

Pacific Gas and Electric Company

Emerging Technologies Program

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Stability and Accuracy of VAV Terminal Units at Low Flow

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1. Executive Summary

A Variable Air Volume (VAV) box with a lower minimum flow setpoint improves energy savings. This study evaluated the lowest points at which VAV boxes can be stably and accurately controlled. Two components affect the stability and accuracy of a VAV box—the flow probe and the zone controller/pressure sensor. During testing, these components were evaluated both separately and as assembled systems to identify stability and accuracy issues. Eight-inch VAV boxes from two manufacturers (Titus and Nailor) were tested under a range of inlet pressures and damper positions. Controllers from four manufacturers—Siemens, Alerton, Johnson (JCI) and ALC—were evaluated in measuring a known velocity pressure signal. A summary of findings is as follows:

- As individual components, the flow probes were stable and accurate under all conditions without loss of amplification or signal quality.
- All controllers tracked fluctuating inlet pressure signals and had good filters for smoothing “noisy” pressure signals.
- All controllers maintained very low flow setpoints without excessive damper adjustments—even when faced with fluctuating inlet pressures.
- The two controllers with hot-wire type flow sensors (Alerton and ALC) were both very accurate at the calibration points. However, they underestimated actual flow at rates above the lowest calibration.
- The pressure-based Siemens sensor was highly accurate immediately after calibration (twice daily). However, accuracy drifted as ambient temperature drifted during the day.
- The pressure-based Johnson (JCI) controller had a software defect that caused mis-calibration over time. (Once corrected, reasonable accuracy can be expected with the JCI controller.)

Stability and reasonable accuracy can be achieved with VAV box minimum flow setpoints as low as 0.005”—approximately 10% of the design flow rate. Switching from a 30% single maximum approach to a dual maximum approach with a 20% minimum would be a significant energy reduction. Considering the billions of square feet in California’s commercial space, annual savings could be millions of dollars. Design engineers can confidently employ lower minimum setpoints to capture potential energy savings.

2. Nomenclature

Variable Air Volume (VAV) Box/Terminal Unit: A device that modulates the volume of air delivered to or removed from a defined space in response to an external demand. A single-duct VAV box includes a flow probe and damper, and may include a reheat coil. Sometimes “VAV Box” refers only to the components supplied by the VAV box manufacturer (damper and flow probe); sometimes it refers to the complete system of the damper, probe, and controller.

Flow Probe / Flow Grid / Flow Cross / Differential Pressure Probe: A set of bore tubes with orifices located in the inlet duct of a VAV box. It measures the differential velocity pressure in the duct and outputs an amplified pneumatic differential pressure signal.

Flow Sensor / Pressure Sensor / Pressure Transducer: A device that accepts a pneumatic differential pressure signal and produces an analog or digital electronic differential pressure signal (e.g. 0-10 volts). A flow sensor is part of most VAV zone controllers. There are at least two types of pressure sensors:

Hot-Wire Type Flow Sensors: The pressure generated by the flow grid in the VAV box induces a small flow across a hot-wire type sensor (a.k.a. hot “thermistor”) in the controller. This air speed is then appropriately scaled to determine the flow rate of the VAV box. The ALC and Alerton controllers tested use this type of sensor. (Note that a hot-wire sensor can also be placed directly in the box inlet and the flow grid eliminated. This type of sensor was not tested.)

Pressure-Based Sensors: The pressure generated by the flow probe deflects a steel diaphragm in the controller. Small changes in the diaphragm are converted to electric analog signals. The Siemens and JCI controllers tested use this type of sensor.

Zone Controller / VAV Controller: A DDC controller for controlling a VAV box. It includes a pressure sensor, A/D converter, and damper actuator.

A/D Converter: A device for converting an analog electronic signal into a digital electronic signal.

Variable Air Volume (VAV): Ventilation equipment used to control air flow, heating and cooling by varying the amount of air flow into the space.

Amplification factor (F-Factor): The ratio of flow probe output to the actual value of what the probe is intended to measure. For example, a flow probe reading of 1.0” of pressure at an actual velocity pressure of 0.43” would have an amplification factor of $1.0/0.43 = 2.3$. The F-Factor may be calculated from K with the following formula:

$$F = \left(\frac{4005 * A}{K} \right)^2, \text{ where } A \text{ is the nominal duct area in ft}^2.$$

Some installers describe “amplification factor” as the factor by which the factory-default “K” value must be multiplied to match the in-situ calibration. This value would normally be about 1.0.

Flow coefficient (K-Factor): Actual flow (in ft³/min) corresponding to a flow probe output of 1” w.g. The K-Factor may be calculated from F with the following formula:

$$K = \frac{4005 * A}{\sqrt{F}}, \text{ where } A \text{ is the nominal duct area in ft}^2.$$

K-Factor is often used in terminal-unit controls to calculate actual airflow using the following equation:

$CFM = K * \sqrt{\Delta P}$, where CFM is airflow in ft³/min and ΔP is flow probe output in inches water gauge.

CFM: The air flow measured in ft³/min.

FPM: The air velocity in ft/min.

Inches Water Gauge ("): Differential air pressure measured in inches of water gauge or water column.

Dead band: An area of a signal range or band where no action occurs (the system is dead). One function of a dead band is to prevent oscillation or repeated activation-deactivation cycles (called “hunting” in proportional control systems). Dead band can be achieved by adding hysteresis within the controller. In a zone-temperature control sequence, dead band occurs when: the space temperature is between the heating and cooling setpoints (or within the throttling range); the zone airflow rate is at the minimum flow rate; and there is no reheat or recooling taking place (e.g. the hot water valve is closed). Zone controllers also typically have a built-in dead band or hysteresis to prevent excessive damper movements when the measured airflow is close to the airflow setpoint.

3. Background

The reliable control of airflow rates in VAV systems is important for a number of reasons, most significantly: acoustics, ventilation, energy management, and occupant comfort. At the low end of the control range, if the airflow setpoint is below the working range of the velocity controller, the unit may cycle between closed and partially open. This results in excessive wear on the damper motor and causes varying sound levels leading to occupant complaints. Furthermore, minimum ventilation rates demand that low-end flows be as accurate as possible. This ensures that the required minimum ventilation is supplied to the zone during periods of low thermal load (Int-Hout 2003).

On the other hand, VAV box minimum air flow setpoints are often set higher than necessary, at the expense of fan energy and reheat energy. One reason is that engineers do not have the tools to determine how low VAV boxes can stably control. Based on lack of information or misinformation they often use general rules for all systems—such as 30-50% of design flow. However, VAV boxes have been shown to stably control well below this point without compromising comfort or ventilation requirements.

Most single duct reheat boxes are controlled using a single minimum control scheme: air flow is constant at some minimum flow setpoint in dead band and in heating mode. Relatively high minimum flow setpoints (e.g. 30-50%) are often necessary to maintain supply air temperatures below some maximum temperature (e.g. 90°F) to prevent short-circuiting in heating mode. Minimum ventilation and control stability/accuracy should also be considered in this scheme; but the maximum temperature issue is usually the driver for setting the minimum flow.

Another control scheme is to use dual maximums. In heating mode, the supply air temperature is reset from minimum (e.g. 55°F) to maximum (e.g. 90°F); then the air flow is reset from minimum (e.g. 15% of cooling maximum) to heating maximum (e.g. 30% of cooling maximum). In this scheme the minimum should be determined only by ventilation requirements and control

stability/accuracy. Most likely, stability/accuracy will be the driver in this scheme (Taylor and Stein 2004).

The minimum controllable setpoint is not easily determined and is in fact the subject of considerable debate in the HVAC industry. It is a function of several factors:

- the basic measurement technology employed—the design of the flow probe (amplification and accuracy);
- the quality and features of the pressure-to-electrical (P/E) transducer (supplied separately or embedded in the controller); and when necessary
- the analog-to-digital (A/D) conversion of the flow signal at the controller.

Both output resolution and measurement precision are critical performance parameters. One controversial issue is the linearity of the flow probe amplification factor at low flow rates. The zone controller software assumes that the amplification is constant across the entire range of possible flows. Some argue that amplification decreases at low flow rates (Troyer 2005). Others argue that it is constant throughout the output range (Int-Hout 2003).

Another controversial issue is the minimum velocity pressure setpoint (VPm) at which the controller can stably control. Several controls manufacturers have said VPm can be as low as 0.004" H₂O (Taylor and Stein 2004). Others in the industry do not recommend setpoints below 0.04" (Santos 2004)—an order of magnitude difference.

While most designers are using single maximum strategies with minimum flows in the range of 30-50%, some designers have had success employing a dual maximum strategy with minimums in the range of 10-20% of the cooling maximum. Simulation models of typical office buildings have shown that switching from a 30% minimum single maximum approach to a dual maximum approach with a 20% minimum airflow setpoint can save \$0.10/ft²-yr (see section below on Energy Analysis). Multiplied across the billions of square feet of commercial space served by VAV boxes, the potential economic and environmental benefits are significant. This research will give design engineers the tools and the confidence to employ lower minimum setpoints and capture some of this untapped potential for energy savings.

4. Project Objectives

- Develop a recommendation for minimum airflow setpoint at which typical VAV boxes can stably and accurately control.
- Determine the factors that contribute to instability or inaccuracy at low flow setpoints.
- Provide a basis upon which further research on this subject can build.
- Make recommendations for future research.
- Develop test methods which can be used to test VAV boxes and controllers.
- Calculate the lowest airflow setpoint at which a particular VAV box and controller combination can accurately and stably control.

5. Test Facility

Testing of the performance of the VAV boxes and the controllers was carried out at the Pacific Energy Center of the Pacific Gas & Electric Company in San Francisco. Two new duct branches were added to an existing system in their HVAC Classroom, and platforms were suspended from

the ceiling support grid. All controller hardware, reference flow meters, and sensors were located on the platforms.

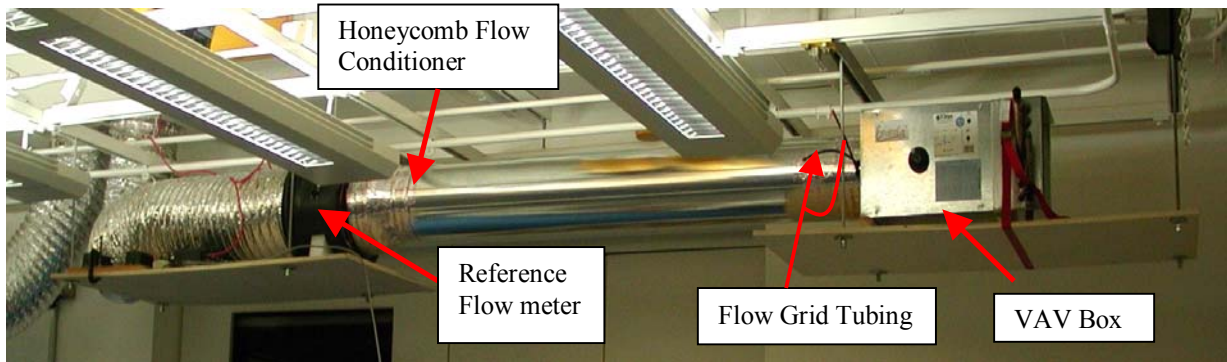


Figure 1: Photo of the test facility layout

The photo shows one of the new branches added to the existing HVAC system. From the left: flex duct comes down from the existing duct, goes across the platform and into the black “Duct Blaster” reference flow meter. From there it goes through a section of honeycomb and a reducer to a section of straight metal duct which enters the VAV unit. The static pressures at the entrance of the VAV box were controlled by means of manually adjusting the HVAC system dampers—including those on the newly-installed flex duct. High flows and inlet pressures required the operation of the fan built into the reference flow meter.

Information about the reference flow meter, pressure sensors, data acquisition system, and background “noise” can be found in Appendix A.

6. VAV Box-Only Test Results

Eight-inch VAV boxes from two manufacturers (Titus and Nailor) were tested under a variety of conditions. The purpose was to determine stability and accuracy of the amplified velocity pressure signal produced by the flow probe. Test conditions included the following:

Table 1: VAV box parameter test ranges		
	<u>Minimum</u>	<u>Maximum</u>
Flow	20 CFM	700 CFM
Velocity	75 FPM	1800 FPM
Probe Signal	0.001 iwc	0.5 iwc
Inlet Duct Pressure	0.1 iwc	1.5 iwc
Damper position	Nearly closed	Full open

Figure 2 shows the results from all the tests made on the Titus VAV box. Figure 3 shows a subset of that data with the Titus box damper 50% open. Other configurations and more detailed information about these tests can be found in Appendices B and C. The flow grid signal closely

follows a line of constant amplification for velocities ranging from 75 to 1700 fpm. The results from all the tests made on the Nailor VAV box are shown in Figure 4.

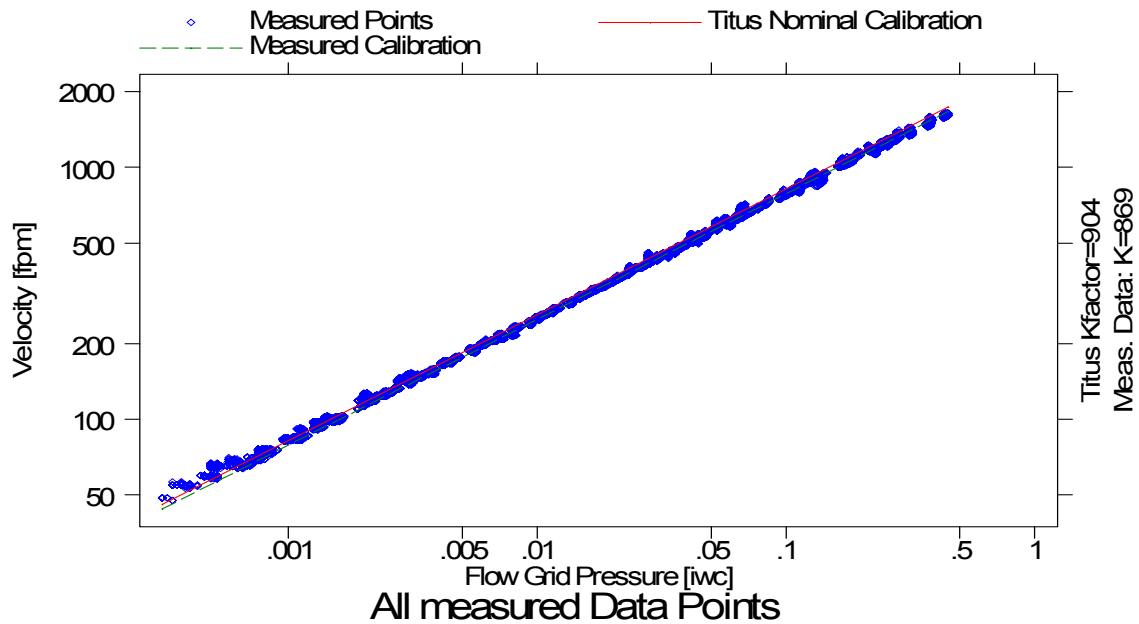


Figure 2. Calibration data for the Titus VAV box from all damper positions

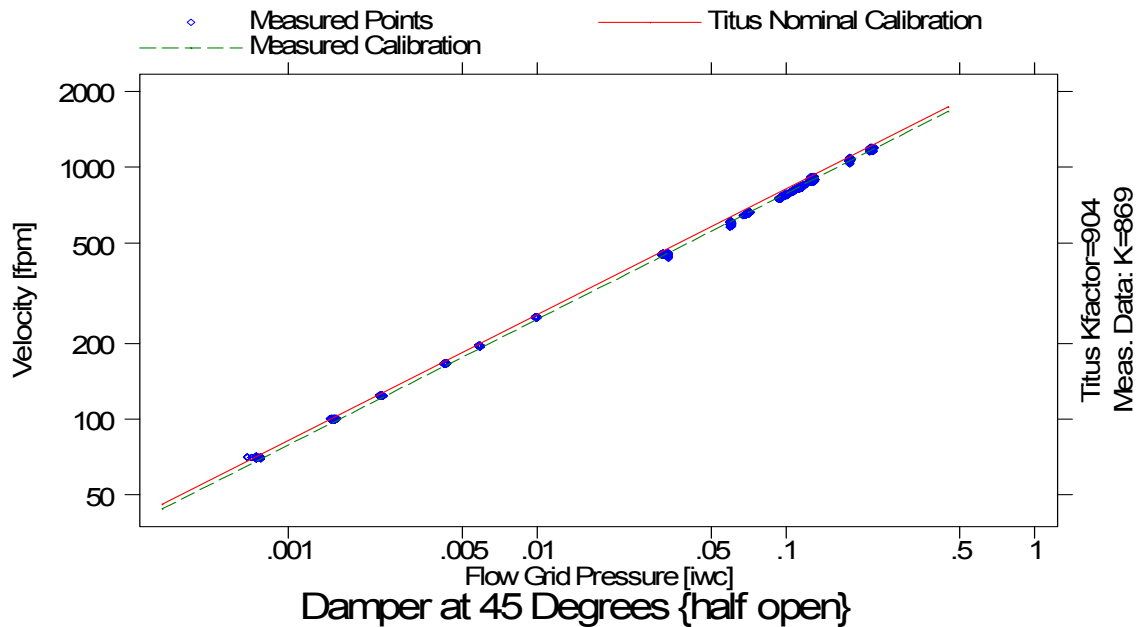


Figure 3. Sample flow probe data from the Titus VAV box at 50% open

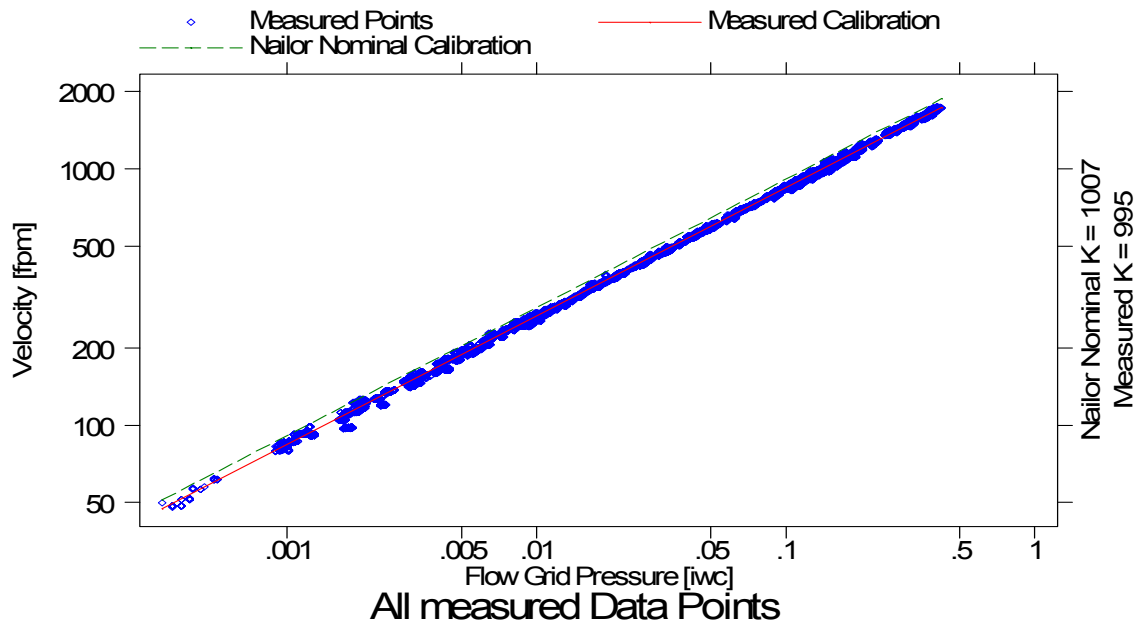


Figure 4: Calibration data for the Nailor VAV box from all damper positions

Additional figures at other damper positions for both VAV boxes can be found in Appendices B and C. The results are similar to Figure 3 with a slight deviation seen in Figure B6—for flows below 50 CFM, at a damper shaft position of 1.5 degrees for the Titus VAV box.

In summary, for the range of flows tested (about 75 to 1700 fpm) the velocity flow grid pressure amplification factor is constant and stable regardless of damper position or inlet pressure. Some controllers re-zero their pressure/velocity sensors by closing the dampers and assuming that this produces zero flow. Any leakage around the damper seals will allow some flow and thus an error in the sensor zero. The damper for the Titus box produced an excellent seal with no measurable leakage. The Nailor damper leakage was found to be 45 CFM at 1" wc or 0.002" wc on the flow grid. In normal operation, the size of this error will depend on the duct system static pressure, and thus may not be a constant. This error will cause the true flow to be higher than the flow which the controller reports.

7. Controller-Only Test Results

7.1 Accuracy

Controllers from four manufacturers were tested under a variety of conditions to determine how stably and accurately the controller could measure a known velocity pressure signal. Details for each controller can be found in Appendices D, E, F, and G. Static and dynamic flow grid pressures were simulated by using pressure-generating devices—either the Setra Micro-Cal pressure generator, similar manual means, or the reference flow meter fan. Reference data was collected at 2 Hz and the controller data was collected at 1 Hz. All controllers, except the ALC, used a two-point in-situ calibration procedure at zero and maximum flow. The ALC controller used a four-point calibration. The zero flow point was always determined by disconnecting the tubing from the controller and shorting it. The non-zero flow points were determined by first the reference flow meter. Then, the controller calibration value was adjusted until the flows agreed.

Each controller's contributions to inaccuracy are summarized in Table 2 and described in more detail below.

Table 2: Contributions to the inaccuracy of the controllers

Controller	Calibration Errors	Zero Drift	Dead band	Software Issues
Siemens (pressure-based)	Inaccurate below 0.001"; highly accurate above 0.001"	Significant temp-correlated drift (can be eliminated with optional bypass kit)	None—results in many damper movements	None
Johnson (pressure-based)	Inaccurate below 0.001"; highly accurate above 0.001"	Minimal drift	~±15 CFM (varies depending on signal noise)	Incorrectly re-zeroed the damper resulting in offset error
Alerton (hot-wire)	Highly accurate at calibration points (no flow and design flow); significantly underestimates actual flow at other values	No noticeable drift	3% of range (~15 CFM)	None
ALC (hot-wire)	Highly accurate at four calibration points with deviations between these points	No noticeable drift	±5 CFM	None

The Siemens and JCI auto-zero procedures will at times produce additional errors for dampers that do not fully seal, such as the Nailor VAV box in this study.

Figure 5 shows an example of how typical accuracy data was collected. In this case the Micro-Cal pressure-generating device was used to make a series of stable pressures which were seen by the reference pressure sensor and the Siemens pressure sensor. The equivalent reference “flow” was

calculated from the “K” value at areas of stable pressure, seen in Figure 5 as green points. These are then averaged together to be compared to the flow reported by the Siemens controller.

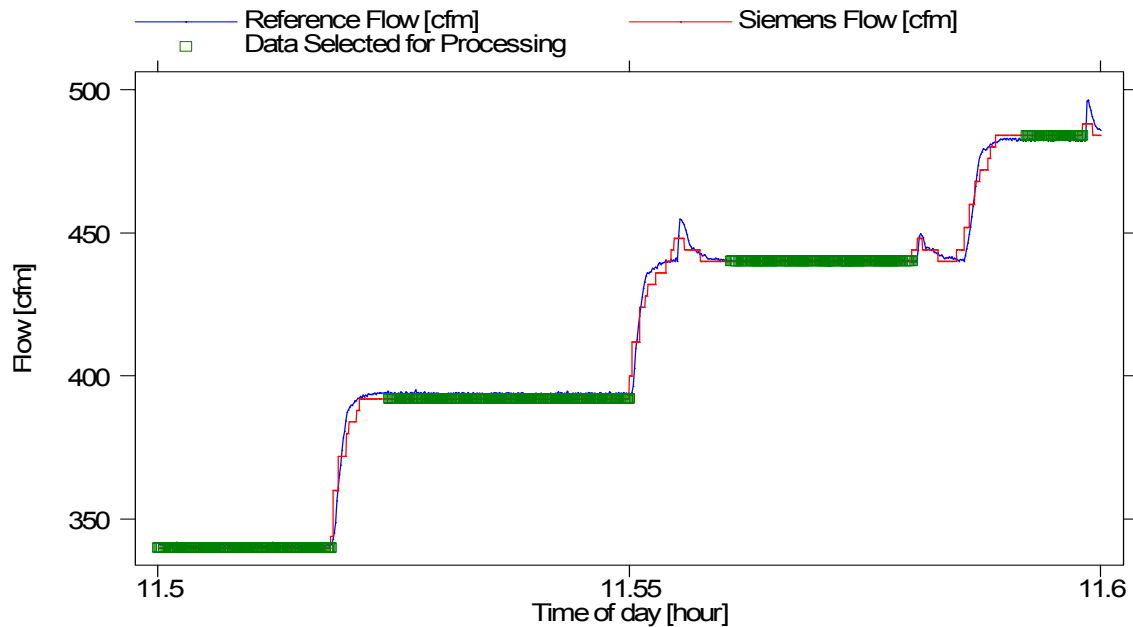


Figure 5: Typical data for determination of the accuracy of the calibration of the controller

The controllers using a “hot-wire” type sensor employ the pressure on the flow grid to produce a flow across the “hot-wire” located in the controller. The Micro-Cal is intended to calibrate a pressure sensor. When attempting to make a constant pressure, it interprets the flow through the controller as a leak and reports an “error.” For these sensors, the accuracy data was generated using real flows from the reference flow meter. Because the pressures thus generated have more “noise,” longer averaging times were used to compensate.

If the zero of the pressure sensor had been recently measured, the Siemens sensor (a pressure sensor) was found to be extremely accurate and stable under all conditions down to about 50 CFM (140 FPM, 0.003” signal, or about 10% of typical design flow). Typically, the accuracy was about ± 5 CFM. Below 50 CFM, the sensor was sometimes inaccurate due to zero drift. If the sensor was recently re-zeroed then it was quite accurate—even below 50 CFM. Figure 6 shows the flow accuracy data for the Siemens controller on the Titus and Nailor VAV boxes.

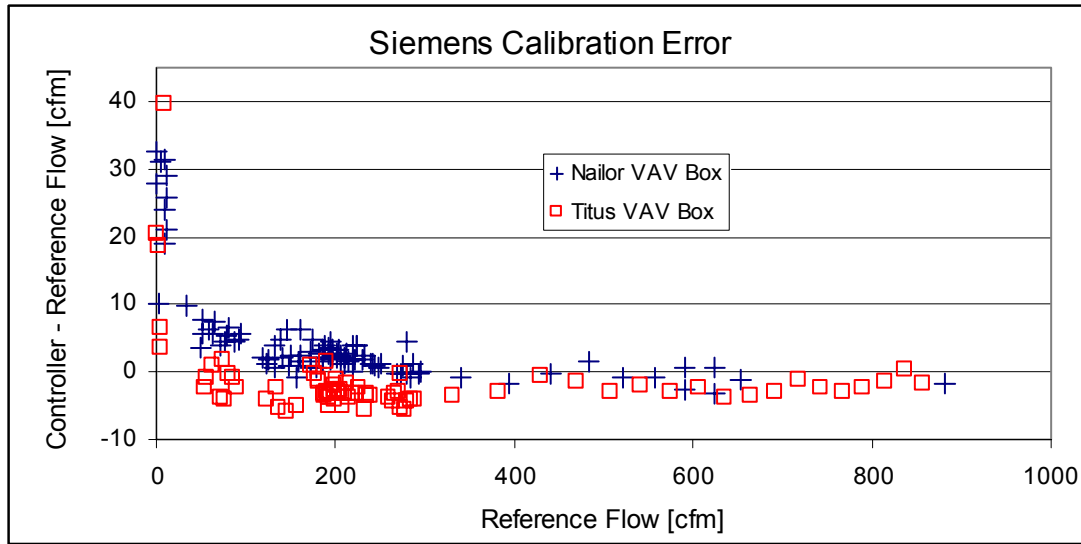


Figure 6: Accuracy of the flow determined by the Siemens controller on the Titus VAV box

Re-zeroing the zero drift could cause the reading below 50 CFM to be off by as much as 100% within hours—and sometimes minutes. This behavior can be seen in Figure 7 where the zero is measured every 12 hours at which time the error in the pressure sensor zero resets to zero and then starts to drift again. See appendix D for the details of how this measurement was made.

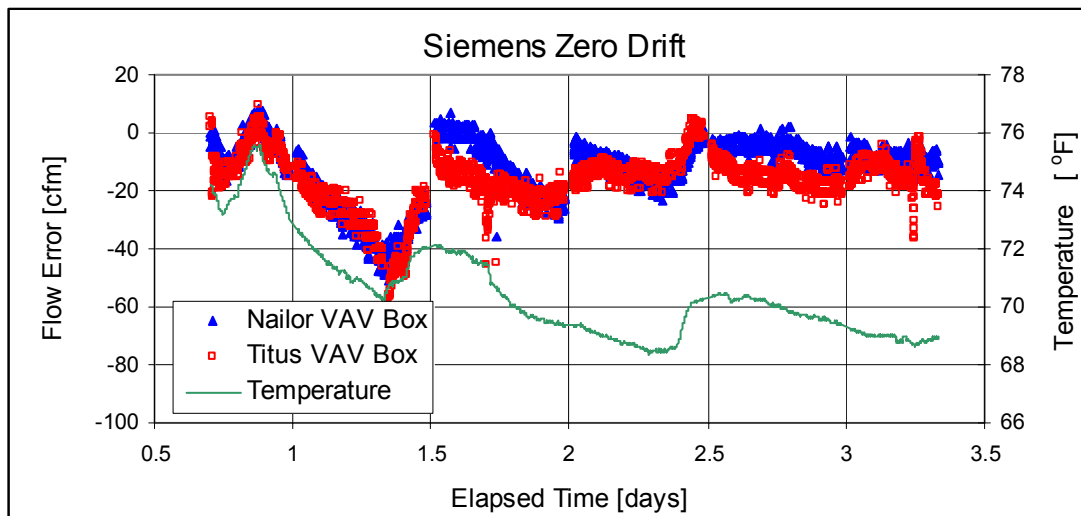


Figure 7: Zero drift of the Siemens pressure sensor

This pressure sensor zero is seen to be closely dependent on changes in ambient temperature. Siemens offers a flow bypass kit which can rapidly re-zero the sensor several times per hour without interrupting the flow. Testing with this optional kit greatly reduced the error in the reported flow caused by zero drift.

The Alerton sensor (a hot “thermistor”) was found to be stable at all flows but its calibration was not well described by a single “K” factor at all flow grid pressures. The cause is believed to be the complex, non-linear nature of the “hot-thermistor” sensor’s response instead of the conventional

pressure sensor. The calibration errors were as high as 50 CFM at about 100 and 300 CFM when the single point calibration was made at ~500 CFM, see Figure 8. Calibration errors were limited to 15 CFM at flows above 400 CFM.

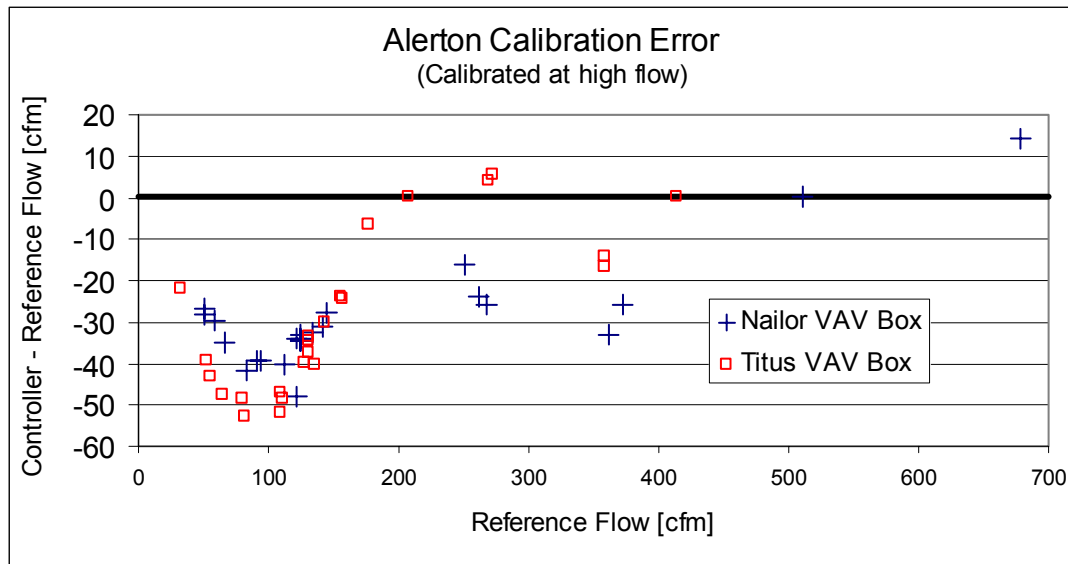


Figure 8: Calibration errors

A multiple-point calibration is an option that was not studied in these measurements but should be investigated in any future research. As discussed in Appendix E, the choice of the flow used in the calibration can be an important factor in determining the accuracy of the calibration. Using a high flow results in an overall calibration that limits the error but may not be particularly good at low flows; using a single low flow for the calibration can result in large extrapolation errors due to the non-linear nature of the “hot-wire” type sensor.

Overnight testing of the Alerton controller, seen in Figure 9, showed that the error in the flow was relatively constant, indicating little drift in the zero value of the sensor.

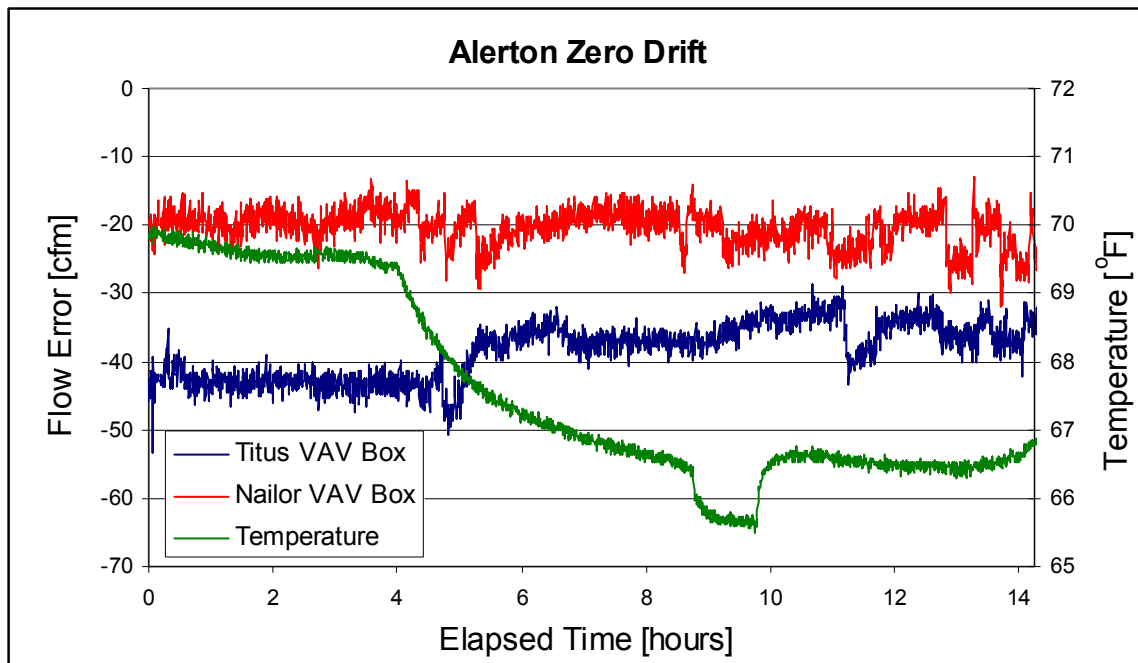


Figure 9: Flow error of the Alerton controller at 70 CFM

The Johnson Controls sensor, like the other pressure based sensor from Siemens, had a calibration error of less than 5 CFM between the maximum flow tested (about 650 CFM and 50 CFM). The calibration errors below 50 CFM, seen in Figure 10, were larger, apparently due to a slight drift of the zero pressure.

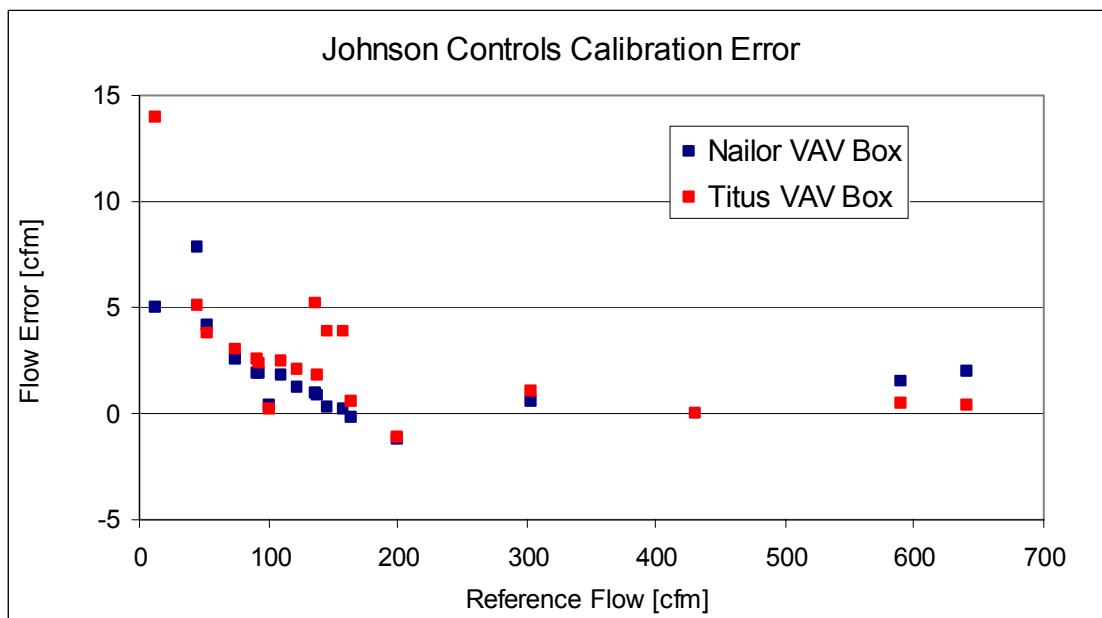


Figure 10: Calibration accuracy of the Johnson Controls controller

Long-term measurements of the Johnson Controls sensor's zero drift indicated that it was quite stable, unlike the Siemens sensor. However the auto-zero procedure, which is automatically performed every two weeks, has an error. The flows calculated after this procedure were off by 50% for one box (see Figure 11) and 100% on the other when the reference flow was about 50 CFM. This is seen as a serious problem, but appears to be a software or firmware problem. Like Siemens, Johnson Controls offers a seldom-used pressure bypass kit so that the zero may be measured frequently without interfering with the flow. It was not evaluated in this study.

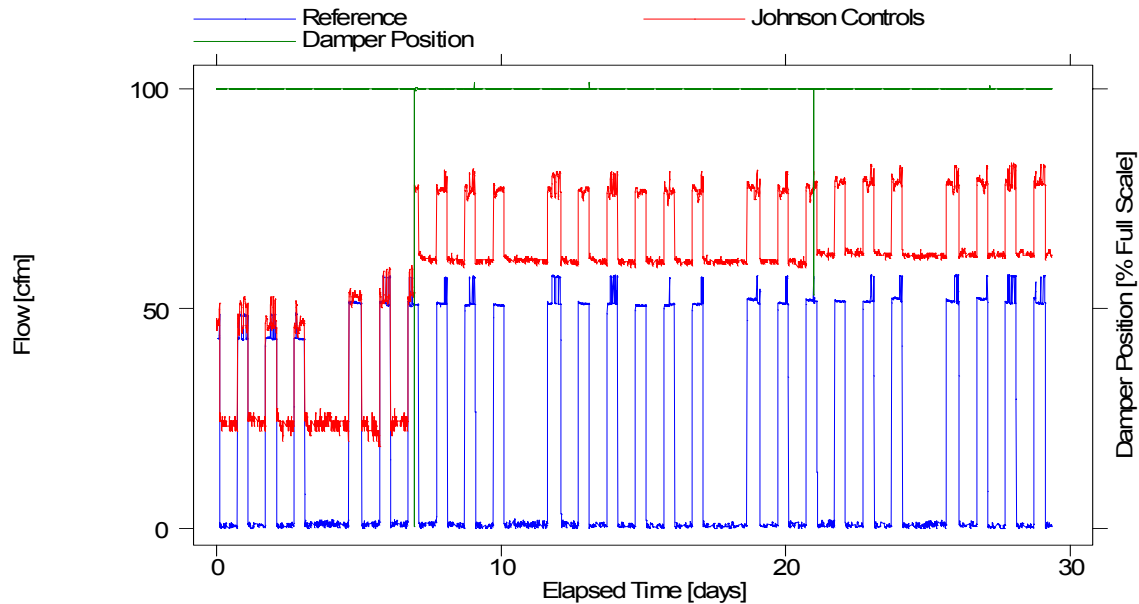


Figure 11: Reference and controller flows for a 29-day test; the spikes in the damper position around days 7 and 21 indicate times when the zero of the pressure sensor is being checked

The **Automated Logic Corporation (ALC)** sensor (a “hot-wire” type) was much like the Alerton “hot-thermistor” except that it uses a four-point in-situ calibration procedure at the selected flows of 0, 75, 300, and 600 CFM. It had a stable response, but using a single “K” factor for all flows resulted in calibration errors (shown in Figure 12). Errors were as high as 20 CFM at about 50 and 150 CFM (approximately midway between the calibration points). Errors of up to 30 CFM were seen at flows below 30 CFM and calibration errors were limited to 15 CFM at flows above 250 CFM.

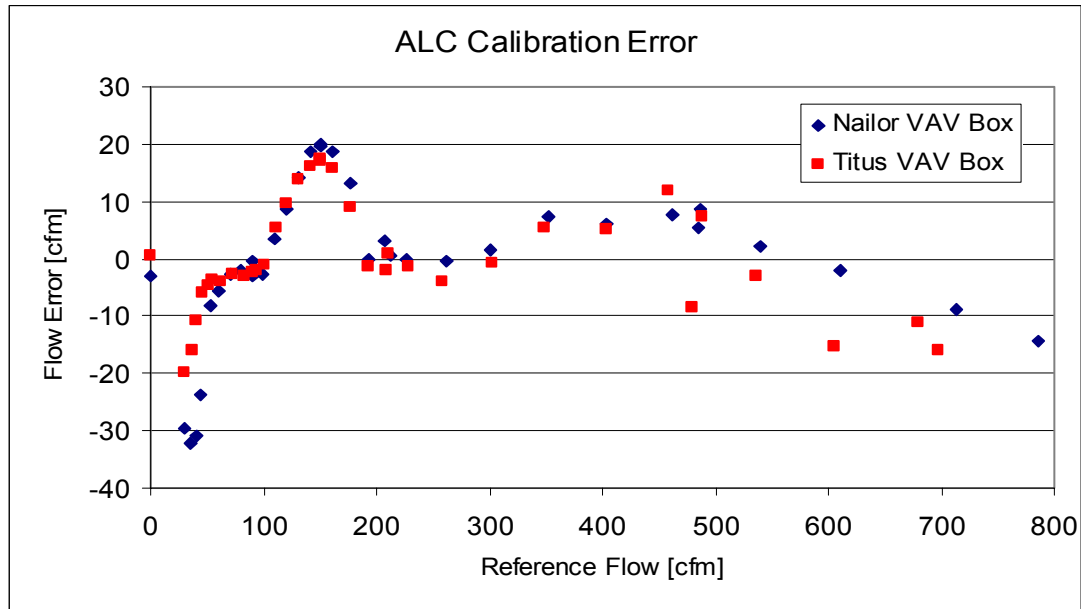


Figure 12: Calibration accuracy of the ALC controller

Overall, the four-point calibration procedure yielded a better calibration result than the two-point procedure used for the Alerton controller, but was still not as good as either controller that used a pressure sensor.

Unlike the other controllers, the ALC controller will report a negative flow rather than forcing a zero value. This could potentially yield a more accurate determination of the flow in situations of extremely noisy signals at very low flows—circumstances where forcing “negative” flows to be zero results in a positive bias. These situations are probably rare, but these negative flows allow a direct measurement of the drift of the sensor at zero flow. Figure 13 shows that the zero was quite stable, at about negative 3 CFM, for several days. It also does not appear to have any correlation to ambient temperature as was seen with the Siemens sensor.

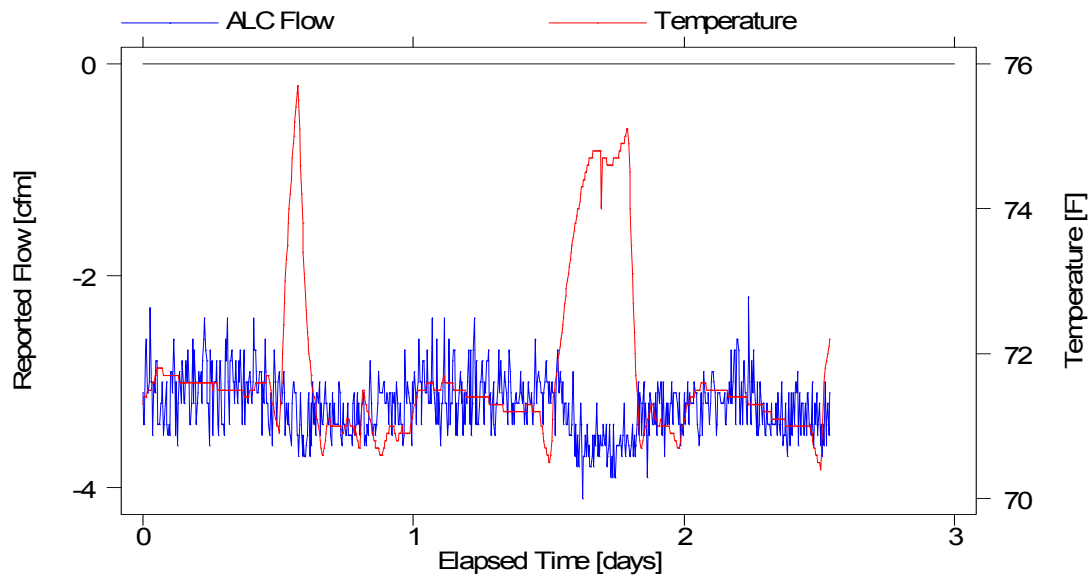


Figure 13: Zero drift of the ALC controller

7.2 Stability

Dynamic flow grid pressure changes were made to assess the ability of the controllers to track changes in the flow. Dynamic behavior was investigated for large and small changes in the flow grid pressure at fast and slow rates of change to the flow grid pressure. All of these controllers were able to track changes to the flow pressure signal when the dynamics used were within the normal operating ranges. This was consistent with the errors previously observed in their calibrations. Tests where the flow pressure cycled rapidly showed a smoothed or filtered value for the controller's reported flow; this was consistent with the filtered value of the reference flow meter. The filter time constant was different for different controllers, but in all cases the flow value was stabilized within 30 seconds.

Figure 14 shows an example of the kind of data generated using the Setra Micro-Cal pressure generating device. Starting from zero, it jumps to a given pressure then ramps up in steps to a higher pressure, and then back down, at which point the operator, after a small delay, can initiate another test. It could not be used for the "hot-wire" type sensors because they determine the VAV flow based on a small flow through the controller; this appeared to the Micro-Cal as a leak. The maximum rate at which the pressure can be adjusted is limited by the Micro-Cal. It allows for an accurate determination of the pressure with its internal sensors.

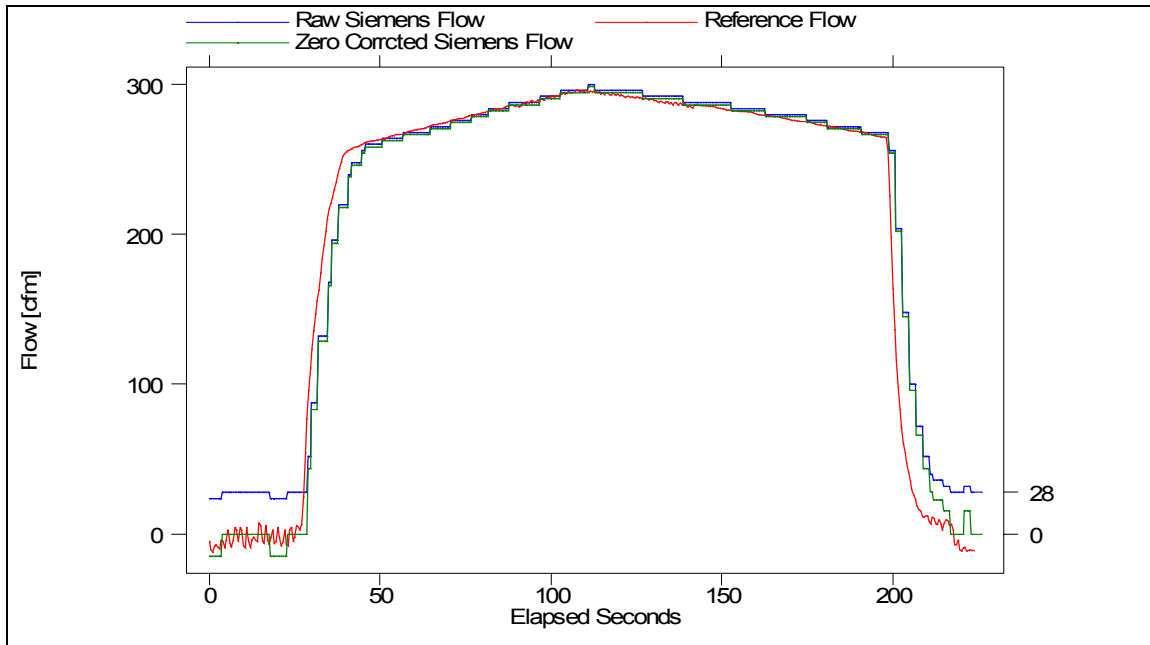


Figure 14: Controller stability data taken using the Micro-Cal pressure generator

Figure 15 shows an example of the dynamic changes generated by “manual” means. This consisted of connecting a closed-end tube to the pressure sensors and pinching the tube to increase the pressure inside it. The tubing and pressure sensors in this arrangement form a closed volume of air which is very sensitive to changes in temperature. Thus, there is the drift in the “unpinched” value of the flow (pressure).

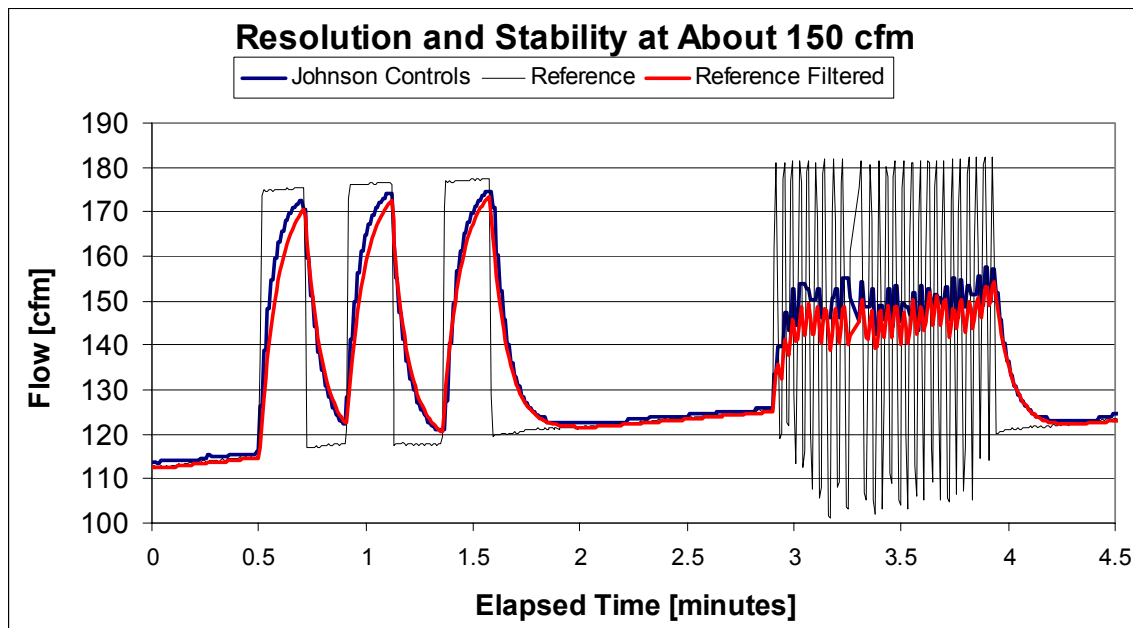


Figure 15: Stability data gathered using “manual” adjustments to a system of closed tubing

Figure 16 is an example of data generated by operating the reference flow meter fan. It has the advantage of being able to make repeated cycles about a given flow (pressure) without returning to zero. Furthermore, it is not sensitive to temperature. Both the “manual” and “reference fan” methods generate flow changes at higher frequencies than the Micro-Cal was able to produce.

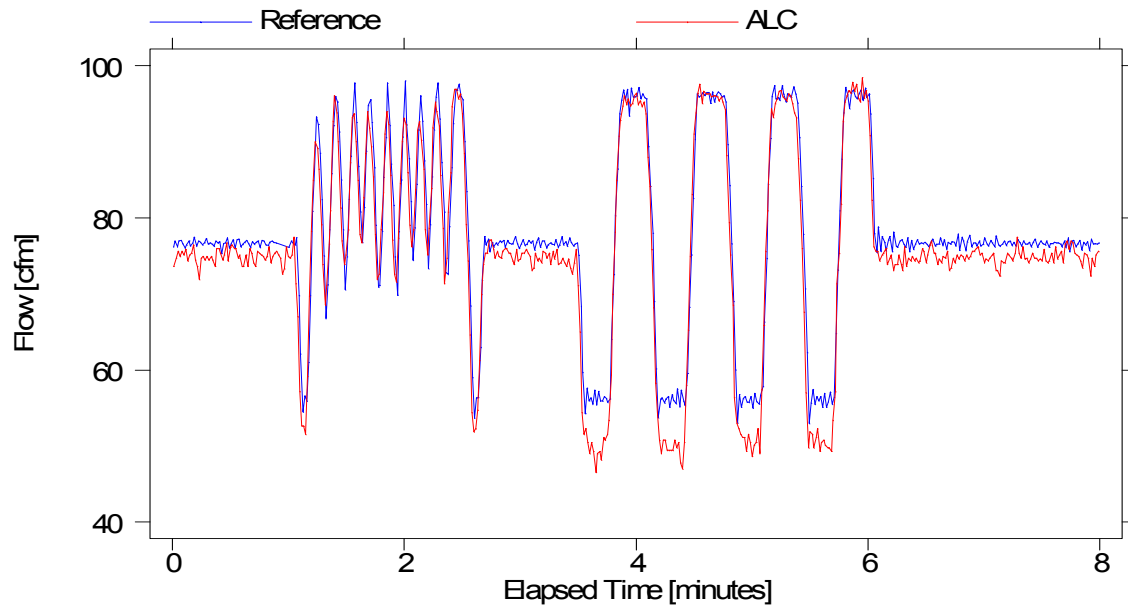


Figure 16: Stability data taken using the reference fan and associated software

The method by which the dynamic pressures were produced does not seem to affect the analysis of the controllers’ performance

8. Controller + Box Test Results

Controllers from the four manufacturers were tested on both boxes (eight complete systems tested) under a variety of conditions. The goal was to determine how stably and accurately each system could maintain a given flow setpoint and how often the damper needed adjustment. Flow setpoints from 50 to 400 CFM were tested at inlet pressures from 0.1" to 1.5". Table 3 summarizes the results for a representative sample of these tests. The results for all tests are in the Appendices.

Most controllers seek to maximize the lifetime of the damper actuator motor by minimizing its use. This is often accomplished by using some sort of dead band around the flow setpoint. If the dead band is large, the flow may be significantly lower than the requested flow. On the other hand, a dead band that is too small can result in oscillating flow and continual adjustment of the damper position.

All these controllers could quickly—in less than four minutes—adjust the dampers to achieve any flow setpoint of 50 CFM or greater, when used with their default dead bands. This was true for any combination of flow set point and inlet static pressure where the static pressure was high enough to produce the requested flow. The Siemens controller is the only controller that does not appear to have a dead band built into the damper control. Thus, it had the most damper adjustments but was still stable (without hunting).

The **Siemens controller** produced a very stable flow with both the **Titus** and the **Nailor VAV** boxes under all conditions. It was able to quickly reach the flow setpoint, usually within 2 CFM, when subjected to inlet pressure changes. Figure 17 shows the Siemens controller response to changes in the inlet static pressure at a flow setpoint of 400 CFM for the Titus VAV box.

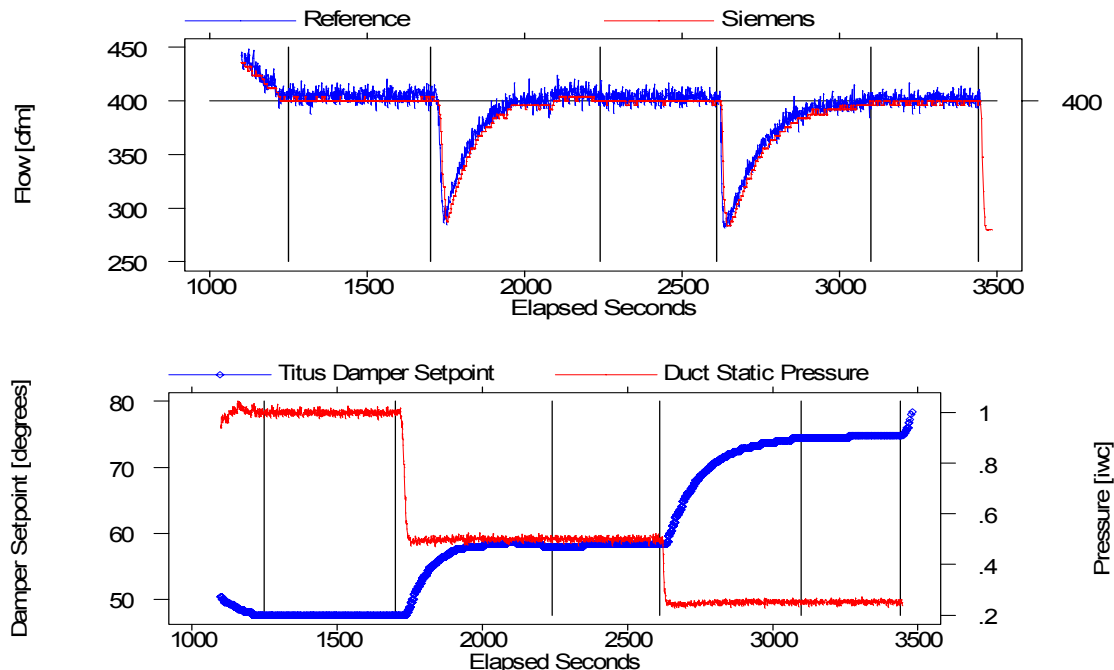


Figure 17: Siemens controller response to inlet static pressure changes at 400 CFM setpoint

Between adjustments to the inlet static pressure, periods of stability were identified at approximately 1250-1700, 2250-2600, and 3100-3450 elapsed seconds (Figure 17). These periods

were investigated to determine how close the flow was to the setpoint and how often the damper was adjusted.

Because it has a very narrow flow dead band—possibly none—the damper is occasionally adjusted without any apparent change in the inlet static pressure. Figure 18 shows the controller response to changes in the inlet pressure at a flow setpoint of 50 CFM for the Siemens controller on the Nailor VAV box. When comparing the Nailor box with the Titus box, it took about twice as long to reach setpoint and twice as many damper adjustments (Figure 19). This can be explained by the fact that the Nailor box has an opposed blade damper with 45 degrees of travel, while the Titus box has a round damper with 90 degrees of travel. The same controller has finer control when used with a damper with more travel.

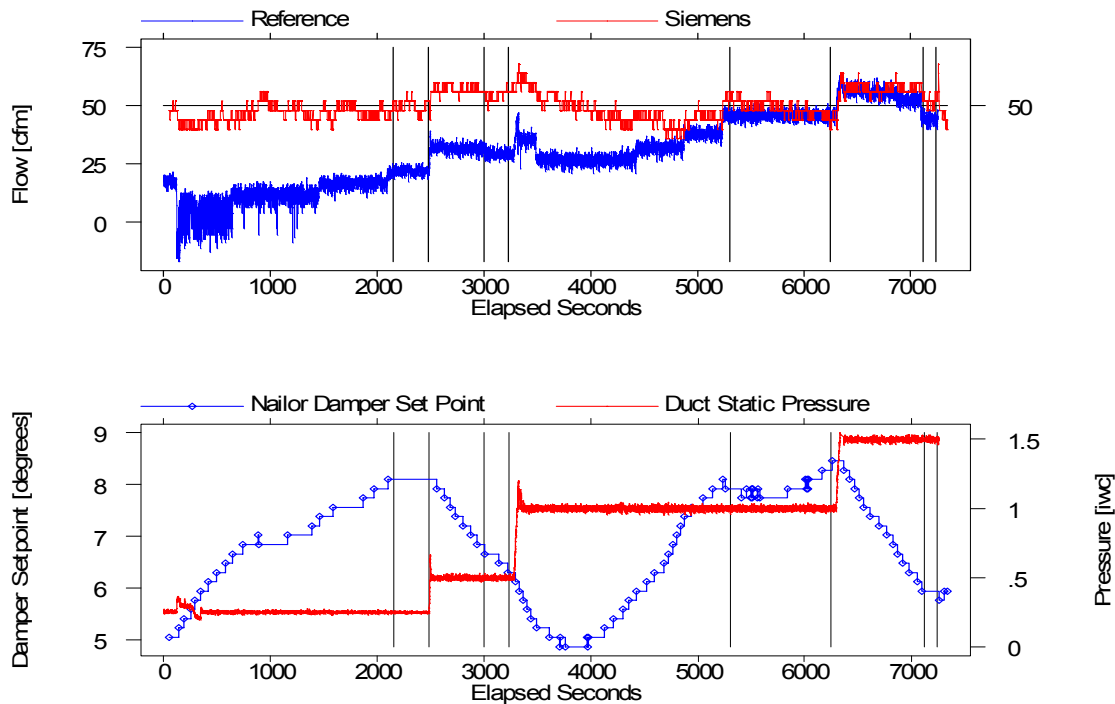
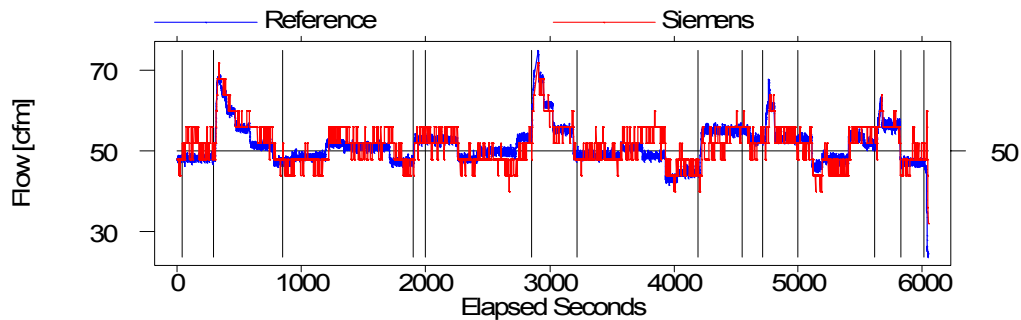


Figure 18. Siemens controller response to changes in the duct inlet static pressure at a flow set point of 50 CFM on the Nailor VAV box

The reference flow starts out much lower than the controller-determined flow because the zero value of the controller's pressure sensor had not been recently measured.



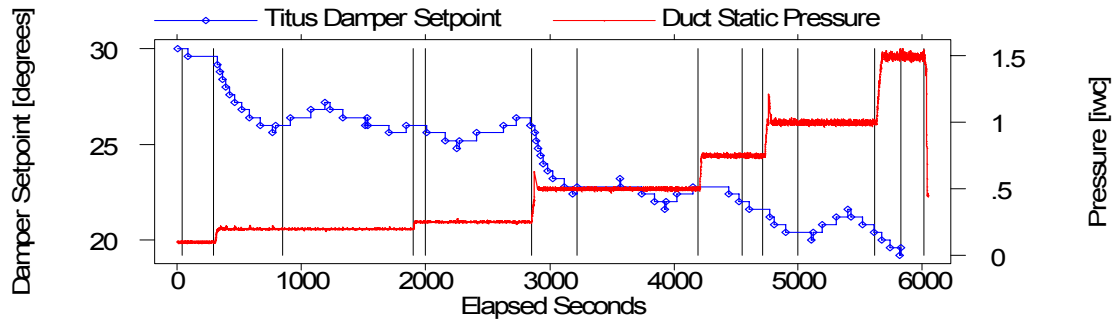


Figure 19 Siemens controller response to changes in the duct inlet static pressure at a set point of 50 CFM on the Titus VAV box

Figure 20 shows similar data for the **Alerton controller** with the Titus VAV Box at a flow set point of 70 CFM. The initial part of the test, until about 10:40, had a dead band of ± 3 CFM. The size of the dead band in the Alerton controller is equal to 3% of the maximum – minimum flow range. Thus to get a ± 3 CFM dead band, the maximum flow was set to 140 CFM and the minimum was 40 CFM. 140 CFM is not a typical flow rate for an eight-inch box and was selected just to evaluate the impact of a smaller dead band. A flow outside of the “maximum” and “minimum” will be measured but cannot be used for the setpoint. After 10:40 the maximum was increased to 1000 CFM and the minimum was lowered to 0 CFM. This resulted in a dead band of ± 30 CFM. Flows and damper position in the initial part of the test were continually being adjusted and did not settle at the flow setpoint. With the larger dead band, the damper settled to a new, constant position, and the flow was closer to the flow setpoint.

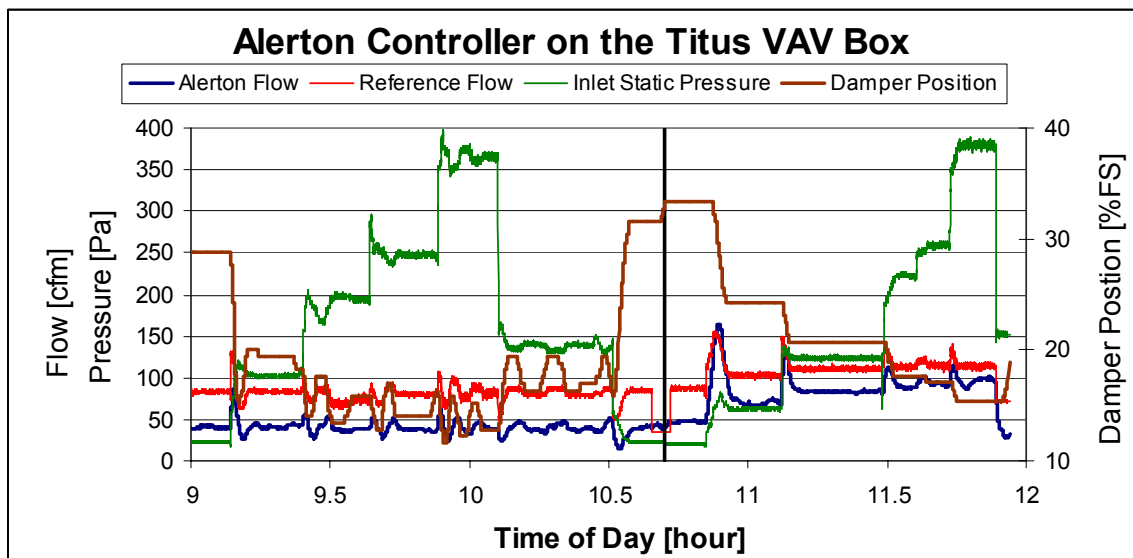


Figure 20: Alerton controller response to changes in the duct inlet static pressure at a set point of 70 CFM on the Titus VAV box

The dead band of the **Johnson Controls controller** is adjusted by the controller based on the amount of signal “noise”. In these tests the dead band was about 15 CFM. Figure 21 shows typical data for the Johnson Controls controller at various inlet static pressures, in this case at a setpoint of 50 CFM. Because of the dead band, the damper position was not changed even when the inlet static pressure was adjusted from 125 Pa (0.5 iwc) to 375 Pa (1.5 iwc)

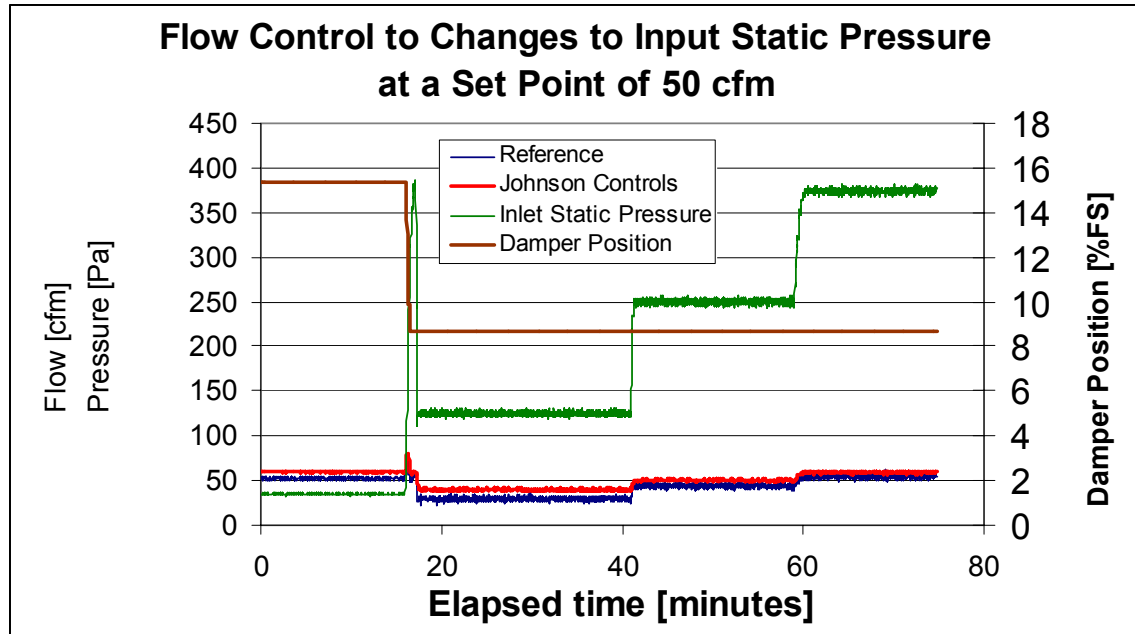


Figure 21: Johnson Controls controller response to changes in input static pressure at a flow set point of 50 CFM

The ALC controller has a flow dead band that corresponds to one second of damper movement. Thus it is dependent on damper position and the inlet static pressure. The dead band is evaluated after every damper movement. In these tests the dead band appears to be about 5 CFM for flows under 200 CFM; it was not determined for higher flows. Figure 22 shows the response of the controller to changes in the flow setpoint. The desired inlet static pressure was 250 Pa (1.0 iwc) which the reference flow meter fan was unable to produce until the flow was reduced to 200 CFM. The data for the ALC controller was recorded every second, and in the accuracy and stability tests the recorded values changed every second. But when put into the normal operating mode—where the controller operates the damper as in these measurements—the recorded flow data remained constant for 10-second intervals.

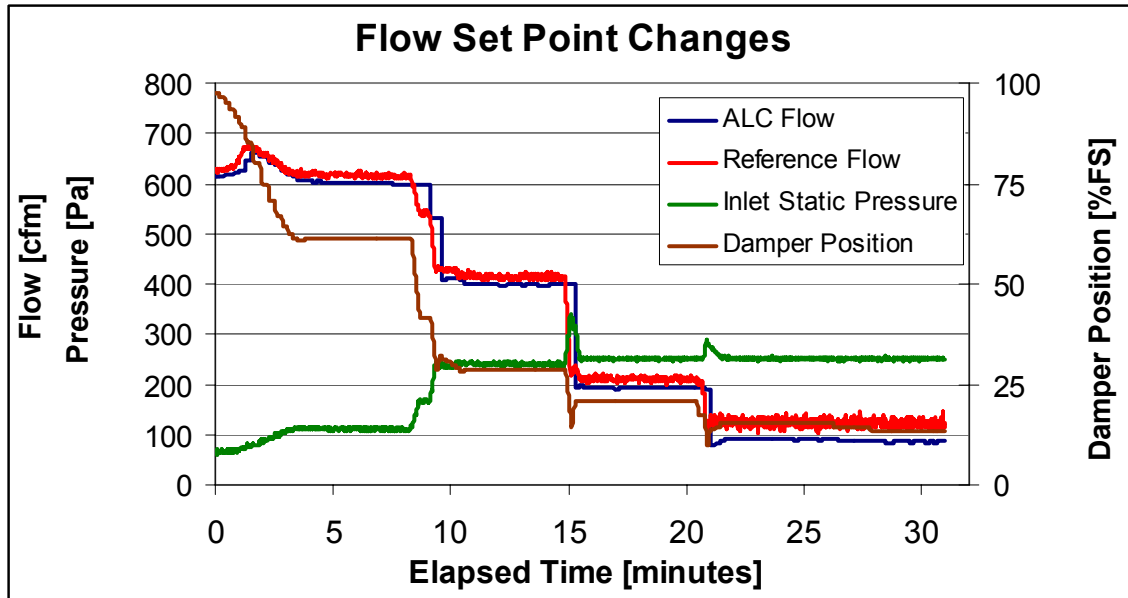


Figure 22: Controller response to a change in flow set point.

Table 3: Complete System Stability Test Results of Selected Examples					
Controller	Flow Set Point [CFM]	~ Inlet Static Pressure 0.5 iwc (125 Pa)		~ Inlet Static Pressure 1 iwc (250 Pa)	
		Controller Reported Flow [CFM]	Damper Adjustments per Hour	Controller Reported Flow [CFM]	Damper Adjustments per Hour
Siemens	50	50	31	50	47
	100	99	27	99	35
	400	400	11	400	1
Johnson Controls	50	57	0	59	0
	100	95	0	106	0
	300	294	0	na	na
Alerton	70	83	0	93	0
	150	144	0	147	0
	300	305	0	315	0
ALC	50	48	0	50	0
	75	76	0	77	0
	200	193	0	192	0

Table 3 has example stability data for the controllers. Data for many other configurations are in the Appendices.

The accuracy of the “Damper Adjustments per Hour” is limited by the relatively short times for each of these tests, often about 5 minutes. These should be viewed as representative only.

Only the Siemens controller continued to make small adjustments to the damper position after the flow setpoint had been reached. The Siemens controller flow was also the closest to the flow setpoint. Forcing the flow dead band to be small—as might happen if the VAV box was greatly oversized—could result in unstable control.

9. Energy Analysis

VAV box minimum-flow setpoints are often set at 30-50% of design flow. There are a number of factors that determine the "right" minimum, including:

1. Control sequence – If a single maximum sequence is used then the minimum must be high enough to prevent stratification in heating (typically 30-50%). With a dual maximum sequence, stratification is not an issue and the minimum is determined by the other factors.
2. Ventilation requirements – Requirements can range from 5-50%, depending on the design cooling load and occupant density. 10% is common for perimeter zones.
3. Stability and accuracy of VAV box controls – This research concludes that under typical conditions, boxes will be stable and accurate down to about 10% flow.
4. Comfort (including "dumping") and air change effectiveness -- Conventional wisdom says that comfort cannot be maintained below about 30%. However, preliminary research shows this is not true. Additional research is required (see Recommendations for Future Work below).

It is hoped that as a result of this research, design engineers will be encouraged to use dual maximum zone controls with low minimum flow setpoints to produce significant energy savings. In order to determine the potential energy savings of dual maximum zone controls a detailed energy analysis was performed.

DOE-2.2 was used to compare the energy performance of three zone control sequences: Single Maximum, Dual Maximum with VAV Heating and Dual Maximum with Constant Volume Heating. These three sequences are depicted schematically below and described in detail in Appendix I. Basically, the minimum flow setpoint in the Single Maximum sequence is limited by the maximum discharge air temperature at which the design heating load can be satisfied. To maintain good mixing and prevent stratification, the supply air temperature cannot exceed approximately 95°F. Thus, the minimum flow setpoint in this sequence is typically limited to about 30-50% by the maximum temperature. The setpoint is not limited by the minimum flow at which the box can stably and accurately control. With a dual maximum sequence, the minimum flow setpoint is not limited by the discharge temperature in heating; it is limited by the ventilation requirement or the controllable minimum. The Dual Maximum with VAV Heating sequence is widely used and is recommended by the authors. The Dual Maximum with Constant Volume Heating is not recommended, but is included in this analysis. Because some engineers use this sequence, it is therefore instructive to see the energy implications.

The basecase model is a typical office building in Sacramento with a packaged VAV and hot-water reheat system. This model was also run in San Francisco, Los Angeles, Chicago, and Atlanta. Numerous parametric analyses were also run to determine the impact of: supply air

temperature reset, single maximum sequences with 40% and 50% minimums, oversized zones, systems that are left running 24/7, and very lightly-loaded buildings.

Note that a 20% minimum was used in the Dual Max simulations even though this research has shown that under typical conditions boxes should be stable and accurate down to 10%. The 20% minimum was used because this energy analysis is also being used to support a new code requirement in Title 24 and ASHRAE 90.1 requiring that minimums be no greater than 20%. Since it is a proposed code requirement, it must be sufficiently conservative so that it does not require people to do something that might not work effectively. If a designer were designing a highly noise-sensitive space, they might oversize the VAV box (e.g. use an eight-inch box for a design flow of 300 CFM.) A 10% minimum flow for an oversized box is likely to be below the setpoints recommended herein for accurate control. One option is to rephrase the code requirements in terms of inlet velocity (e.g. minimum shall be less than 200 FPM) or even probe signal (e.g. minimum shall be less than 0.005"). Such a paradigm shift would require a major education campaign to make sure engineers understood it. Therefore, 20% was used because it is familiar to engineers and is sufficiently conservative to cover the vast majority of realistic scenarios.

In the basecase model the Dual Max-VAV saved 5 cents/ft²-yr compared to the single maximum. The Dual Max-Constant Volume actually used 2 cents/ft²-yr more energy than the Single Maximum case—even though it has a lower flow in dead band (20% versus 30%). As shown in Figure 23, the Dual Max-VAV savings decrease if supply air temperature reset is employed. They increase if: the zones are oversized, the fan runs 24/7, or the minimum flow for the Single Maximum sequence is higher than 30%. It is estimated that the average savings of the Dual Max-VAV sequence for a typical office building would be approximately 10 cents/ft²-yr.

According to the California Energy Commission there are approximately 6 billion square feet of existing commercial buildings in California.¹ Of this area, about 2 billion square feet is office and university/college space. This sector is expected to add about 50 million square feet every year through the end of the decade.

Assuming that a) half of existing and new buildings in these sectors are VAV systems; and b) 0.5% of existing VAV systems will be retrofit annually with new lower minimum setpoints; and c) that 20% of new VAV systems will be installed with lower minimum setpoints, then the penetration will be about 10 million square feet per year. At an estimated savings of \$0.10/ft² this comes out to \$1 million in energy savings the first year, \$2 million the second year, and \$10 million per year in year 10.

¹ http://www.energy.ca.gov/reports/2000-07-14_200-00-002.PDF

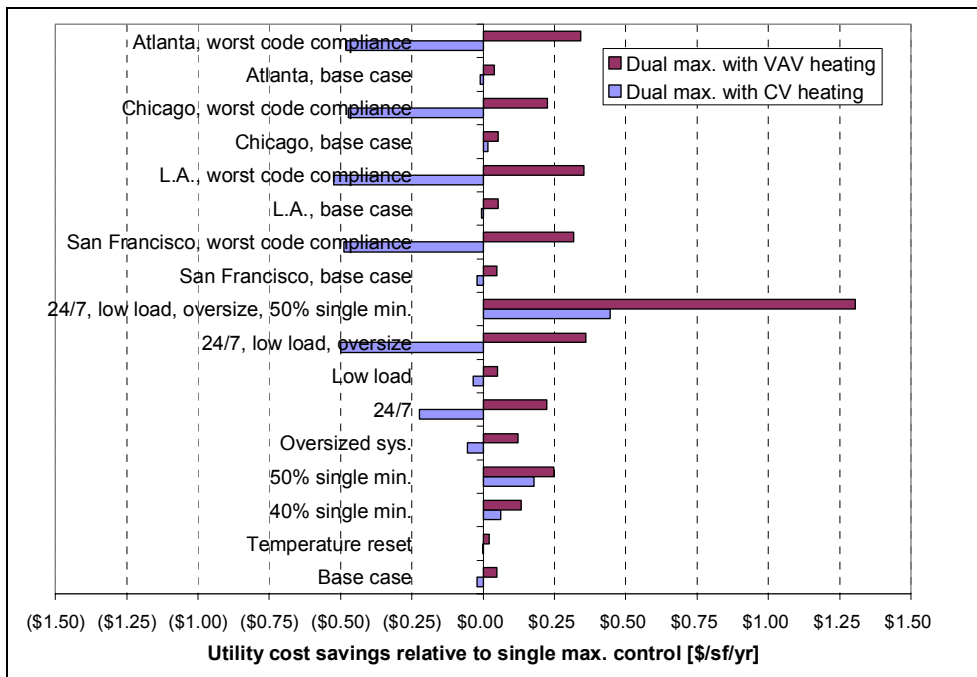


Figure 23 Annual utility cost savings

Schematics of Modeled Zone Control Sequences

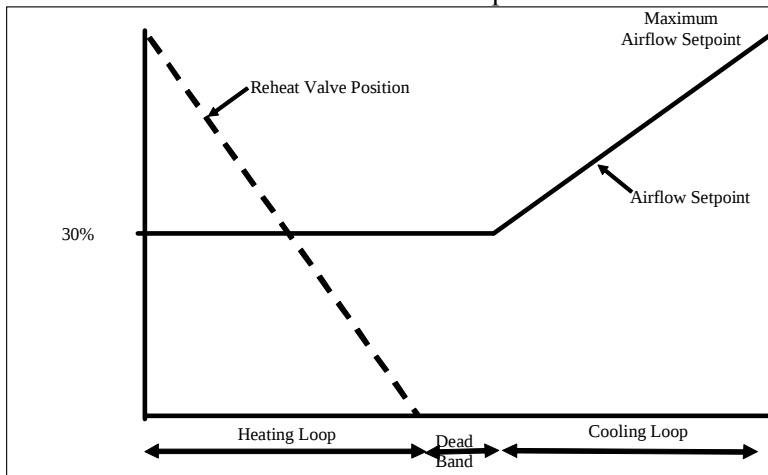


Figure 24. Single Maximum Zone Control Sequence

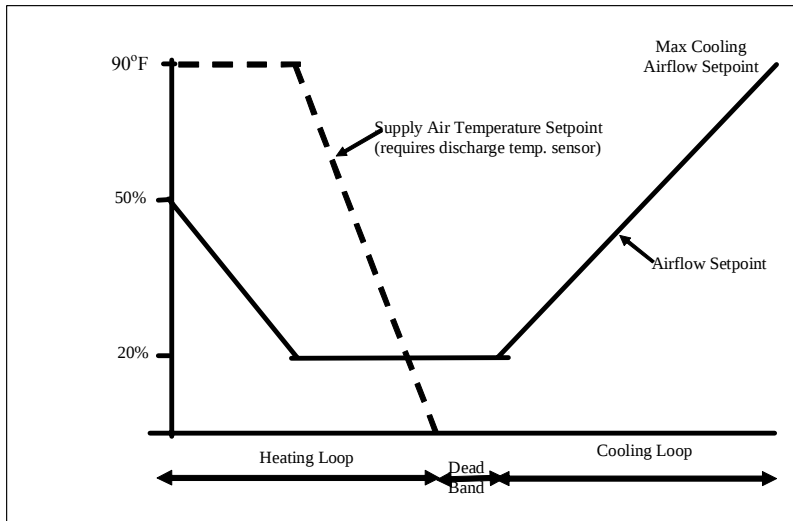


Figure 25. Dual Maximum with VAV Heating – Temperature First

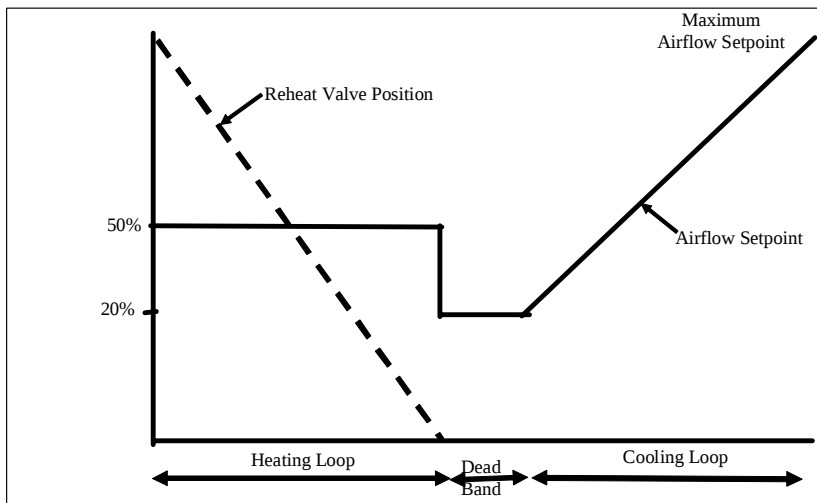


Figure 26. Dual Maximum with CV Heating

10. Conclusions

Table 2 summarizes the sources of inaccurate flows reported by the controllers. The following conclusions are made:

- 10.1.1 Flow probes in the VAV boxes are accurate and stable under all conditions, including flows down to 0.001" (85 FPM) at any damper position.
- 10.1.2 All controllers tested were stable at flow setpoints as low as 0.003" (140 FPM).
- 10.1.3 Steel diaphragm pressure sensors, such as the one in the Siemens controller, can have a zero drift within hours of re-zeroing of 0.003" or more. However the Johnson Controls controller, like the Alerton and ALC controllers, had a very stable zero drift.

- 10.1.4 The reason for the error in the zeroing procedure of the Johnson Controls controller needs to be determined. It is possible it was due to an installation problem, but the error did not become apparent for over two weeks.
- 10.1.5 Tight temperature control (within 2 degrees) will reduce the zero drift seen in the Siemens controller. Conversely, if temperature drifts significantly at night when the fan is off and when the sensor is re-zeroed, then zero drift during the day could be greater.
- 10.1.6 High accuracy at low flow can be achieved with a controller such as the Siemens controller at setpoints down to:
- 0.003" (140 FPM) if an auto-zero bypass feature is installed; and
 - 0.01" (300 FPM) without an auto-zero bypass (accurate to about 15% of reading at 300 FPM).
- 10.1.7 Controllers with hot-wire anemometer sensors, such as the Alerton and ALC controller, do not have significant zero drift. However, they have significant accuracy problems at flows different from the flow at which the sensor was calibrated. Conclusions are:
- calibration at more than one point may improve accuracy; and
 - calibration at the "minimum" set point instead of zero flow may improve accuracy, though proper in-situ measurement of this flow is unlikely.
- 10.1.8 Large dead bands used by some controllers to reduce the amount of damper-actuator usage may be too big in low-flow applications. Conversely, dead bands that are too small could lead to either unstable control or frequent damper adjustments.
- 10.1.9 Accuracy specifications (generally unavailable) should include the minimum and maximum velocity to be measured and maximum drift due to all sources. Moreover, they should include a temperature coefficient and information about long-term stability with recommended recalibration intervals.
- 10.1.10 Based on typical VAV box selections, VAV box minimum flow setpoints of 10% of design flow will be stable and accurate.
- 10.1.11 Using a dual maximum zone control sequence with a 20% minimum will save about \$0.1/ft²-yr compared to a single maximum sequence with a 30% minimum.
- 10.1.12 If dual maximum control sequences are used in only a small fraction of the VAV boxes installed every year in new construction and HVAC retrofits, millions of dollars of annual energy savings could be achieved statewide.

11. Discussion

Two objectives of this research were to recommend test methods which can be used to test VAV boxes and controllers, and calculate the lowest airflow setpoint at which a particular VAV box and controller combination can accurately and stably control. Based on this research, a test method for VAV box flow probes does not appear to be necessary since the probes tested were stable and accurate under all conditions tested. One potentially significant condition that was not evaluated in this research is inlet condition. Additional research should be conducted to determine the effect of non-straight inlet conditions on probe performance.

Arriving at a good test method for VAV controllers is challenging because of all the factors that appear to affect controller stability and accuracy. These factors include:

- Ambient temperature drift (e.g. Siemens)
- Auto zero software issues (e.g. JCI)
- Auto zero frequency (e.g. 12 hours for Siemens and 2 weeks for JCI)
- Auto zero bypass valve option (e.g. Siemens and JCI)
- Choice of calibration points (e.g. ALC and Alerton)
- Other factors not covered by this research (e.g. long-term drift issues such as accumulation of dust on hot-wire sensors over months or years)

Based on this research, a very preliminary controller test plan is described below:

1. Connect the controller to a standard commercial VAV box.
2. Record the ambient temperature.
3. Calibrate the controller using standard calibration procedures at max flow setpoint of 0.6" pressure signal and minimum flow setpoint of 0.01".
4. Wait at least one week or two auto-zero cycles (whichever is longer). If the controller does not have an auto-zero, then the wait period will be at least one week.
5. Perform both the Stability Test and Accuracy Test (see following steps). The controller "passes" the test at a given minimum pressure signal if it passes both tests at that signal.
6. Stability Test
 - a. Stabilize the inlet duct pressure at 1.5".
 - b. Set the controller to the desired flow setpoint (VPsignal).
 - c. Begin recording damper movements (time T). After 15 minutes (T+15), the duct pressure shall slowly fall to 0.5" over at least 10 minutes and no more than 30 minutes.
 - d. Stop recording damper movements at T+60 minutes.
 - e. Review the total number of damper movements. If it is less than 50, then the test is passed.
7. Accuracy Test
 - a. Stabilize the inlet duct pressure at 1.0" (Perhaps a minimum/maximum of 0.95-1.05 with a standard of 0.02).
 - b. Set the controller to the desired flow setpoint (VPsignal).
 - c. Record actual flow rate with a reference flow meter every minute (or less) for at least 12 hours. During the test period, the ambient temperature must fluctuate by at least 5°F with a change of no more than 2°F per hour (to prevent someone from quickly changing the temperature and then quickly changing it back)
 - d. Determine if the following are met to pass the test:
 - i. the average actual flow is within 20% of the desired flow; and
 - ii. the average actual flow during any 60-minute period is within 40% of the desired flow.

12. Recommendations for Future Work

In order to achieve the energy savings that this research has shown are possible, there are two important areas where additional research is needed: human comfort and additional box/controller tests.

12.1 Human Comfort

Stability and accuracy are not the only concerns that engineers have when selecting the minimum flow setpoint. Another concern is comfort (including "dumping") and air change effectiveness. This is where more research is needed.

Researchers at UC Berkeley (Fred Bauman, Charlie Huizenga, Tengfang Xu, and Takashi Akimoto) did some very important work on this topic in 1995. Using a test chamber, they found that acceptable comfort conditions could be maintained at 25% flow. This is in sharp contrast to the ADPI information (found in the ASHRAE Handbook and in diffuser manufacturers' literature) that suggests that comfort cannot be maintained below about 30-50% flow. Unfortunately, the researchers' findings were never published.

More research is needed on this subject in order to convince engineers and diffuser manufacturers that acceptable comfort can be achieved with standard overhead VAV diffusers at 10-20% flows. The research should include lower flow rates than the 1995 UC Berkeley work. It should also evaluate the impact of other variables such as different supply air temperatures and zone loads. In addition to lab tests, this research should also include field measurements and occupant surveys at real buildings with low minimums. These findings will be extremely valuable to engineers in terms of diffuser selection. It may also encourage diffuser manufacturers to develop new products that perform better at very low flows.

Hopefully, results will show that acceptable comfort can be maintained at 10-20% flow—at least under certain conditions (i.e. diffuser type, supply air temperature, etc.). If so, the research could have far-reaching implications in terms of affecting the ASHRAE Handbook, manufacturers' literature, and engineers' calculation of minimum flow rates. It could also lead to changes in Title 24 and ASHRAE 90.1 that would require lower minimum flow rates.

12.2 More Box/Controller Experiments

ASHRAE plans on sponsoring a continuation and expansion of this work to other inlet conditions and other equipment manufacturers. Here are some recommendations for that work based on the results reported here:

- The calibration accuracy of the Alerton controller should be retested using their multi-point calibration procedure. This might be done in several combinations of selected flows in order to determine the optimal set.
- The problem with the zeroing procedure of the Johnson Controls controller should be determined. If this was due to incorrect installation or setup configuration, then a check for these during installation should become standard practice.
- Measurements over longer times (i.e. at least a month) should be planned to assess the issue of long-term drift and to uncover unknown issues as was found while testing the Johnson Control controller. These should include a wider range of ambient temperatures than the current study. Introduction of pollutants (ASHRAE "dust") into the air stream should be considered to simulate long-term aging.

- Both “excessive damper movement” and “inlet pressure stability” should be defined and then used to determine how long the “complete system tests” must be to assess damper movement.
- It takes many points to assess the accuracy of the controllers’ calibration. It is likely that at least 10 points must be evaluated from the lowest proposed setpoint and twice its value, and at least 5 points from the proposed setpoint to half its value. An additional 10-20 evenly-spaced points (approximately) between the maximum and twice the lowest setpoint values should also be evaluated.
- Obtaining a better understanding of what pressure fluctuations are in real buildings will help in assessing the previous concern. These “pressure fluctuations” can be from real changes in the bulk flow, turbulence that is transmitted back to the flow sensor, or vibrations from various sources.
- Agreement should be reached on what range limit the test should encompass. These should include:
 - the minimum and maximum inlet static pressure to be used in the “complete system tests” (the values of 1.5”, 1”, 0.5”, and 0.25” WC are suggested); and
 - the size and frequency of the pressure fluctuations to be used in the “stability” tests. The two tests suggested are the “stability” test (Section 6) and a second test to evaluate the controller response to the largest expected “noise” installed in buildings.
- A metric should be defined to assess the results of the “stability” tests. Specifically, what rate of change in the flow should a controller be able to track? Is getting the correct average sufficient? At what frequency should the average be obtained? A slow response is acceptable, and often desirable, in most applications.
- Investigating some of the software issues seen might be helpful, including: trend limits (both trend rate and resolution) and the ability to control dead bands and other control variables. Although the controller software used was not designed for research, yet for the most part, it worked remarkably well.
- Evaluate what low flows might be used with CO² based ventilation controls. Should these tests be conducted at these flows, or does accuracy matter at all in this case?
- Determine which method is best for overall testing. The Micro-Cal was a great tool to calibrate pressure sensors, which is what it was designed for. But the Duct Blaster (reference flow meter) was used for most of these test results as the Micro-Cal could not be use with “hot-wire” type sensors. It is probably easier to use one method than two.

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