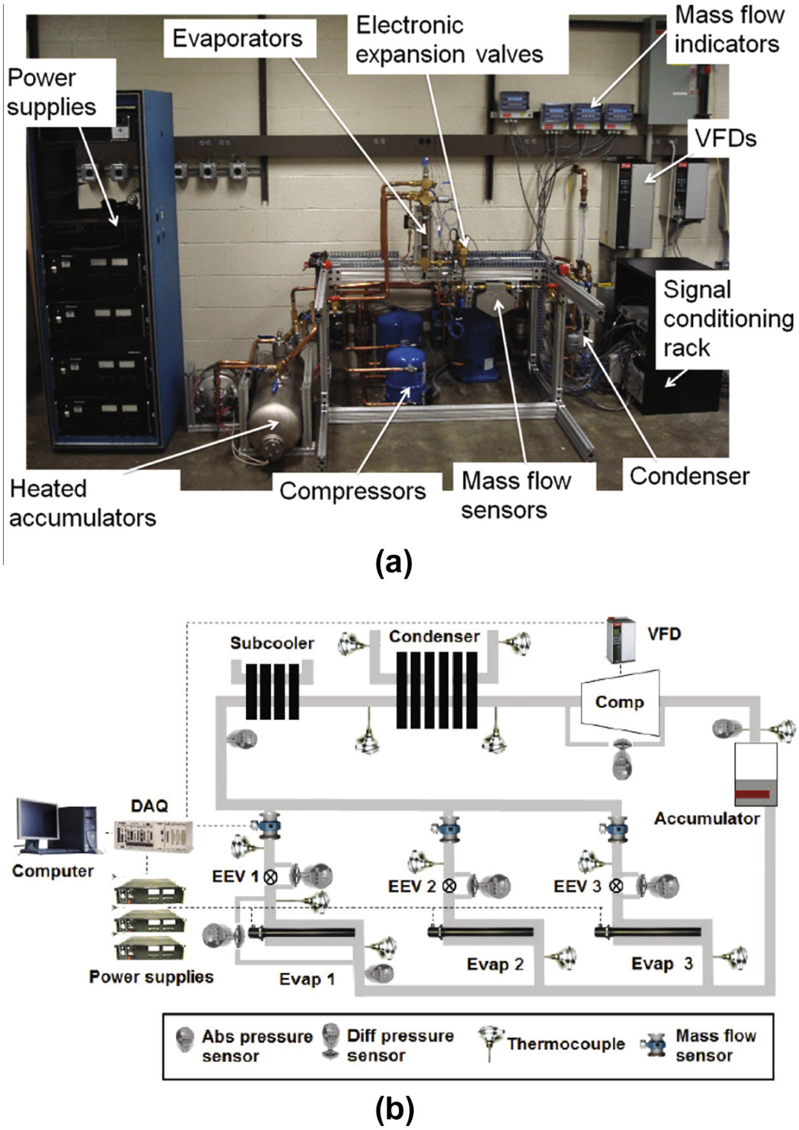

Fig. 1. Experimental set-up (a) Picture of multiple-evaporator vapor compression refrigeration cycle experimental set-up for electronics cooling (b) Schematic of experimental set-up.