Cooling Capacity Control for Multi-Evaporator Vapor Compression Systems

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Abstract

Multi-evaporator vapor compression systems (ME-VCS) provide cooling to multiple zones. The thermodynamic conditions in these zones are independent: the heat loads often differ, and the occupants of these spaces often have different desired room temperatures. Therefore, in order to regulate each zone to its desired setpoint temperature, the amount of thermal energy removed by each evaporator must be controlled independently. However, a common evaporating pressure introduces coupling between all the evaporators that makes this objective difficult- the valve and piping arrangement imposes the constraint that all evaporators operate at the same temperature. In order to control the per-zone cooling, a common control strategy employed in the literature is to duty cycle the evaporator (alternate between a fully-open and fully-closed valve). However, duty cycling causes periodic disturbances to not only the local zone, but also to many critical machine temperatures and pressures, and these disturbances are often not transient but instead persist indefinitely. Fluctuations induced by the periodic disturbances can degrade the ability of the machine to regulate zone temperatures with zero steady state error, cause excessively high or low temperatures during peaks of the period, and couple into most machine signals of interest in ways that are difficult to describe with low order dynamical models. An observed behavior of refrigerant mass distribution in multi-path heat exchangers is exploited for control purposes. Multi-path heat exchangers are characterized by an inlet header pipe that splits refrigerant flow to two or more parallel paths through the heat exchanger and collects those paths into a common outlet header pipe. In the paper, we describe the following empirical phenomenon exploited for control: as the inlet valve is decreased, refrigerant mass flow rate entering the heat exchanger is reduced, and at some critical flow rate, refrigerant is shown to preferentially flow in some paths more than others, causing maldistribution. This uneven refrigerant distribution is repeatable, reduces the capacity in a continuous manner and can be exploited with feedback controllers to regulate the per-zone cooling. A feedback controller is designed to provide stability and robustness to per-zone conditions and setpoints for this controller that relate per-path superheat temperature to overall evaporator capacity is created in such a way as to be robust to changes in local zone temperatures and the overall system evaporating temperature. This strategy provides zone decoupling and ultimately creates a virtual control input for a supervisory controller such as a model predictive controller. Experiments demonstrate the effectiveness of this approach on a two-zone air conditioner in laboratory tests.

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An observed behavior of refrigerant mass distribution in multi-path heat exchangers is exploited for control purposes. Multi-path heat exchangers are characterized by an inlet header pipe that splits refrigerant flow to two or more parallel paths through the heat exchanger and collects those paths into a common outlet header pipe. In the paper, we describe the following empirical phenomenon exploited for control: as the inlet valve is decreased, refrigerant mass flow rate entering the heat exchanger is reduced, and at some critical flow rate, refrigerant is shown to preferentially flow in some paths more than others, causing maldistribution. This uneven refrigerant distribution is repeatable, reduces the capacity in a continuous manner and can be exploited with feedback controllers to regulate the per-zone cooling.

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1 INTRODUCTION

Vapor compression systems (VCS) are widely used in industrial (Chua *et al.* (2010)), commercial (Hepbasli and Kalinci (2009)) and residential (Chen *et al.* (2015)) applications for cryogenics (Burger *et al.* (2001)), refrigeration (Tassou *et al.* (2009)) and air conditioning (Burns and Laughman (2012)). Recent advancements in power electronics, embedded computing and the electrification of restriction valves have led to wide deployment of actuators with variable control authority such as inverter-driven compressors, variable speed fans and electronically-positioned expansion valves (Choi and Kim (2003)). Additionally, market pressure has driven VCS manufacturers to reduce the number of actuators and sensors where possible (Gopal *et al.* (2014)). As a result of these trends, there are emerging

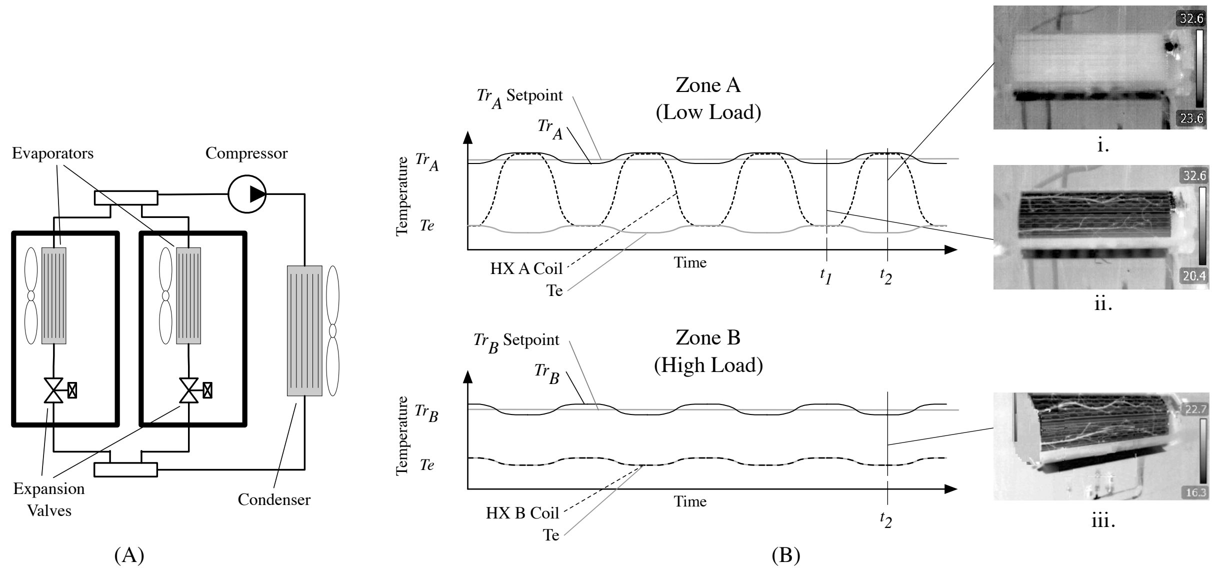

Figure 1: (A) Piping diagram of the multi-evaporator vapor compression system considered in this work. The absence of expansion valves at the outlet of each evaporator imposes a single evaporating pressure and therefore temperature. (B) Example of an duty cycling control strategy commonly used in the literature to modulate cooling capacity by operating the associated valves in an 'on-off' manner, which induces large variations in heat exchanger coil temperatures (shown in inset thermographic images) that couple into other signals such as the evaporating temperature Te and even other zone air temperatures.

opportunities for more advanced control of variable-actuation vapor compression systems, but these new strategies must conform to the restrictions imposed by a limited number of sensors and the valving/piping arrangement that meets performance expectations with the fewest number of machine components.

Multi-evaporator vapor compression systems (ME-VCS), such as those used in refrigeration systems and multi-room residential air conditioning applications, split refrigerant flow among several low-side heat exchangers to simultaneously provide cooling to multiple zones. Many studies on the control of multi-evaporator systems often include expansion valves on both the inlet and outlet sides of each evaporator, simplifying the control objectives as evaporator pressures become decoupled (Elliott and Rasmussen (2013)). However, due to economic pressures previously mentioned, restriction valves on the exit side of each evaporator are often eliminated, resulting in the type of system shown in Figure 1A. This parallel arrangement of valves in the refrigeration circuit results in a common evaporating pressure for all evaporators that are 'on,' that is, for all evaporators where the associated inlet expansion valves are not closed. Although the expansion valves may be individually set to different openings, the overall high and low pressures are determined by the joint combination of the inlet valve openings. And since the evaporation process is isothermal when it is isobaric, all active evaporators are constrained to operate at a single temperature. Therefore, the lack of valves at the outlet of each evaporator imposes a constant evaporating temperature for the entire multi-evaporator system.

While evaporators within the ME-VCS may be mutually coupled, the heat loads and desired zone air temperatures for each zone are not—the cooling required by each zone are independent. Therefore, the challenge a ME-VCS controller must address is how to modulate cooling for each evaporator in a coupled system given the independent zone thermal requirements.

A typical control strategy employed in the literature modulates the cooling capacity by operating the evaporator in a duty cycled fashion (Whitman *et al.* (1999)). That is, despite including a valve that is capable of variable openings, many commercial systems use the valve as an 'on–off' style actuator with two possible operating states. An example of this approach is shown in an illustration in Figure 1B, where the heat load in Zone A is lower than that of Zone B. In order to satisfy the higher load of Zone B, a relatively low system evaporating temperature is selected which results in continuous operation of the evaporator in Zone B. However, the evaporating temperature is too low for the conditions in Zone A, and as a result, the zone becomes overcooled relative to the setpoint. A duty cycling controller periodically closes the expansion valve associated with Zone A, thereby stopping refrigerant flow into that heat exchanger. After the zone air then warms to a temperature above the setpoint, the valve is reopened. When the associated expansion valve is opened, the entire heat exchanger temperature (labeled 'HX A Coil') operates at the system evaporating temperature, and when closed, the heat exchanger warms to the zone air temperature. These two operating states are shown in thermographic (infrared) images in Figure 1B-i and 1B-ii, whereas the heat exchanger for Zone B ('HX B Coil') operates continuously at the evaporating temperature as in Figure 1B-iii. Note that the periodic opening and closing of expansion valves induces disturbances in many internal temperatures and pressures. The evaporating temperature (labeled 'Te' in Figure 1B) is affected by duty cycling the expansion valve associated with Zone A, which then perturbs the air temperature in Zone B.

Additionally, for equipment protection and efficient operation, a ME-VCS controller should enforce limits on many machine temperatures and pressures. Model predictive control is a natural fit for this problem, but duty cycling introduces perturbations into these constrained outputs that are difficult to predict. Moreover, while the previous example described a two-zone system where one zone was duty cycling, in general, for an N-unit system, $N-1$ evaporators may be duty cycling with different periods that depend on the local zone conditions. Therefore, $N-1$ large-amplitude disturbances, each with unpredictable periods are likely to induce perturbations into the system outputs to be constrained, precluding development of prediction models and therefore development of model predictive controllers.

In order to smoothly and continuously modulate the cooling capacity of evaporators in a multi-evaporator vapor compression system, this paper reports an observed behavior of refrigerant mass distribution in multi-path heat exchangers and exploits this behavior for control purposes. This refrigerant distribution within a heat exchanger is repeatable, and although unstable with respect to local conditions, it can be stabilized with a simple feedback controller and a low cost temperature sensor arranged on each path. Using the method presented here, individual heat exchangers that are coupled through the pressure dynamics can be independently regulated to meet the local zone loading conditions without inducing perturbations, thereby enabling the subsequent development of model predictive control for equipment control.

The remainder of this paper is organized as follows: Section 2 introduces a multi-path heat exchanger and describes an observed dependency of refrigerant distribution on expansion valve opening. Section 3 details how a feedback controller can be designed to stabilize the evaporation process by controlling the superheat temperatures of each path within the heat exchanger according to a specific setpoint function. Experimental validation of the approach is provided in Section 4, which demonstrates capacity control in a commercial two-zone ME-VCS. Finally, concluding remarks and extensions to model predictive control are offered in Section 5.

2 REFRIGERANT DISTRIBUTION

This section describes an observed characteristic of multi-path heat exchangers as the associated expansion valve position is changed. A commercially-available two-zone variable refrigerant flow (VRF) type air conditioner is installed in three adiabatic test chambers (one for each indoor unit and one for the outdoor unit). The air temperatures and heat loads in each test chamber are controlled by a secondary balance-of-plant (BOP) system.

Refrigerant flow within the indoor unit heat exchangers are split among two paths as shown in Figure 2A. Two temperature sensors (labeled points '1' and '2' in Figure 2A) are configured to measure the surface temperatures of the heat exchanger coil for each path. The system is configured such that both zones operate in steady state with both expansion valves in their open positions. While one zone continues to operate with a fully-opened valve, the other valve is slowly closed in a quasi-steady state manner. The heat exchangers are a wall-mount style where the covering has been removed so that an infrared camera can measure the heat exchanger surface temperatures.

Figure 2B shows thermographic images of the heat exchanger as the expansion valve position is changed, and Figure 2C is an illustration of the corresponding path temperature response. With the valve fully opened, both paths are filled with mostly two-phase refrigerant and therefore both path temperatures are at the system evaporating temperature (right side of Figure 2C). However, as the valve is closed, refrigerant in path 1 becomes superheated while path 2 remains at the evaporating temperature (labeled ‘iv’ in Figure 2B and C). The valve is further reduced and more superheating occurs in path 1 (Figure 2C-ii) until the temperature in that path of the coil warms to the room temperature. Subsequent reduction in the valve opening causes superheating to occur in path 2 (Figure 2C-i).

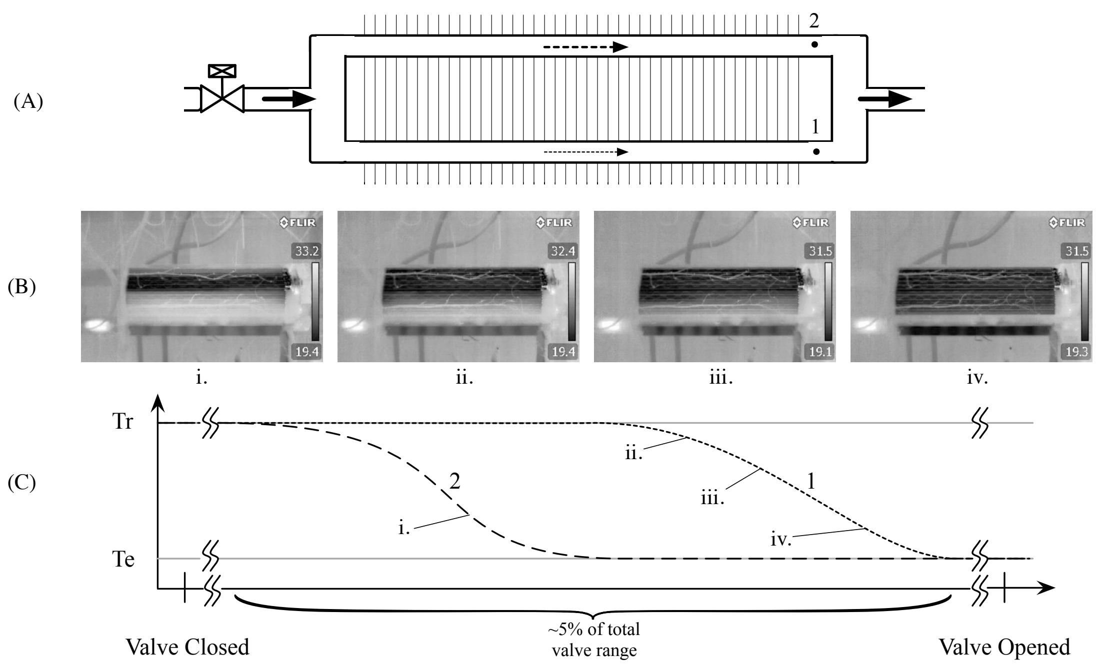

Figure 2: (A) A schematic representation of a multi-path tube-and-fin heat exchanger where each path is measured with a temperature sensor (shown as points 1 and 2). (B) Thermographic images of a multi-path heat exchanger for different valve openings at controlled conditions showing how refrigerant becomes distributed as the valve position changes. The thermographic images i.–iv. correspond to different valve openings for a particular set of test conditions as indicated in subfigure C. (C) Illustration of the dependency of two heat exchanger path temperatures on valve position, showing superheating occurring preferentially in one path. The function labeled ‘1’ corresponds to temperature sensor 1 on the first path, and the function labeled ‘2’ corresponds to temperature sensor 2 on the other path.

The observation that superheating for each path occurs at different operating conditions establishes that two-phase refrigerant preferentially flows along one path as the mass flow rate is reduced. As one and then both paths become superheated, a smaller fraction of the evaporator surface area is used for heat exchange. Therefore, by controlling the per-path temperature with a single expansion valve, the cooling capacity of the entire heat exchanger can be smoothly and continuously reduced.

Note that a smaller total cooling capacity and therefore a wider range of operating conditions can be achieved with per-path measurements than by the controlling the conditions only at the evaporator outlet (as is common in typical superheat regulation controllers). Once the refrigerant at the outlet of the heat exchanger has become superheated to the point where the refrigerant temperature reaches the air temperature, that measurement is saturated and provides no additional sensible information useful for control. This outlet saturation point can occur even though a substantial fraction of the refrigerant in the heat exchanger remains in two-phase, depending on the specific design and configuration of the heat exchanger. In contrast, by directly controlling per-path temperatures, a greater reduction in cooling capacity can be achieved before the per-path temperature measurements are saturated, and therefore a wider operating range of the overall ME-VCS can be obtained.

However, the range of valve openings over which the per-path temperatures change sensibly is narrow and sensitive to the operating conditions. Specifically, Figure 2C shows a zoomed-in range of valve positions that provide sensible changes in path temperatures, where most of the range occurs with no sensible change in path temperatures (evaporator flooded or starved). For the systems tested, it is found that about 5% of the total valve operating range spans the heat exchanger operation from mostly two-phase to mostly superheated. But this narrow range of valve positions for which the path temperatures are controllable depend on the particular operation of the machine—*e.g.,* the refrigerant mass flow rate through the heat exchanger, the air flow rate, the operating pressures, the heat load, *etc*. Furthermore, the heat exchanger state is unstable: if the heat exchanger is operating such that one path is within the sensible range, then small changes in heat load will increase the heat transfer, causing more superheating, reducing the cooling capacity and ultimately leading to the saturation of one or both measurements. However, this phenomenon can be stabilized with feedback, enabling a smooth reduction in cooling capacity with capacity controller as described in the next section.

3 CONTROLLER ARCHITECTURE

The measurable refrigerant distribution within a multi-path heat exchanger (and the corresponding reduction in cooling capacity) is used here to create cooling capacity controllers for each evaporator in a multi-evaporator vapor compression system. Referring to Figure 3A, these capacity controllers accepts signals by a supervisory controller indicative of a requested cooling capacity for a particular zone and in turn, issues commands to an associated expansion valve. The valve command is computed by the capacity controllers such that a selected path temperature sensor is driven to a coil setpoint, which is computed to achieve a fractional cooling capacity.

Figure 3B provides more details about the capacity controller, which consists of (i) linearization logic, (ii) a coil setpoint function, (iii) a feedback regulator, and (iv) a switch for selecting path temperature sensors. The linearization logic acts on the received capacity command and selects a path of the heat exchanger to be used for control. It may

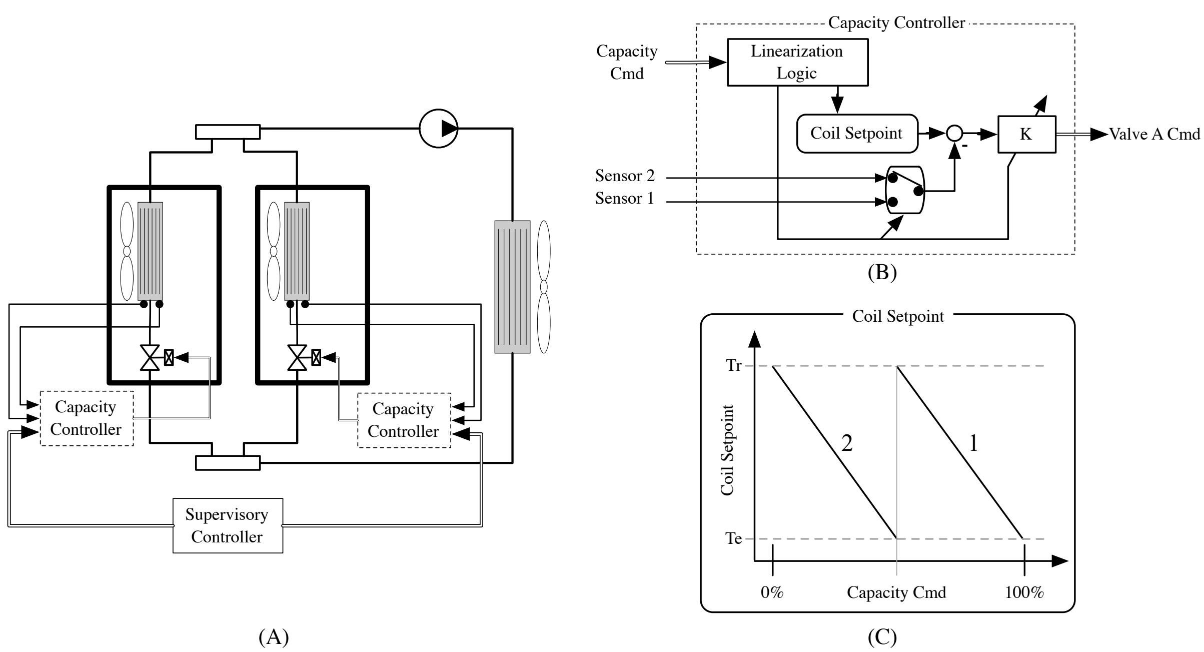

Figure 3: (A) Controller architecture overview. A supervisory controller issues desired cooling capacities to separate capacity controllers, which in turn, issue commands to the expansion valves. (B) Each capacity controller consists of setpoint logic, a feedback regulator and a coil setpoint function. (C) The coil setpoint function relates desired cooling capacity to per-path temperatures and is scheduled on the system evaporating pressure and local zone temperature.

also select predetermined feedback gains for the regulator in the case that the feedback regulator is gain scheduled (the heat exchanger dynamics may vary depending on which path is controlled because vapor compression systems operating at low load tend to have higher system gains and therefore require lower controller gains to ensure stability). Additionally, the linearization logic provides the capacity command to a coil setpoint function.

The coil setpoint function (Figure 3C) codifies the observed relationship between coil path temperatures and different refrigerant distributions that lead to changes in cooling capacity. Specifically, note the similar shape of curves between Figures 2C and 3C. The coil setpoint function maps the desired cooling capacity (expressed as a fraction of the full designed capacity) to path temperatures. Note that these path temperatures are bounded from below by the common system evaporating temperature and from above by the associated zone temperature. In general, these bounds can be time-varying and change with the local zone conditions. Therefore, by scheduling the path setpoint temperature on these bounds (measured at the time the setpoint is computed), robustness in achieving the desired cooling capacity is improved because the dependency on local conditions is included in the setpoint calculation. Further, by upper bounding this map on the local zone temperature, saturation of the measurement (and therefore loss of feedback control) is avoided. As a result of the form of this coil setpoint function, these capacity controllers serve to robustly linearize the cooling capacity and reject disturbances from changes in zone conditions. To demonstrate the performance of this control architecture, experiments are performed comparing the capacity control method to a duty cycling approach in the next section.

4 EXPERIMENTAL DATA

In this section, experimental results are presented for modulating cooling in a multi-evaporator vapor compression system by comparing the capacity control method to a duty cycling method. A description of the experimental apparatus is provided, the experimental results are described followed by a brief discussion.

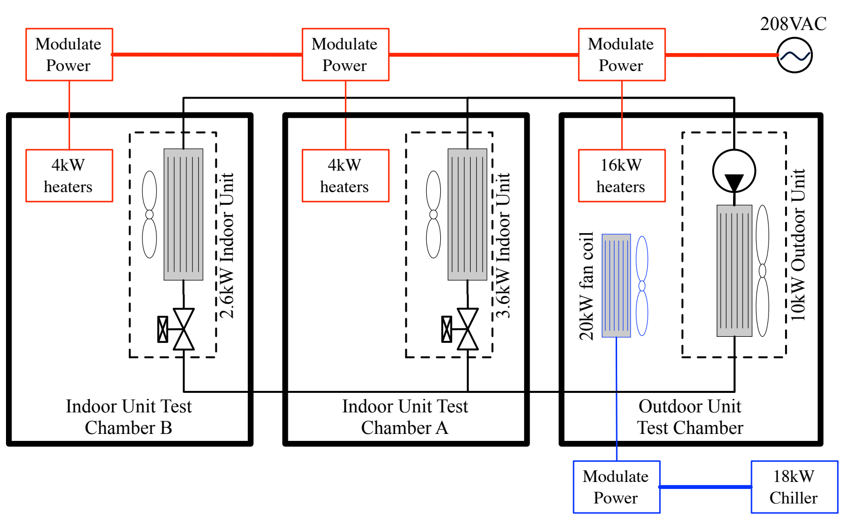

Figure 4: The outdoor unit and two indoor units of a multi-evaporator vapor compression system is installed in three adiabatic test chambers. A balance-of-plant (BOP) system consists of a set of adjustable-power heaters (red) and an adjustable-power chilled-water fan coil (blue), and is used to manage the boundary conditions of the vapor compression system. Specifically, the air temperature in the outdoor unit test chamber is regulated by the BOP heaters/fan coil, and the heat loads in both indoor unit test chambers are regulated by the BOP heaters.

4.1 Lab Description

A two-zone vapor compression system, and a supporting HVAC system necessary for generating loads and regulating boundary conditions are installed in a laboratory as shown schematically in Figure 4. The ME-VCS outdoor unit (consisting of the compressor, condensing heat exchanger and associated fan) is installed in a 6.3 m^3 adiabatic test chamber and is connected with two refrigerant lines to two indoor units, which are installed in separate 9.9 m^3 adiabatic test chambers. For these experiments, the vapor compression system is operated in cooling mode where heat injected into the indoor unit test chambers is moved by the ME-VCS to the outdoor unit where it is rejected to the air in the outdoor test chamber. The thermodynamic boundary conditions for this system are the heat loads injected in the indoor unit test chambers and the air temperature in the outdoor unit test chamber.

In addition to the vapor compression system under test, the experimental facility also includes a balance-of-plant (BOP) system to provide loads, remove the heat rejected by the condenser, and regulate the thermodynamic boundary conditions. The BOP consists of variable power heaters of up to 16 kW in the outdoor chamber and up to 4 kW in both of the indoor unit test chambers. The voltage applied to the heaters is duty cycled over a 2-second period in order to modulate the heating power, which is measured by electrical power meters (Continental Control Systems, LLC). Additionally, an 18 kW chiller (Advantage Engineering, Inc.) provides cold water to a 20 kW fan coil (Multiaqua, Inc.) in the outdoor unit test chamber. The flow rate of the chilled water can be modulated with a variable speed pump (ITT Goulds Pumps) and variable opening valves (Belimo Aircontrols, Inc.). The cooling power supplied by the fan coil is computed from the measured mass flow rate (Dwyer Instruments, Inc.) of the water passing through the coil and the associated temperature increase. A data acquisition and control system (National Instruments, Inc.) is used to measure boundary conditions, control the balance-of-plant, and read sensors and issue actuator commands to the vapor compression system. The BOP feedback controllers are configured to regulate (1) the heat loads in the indoor chambers by modulating the heater power, and (2) the air temperature in the outdoor chamber by modulating the heater power and fan coil cooling power.

4.2 Experimental Results

Two experiments are performed to compare control methods for reducing cooling capacity—the capacity control method is compared to a duty cycling method. The test conditions used for both control methods are as follows: the outdoor air temperature setpoint is 35°C, and the heat load setpoints are approximately 1400 W for both indoor zones. These are the boundary conditions regulated by the BOP system. Additionally, the air temperature setpoint in zone A is set to 20°C, and the air temperature setpoint in zone B is set to 25°C. These are the control objectives regulated by the ME-VCS controllers under evaluation. The test conditions were chosen so that the zone setpoints are substantially different, and therefore require zone B to reduce its cooling capacity in order to regulate the air temperature to higher setpoints. In the data that follows, only zone B is shown.

The experimental results for the step increase in zone B are shown in Figure 5. At t = 10 min in both experiments, the zone setpoint temperature is increased from 25°C to 27°C, which requires the respective control methods to reduce the cooling capacity in zone B while still satisfying the cooling requirements of zone A. For Figure 5A the capacity control method of this paper is shown, and in Figure 5B a duty cycling method is shown. For the case of the capacity controller, the capacity command signal originating from the supervisory controller is available and presented in the top subfigure (no corresponding command is available for the duty cycling controller). Additionally thermographic images at selected times are shown below both figures to illustrate differences in heat exchanger utilization between the two methods.

For these test conditions, the initial steady state occurs with the heat exchanger at a relatively high cooling capacity (around 80%), and the coil setpoint temperature (shown as the black line of Figure 5A) is coincident with the path temperature measured by sensor 1 (shown as a blue line) in the time leading up to $t = 17$ min. At $t = 10$ min, the zone setpoint temperature is increased. The supervisory controller determines that the corresponding zone is therefore overcooled, and the capacity command (top plot) is reduced accordingly. As the capacity command is reduced between times $t = 10$ min and $t = 17$ min, the coil setpoint temperature is increased and ultimately approaches the zone temperature upper bound.

At time $t = 17$ min, the zone is still overcooled and the supervisory controller continues to decrease the capacity command. At t = 17 min, the capacity command crosses 50%, which is the point at which the alternate heat exchanger path is selected by the coil setpoint function. This is shown in Figure 5A as an abrupt change in the coil setpoint temperature at time $t = 17$ min. This switch occurs bumplessly because both the path setpoint temperature and the selected sensor are switched at the same time so that the error signal provided to the feedback regulator is smooth and

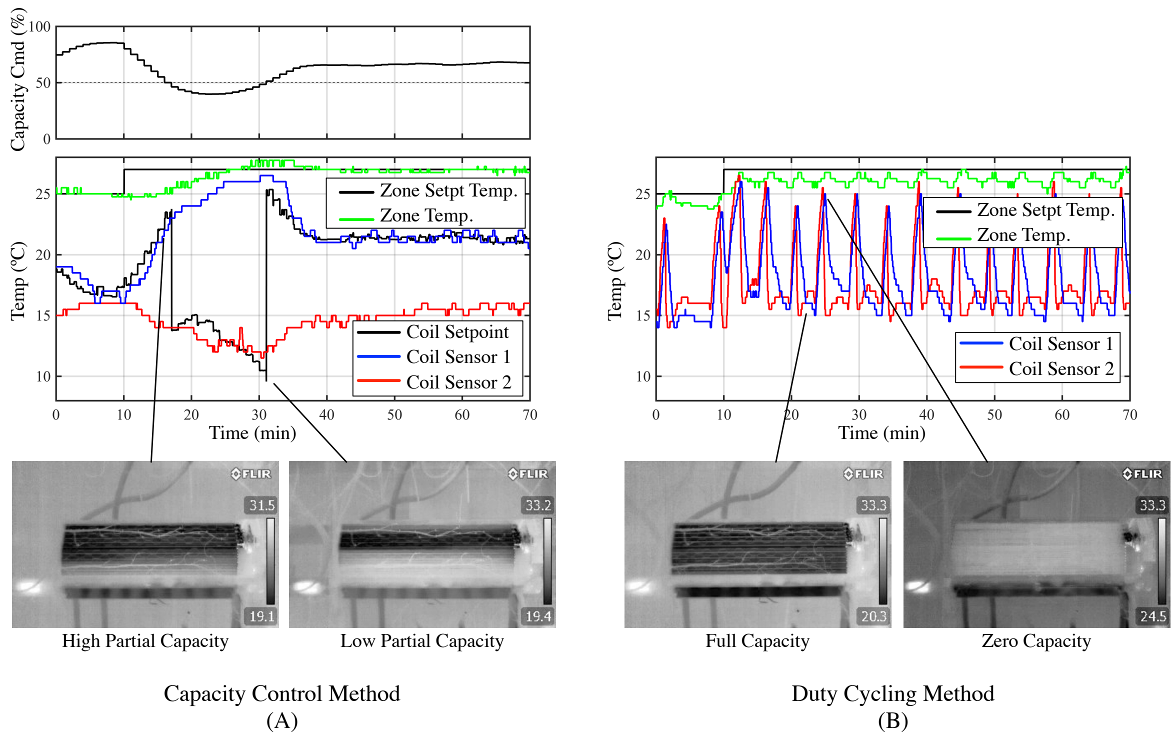

Figure 5: Two control methods for modulating cooling capacity are compared. (A) The capacity control method of the previous section is used to reduce the cooling capacity in zone B such that the zone air temperature is increased to a setpoint. A capacity command (top) originates from a separate supervisory controller. Different path temperatures (middle) are selected as the control variable during the transient as conditions require modulating the capacity. Thermographic images (bottom) of the heat exchanger at two points during the transient are shown. (B) A duty cycling method is used to alternative between full capacity and zero capacity and shown in thermographic images. However, the zone air temperature never reaches the setpoint.

continuous across the switch, and therefore the command provided to the expansion valve is also continuous.

From time $t = 17$ min to $t = 32$ min, the path corresponding to sensor 2 (red line) is used by the capacity controller to determine expansion valve commands. Also within this time period the zone has become overheated, so the supervisory controller begins to increase the capacity command. At time $t = 32$ min, the capacity command crosses the predetermined transition value (a capacity command of 50%) and the path corresponding to sensor 1 is again selected for control. At the end of the transient, the zone temperature reaches the setpoint with zero steady state error.

A similar experiment is conducted using the duty cycling method and the results are shown in Figure 5B. In order to reduce the cooling capacity of zone B, the duty cycling controller alternates the operation of the expansion valve from open (in which case two-phase refrigerant fills the evaporator and shown in the thermographic image on the left of Figure 5B) to closed (in which case no refrigerant enters the heat exchanger which warms to the surrounding air temperatuere as shown in the thermographic image on the right of Figure 5B). The period of oscillation depends on the local thermodynamic conditions and controller tuning. Note that the zone air temperature never warms to the setpoint before another duty cycle period begins.

5 CONCLUSION

In this paper, an empirical refrigerant distribution phenomenon observed for multi-path heat exchangers is be exploited for capacity control, provided that each path temperature is measured. As the single inlet expansion valve is closed, refrigerant is observed to preferentially flow in one path more than another, leading to a gradual reduction in cooling capacity of the evaporator. This method circumvents the coupling induced by the lack of exit expansion valves that create a single evaporating pressure and therefore temperature among all evaporators.

A control architecture is developed to stabilize this behavior and used to achieve fractional cooling capacity when directed by a supervisory controller. In this manner, the cooling capacity for mutually coupled evaporators can be independently modulated to precisely match the per-zone thermal requirements, and a smaller fractional capacity is achievable by controlling per-path superheat temperatures than the traditional evaporator outlet superheat control method.

The experiments demonstrate that by controlling per-path temperatures, the cooling capacity can be smoothly reduced. Moreover, by computing coil setpoints with a function that incorporates the evaporating temperature and local zone temperature, disturbances entering the plant from these sources can be rejected, which helps a multivariable supervisory controller manage multiple zones simultaneously.

A primary benefit of this approach is the avoidance of duty cycling, which couples large amplitude disturbances into many machine pressures and temperatures that should be constrained. Since the perturbations induced by duty cycling are difficult to describe with low-order models, and therefore simple model-based controllers that account for these perturbations are difficult to implement. However, a supervisory controller acting on the augmented dynamic system consisting of the capacity controller and the ME-VCS, will observe a linear response in the transfer functions from capacity commands to zone temperature. Therefore, these capacity controller serve to linearize otherwise nonlinear and unpredictable phenomena and enable the application of linear model predictive control.

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