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Experimental Analysis of Measurement and Control Techniques of Outside Air Intake Rates in VAV Systems

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ABSTRACT

This paper presents the results of an experimental evaluation of four airflow measurement techniques and six control techniques used for maintaining minimum outside air intake rates in variable air volume (VAV) systems. The experimental testing was conducted in a controllable environment using a laboratory equipped with a full-size HVAC system. The experimental study indicated that control strategies using the direct measurement of the outside airflow from an averaging pitot-tube array or an electronic thermal anemometer provided the best ventilation control. System control using the outside airflow rate calculated from a CO_2 concentration balance also provided adequate control of ventilation rates expect when occupancy was low or when the outside air represented a small fraction of the supply air delivered. In addition, results showed that the use of a temperature balance to calculate outside air intake rates is not valid under common building operating conditions. When measurement of the outside airflow rate was not possible, plenum pressure control was capable of providing adequate control of outside air intake rates. Finally, a fixed minimum outside air damper position and volumetric fan tracking control strategies both proved to be inadequate control techniques for maintaining minimum ventilation rates in VAV systems.

INTRODUCTION

Control of minimum outside air intake rates is critical to meet standards set by the Ventilation Rate Procedure to maintain adequate indoor air quality within conditioned spaces as outlined in *ASHRAE Standard 62-1999, Ventilation for Acceptable Indoor Air Quality.* Control of ventilation rates in variable air volume (VAV) systems presents additional complications compared to constant air volume (CAV) systems. Pressure in the mixed air plenum can fluctuate with changing supply air volumes making commonly used control strategies for CAV systems inadequate for use in VAV systems.

A theoretical analysis of several airflow measurement and VAV control strategies was presented in a companion paper (Shroeder et al. 2000). This paper presents experimental test results for the same airflow measurement and VAV control techniques described in the companion paper.

LABORATORY DESCRIPTION

This section provides information specific to the laboratory and to the preparatory work that was conducted prior to testing. A detailed description of the laboratory is provided by Brandemuehl and Kreider (1990).

Laboratory Air System

The laboratory HVAC system consists of two air handlers, four VAV boxes, and a return fan as illustrated in Figure 1. The central air system component is a single zone, draw-through, built-up air-handling unit. This air-handling unit is composed of, in order, an outside air economizer, a filter bank, a chilled water coil, a hot water coil, and a variable speed drive supply fan. The main air-handling unit supplies medium pressure conditioned air to the parallel fan-powered mixing boxes (FPMB) serving two full-size zones and two zone simulators. A second air-handling unit located upstream of the main air handler provides control of ventilation air conditions supplied to the main air-handling unit. This second unit is referred to as the outside air conditioning station (OACS). The system is also equipped with a variable speed drive return fan.

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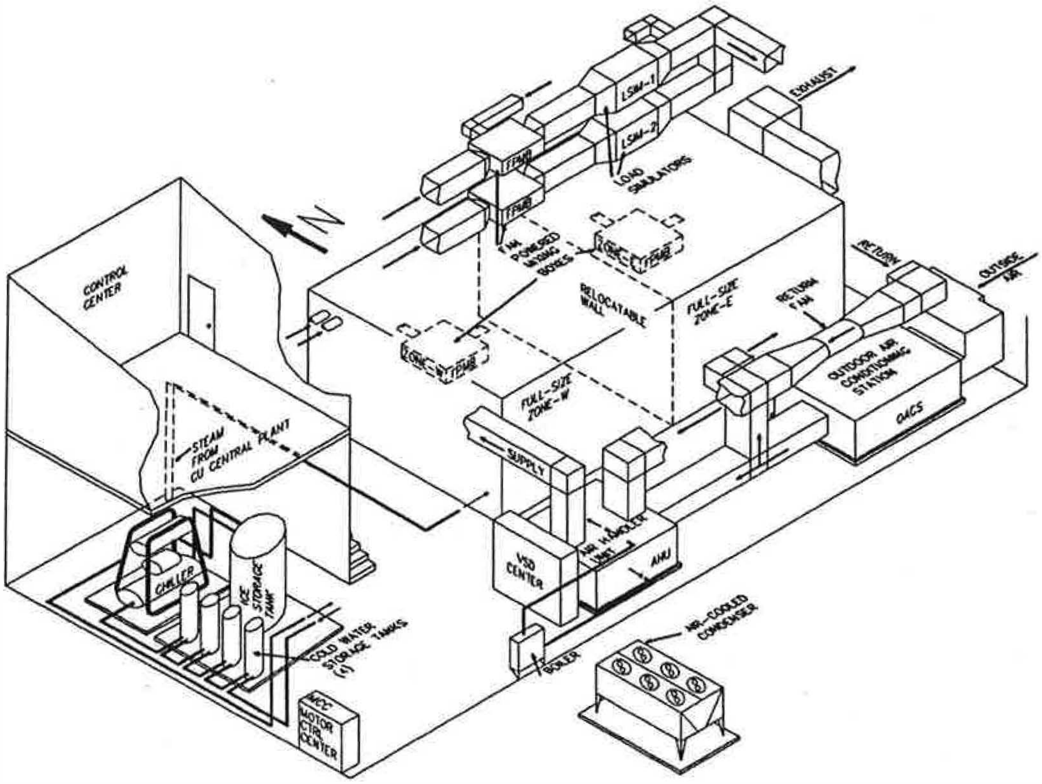

Figure 1 *Laboratory isometric.*

Control and monitoring of the laboratory are performed through a central DDC and data acquisition system.

Laboratory Modifications

Some changes were made to the laboratory specifically for the experimental study described in this paper. These changes included the following:

(i) In the outside air ductwork, a new ultra-low-leakage damper was installed just upstream of the main air-handling unit. The existing outside air damper on the air-handling unit was decoupled from the recirculated damper and locked in the full open position. This new damper is approximately 70% smaller than the original damper, allowing for much better control of the outside airflow intake rates.

(ii) For systems requiring a dedicated outside air duct, an existing section of the outside air duct upstream of the new outside air damper and main air-handling unit was removed and replaced with a new section of ductwork. The cross-sectional size of the existing ductwork is 7.11 ft^2, and the new ductwork is only 2.67 ft^2, a reduction in size of over 60%. A schematic diagram of the new ductwork is shown in Figure 2.

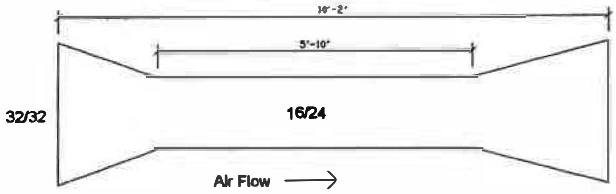

Figure 2 *Schematic diagram of the dedicated outside air ductwork.*

Supply Duct Averaging Pitot-Tube Array Calibration

To calibrate the averaging pitot-tube array measurement stations in the supply air ducts, pitot static tube traverses were performed for several flow rates. Calibrations were also performed for the dedicated outside air duct when a conventional (rather than auto-zeroing) differential pressure transmitter was used. In the supply duct, each traverse was performed with a pitot static tube manufactured in accordance with ASHRAE Standard 111-1988 (ASHRAE 1988) and a NIST traceable micromanometer with an accuracy of ±0.00025 in. w.g. Measurements were made at 25 separate points for each traverse following the Log-Tchebycheff rule

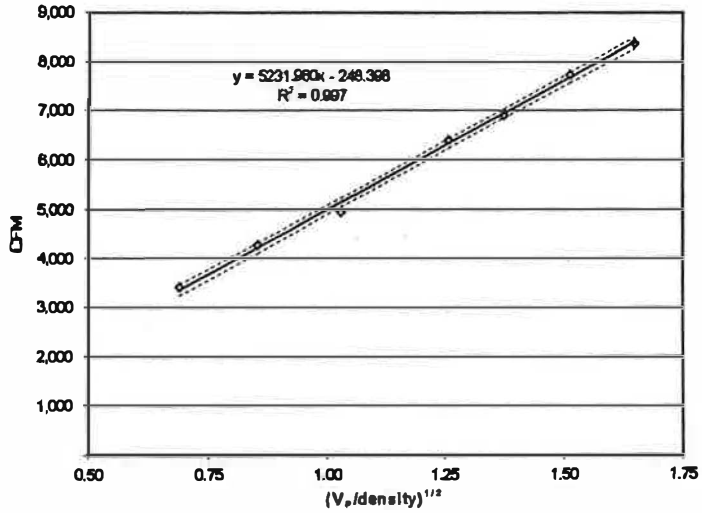

Figure 3 Calibration of supply duct pitot-tube averaging array with 95% confidence intervals.

for rectangular ducts (ASHRAE 1988). Each individual point was measured three times and then averaged. The atmospheric pressure in the laboratory and air temperatures in the ducts were also recorded to account for air density in the calibrations.

ASHRAE Standard 111-1988 provides recommendations for suitable velocity profiles when performing a pitot-tube traverse of a duct (ASHRAE 1988). All traverses performed in the laboratory had "ideal distributions" where more than 90% of the measurements were greater than 10% of the maximum reading. Figure 3 shows the results of the calibration of the supply duct averaging pitot-tube array in the laboratory.

Confidence intervals for the supply duct calibration were calculated from Equations 1 through 3, which provide the uncertainty in the response variable (y) when a particular value of the predictor variable (x) for a simple linear regression is considered (Montgomery and Runger 1994).

$$u(\hat{y}) = \pm t_{\alpha/2,\, n-2}\sqrt{\hat{\sigma}_y^2\left(\frac{1}{n} + \frac{(x_o - \bar{x})^2}{S_{xx}}\right)} \tag{1}$$

$$\hat{\sigma}_y^2 = \sum_{i=1}^{n} \frac{(y_i - \hat{y}_i)^2}{n-2} \tag{2}$$

$$S_{xx} = n\left(\sum_{i=1}^{n} x_i^2\right) - \left(\sum_{i=1}^{n} x_i\right) \tag{3}$$

where

$t_{\alpha/2,\, n-2}$ = value of the t-distribution with n-2 degrees of freedom at a confidence level of (1-α)

$\hat{\sigma}_y^2$ = standard error regression

S_{xx} = sum of squares for x

Laboratory Test Conditions

To provide a fair basis for a quantitative analysis of the various airflow measurement and VAV control techniques, several aspects of the testing are kept the same for all tests. Descriptions of these characteristics are included in this section.

Laboratory Control. Control of the laboratory is accomplished through a DDC control and data acquisition system. All relevant measurements needed in the laboratory are recorded every 10 seconds. For the purpose of these tests, only the two zone simulators in the laboratory were used.

Table 1 lists the key characteristics used during the testing process including static pressure set points, temperature set points, and duct areas. To investigate the effects of various outside air fractions, tests were performed using 20%, 30%, and 40% outside airflow fractions. Each test was four hours

TABLE 1
Key Physical and Control Characteristics of the Laboratory

Design supply airflow rate	8,000 cfm
Supply air temperature	55°F
Supply duct static pressure	1.85 in. w.g.
Return duct static pressure	−1.00 in. w.g.
Outside duct static pressure	0.00 in. w.g.
Supply duct area	5.44 ft²
Return duct area	6.00 ft²
Economizer duct area	7.11 ft²
Dedicated outside duct area	2.67 ft²

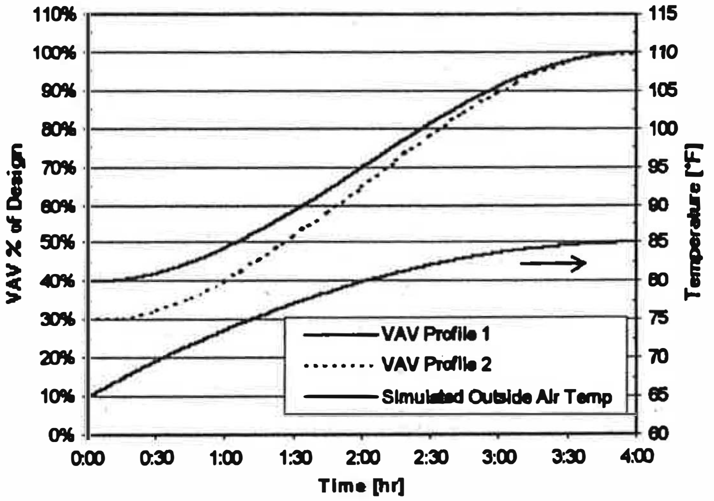

Figure 4 *VAV airflow and outside temperature profiles used for testing.*

long and simulated a full day of air system operation. A reduced time scale was used due to the absence of mass in the zone simulators and the accompanying time-delayed effects of mass within a building.

Load and Temperature Profiles. To investigate the effectiveness of the various airflow measurement and VAV control methods, VAV flows were varied throughout the tests. Figure 4 shows the VAV flow profiles used for the tests. For the tests with either a 30% or 40% outside airflow fraction, the VAV flow varied from 40% to 100% of the design flow (VAV Profile 1). For all tests using a 20% outside air fraction, the VAV flow varied from 30% to 100% of the design flow (VAV Profile 2). Control of the flow was achieved by imposing loads within the zone simulators using electric resistance coils. The VAV boxes in the zone simulators maintained a constant zone outlet temperature of 70°F by controlling the supply airflow rate.

Also shown in Figure 4 is the outside air temperature profile used during testing. To investigate the effect of varying outside air temperatures on the measurement and control of outside air intake rates, a typical cooling day outside temperature profile was used. The temperature profile shown in Figure 4 was sufficient to test the effects of varying temperatures on the measurement and control of outside air intake rates. Due to some concerns regarding the accuracy of electronic thermal anemometry at low temperatures, a separate test was run to compare these readings with those from an averaging pitot-tube array with a high-accuracy, auto-zeroing differential pressure transmitter. The outside airflow was controlled to a flow rate of 750 fpm as measured by the averaging pitot-tube array. The outside air temperature was then varied from approximately 35°F to 65°F. Figure 5 shows the percentage difference between the electronic thermal anemometer and the averaging pitot-tube array. As illustrated in Figure 5, the maximum difference is within approximately 5% throughout the temperature range investigated with higher readings from the electronic thermal anemometer at lower temperatures, well within the predicted error ranges of the two measurement techniques. The difference between these findings and those of Drees et al. (1992) may be due to the use of newer electronic thermal anemometry sensors.

Summary of Tested Control/Measurement Systems. Table 2 summarizes the control/measurement systems tested for this project in the laboratory. Control/measurement systems marked with an "X" in the table were not tested in the laboratory. Each system can be represented by a case number, i.e., 3-A for the direct control in a system with an economizer duct for a 20% outside air fraction, using the airflow measurements from the averaging pitot-tube array for control.

LABORATORY TEST RESULTS

Experimental results for each tested control and airflow measurement technique are summarized in this section. During testing in the laboratory, direct outside airflow measurements were recorded from both the averaging pitot-tube array with auto-zeroing differential pressure transmitter and the electronic thermal anemometer for all tests. In tests where a system was controlled by a specific airflow measurement technique, the other method was used only to monitor the outside airflow rate for the same test. Illustrated in Figure 6 are temperature values during a representative laboratory test.

Measurement Technique Analysis

Figure 7 shows a representative comparison of various airflow measurement techniques: averaging pitot-tube array with auto-zeroing differential pressure transmitter, electronic thermal anemometry, temperature balance and CO_2 concen-

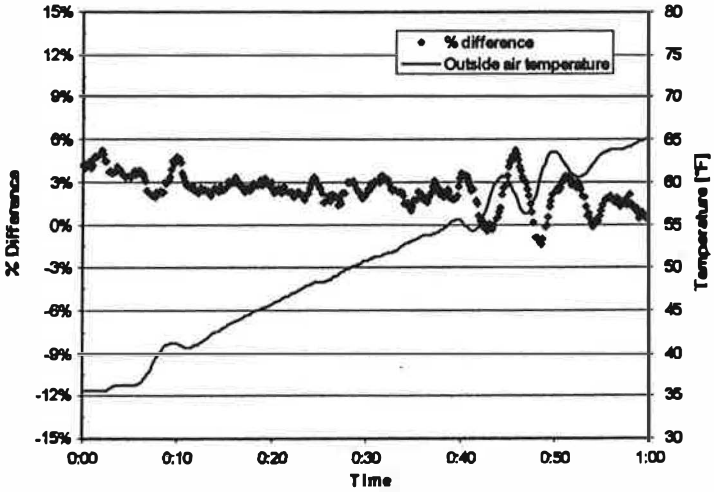

Figure 5 *Comparison of electronic thermal anemometer and averaging pitot-tube array airflow measurements as a function of air temperature.*

TABLE 2
Control/Measurement Systems Tested in the Laboratory

System Description	Measurement Technique Used for Control	Outside Air Function			
		20%	30%	40%	
Fixed minimum damper position	-NA-	✓	✓	✓	1
Plenum pressure control	-NA-	✓	X	✓	2
Direct control with economizer duct	Averaging pitot-tube array	✓	X	✓	3
	Electronic thermal anemometry	✓	X	✓	4
Volume tracking	Electronic thermal anemometry	✓	X	X	5
Direct control with dedicated duct	Averaging pitot-tube array	✓	✓	X	6
	Electronic thermal anemometry	✓	✓	X	7
Injection fan	Averaging pitot-tube array	✓	✓	X	8
	Electronic thermal anemometry	✓	✓	X	9
		A	B	C	

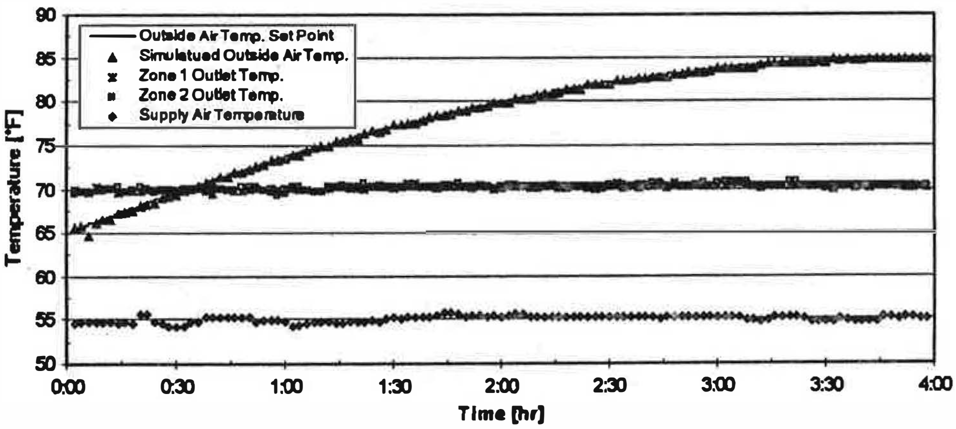

Figure 6 *Representative temperature values during laboratory testing.*

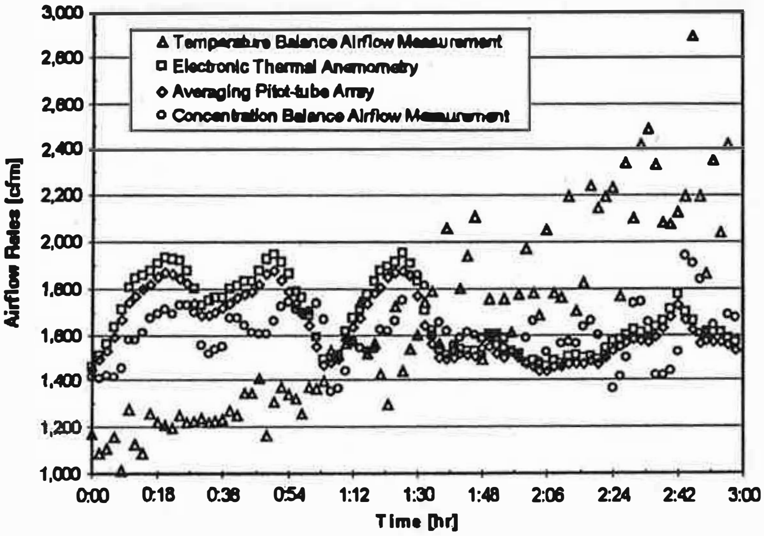

Figure 7 *Comparison of various airflow measurement techniques.*

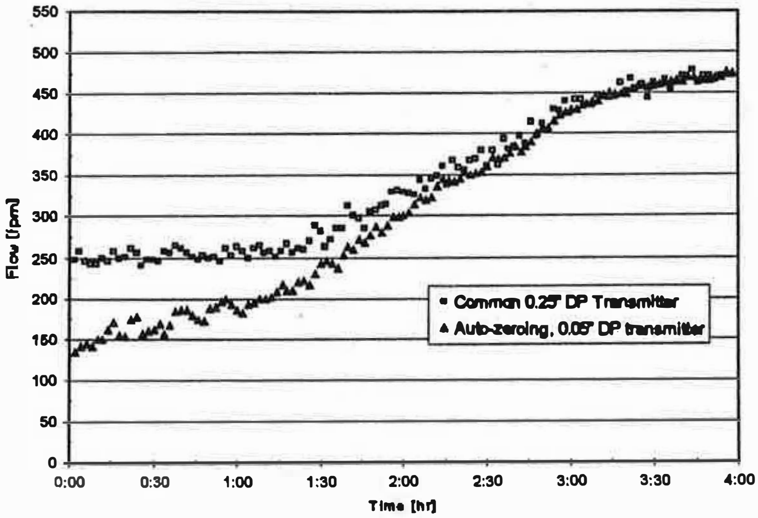

Figure 8 *Comparison of airflow measurements made with differential pressure transmitters.*

tration balance. As illustrated in Figure 7, agreement between the two direct airflow measurement techniques was very good.

Also illustrated in Figure 7 are the two indirect airflow measurement techniques, the concentration balance and temperature balance methods. Values measured by the CO_2 concentration balance method are close to the two direct measurement techniques. More information regarding the concentration balance technique is included later in this section. However, values calculated using the temperature balance method are not in agreement with those measured with any other technique. No further experimental tests were performed using the temperature balance airflow measurement technique.

A comparison of airflow measurements made using the averaging pitot-tube array with both the high-accuracy, auto-zeroing differential pressure transmitter and a more common, "off-the-shelf," differential pressure transmitter (0-0.25 inch range) is illustrated in Figure 8. As predicted in the error analysis (Shroeder et al. 2000) for the averaging pitot-tube array, the accuracy of the common differential pressure transmitter drops off as the airflow velocity decreases. In the subsequent tests, a smaller range (0-0.1 inch range) for the conventional differential pressure transmitter is selected. For the analysis of the experimental results presented in this paper, measurements made using the averaging pitot-tube array with auto-zeroing differential pressure transmitter were taken as the reference airflow rate.

The absolute measurements of outdoor airflow rates for the tested systems are summarized in Table 3. Note that the results for the averaging pitot-tube array with auto-zeroing differential pressure transmitter are provided for all the systems. As mentioned earlier, these results are considered as "reference" values. The measurements obtained with the thermal anemometry device are provided for all tests except for the direct control that uses the CO_2 concentration balance technique. Finally, the measurements using the averaging pitot-tube with a conventional (e.g., with no auto-zeroing capability) differential pressure transmitter are performed and listed for the dedicated duct and injection fan systems (e.g., tests 6-A, 6-B, 8-A, 8-B, 9-A, and 9-B) as the values obtained for non-auto-zeroing averaging pitot-tube array. From the results summarized in Table 3, it is clear that the outdoor airflow rates measured using an averaging pitot-tube with a conventional differential pressure transmitter (0-0.1 inch range) agree very well with those obtained using the averaging pitot-tube array with high-accuracy auto-zeroing differential pressure transmitter.

TABLE 3
Comparison of Outside Airflow Measurements

			Auto-Zero, Averaging Pitot-Tube Array		Non-Auto-Zero, Averaging Pitot-Tube Array (or CO_2 Balance)			Electronic Thermal Anemometry		
System Description	**Measurement Control[*]**	**Case**	**Set Point (cfm)**	**Mean (cfm)**	**Mean (cfm)**	**St. Dev. (cfm)**	**RMS (cfm)**	**Mean (cfm)**	**St. Dev. (cfm)**	**RMS (cfm)**
Fixed damper position	-NA-	1-A	1600	656	-NA-	-NA-	-NA-	682	564	1048
Fixed damper position	-NA-	1-B	2400	1410	-NA-	-NA-	-NA-	1407	680	1199
Fixed damper position	-NA-	1-C	3200	2178	-NA-	-NA-	-NA-	2124	870	1513
Plenum pressure control	-NA-	2-A	1600	1630	-NA-	-NA-	-NA-	1544	70	89
Plenum pressure control	-NA-	2-C	3200	3288	-NA-	-NA-	-NA-	3279	88	118
Direct control with economizer duct	P	3-A	1600	1635	-NA-	-NA-	-NA-	1546	46	71
Direct control with economizer duct	P	3-C	3200	3192	-NA-	-NA-	-NA-	3225	47	53
Direct control with economizer duct	E	4-A	1600	1695	-NA-	-NA-	-NA-	1637	55	67
Direct control with economizer duct	E	4-C	3200	3228	-NA-	-NA-	-NA-	3263	50	80
Volume tracking	E	5-A	1600	2427	-NA-	-NA-	-NA-	2436	458	953
Direct control with dedicated duct	P	6-A	1600	1639	1636	56	66	1593	62	62
Direct control with dedicated duct	P	6-B	2400	2430	2424	44	49	2403	37	37
Direct control with dedicated duct	E	7-A	1600	1643	-NA-	-NA-	-NA-	1640	43	58
Direct control with dedicated duct	E	7-B	2400	2404	-NA-	-NA-	-NA-	2428	42	50
Injection fan	P	8-A	1600	1621	1601	44	44	1535	28	71
Injection fan	P	8-B	2400	2429	2401	56	56	2393	35	36
Injection fan	E	9-A	1600	1622	1656	54	78	1600	31	31
Injection fan	E	9-B	2400	2418	2404	46	46	2400	25	25
Direct control	C	-NA-[†]	1600	1632	1605[‡]	119[‡]	119[‡]	-NA-	-NA-	-NA-

[*] P = Averaging pitot-tube array, E = electronic thermal anemometer, C = CO_2 concentration balance
[†] A different system setup was used for testing the concentration balance measurement technique.
[‡] Value is for the CO_2 concentration balance measurement technique, not electronic thermal anemometry.

A comparison of the two direct airflow measurement techniques for the systems tested in the laboratory is shown in Table 4. Values listed in Table 4 are based upon the absolute volumetric difference of the reference measurement (e.g., the averaging pitot-tube array with auto-zeroing differential pressure transmitter) and the other measurement techniques (e.g., electronic thermal anemometry, averaging pitot-tube with a differential pressure transmitter (0-0.1 inch range), or CO_2 concentration balance):

$$\left| \begin{array}{l} (reference\ pitot-tube\ array\ value) \\ -(control\ measurement\ value) \end{array} \right|$$

In Table 4, the value of the root mean square (RMS) was found from Equation 4:

$$RMS = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(x_i - Set\ Point)^2} \qquad (4)$$

where

x_i = measured value for a specific time i (a 10-second time step was considered for the duration of each test)

Set Point = target outside air intake value

n = total number of data points over the duration of the test

As shown in Table 4, the accuracy of the two direct airflow measurement techniques (relative to the reference measurement technique, which is the averaging pitot-tube array with auto-zeroing differential pressure transmitter) is extremely good for all of the tests completed. It should be mentioned that this result may be partially due to the fact that the airflow profiles within the laboratory are very uniform and that the measurement devices were installed according to manufacturer's recommendations.

VAV System Control Results

Table 5 contains the results of the outside airflow intake rates for the tested systems. Specifically, Table 5 provides the average value, the standard deviation, the root mean square of the outdoor air intake flow rate, and the validity of each measurement and control method.

TABLE 4
Absolute Difference Between Control Airflow Measurements and Reference Values

System Description	Case	Set Point (cfm)	Mean (cfm)	St. Dev. (cfm)	Mean % error*	Max. % error*
Fixed damper position	1-A	1600	116	128	5.0%	10.7%
Fixed damper position	1-B	2400	21	16	1.0%	5.6%
Fixed damper position	1-C	3200	62	52	2.6%	12.1%
Plenum pressure control	2-A	1600	85	27	5.2%	10.3%
Plenum pressure control	2-C	3200	25	20	0.8%	3.2%
Direct control with economizer duct	3-A	1600	-NA-	-NA-	-NA-	-NA-
Direct control with economizer duct	3-C	3200	-NA-	-NA-	-NA-	-NA-
Direct control with economizer duct	4-A	1600	58	24	3.4%	8.7%
Direct control with economizer duct	4-C	3200	35	16	1.1%	2.8%
Volume tracking	5-A	1600	26	18	1.0%	3.8%
Direct control with dedicated duct	6-A	1600	14	10	0.9%	3.5%
Direct control with dedicated duct	6-B	2400	17	12	0.7%	2.2%
Direct control with dedicated duct	7-A	1600	12	10	0.7%	2.8%
Direct control with dedicated duct	7-B	2400	26	16	1.1%	3.2%
Injection fan	8-A	1600	19	13	1.2%	4.5%
Injection fan	8-B	2400	16	14	0.7%	3.8%
Injection fan	9-A	1600	45	20	2.8%	7.6%
Injection fan	9-B	2400	22	17	0.9%	3.7%
Direct control w/ CO_2 balance†	-NA-	1600	126	69	7.7%	22.2%

* Error is percentage of reading using the averaging pitot-tube array as the reference.
† A different system setup was used for testing the concentration balance measurement technique. Values shown here are concentration balance measurement values.

TABLE 5
Summary of Results for the Control/Measurement Systems Tested

System Description	Measurement Control*	Case	Set Point (cfm)	Validity	Results of Outside Air Intake Rate Measurements: Mean (cfm)	St. Dev. (cfm)	RMS (cfm)
Fixed damper position	-NA-	1-A	1600	14%	682	564	1048
Fixed damper position	-NA-	1-B	2400	23%	1407	680	1199
Fixed damper position	-NA-	1-C	3200	26%	2124	870	1513
Plenum pressure control	-NA-	2-A	1600	100%	1544	70	89
Plenum pressure control	-NA-	2-C	3200	100%	3279	88	118
Direct control with economizer duct	P	3-A	1600	100%	1635	38	52
Direct control with economizer duct	P	3-C	3200	100%	3192	50	51
Direct control with economizer duct	E	4-A	1600	94%	1637	55	67
Direct control with economizer duct	E	4-C	3200	100%	3263	50	80
Volume tracking	E	5-A	1600	0%	2436	458	953
Direct control with dedicated duct	P	6-A	1600	100%	1635	56	66
Direct control with dedicated duct	P	6-B	2400	100%	2424	4	59
Direct control with dedicated duct	E	7-A	1600	100%	1640	43	58
Direct control with dedicated duct	E	7-B	2400	100%	2428	42	50
Injection fan	P	8-A	1600	100%	1601	44	44
Injection fan	P	8-B	2400	100%	2401	56	56
Injection fan	E	9-A	1600	100%	1600	31	31
Injection fan	E	9-B	2400	100%	2400	25	25
Direct control	C	-NA-†	1600	75%	1632	137	141

* P = Averaging pitot-tube array, E = electronic thermal anemometer, C = CO_2 concentration balance.
† A different system setup was used for testing the concentration balance measurement technique.

The percentages listed in Table 5 in the column labeled "validity" were calculated from Equation 5:

$$validity = \frac{n_v}{n} \quad (5)$$

where

n_v = the number of valid data points.

Each test presented in Table 5 is subject to errors from the airflow measurement and the control technique used. Each 10-second data point, x_i, recorded during testing was considered valid if it met the following two conditions:

1. $|x_i - set\ point| \le (set\ point \cdot 10\%)$

and

2. $\frac{e_i}{x_i} < 15\%$

where

e_i = the predicted error for the airflow measurement in the laboratory.

The first condition attempts to account for the accuracy of the control technique by requiring the data point to be within 10% of the set point. The second condition attempts to account for the accuracy of the airflow measurement technique by requiring the predicted error of the data point to be less than 15%.

Fixed Minimum Position Outside Air Damper. As indicated in Table 5, the fixed minimum outside damper position control methods did not maintain the required minimum outside air intake rates during times of reduced flow in the VAV system. Outside air intake rates were much closer to a constant percentage of the supply airflow than to a constant flow rate, as illustrated in Figure 9. Obviously, the use of a fixed minimum outside air damper position in VAV systems does not maintain minimum outside air intake rates and is therefore not a recommended control technique.

Direct Control with Economizer Duct. In contrast to using a fixed minimum outside damper position, this control technique was able to maintain minimum outside airflow rates during all tests completed at the laboratory as shown in

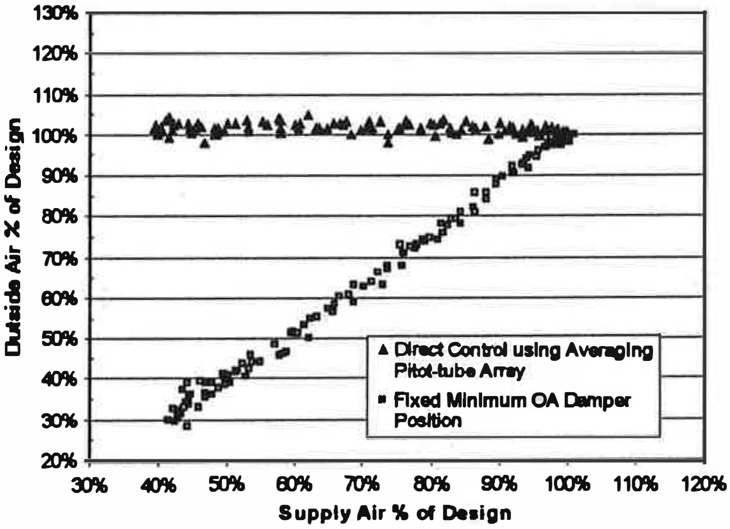

Figure 9 *Outside airflow percent of design for two laboratory tests.*

Table 5. These results were independent of the direct outside airflow measurement technique used. Figure 9 shows the results from one test using the direct measurement of the outside airflow rate for controlling the system. However, these results are dependent upon the fact that the averaging pitot-tube array in the laboratory was used with a high-accuracy, auto-zeroing differential pressure transmitter and that airflow profiles in the laboratory were very uniform. Without the use of the auto-zeroing differential pressure transmitter, the airflow rates in the economizer duct would have been too low to measure accurately with the averaging pitot-tube array. The electronic thermal anemometer requires no special additional apparatus to measure the low airflow rates typically found in economizer systems during minimum outside air intake mode.

In systems where direct airflow measurement devices can be installed according to manufacturer's recommendations, direct control of the outside airflow rate using electronic thermal anemometry or an averaging pitot-tube array with a high-accuracy (predicted errors < 10%) differential pressure transmitter is an adequate control technique.

Direct Control with Dedicated Duct With and Without an Injection Fan. As indicated in Table 5, this control technique was able to maintain minimum outside airflow rates during all tests completed at the laboratory. These results were independent of the direct outside airflow measurement technique used and of whether or not an injection fan was used. It is important that the duct be sized such that outside airflow rates will be high enough to measure accurately (predicted errors of < 10%) using an averaging pitot-tube array or electronic thermal anemometer. Additionally, the proper selection of the differential pressure transmitter is essential for reliable airflow measurements using an averaging pitot-tube array. The transmitter's range should be selected to match the expected airflow velocities in the dedicated duct.

Accurate control of the minimum outside air intake rate appears to be possible without the use of an injection fan. Therefore, the use of an injection fan in a dedicated outside air duct is not recommended. The use of an injection fan increases both equipment and operating costs for the system. Additionally, the use of an injection fan may require longer lengths of unobstructed ductwork to obtain uniform flow profiles. Therefore, when a dedicated outside air duct is available, control using a direct measurement of the outside airflow rate is an adequate control technique.

Volumetric Fan Tracking. The results for the volumetric fan tracking control technique in Table 5 indicate that this technique does not provide adequate control of outside air intake rates in VAV systems under typical building operating conditions. This inadequacy is due mainly to the following:

- *Damper Positioning Limitations*—In the tests conducted at the laboratory, no combination of fixed damper positions for the outside, return, and exhaust air dampers allowed for the minimum outside air intake rates to be met under all VAV percentages tested. Additionally, fixed damper positions impose a large pressure drop at some operating conditions, resulting in excess fan energy usage. It is expected that these limitations would be common to most building HVAC systems.
- *Neglecting Exhaust Airflow Rates*—As mentioned in the error analysis, when the exhaust flow in the system is not zero, the actual outside air intake rate will be increased.

For these reasons, and from the test results, the use of volumetric fan tracking is not recommended as a method to maintain minimum outside air intake rates for VAV systems.

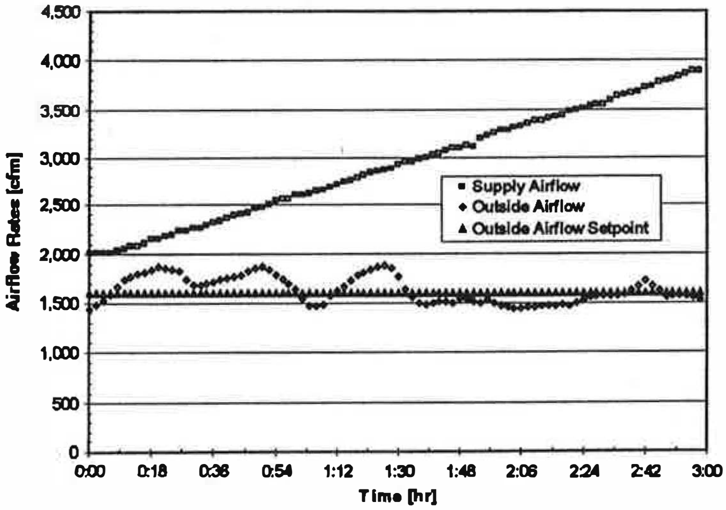

Figure 10 *Supply and outside airflow for the concentration balance control test.*

Plenum Pressure Control. As shown in Table 5, the plenum pressure control technique was able to maintain the minimum outside air intake rates 100% of the time during testing. Essential to the success of this control technique is the proper selection of the differential pressure transmitter used to measure the pressure drop across the outside air damper. Also important for the proper use of this control technique is to set the pressure drop large enough to be measured accurately but not so large as to impose an excessive energy penalty on the system.

A potential drawback to the use of this control technique is the careful commissioning that must take place for proper control. For each desired outside airflow rate, an accurate measurement of both the pressure drop and the actual airflow rate must be performed. A pitot static tube or electronic thermal anemometry traverse could be used to measure the outside airflow rates during commissioning. To ensure that minimum outside airflow rates are being maintained, periodic calibration of the sensors and of the actual airflow rate should be performed.

Plenum pressure control is best suited for systems where the installation of direct airflow measurement devices is not possible and only one or two minimum outside air intake rates are required for typical building operation.

Direct Control using Concentration Balance Measurement Technique. Due to the difficulty in maintaining a large difference in the return and outside air CO_2 concentrations at high flow rates, a different system setup was used for this system than that described in the "Laboratory Setup" section. For this test, the supply airflow rate was varied from 2,000 cfm to 4,000 cfm. The outside airflow rate was then controlled to 1,600 cfm, or 40% of the design airflow rate for this test. Actual measured flow rates from the test are illustrated in Figure 10. Since air temperatures were not found to be a factor in previous tests, the outside air temperature was controlled to a constant 65°F for the duration of the test. CO_2 was injected into the return airflow at a rate to maintain a difference between the return and outside concentrations of approximately 200 ppm. The predicted error for the concentration balance airflow measurement technique was below 15% during the entire test.

In order to measure the various CO_2 concentrations with the required repeatability, each airflow was sampled for a duration of three minutes. Because the outside air CO_2 concentration changes very slowly with respect to the return and supply CO_2 concentrations, it was not sampled every cycle. During the test, concentrations were sampled in the following order: supply, return, supply, return, and outside. Figure 11 illustrates the measured outside air percentage of design versus the supply airflow percentage of design. All measurements for the actual outside airflow rate were made with the averaging pitot-tube array with auto-zeroing differential pressure transmitter. Error bars shown in Figure 11 were calculated using the error analysis outlined for this measurement technique in Shroeder et al. (2000).

As indicated in Table 5, the validity of the test was about 75%. While the ability of the concentration balance airflow measurement technique to control the minimum outside air intake rates was not as good as other direct measurement methods, it does show promise as an adequate control strategy. Figure 12 illustrates the percent error between the measured reference outside airflow rate (using the averaging pitot-tube array) and the one calculated from the concentration balance. During this test, the CO_2 concentration balance airflow rate was calculated every three minutes, while the averaging pitot-tube array value was measured every 10 seconds. This time difference is responsible for the noisy variation of the data shown in Figure 12.

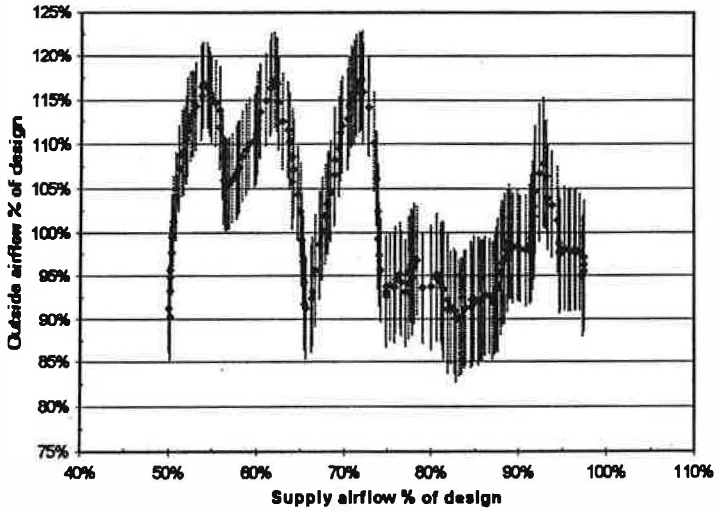

Figure 11 Outside airflow percent of design.

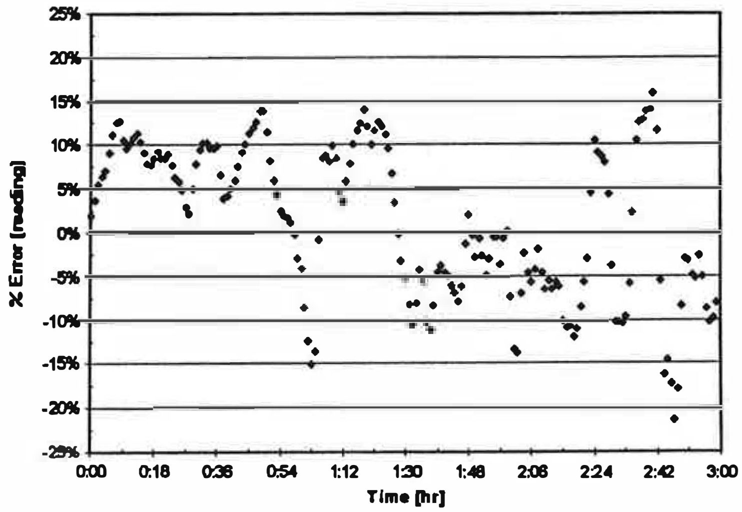

Figure 12 Comparison of airflow measurement techniques for concentration balance control test.

The results presented in Table 5 show that the average absolute error between the two methods is approximately 8%. Over the duration of the test, however, the average of the two measurement techniques differed by less than 2%. This implies that with refined control loop tuning (i.e., slowing down the system update time to match that of the calculated outside airflow rates), using the concentration balance airflow measurement technique to control the minimum outside air intake rate could be an adequate control technique.

Additionally, it is expected that the difficulty in maintaining a stable CO_2 concentration in the return air in the laboratory made accurate control harder to achieve. In a typical office building, the return air CO_2 concentration would be more stable, allowing a more accurate airflow measurement to be made. However, this requirement for relatively stable CO_2 concentrations limits the applicability of the concentration balance technique. In spaces where large, abrupt changes in occupancy (and, hence, CO_2 levels) can occur, this method may prove unreliable. This fact may rule out the use of this control strategy in spaces such as conference rooms and auditoriums or any building where large transient effects are possible. Typical office space should present a suitable application of the control technique using CO_2 balance.

As shown in the error analysis of this technique in Krarti et al. (2000), the accuracy of the concentration balance technique is reduced as the difference in the return and outside air CO_2 concentrations becomes small and as the outside air becomes a smaller fraction of the supply airflow. For these reasons, direct control using the concentration balance technique to measure the outside airflow should not be the only method used to maintain outside air intake rates in VAV systems. During periods when the predicted errors indicate that the technique will be unable to accurately maintain minimum outside airflow rates, another control technique should be used.

SUMMARY AND CONCLUSIONS

Control of minimum outside air intake rates is critical to meet the standards set by the ASHRAE Ventilation Rate Procedure for maintaining adequate indoor air quality within conditioned spaces. VAV systems present additional complications compared to CAV systems. Pressure in the mixed air plenum can fluctuate with changing supply air volumes, making commonly used control strategies for CAV systems inadequate for use in VAV systems. Recommendations listed here are based upon findings from both the error analysis summarized in Shroeder et al. (2000) and laboratory test results presented in this paper.

In particular, findings of both the theoretical and experimental analysis indicate that the use of a fixed minimum outside air damper position and volumetric fan tracking are inadequate control strategies to maintain minimum outside air intake rates in VAV systems. These strategies are unable to provide the required outside airflow under all operating conditions.

The best control techniques are those based on direct measurement of outside airflow rates. The use of direct airflow measurement devices such as averaging pitot-tube arrays and electronic thermal anemometry, however, is often limited by physical constraints. An adequate length of unobstructed ductwork is required for uniform flow profiles. Minimum lengths are usually specified by the manufacturers of the measurement devices. The expected outside airflow velocity in systems having the required lengths of unobstructed ductwork must be considered to select the proper direct airflow measurement technique.

In systems sized for use with economizer cycles, outside airflow rates for minimum outside air intake mode are typically too small to be measured with an averaging pitot-tube array with properly selected differential pressure transmitter (e.g., if the transmitter is selected to have a range that is low enough to measure accurately minimum outside airflow rates, it will not be able to be used for economizer rates of 100% outside air intake). Electronic thermal anemometry may be a good alternative in this case. Another alternative is the use of a dedicated duct to provide outside air when only minimum outside air intake is needed. The dedicated duct can be sized such that airflow velocities will be high enough to measure accurately with either an averaging pitot-tube array or electronic thermal anemometry.

An alternative control technique is to use a plenum pressure control strategy. Here, the pressure drop across a fixed orifice, such as the outside air damper and louver, is measured and maintained at a constant, predetermined value. Generally, this requires that a dedicated minimum outdoor air damper be used in order to create a reliable fixed orifice. For systems with economizers, using a minimum damper position to create the fixed orifice is usually not accurate due to lack of repeatability of the damper assembly (damper, actuator, and linkage).

Finally, another control alternative is to use the CO_2 concentration balance technique to indirectly measure the outside air intake rate and use this value for direct control of the system. Due to the current CO_2 sensor limitations, this technique only works accurately when a single sensor is used to measure outdoor air, return air, and mixed air CO_2 concentrations; and it will not provide reliable and accurate control when rapidly changing CO_2 concentrations occur in the return air. Additionally, this technique should not be used exclusively to control the outside air intake rate. When the CO_2 concentration difference between the return air and the outside air is low, or when the outside air is a small percentage of the supply air, large errors may result by using this control technique. For these conditions when the predicted error is large, another control technique should be used.

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