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Experimental performance investigation of cooling or heating coil valves and their impact on temperature controls

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ABSTRACT

Hysteresis and nonlinearity exist in most valves that are utilized in building HVAC systems, such as in cooling or heating coil valves. The hysteresis mainly comes from the manufacturing clearance in an actuator gearbox and nonlinearity in the variation of the regulated flow with respect to control signal originates from valve design. The combination of valve hysteresis and nonlinearity poses significant difficulties in obtaining satisfactory control performance when utilizing a conventional PI controller. This paper presents experimental testing results for a set of valves in an operating HVAC system serving an office building. The test valves include VAV reheat coil and AHU cooling coil valves provided by two mainstream manufacturers. Open-loop experiments were carried out that are used to analyze valve performance in terms of hysteresis and nonlinearity. Valve closed-loop performance was also investigated and the results showed that valves with significant hysteresis and nonlinear characteristics lead to unsatisfactory supply air or zone air temperature controls with severe temperature oscillations and control chattering.

1. INTRODUCTION

Valves are widely utilized in industrial and building applications as a means of regulating fluid flow for different purposes, e.g., in controlling heat exchange capacity or chemical reactions. In some circumstances, valves are combined with actuators to enable process automatic control where PID-type controllers are employed to modulate valve opening to achieve setpoint tracking. In building applications, valves are mostly used to deliver varying hot- or chilled-water flow to modulate heat/mass exchange capacity and maintain some temperature or humidity setpoint. Valve performance can have significant impacts on the smoothness of control actions and the efficiency of a HVAC system.

Several studies can be found in the literature that investigated valve performance in general applications. However, there are very few works that investigated HVAC valve performances and their impact on control stability. The Control Valve Handbook (2005) provides a good reference for understanding valve characteristics and the corresponding applications. Hysteresis is commonly seen in an actuated valve where the stem position differs at a given input command when the actuation changes its direction. Valve hysteresis is mostly caused by stick friction within the valve and manufacturing tolerance in the actuator. Within the handbook, valve hysteresis effect is thoroughly discussed and a set of open-loop test results are included that demonstrate the different dead band (or backlash) behaviors between poorly and finely manufactured valves. Song et al. (2011) carried out an open-loop test for a cooling coil valve to understand valve hysteresis and its impact on the accuracy of a virtual flow meter. Some hysteresis effects on the loop resistance coefficient within the operating range have been demonstrated, although flow hysteresis was not studied explicitly. Ruel (1999) discussed generic valve performances in terms of resolution, static friction-type hysteresis, backlash hysteresis and their impacts on control stability with different PI control settings. The study specifically mentioned that in most applications, valves should have backlash hysteresis near 1% and a backlash of less than 2 or 3% is acceptable with fine tuned controllers. It was also emphasized in ValveLink (2012) and in the Control Valve Handbook (2005) that allowable backlash hysteresis in valves is typically specified to be less than 1% to achieve satisfactory control performance. However, as will be shown in the present paper, backlash hysteresis of valves within HVAC applications is mostly more than 5% which poses difficulties in establishing stable control.

The present study was motivated by poor comfort control performance observed in the HVAC systems serving the case study building, which was believed to be caused by significant valve hysteresis for both the chilled- and hot-water valves. Conventional PID control was not able to provide stable control due to valve hysteresis and highly non-linear behavior and the control variables were observed to oscillate significantly.

This paper presents a range of experimental test results on the performance of different types of AHU cooling coil and VAV reheat coil valves from two different manufacturers. Open- and closed-loop tests were carried out separately for all tested valves. Open-loop test results can clearly reflect the valve characteristics in terms of hysteresis and nonlinearity while closed-loop test results imply the feedback control performances associated with different valve characteristics. Testing results show significantly different behaviors in the valves from different manufacturers and under different pressure independent control schemes. The different valve behaviors have led to varied control performances: valve hysteresis and nonlinearities led to significant temperature fluctuations and control chattering; valves with only hysteresis provided smoother control actions but still exhibited low-frequency temperature fluctuations; valves with good linearity and negligible hysteresis resulted in the tightest temperature control and smoothest control actions. The presented results and analysis are helpful in understanding the impact of different valve characteristics to system comfort delivery capability and will also be useful in motivating better controller design for HVAC applications.

2. EXPERIMENT SETUP

Comparative testing of the valves was carried out for variable-air-volume (VAV) terminal box reheat coils and air handling unit (AHU) cooling coils that serve graduate student offices, termed Living Laboratories (LLs) within the Center for High Performance Buildings at Purdue University. The LLs are four nearly identical office spaces identified as LL #1-4. Each office is reconfigurable in different ways that can enable direct comparisons of alternative technologies for windows, lighting comfort delivery, control and acoustic treatments. Comfort delivery options include air supply from the ceiling, floor or side wall along the radiant floor heating and radiant chilled beam cooling.

Figure 1 shows the air conditioning (AC) system layout of LL #3 as a case study test bed. The cooling coil in the AHU receives chilled water at a relatively constant temperature of 8.5 ℃ from a central campus cooling plant and the entering chilled water flow rate is varied with a feedback control on the cooling coil valve to maintain the supply air temperature (SAT) setpoint. The AC system has two air distribution modes: overhead air distribution (OAD) mode and underfloor air distribution mode (UAD) and only one mode can be enabled at any time in normal operation. The OAD system has three VAV terminal boxes that deliver conditioned air to the indoor space through ceiling diffusers and the UAD system has two VAV boxes providing conditioned air to floor diffusers. Each VAV box has an air damper that modulates airflow rate entering the indoor space to maintain the space temperature setpoint in cooling mode. When the airflow reaches the minimum level set forth within the corresponding VAV box and the space has a lower cooling demand, the VAV box controller will switch to heating mode where the VAV reheat will be enabled to reduce the cooling (or increase the heating) capacity.

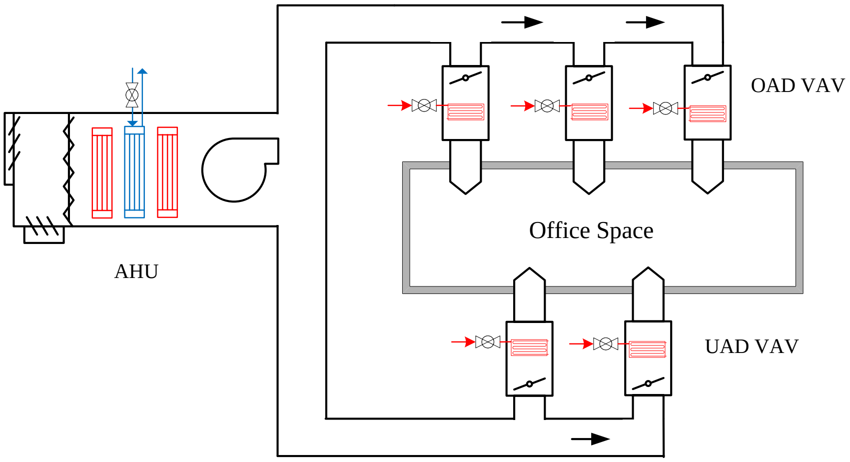

Figure 1. Air distribution system layout of the test room (LL #3).

Table 1 lists the test valves and the key information. Note that all considered valves are pressure independent valves that rely either on mechanical pressure regulators or electronic flow feedback control to main invariant flow characteristics with respect to varying pressure differentials. The electronic flow feedback control option, which is also termed electronic pressure independent control (EPIC), is available in VAV-2 and AHU-2 valves that have built-in ultra-sonic flow meters and internal feedback controllers to maintain the flow rate at a level dictated by external control command. In addition, all test valves follow an equal percentage flow control scheme where the flow rate has an exponential-type relationship with respect to control command so that the coil cooling/heating capacity exhibits a linear relationship with respect to the control command.

Three types of VAV reheat valves and two types of AHU cooling coil valves were considered that are identified as VAV-1 to VAV-3 and AHU-1 to AHU-2, respectively. VAV-1 and VAV-3 are both mechanical pressure independent control (MPIC) valves but were provided by different manufacturers. These two valves were tested sequentially under the OAD mode where the detailed testing periods are provided in Table 2. VAV-1 valves were replaced with VAV-3 valves after all tests were finished for VAV-1. VAV-2 differs from the other two VAV valves in that VAV-2 features an EPIC and has been tested within the UAD system. AHU-1 and AHU-2 differ in both the manufacturer and the control scheme. In addition, AHU-1 and AHU-2 valves are installed in the AHU cooling coils in LL #2 and LL #3, respectively, where the AHUs serving these two LLs are identical.

Table 1: Information of the test valves

Valve ID	Qty	Location	Common Features	Nominal Flow	Brand	Control Scheme
VAV-1	3	OAD VAV reheat coil	Pressure independent valves; equal percentage flow control	3 GPM	A	MPIC
VAV-2	2	UAD VAV reheat coil			B	EPIC
VAV-3	3	OAD VAV reheat coil				MPIC
AHU-1	1	AHU cooling coil (LL2)		30 GPM	A	
AHU-2	1	AHU cooling coil (LL3)			B	EPIC

Table 2: Valve testing periods

Valve ID	Open-loop testing days (mm/dd/yyyy)	Closed-loop testing days (mm/dd/yyyy)
VAV-1	09/05/2014	08/06/2015-08/10/2015
VAV-2	08/02/2015	08/02/2015-08/06/2015
VAV-3	02/08/2016	02/09/2016-02/13/2016
AHU-1	09/04/2014	02/02/2016
AHU-2	11/30/2015	02/02/2016

Table 3 shows settings for the experiments. In the VAV tests, AHU SAT (supply air temperature) setpoint was maintained at a constant value of 55F and airflow through the VAV boxes were kept at the minimum levels. In the VAV valve closed-loop tests, the reheat valves modulated to maintain a space temperature setpoint of 72.1 ℉. These settings are based on the actual operation sequences in VAV heating mode when the VAV reheat is enabled. During the AHU cooling coil valve tests, AHU mixed air temperature (MAT) was controlled at 70 ℉ which was achieved by feedback control on the outdoor air mixing ratio through outdoor air damper modulation. In the AHU valve closed-loop tests, the SAT setpoint was implemented to follow a pre-defined trajectory to reduce the need for VAV reheat where the trajectory will be presented along with the AHU testing results. In the open-loop tests of both VAV and AHU valves, the valve control signal was stepped from 0% to 100% and then back to 0% with a 5% increment (6.25% increment for VAV-3 and AHU-2 tests) and 8 minutes hold time for each step. The open-loop tests spanned 4-6 hours each and were carried out in LLs #2 and #3 in unoccupied periods. In the closed-loop tests, PI control settings were identical within each test group and the PI gains were fine tuned by field engineers in the commissioning phase.

Table 3: Experiment parameters

Valve Category	Test Category	Upstream Air Temperature	Air Volume	Closed-Loop Setpoint
VAV	Open-loop	AHU SAT setpoint =55 ℉	OAD total vol.=1200CFM; UAD total vol.=1250CFM;	-
	Closed-loop			Space temp. setpoint =72.1 ℉
AHU	Open-loop	AHU MAT setpoint =70 ℉	In OAD mode with total vol.=1200CFM	-
	Closed-loop			Resetting SAT setpoint

3. VAV VALVE TEST RESULTS

3.1 Linearity and Hysteresis Effect Tests: Open-Loop

Open-loop tests were effective in revealing the linearity and hysteresis characteristics of the tested valves. **Figure 2** shows the VAV valve testing results. The x-axis is the control signal that was fed to the valves and the y-axis is the temperature difference across the reheat coil in degrees F. Since the airflow rate was maintained constant, the y-axis data provides a direct indication of heating rate of the reheat coil.

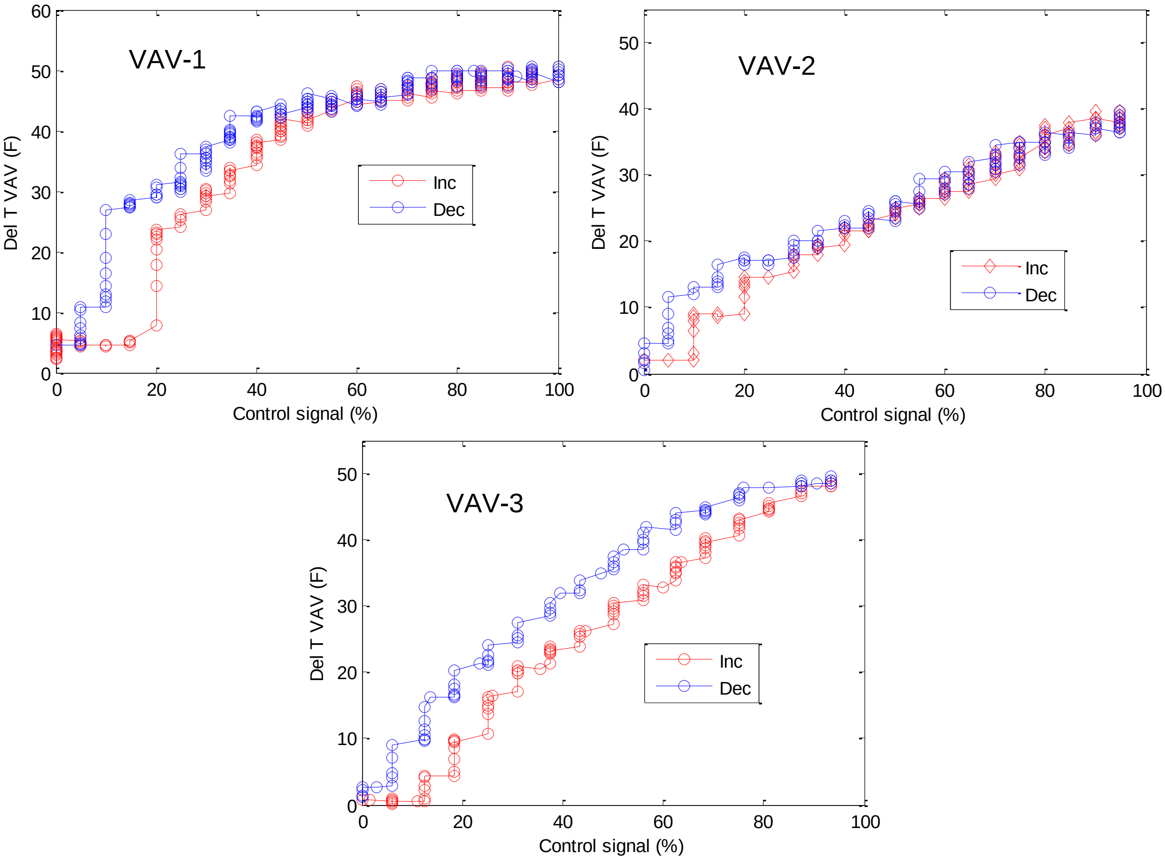

Figure 2. Open-loop test results of the VAV valves.

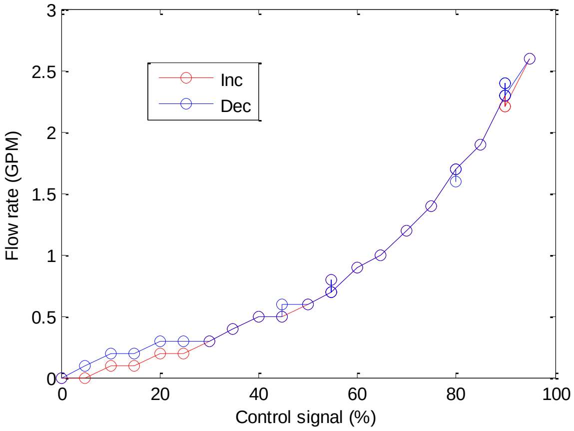

Figure 3. VAV-2 flow rate characteristics from the open-loop test.

It can be observed that when the valve was opening from fully closed, VAV-1 provided almost no capacity when the control signal was below 20%. Once the control signal reached 20%, there was a significant jump in the heating rate to almost 50% of the maximum heating capacity. This discontinuity and nonlinearity in the control effect causes severe problems in the control stability when the reheat demand is moderate since effective control is lost in the capacity range of 0 to 50%. When the valve was closing from a fully open position, a similar significant drop occurred when the control signal reached 10%. VAV-2, however, had a much smoother behavior over the whole testing range and the non-smoothness occurring below 20% control signal was caused by a 5% tolerance for the valve internal flow controller: when the measured flow is within 5% of the control setpoint, the internal controller will not take any actions until the flow deviation rises beyond 5%. VAV-2 also outputs the flow reading and the flow rates were recorded within the open-loop test of VAV-2 which are plotted in **Figure 3**. It can be seen that the VAV-2 flow rate curve is close to exponential to achieve equal percentage capacity control. In the low end of the operation range, the curve has a small slope so that a 5% step change in the control signal translates to a flow setpoint change that is smaller than 5%. So the valve internal controller did not take actions for each step change in the control signal when it was below 20% and that caused the non-smoothness in the flow rate and temperature rise across the reheat coil. VAV-3 also exhibits good continuity and linearity in the flow characteristic curve.

Hysteresis can lead to poor control performance in these aspects: (1) there is always a delay in the control action that slows down the control effect; (2) chattering can occur when control is aggressive. The combination of hysteresis and non-smooth behavior could lead to significant chattering, as will be discussed in the closed-loop test results. VAV-1 exhibits hysteresis in the low operating range, i.e., 5% - 40% with a very significant hysteresis occurring at 15% control signal. VAV-2 shows no hysteresis as it controls the flow directly, although the internal control tolerance caused a small gap between the increasing and decreasing curves in the low operation range. This hysteresis-like gap makes the external valve controller to work in a manner similar to a buffered PI controller and can lead to control chattering when the control action falls within this region. Although VAV-3 exhibits good linearity, it shows obvious hysteresis in the whole operation range which will cause some control stability issues as will be discussed in the next subsection.

3.2 Operation Tests: Closed-Loop

In the closed-loop tests, the system operated under its default control logic where the VAV box reheat valve was modulated to maintain the space temperature at the setpoint of 72.1 ℉. **Figure 4**, **Figure 5** and **Figure 6** show the test results for VAV-1, VAV-2 and VAV-3, respectively. It can be seen from **Figure 4** that the non-smooth behavior and significant hysteresis within VAV-1 led to significant fluctuations in the space temperature. In addition, due to the nonlinearity in the VAV-1 performance curve, the PI control output range of VAV-1 was much smaller than those for the other two VAV valves. **Figure 5** shows that VAV-2 was able to regulate the space temperature within a tighter band around the setpoint and the control signal reflects a smooth heating load in the space. In **Figure 6**, no chattering occurred in the VAV-3 test due to the good linearity and relatively smooth control was achieved. However, the valve hysteresis induced significant low-frequency temperature oscillations mostly occurring right after midnight. The oscillations were caused by sudden disturbance changes due to leaving occupants at midnight

(LLs serve as offices of graduate students that typically work in the office until midnight) and the valve hysteresis led to delayed control action in response to the sudden disturbance change. Note that although tests for VAV-2 and VAV-3 were performed during different seasons, the space heating/cooling loads are very similar which are plotted and compared in **Figure 7**, because the building is well insulated and internal loads are dominated by internal heat gains which do not differ much with seasons. The low-frequency oscillations were also present in the load profile for VAV-3 that created multiple power peaks for mechanical heating/cooling. If the building were subject to demand charges, the oscillation peaks would lead to increased demand cost.

Figure 8 shows scatter plots of the temperature rise across the reheat coils versus the valve control signal for the tested VAV valves. It can be noted that due to severe nonlinearity and hysteresis in VAV-1, the scatter plot exhibits a nearly random and uncorrelated behavior. The plots for VAV-2 and VAV-3 show that the reheat capacities have clear correlations with control signal and the relationships are close to linear. Due to the low-frequency oscillations, VAV-3 operation results spanned the whole operation range while VAV-2 only operated within 40% of the full range. Note that both VAV-2 and VAV-3 point clusters show approximately 10% width of full scale with respect to control signal but the causes were different: the VAV-2 data disparity in the control signal axis was caused by the 5% flow control tolerance while the VAV-3 data disparity was due to valve hysteresis.

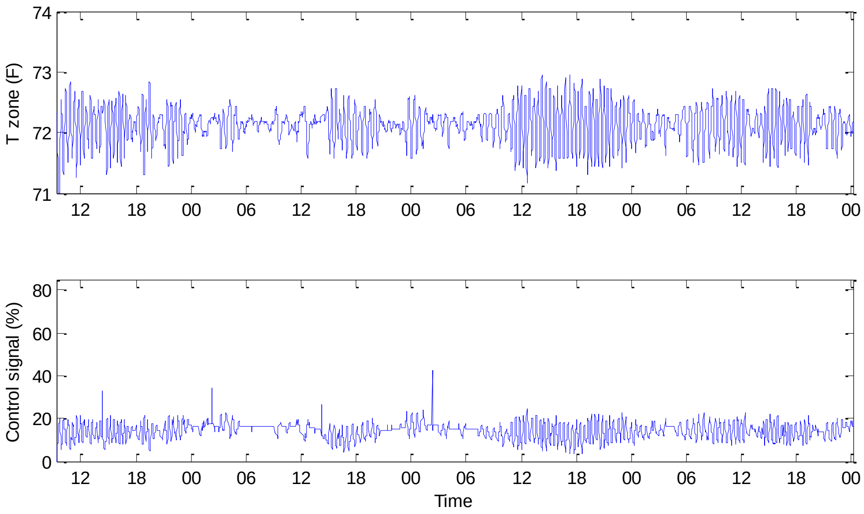

Figure 4. VAV-1 closed-loop test results.

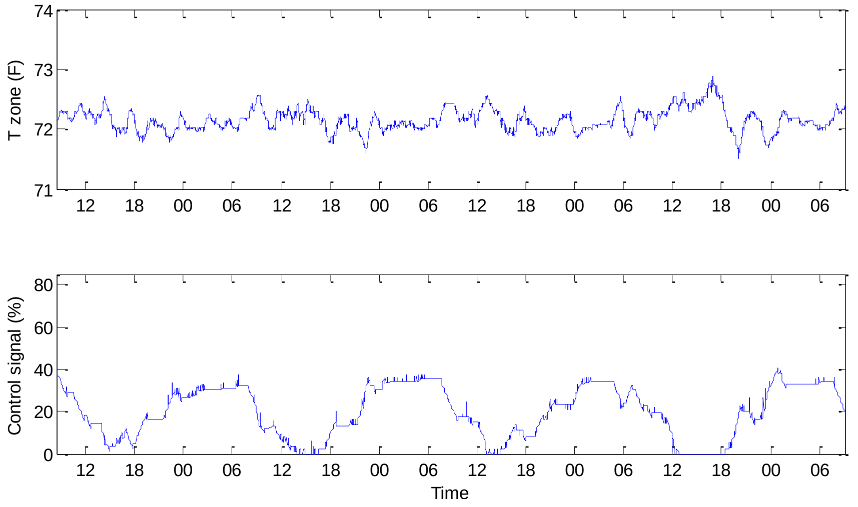

Figure 5. VAV-2 closed-loop test results.

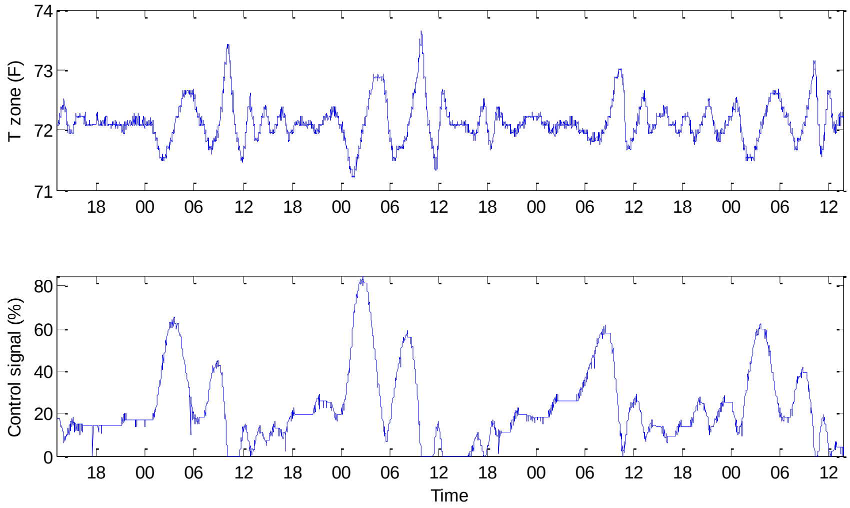

Figure 6. VAV-3 closed-loop test results.

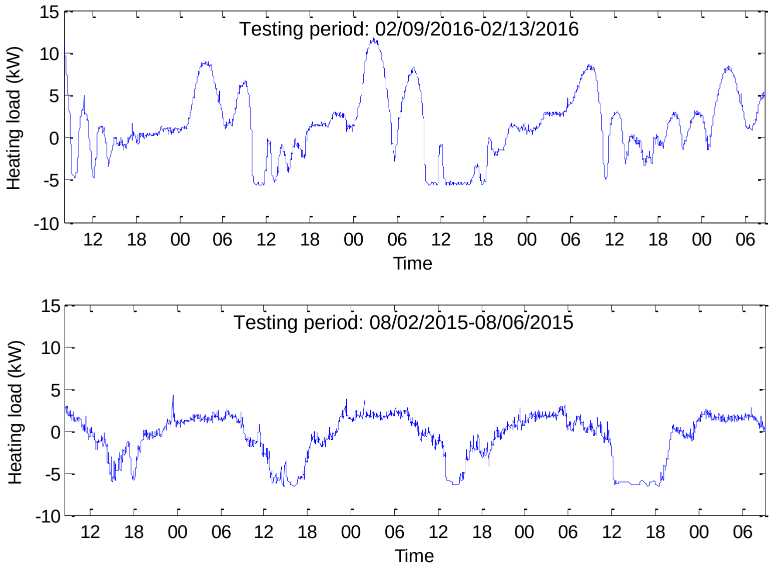

Figure 7. Heating load comparison between the VAV-2 (bottom) and VAV-3 (top) test periods.

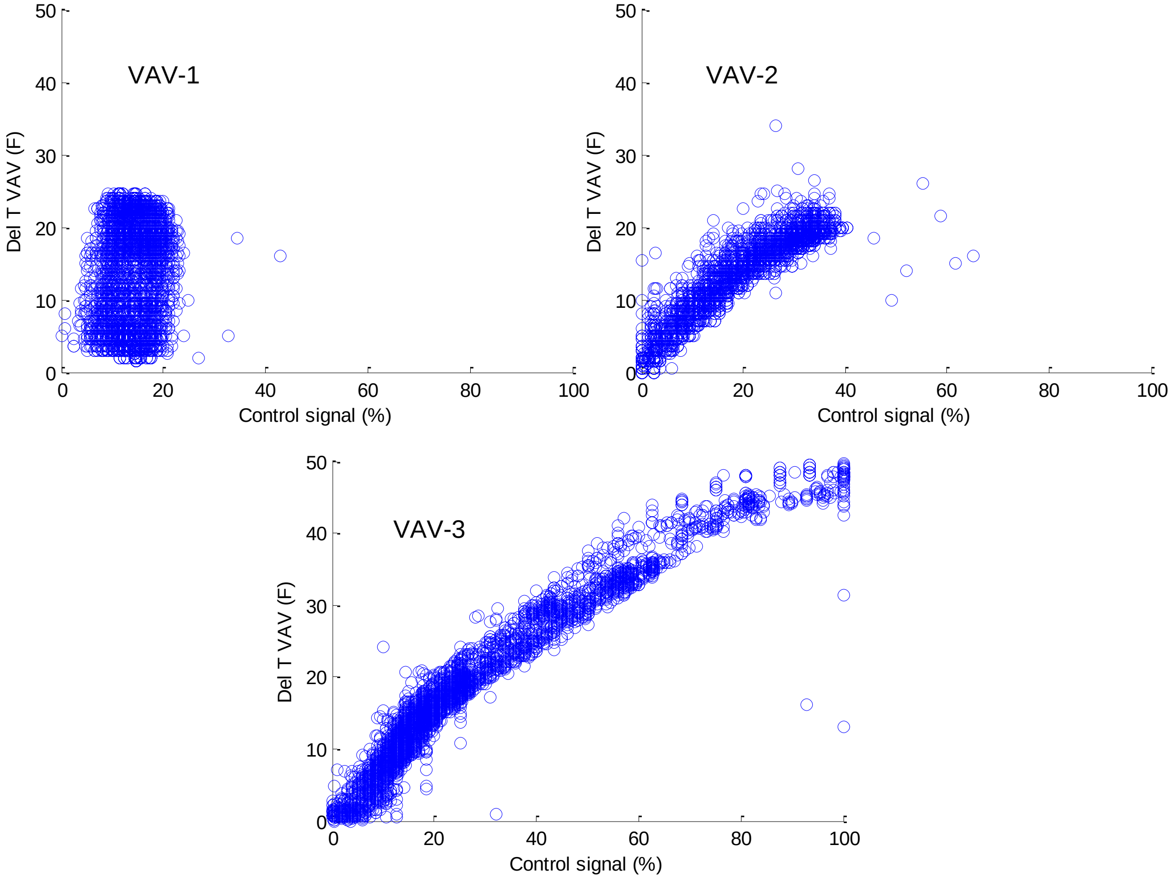

Figure 8. Valve characteristic comparison under closed-loop operation.

4. AHU VALVE TEST RESULTS

4.1 Linearity and Hysteresis Effect Tests: Open-Loop

Similar to the tests carried out for VAV valves, the two AHU valves were first tested in an open-loop scheme by sweeping the control signal through the operation range. The difference is that flow meters are installed for all AHU coils and thus, the valve characteristics could be directly evaluated by looking at the flow rate variation with respect to control signal. **Figure 9** shows the open-loop test results for the two AHU valves where the y axis is the measured flow rate (instead of temperature rise used for the VAV reheat coils). AHU-1 shows obvious hysteresis and significant nonlinearity in the low operation range. When the control signal rose above 50%, the valve lost its authority (Chapter 47 of ASHRAE Handbook-HVAC Systems and Equipment, 2012) where the flow rate curve became flat and some random behavior occurred causing flipped hysteresis. Since the AHU-2 test was carried out in the EPIC scheme, the open-loop results show negligible hysteresis and the overall behavior is closer to linear compared to AHU-1 results.

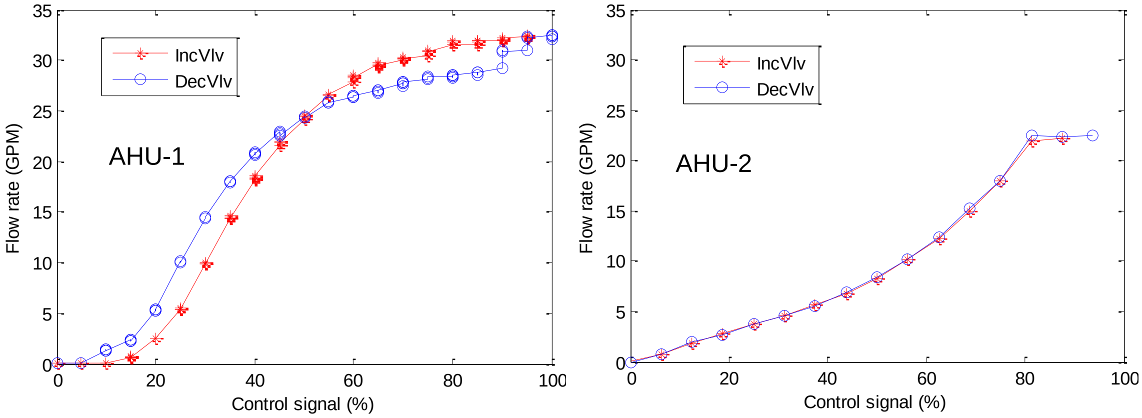

Figure 9. AHU valve open-loop test results.

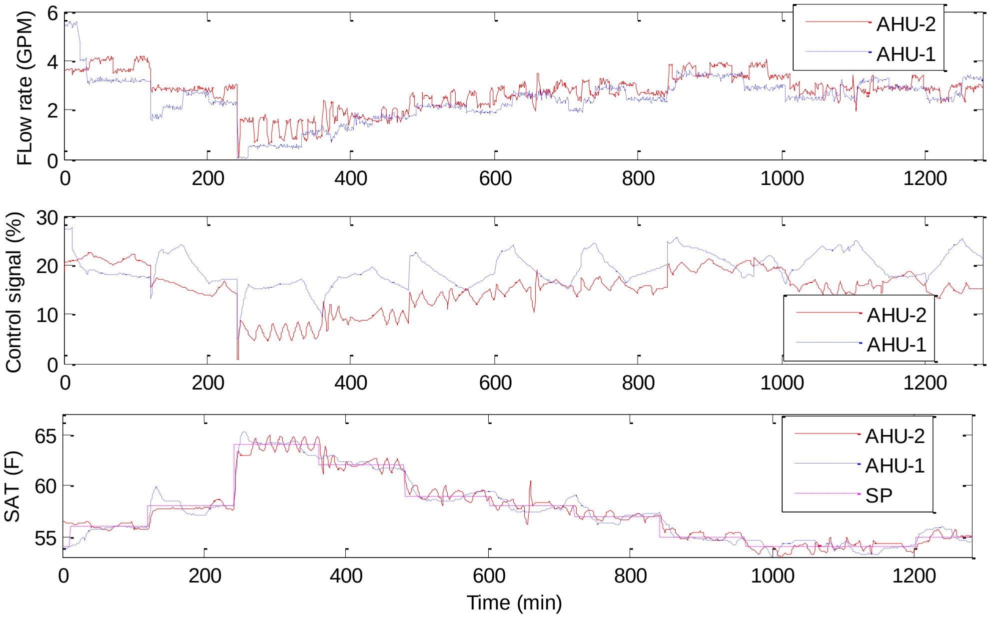

Figure 10. AHU valve closed-loop test results.

4.2 Operation Tests: Closed-Loop

Figure 10 shows the time plots of the AHU valve closed-loop test. In normal AHU operation, the cooling coil modulates to maintain the SAT setpoint. In this test, a setpoint resetting strategy was implemented to reduce the VAV reheat need and the setpoint trajectory is shown in the bottom plot of **Figure 10**. Similar to the VAV valve tests, the hysteresis in AHU-1 led to low-frequency oscillations in both the control action and SAT profile. In addition, significant overshoot can be observed in the SAT control at setpoint changes due to the delayed control effect. AHU-2 has negligible hysteresis but the 5% internal flow control tolerance led to obvious control chattering which caused some high-frequency oscillations in SAT. The chattering is more severe at low load conditions. As already discussed in the VAV-2 test results, the intensive chattering at low load conditions is because of the exponential-type flow curve in AHU-2 where a fixed step change in the control signal translates to a small flow setpoint change and thus the operation more commonly falls within the 5% deadband in the low operation range. Although AHU-2 has the control chattering issue, the tracking error histograms of **Figure 11** show that it still outperformed AHU-1 with a tighter temperature control. **Figure 12** shows scatter plots of the closed-loop flow rate versus control signal for the two AHU valves. AHU-2 shows a clear and close-to-linear correlation while AHU-1 exhibits highly stochastic behavior caused by hysteresis.

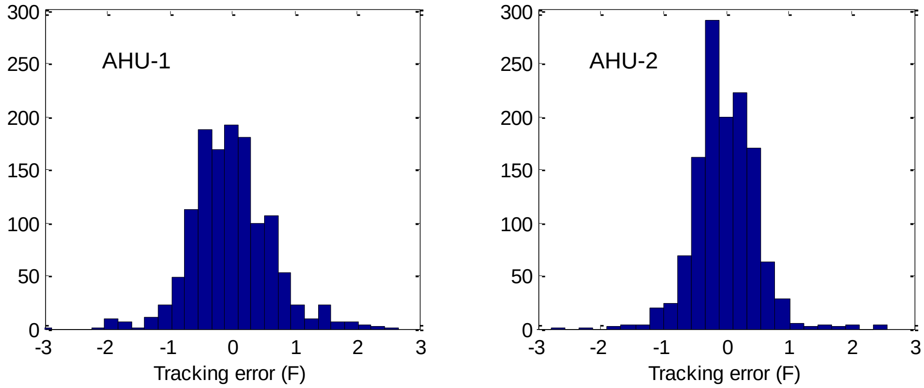

Figure 11. Histogram plots of AHU valve setpoint tracking errors.

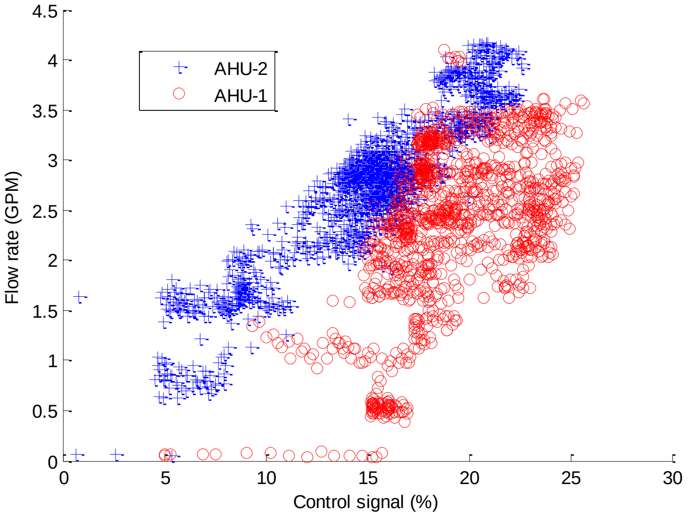

Figure 12. Closed-loop AHU valve behavior comparison.

5. CONCLUSIONS & DISCUSSIONS

This paper presented performance comparisons of different valves used for water regulation in VAV reheat and AHU cooling coils. The tested valves are from two different manufacturers and cover two control schemes: MPIC (mechanical pressure independent control) and EPIC (electronic pressure independent control). Open- and closed-loop tests were carried out separately. The open-loop test results showed significantly different valve performance characteristics in terms of linearity, continuity and hysteresis. The closed-loop test results were helpful in understanding the impact of different valve characteristics on feedback control performance in terms of setpoint tracking. It was shown that VAV valves with severe nonlinearity and hysteresis led to significant control chattering and high-frequency temperature oscillations. VAV valves with good linearity but significant hysteresis provided smoother control actions but suffered from low-frequency control oscillations. Good linearity and negligible hysteresis within valves provided the smoothest control actions and tightest temperature control. The AHU valve with EPIC had improved performance compared to the valve with hysteresis, although some control chattering occurred under low load conditions due to the valve internal flow control tolerance.

In addition to unsatisfactory comfort delivery, poorer performing valves also lead to oscillations in the control actions and fluctuations in cooling/heating demands with the following consequences: (1) reduced cooling/heating plant efficiency due to increased cycling losses; (2) reduced equipment life; (3) unnecessarily high peaks in electricity usage leading to increased demand costs.

Backlash is the most common hysteresis in regulation valves that is attributed to manufacturing tolerances in the actuator gearbox. For more complicated hysteresis, e.g., the AHU-1 hysteresis, the characteristic curve can still be approximated with a backlash hysteresis model locally within the typical operation range. A companion paper (Cai and Braun, 2016) proposes a self-learning backlash inverse control approach for such valves to mitigate the backlash hysteresis effect. The approach has been applied to AHU-1 and significantly improved performance was achieved even outperforming AHU-2. Due to the wide deployment of valves in buildings and industrial processes, such a control approach could be a significant contribution in improving control performance, enhancing energy efficiency and prolonging the life cycle of the target systems.

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