2011 American Control Conference
on O'Farrell Street, San Francisco, CA, USA
June 29 - July 01, 2011

Cascaded Superheat Control with a Multiple Evaporator Refrigeration System

Matthew S. Elliott, Carolyn Estrada, and Bryan P. Rasmussen

***Abstract*— Variable refrigerant flow (VRF) systems are increasingly being used in commercial buildings in preference to chilled water or ducted air systems. The closely coupled dynamics of VRF systems, however, create a need for effective control strategies to ensure safe and effective operation. Of particular interest is the regulation of evaporator superheat. In this paper a cascaded architecture for controlling superheat is applied to a multiple evaporator system, and compared to traditional PID-controlled evaporators. The effects of the architecture on dynamic coupling are explored, and efficacy is demonstrated with experimental results.**

I. Introduction

AIR conditioning has traditionally been performed by chilling air with a vapor compression cycle (VCC), then passing the air to the appropriate region through ducting. In large building air conditioning systems, water is chilled, then piped to air handling units, which cool the air for each region. In both cases, ducting or water pipes are required, creating the potential for cooling losses through friction or duct leakage. Variable refrigerant flow (VRF) systems, on the other hand, use a separate evaporator for each cooling zone; refrigerant is piped directly to the individual evaporators from a central compressor/condenser unit, minimizing the transport losses of the system.

The use of multiple evaporators, however, creates a new set of control challenges, since the dynamics of the evaporators are tightly coupled to each other. This paper shows that the use of a cascaded control architecture to regulate the superheat of each evaporator decouples the dynamics of the evaporators, provides superior control as compared to traditional PID approaches, and does so without requiring a centralized, computationally expensive MIMO controller.

A. Superheat Control

A vapor compression cycle consists of four processes: isentropic compression, isobaric heat rejection and condensation, isenthalpic expansion, and isobaric heat absorption and evaporation. Fig. 1 shows the cycle components for an ideal multiple evaporator VCC; Fig. 2 is the corresponding pressure-enthalpy (P-h) curve for the cycle.

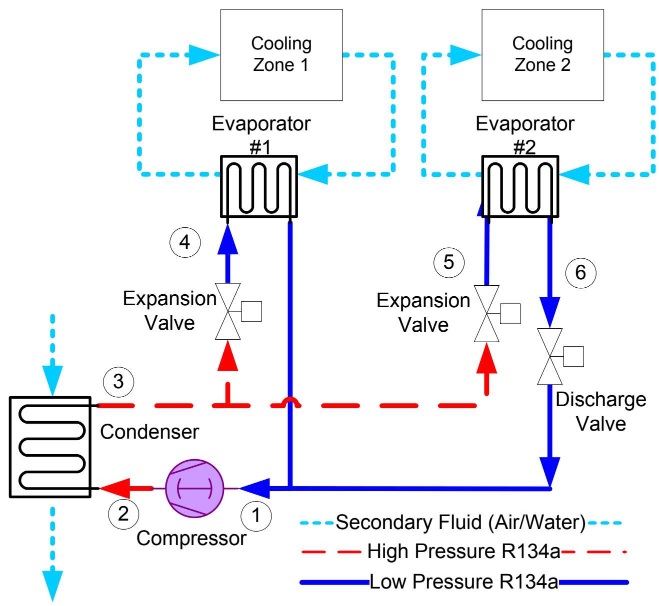

Fig. 1. Vapor compression cycle (VCC) components.

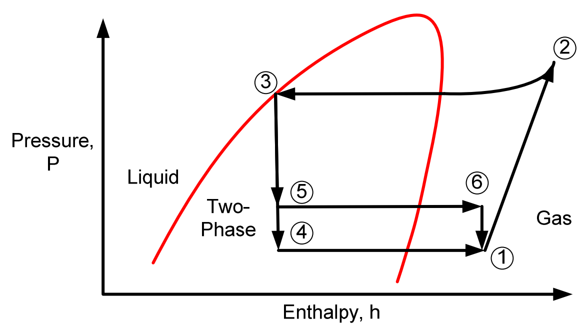

Fig. 2. Pressure-enthalpy (P-h) diagram.

Superheat control is a critical control problem for VCC-based systems, both in terms of optimizing system efficiency and preventing component failure. As the fluid passes through the evaporator, it absorbs heat and transitions from a liquid-gas mixture to a saturated vapor, and then further to a superheated vapor. If the refrigerant is allowed to leave the evaporator without completely vaporizing (i.e., no superheat), it will enter the compressor as a two-phase mixture, with the potential of causing catastrophic failure of the compressor. However, since the majority of the heat

Manuscript received September 27, 2010. This work was supported in part by NSF CAREER AWARD CMMI-0644363.

Matthew S. Elliott is a graduate researcher with the Texas A&M University Department of Mechanical Engineering, College Station, TX.

Carolyn Estrada is an undergraduate researcher with the Texas A&M University Department of Mechanical Engineering, College Station, TX.

Bryan P. Rasmussen is an Assistant Professor of Mechanical Engineering at Texas A&M University, College Station, TX. (phone: 979-862-2776, fax: 979-845-3081, email: brasmussen@tamu.edu).

transfer occurs during the vaporization process, excessively high superheat results in reduced cooling capacity of the system. Therefore, the portion of two-phase flow in the evaporator should be maximized in order to obtain maximum cooling capacity of the system. In general, an acceptable compromise between efficiency and safety is for the refrigerant at the evaporator exit to be a few degrees above its saturation temperature. Regulating this temperature difference is called superheat control, a perennial control problem for HVAC&R applications. Historically, this control was performed with a mechanical actuator called a thermostatic expansion valve (TEV). A well-known problem with these devices was oscillatory behavior at non-design conditions, called valve hunting. This phenomenon was shown to be a result of the interplay between the actuator and the evaporator dynamics [1]. Adoption of the electronic expansion valve (EEV) allowed for automatic control techniques such as PID to be applied to the evaporator, with improved performance over the TEV [2].

For VRF systems, which feature variable speed compressors and fans as well as EEVs, the dynamic coupling between components means that the success of SISO systems can be severely limited [3]. Systems with multiple evaporators can be even more difficult due to the tight coupling between evaporators [4]. This paper shows how a simple control architecture that requires no model and uses system outputs ordinarily available can be used to control a multiple evaporator system.

II. Cascaded Architecture

Earlier research efforts explored the application of a cascaded control architecture to superheat control for a single evaporator; this architecture is shown in Fig. 3. This was first embodied with the hybrid expansion valve (HEV), so called because it combined electronic and mechanical feedback to achieve superior superheat regulation [5]. The cascaded loops can also be implemented with a standard electronic expansion valve (EEV), although actuator limitations of traditional EEVs suggest that the use of MEMS-based expansion valve technology is preferred for this application [6]. An additional benefit to the architecture is that it linearizes the plant without a priori knowledge of the valve or system characteristics; the extent to which the plant is linearized depends upon the magnitude of the inner feedback loop gain, K_F [7]. Fig. 4 shows the step responses for a typical EEV as well as that of the HEV; the response of the HEV is the same for high flow and low flow conditions, while the gain of the EEV is noticeably different. A larger K_F gain also leads to better performance, although the actuator must have sufficiently high bandwidth to carry out this task.

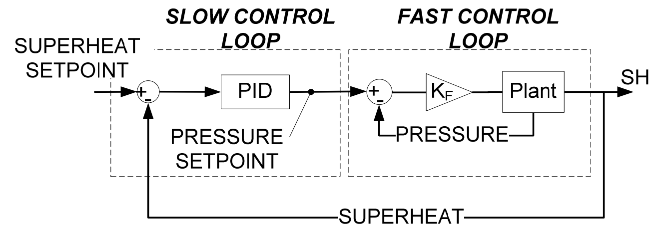

Fig. 3: Cascaded control architecture.

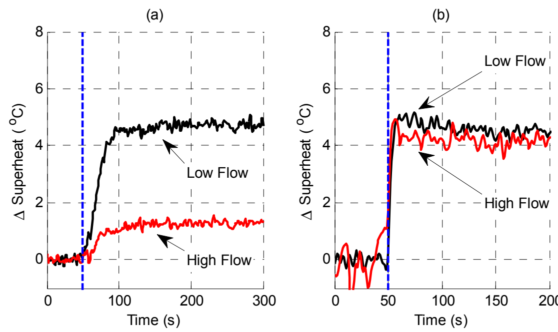

Fig. 4: Step responses for (a) EEV and (b) HEV. The HEV gain is independent of the operating condition.

Since VRF systems will generally have multiple evaporators, and the cascaded superheat control architecture is generally superior to simple PID superheat control due to the richer information stream available to the cascaded controllers, the application of cascaded control to multiple evaporator systems is a natural progression. As noted, these systems are tightly coupled dynamically, which makes decentralized control difficult to implement successfully. Multiple-input, multiple-output (MIMO) control could be used to accommodate this coupling, assuming an accurate model could be developed (which is a significant undertaking). Since the evaporators are in general spatially distributed—spread out between different locations in a large building—the communication requirements between sensors and controllers for MIMO controllers become difficult to meet. Also, the addition or removal of evaporators would require a new model to be developed every time. These factors point to a need for a locally based, distributed set of controllers, preferably with no need for communication between them. To this end, a Relative Gain Array (RGA) analysis allows exploration of the feasibility of applying decentralized control to a MIMO system [8]. From the RGA, an RGA number can be calculated that gives the follows that shows that the cascaded control architecture serves to decouple the dynamics of a multiple evaporator system. The equations for calculating the RGA and RGA number for a MIMO system G(s) at a frequency ω are given in (1) and (2), respectively.

$$RGA: \ \Lambda(G(j\omega)) = G(j\omega) \times \left(G(j\omega)^{-1}\right)^T \quad (1)$$

$$RGA\ Number: \ N(G(j\omega)) = \left\| \Lambda(G(j\omega)) - I \right\|_{sum} \quad (2)$$

Fig. 5 shows the two plants used in the analysis; the model for the two-evaporator system G(s) was developed experimentally from a small-scale two evaporator water chiller, and the cascaded system Q(s) was derived from this model. The RGA for the system G(s) at steady state is shown in (3).

$$\Lambda(G(0)) = \begin{bmatrix} 1.2208 & -0.2208 \\ -0.2208 & 1.2208 \end{bmatrix} \quad (3)$$

The RGA number is a parameter that gives a measure of coupling between SISO pairs; the closer to zero, the more decoupled the system dynamics [8]. Fig. 6 shows the RGA number as a function of inner feedback gain K_F, as well as the RGA number of the open loop plant G(s). For G(s) in this analysis the two EEV positions are the inputs and the superheats are the outputs; for the cascaded plant Q(s) the pressure setpoints are the inputs and the superheats are the outputs. The introduction of the inner feedback loop immediately improves the decoupling of the evaporators, giving a minimum amount at a K_F of approximately 0.07. While larger values create a more closely coupled system, higher K_F terms are generally used because they are required to achieve nonlinear compensation and better performance of the cascaded system. The range of typical values used is indicated in Fig. 6. This figure shows that cascaded control loops can be used to decouple the dynamics of a multiple evaporator system.

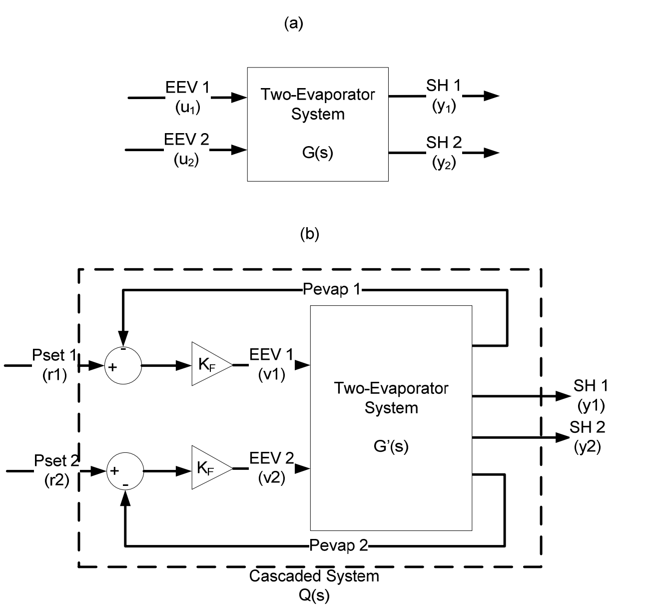

Fig. 5: Two plants studied in the RGA analysis: (a) G(s)—EEV inputs, superheat outputs. (b) Q(s)—Pressure setpoint inputs, superheat outputs.

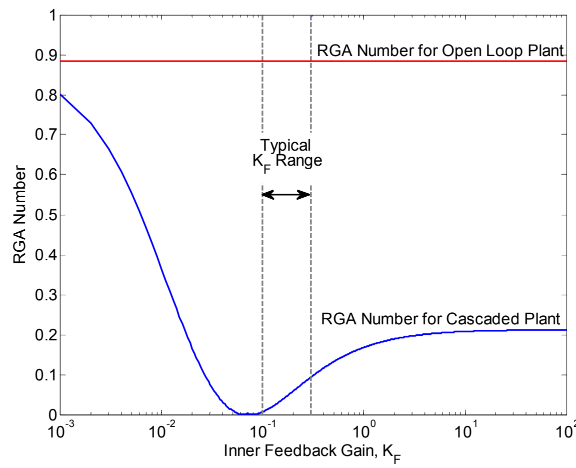

Fig. 6: RGA Number vs. Inner Feedback Gain, K_F

III. Experimental Results

Experimental tests were conducted on a small scale two-evaporator water chiller to compare the performance of cascaded control loops with traditional PID controllers. The EEVs used on this system are piloted valves that use a MEMS based pilot to actuate the valve. This construction features faster response than typical EEVs, which use a stepper motor to control the valve. The first test is a comparison of the disturbance rejection performance of the system when controlled by cascaded and PID architectures; the superheat setpoint for both evaporators in both cases is 10°C. The disturbance is a 33% step increase in compressor speed, corresponding to a sudden increase in cooling load demand for the system as a whole. The results of the test are seen in Fig. 7 (cascaded control) and Fig. 8 (PID control). The cascaded controller does a much better job of rejecting the disturbance than the PID-based controllers, as the superheat tracks the setpoint very closely despite the change in compressor speed at 50 s. The change in system operating conditions causes the PID controllers to struggle, as the dynamic responses of each interfere with the other. The controller signals for the two cases are given as well; the pressure setpoints seen in Fig. 7(b) simply rise slowly to accommodate the compressor speed increase, while the PID controlling the EEVs directly in Fig 8(b) are seen to engage in hunting behavior as the dynamics interfere with each other. Table I quantifies the performance of the two architectures in terms of the maximum absolute error (MAE) and the root mean square of the error (RMSE); the formulae for calculating these quantities over n samples are given in (4) and (5).

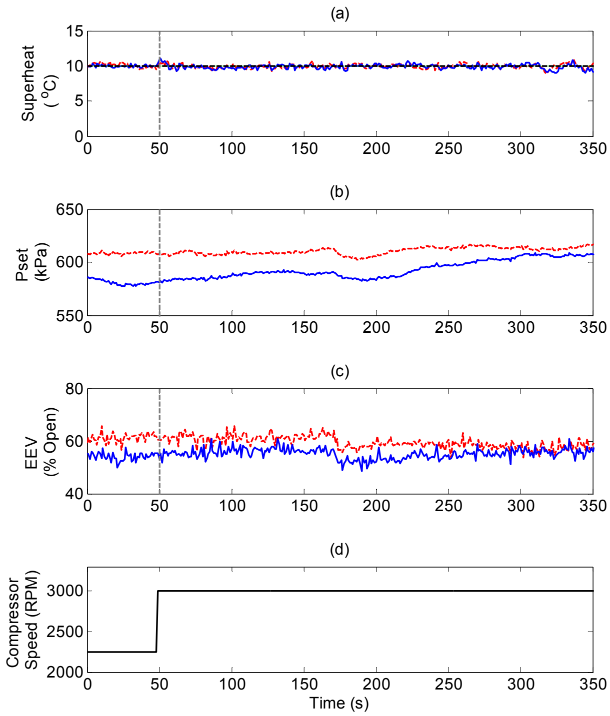

Fig. 7: Cascaded control response to step disturbance. (a) Superheat in evaporators 1 and 2, (b) Outer PID controller pressure setpoints, (c) EEV opening, (d) Compressor speed.

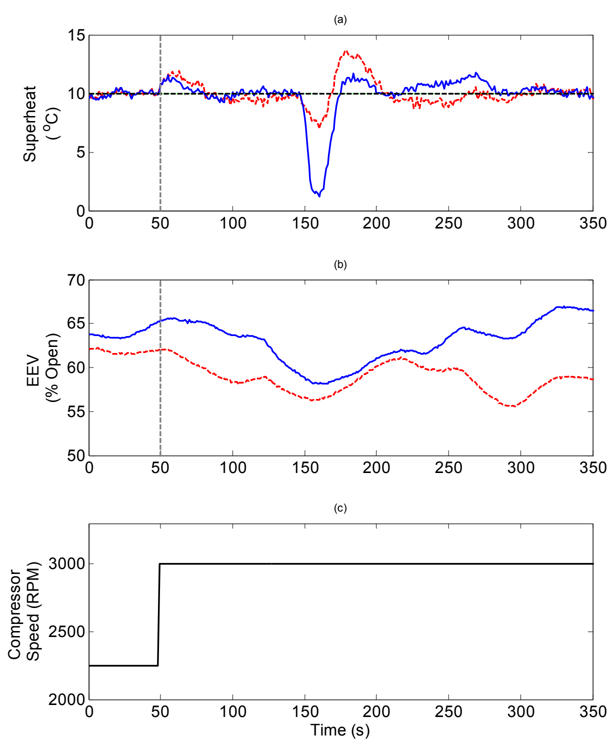

Fig. 8: PID control response to step disturbance. (a) Superheat, (b) PID-controlled EEV opening, (d) Compressor speed.

TABLE I
PERFORMANCE COMPARISON FOR CONTROL ARCHITECTURES

Architecture	Evaporator 1		Evaporator 2	
	RMSE	MAE	RMSE	MAE
PID	0.62	3.65	0.90	8.79
Cascaded	0.29	1.29	0.40	1.83
% Improvement	53.2%	64.7%	55.6%	79.2%

$$MAE = \max_i \left| SH_i - SH_{set} \right| \tag{4}$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} \left(SH_i - SH_{set} \right)^2}{n}} \tag{5}$$

In general, as low a superheat as can safely be maintained is desirable, since this means that the evaporators are being used most efficiently. However, at lower superheat levels the regulation must be tighter, since superheat must be retained for safe operation. In addition to separating the evaporator dynamics, the cascaded loop has the effect of linearizing the plant's response to the outer controller's action, so the same controller can be used effectively at different operating conditions. This is not true of the PID controllers, which must be re-tuned to achieve comparable results over all operating regions. One of the difficulties experiences in tuning the PID controllers is that they must be tuned very conservatively with low gains, since the outputs are so tightly coupled that the controllers fight each other, displaying oscillatory behavior (valve hunting).

The second test, shown in Fig. 9, further displays the decoupling achieved by the cascaded controller. The setpoint of evaporator 1 is decreased from 10°C to 4°C, which has the effect of increasing the cooling performed by this evaporator. In the case of the cascaded controller, the new setpoint is achieved with a minimum of disturbance to the other evaporator. In the PID controlled case, the change in the evaporator's condition excites the dynamics of the other evaporator, which sets up severe hunting in both evaporators. Additionally, the PID controllers are unable to keep the system operating at a low superheat consistently, which means that the cascaded controller can be used to achieve better system efficiency.

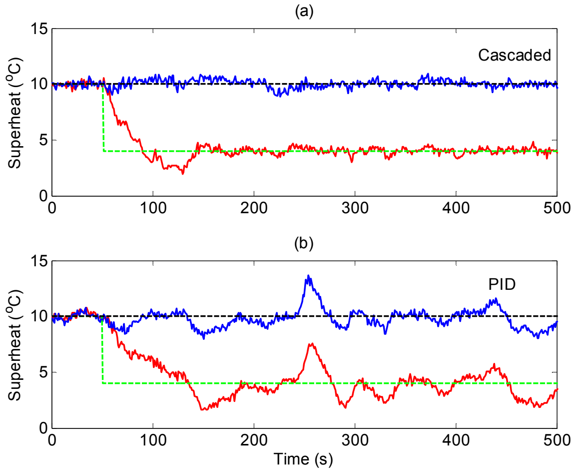

Fig. 9 Response of both evaporators to a setpoint change in evaporator 1. (a) Cascaded Control (b) PID control.

An important test for a VCC controller is the ability to quickly achieve steady state operating conditions upon system startup. An effective controller will bring superheat to the desired setpoint quickly once the compressor is turned on; this means that the desired level of cooling capacity (evaporator heat transfer) is reached and stabilized quickly, and the evaporator exit temperature of the water or air being chilled reaches its final value quickly. This is sometimes referred to as a pulldown test. Figs. 10 (cascaded control) and 11 (PID control) show the results of this test.

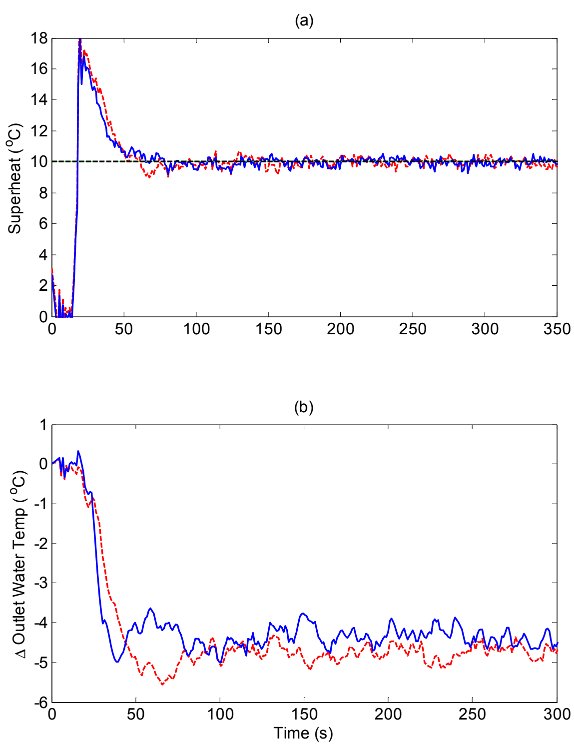

Fig. 10 Startup test of cascaded controllers. (a) Evaporator superheat and (b) Change in water temperature at evaporator outlet.

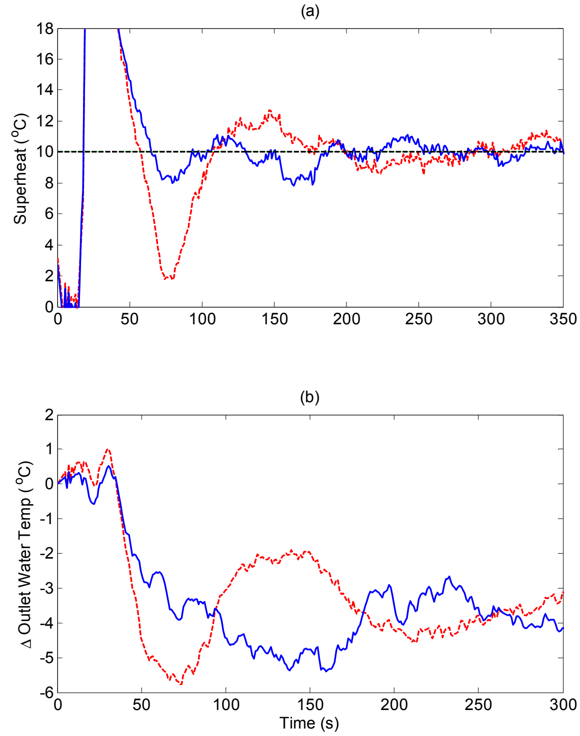

Fig. 11 Startup test of PID controllers. (a) Evaporator superheat and (b) Change in water temperature at evaporator outlet.

From these tests, the cascaded controller's ability to decouple the evaporators' dynamics means that stable superheats can be achieved quickly. An additional benefit can be seen, as well—the valve hunting exhibited by the PID-controlled system creates an oscillation of several degrees in the outlet temperature of the water. For an air conditioning system, the desired effect is for the air outlet temperature to be pulled down to a desired level and kept constant at that level. Oscillations in the temperature can have a serious and negative impact on the comfort of the individuals in the controlled space. This can also have a negative impact in a situation where good regulation is operationally imperative, such as a supermarket case, refrigerated truck, or a computer server room. All of these are common applications of VRF and multiple evaporator technology, so they are highly relevant to those interested in system and control design of these VCC systems.

During the normal operation of multiple evaporator systems, a frequent occurrence will be the shutting off or restarting of various evaporators as the cooling load demands change. This obviously has a major impact on the dynamics of all of the evaporators in the system, so any superheat controller must be able to reject this disturbance and continue to regulate its own superheat objective. The final tests presented here involve this scenario. Evaporator 1 is shut off at 50 seconds; this shutoff involves closing the valve completely and turning off the water pumped through that evaporator. The compressor speed is kept constant during this test. Fig. 12 shows the results of the test, namely the superheat in evaporator 2 for (a) the cascaded controller and (b) the PID controller. Again, the cascaded controller is able to reject the disturbance much more quickly and achieve good regulation, while the PID controller oscillates over the duration of the test after the first evaporator is shut off.

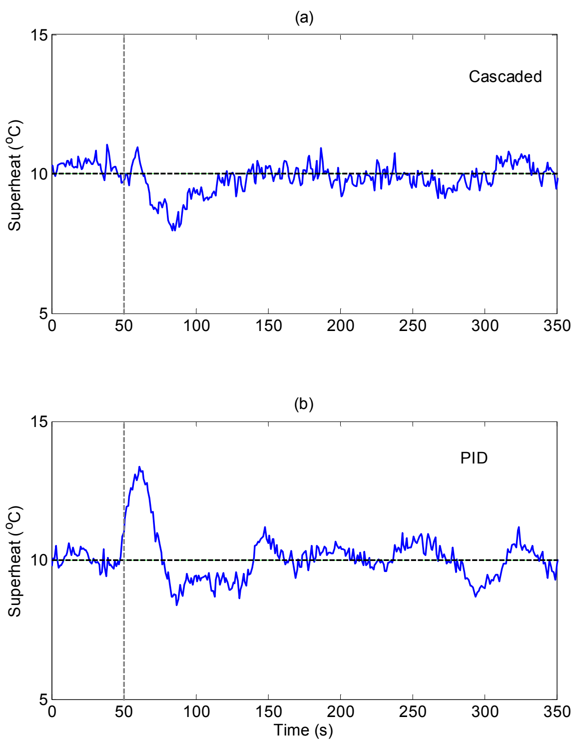

Fig. 12 Evaporator shutoff test. The first evaporator is shut off at 50 s, and the superheat of evaporator 2 is shown for (a) Cascaded control and (b) PID control.

IV. Future Work

This paper has only considered control of the EEVs to regulate evaporator superheat, but the multiple actuators in a VRF system—compressor, evaporator fans, condenser fan—give several more degrees of freedom for system control. Future work will involve the integration of cascaded superheat control into a larger control framework that involves these actuators to balance user comfort, system energy efficiency, and operational safety.

V. Conclusions

VRF refrigeration and air conditioning systems require effective regulation of the individual evaporators' superheats into order to operate safely and effectively. In order to simplify implementation, a control architecture that does not require a model of the system as a whole is preferable to a more advanced MIMO-style controller. However, the tightly coupled dynamics of such a system make the use of decentralized controllers difficult. The use of cascaded controllers to regulate superheat by calculating a pressure setpoint for a proportional controller to meet has been shown to be more effective than a traditional PID controller because it decouples the system dynamics from each other, allowing tighter regulation of superheat. Furthermore, this allows the system to be safely operated at a lower setpoint, which means the system can be operated with greater energy efficiency while retaining component safety.

Acknowledgment

The authors gratefully acknowledge the support provided by the National Science Foundation under grant CMMI-0644363, and the assistance of anonymous reviewers for their constructive and useful comments.

References

[1] P. M. T. Broersen and M. F. G. van der Jagt, "Hunting of evaporators controlled by a thermostatic expansion valve," ASME Journal of Dynamic Systems Measurement & Control, vol. 102, pp. 130-135, Jun. 1980.

[2] W. Gruhle and R. Isermann, "Modeling and control of a refrigerant evaporator," ASME Journal of Dynamic Systems Measurement & Control, vol. 107, pp. 235-240, Dec. 1985.

[3] X. He, S. Liu, and H. Asada, "Modeling of vapor compression cycles for multivariable feedback control of HVAC systems," Journal of Dynamic Systems Measurement and Control, vol.119, pp.183-191, Jun. 1997.

[4] R. Shah, A. Alleyne, and C. Bullard, "Dynamic modeling and control of multi-evaporator air-conditioning systems," ASHRAE Transactions, vol. 110, pp. 109-119, 2004.

[5] Elliott, M., Walton, Z., Bolding, B., and Rasmussen, B., "Superheat Control: A Hybrid Approach," HVAC&R Res., vol. 15., no. 6, pp. 1021-1043, 2009.

[6] Elliott, M.S., Rasmussen, B.P. "Evaporator superheat regulation via emulation of semi-active flow control," Proceedings of the 2009 ASME Dynamic Systems and Control Conference, in press.

[7] M. S. Elliott, B. P. Rasmussen, "On reducing evaporator superheat nonlinearity with control architecture," International Journal of Refrigeration, Volume 33, Issue 3, May 2010, Pages 607-614

[8] S. Skogestad and I. Postlethwaite, Multiple Feedback Control: Analysis and Design, 2nd ed. West Sussex, England: John Wiley & Sons, Ltd., 2005.