Title

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Publication Date

2004-10-28

LBNL-56603

AN EVALUATION OF THREE COMMERCIALLY AVAILABLE TECHNOLOGIES FOR REAL-TIME MEASUREMENT OF RATES OF OUTDOOR AIRFLOW INTO HVAC SYSTEMS

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October 28, 2004

This work was supported by the Assistant Secretary for Energy Efficiency and Renewable Energy, Building Technologies Program of the U.S. Department of Energy under contract DE-AC03-76SF00098.

AN EVALUATION OF THREE COMMERCIALLY AVAILABLE TECHNOLOGIES FOR REAL-TIME MEASUREMENT OF RATES OF OUTDOOR AIRFLOW INTO HVAC SYSTEMS

Abstract

During the last few years, new technologies have been introduced for real-time continuous measurement of the flow rates of outdoor air (OA) into HVAC systems; however, an evaluation of these measurement technologies has not previously been published. This document describes a test system and protocols developed for a controlled evaluation of these measurement technologies. The results of tests of three commercially available measurement technologies are also summarized. The test system and protocol were judged practical and very useful. The three commercially available measurement technologies should provide reasonably, e.g., 20%, accurate measurements of OA flow rates as long as air velocities are maintained high enough to produce accurately measurable pressure signals. In HVAC systems with economizer controls, to maintain the required air velocities the OA intake will need to be divided into two sections in parallel, each with a separate OA damper. All of the measurement devices had pressure drops that are likely to be judged acceptable. The influence of wind on the accuracy of these measurement technologies still needs to be evaluated.

Background

Ventilation, i.e., providing outdoor air (OA), has a substantial influence on building energy consumption, occupant health, and occupant satisfaction with the indoor environment. The quantity of energy used for ventilation in the U.S. service sector (i.e., commercial, institutional, and government buildings) is uncertain, but clearly substantial. Emmerich and Persily (1998) predicted that 10.9 kBTU/ft^2 (124 MJ/m^2) of heating and cooling energy would be used for ventilating U.S. office buildings, if all offices had a ventilation rate of 20 cfm (10 L s^{-1}) per person. However, existing data from office buildings indicate that the average minimum ventilation rate is above of 20 cfm (10 L s^{-1}) per person. The most representative data for estimating ventilation rates is from U.S. Environmental Protection Agency (EPA) survey of a representative sample of 100 office buildings (Womble et al. 1996). The survey included 40 measurements taken when ventilation rates should be at the minimum because outdoor air temperatures were greater than 75 ^{o}F (24 ^{o}C). If we use the carbon dioxide data collected from these 40 buildings, the estimated[1] average minimum rate of outdoor air supply during this survey was 28 cfm/occupant (14 L/s), or 140% of the value assumed in the analysis by Emmerich and Persily (1998). Because energy used for ventilation increases almost linearly with the minimum ventilation rate, the estimated energy consumption for ventilation is then 15.3 kBTU/ft^2 (170 MJ/m^2). If we assume that, on average, all service sector buildings in the US use this amount of energy per unit floor area for ventilation, the total energy consumed is roughly 1 Quad (1 EJ). We expect that the actual energy use for ventilation could be considerably higher because many types of service sector buildings have a higher occupant density or are ventilated for longer periods of each day than offices. If the average minimum rate of OA supply was reduced[2] to bring rates in alignment with the current standards, the energy savings would be approximately 0.3 Quad (0.3 EJ).

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[1] For this estimate, we assumed that on average indoor CO_2 concentrations only reached 80% of the true equilibrium value and that the CO_2 generation rate per person was 0.011 cfm (0.0052 L/s).

[2] Based on the available data from the BASE Study, to bring the average rate in accordance with standards, rate s of outdoor air supply would be reduced in two thirds of buildings and increased in one third of buildings.

The “correct” minimum rate of outdoor air supply to maintain occupant health and satisfaction with air quality is not well known. The minimum recommended rate for offices in the ASHRAE ventilation standard (ASHRAE 1999) was, until recently, 20 cfm (10 L/s) per occupant. The current ventilation standard (ASHRAE 2001) has a minimum ventilation requirement per person and per unit floor area that, with typical occupant density assumptions, translates into approximately the same per person requirement as the older standard. The scientific literature on the relationship of ventilation rates with health and occupant satisfaction was reviewed by Seppanen et al. (1999). On average, lower ventilation rates were associated with increased prevalences of communicable respiratory illnesses (e.g., common colds), increased prevalence rates of sick building syndrome (SBS) symptoms, and diminished satisfaction with indoor air quality. The evidence of adverse effects was strongest when ventilation rates were reduced below 20 cfm (10 L s^{-1}) per person; however, several studies reported benefits of increasing ventilation rates above 20 cfm (10 L s^{-1}) per person. Clearly, there is a need to strike a balance between the potential benefits to health of increased ventilation and the beneficial energy savings from reduced ventilation.

Despite the substantial influences of OA ventilation rates on energy use and health, most U.S. buildings do not have an integral system for measuring ventilation rates. The typical practice[3] in office and institutional buildings, which are the primary focus of this report, is to have an air balance company measure the OA flow during a period of building commissioning or airflow balancing and adjust the positions of the dampers for OA, recirculation air, and exhaust air to obtain the desired minimum rate of OA supply. However, accurately measuring OA airflow into HVAC systems is technically very challenging, even for researchers with special instrumentation and considerable time to devote to the task. Even if air balance professionals could provide perfect measurements of OA flow rates during their occasional visits to buildings, the OA flow is not always stable. The actual rates of OA flow may vary with changes in wind and as the supply air flow rates of variable air volume (VAV) HVAC systems are modulated. In addition, minimum damper positions, which affect OA flow rates may change from those set by the air balance professional due to deliberate adjustments by building operators and to wear or failures in the damper actuators and linkage.

Given these measurement challenges it is not surprising that the ventilation rates measured in surveys by researchers using tracer gas based measurement systems or other methods (e.g., Turk et al. 1987, Lagus Applied Technologies 1995, Persily 1989, Persily and Gorfain 2004) vary widely and often differ substantially from the minimum ventilation rates specified in the applicable codes and in design documents. Because the available data indicate that most buildings have minimum ventilation rates substantially exceeding code requirements, routine use of OA measurement systems may be one of the most cost-effective methods of reducing energy use in these over ventilated buildings. A significant but smaller fraction of buildings provide less ventilation than specified in codes, and OA measurement systems could reduce IAQ problems associated with insufficient ventilation.

There are significant obstacles to cost-effective and accurate measurements of OA flow rates. First, measurements are challenging because OA intake velocities are intentionally kept low in order to minimize rain and snow from being drawn into the air handler. Sizing of the OA air inlet for the entire OA flow into the air handler during economizer operation compounds the problem. The result is particularly low OA intake velocities during periods of minimum OA supply (e.g., 20% of maximum OA supply), when measurements are most important. Based on a review of specifications of louvers, the maximum recommended air velocity within the “free area[4]” of an intake louver is usually 700 to 2500 fpm (3.5 to 13 m s^{-1}) to minimize entrainment of rain and snow. These velocities occur with the maximum flow at the OA intake during economizer operation with 100% outdoor air. Since the

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[3] In some larger buildings, a separate OA injection fan is used to provide minimum OA. The injection fan could have an accompanying system for measuring OA flow rates.

[4] Minimum total cross sectional area for airflow through a louver.

minimum OA supply may be only 20% of the full supply air flow rate, the velocities of OA in the free area of the louver during periods of minimum OA flow will be only 140 to 500 fpm (0.5 to 2 m s^{-1}). Because the cross sectional area for flow inside the louver is less than the nominal face area of the louver, the velocities upstream of the outside air louver may be 30% to 50% of the velocities in the free area of the louver. At these low velocities the dynamic pressure of the moving air, which is often used in to measure air speed, is only thousandths of an inch of water (a fraction of a Pascal), which is too low for accurate measurements in field settings.

The geometry of the OA intake and its impact on velocity profiles further complicates the measurements. The outdoor air passes through a bird screen, a set of louvers, and an adjustable OA damper. Downstream of the louvers or OA dampers the speed and direction of airflow will normally vary markedly across the flow cross section; thus, averaging of velocity measurements made at a few locations in the cross section may also lead to large measurement errors. At the exterior face of the OA intake, measurements are problematic because even normal winds cause a large fluctuation in air velocity. While these problems and the need for better measurement and control of OA ventilation rates have been recognized for many years, until recently there has been little progress toward meeting this need. The review of Krarti et al. (1999) on measurement and control of OA flow in variable air volume systems includes a summary of much of the recent research. In particular, Krarti et al. (1999) point out that the long unobstructed OA ducts needed for most flow rate measurements will generally be impractical, and they identify the following as promising alternatives:

1. providing a separate outdoor air duct for the minimum outdoor airflow with air velocities maintained sufficiently high for use of Pitot-static tube arrays;

2. maintaining a constant pressure drop across the OA louvers and dampers during minimum outdoor air conditions; and

3. using a CO_2 mass balance to compute the percentage of outdoor airflow (%OA) and multiplying by the separately metered supply airflow to determine the outdoor airflow.

While each of these alternatives has merit, they also have some drawbacks. Alternative 1 (providing a separate OA duct) will often be unattractive to designers because of space constraints and costs, especially for small to moderate size HVAC systems. Alternative 2 is a flow control strategy but requires a separate measurement system for calibration of flow versus pressure drop in field settings. As indicated above, accurate field-based calibrations will be difficult. Alternative 3 requires an accurate measurement system for supply flow rates[5] and is not applicable unless indoor CO_2 concentrations are substantially above outdoor concentrations. Persily and Gorfain (2004) estimated that errors in alternative 3 exceeded 80% in almost 90% of 320 measurements. Also, alternatives 1 and 2 only provide a measurement during periods of minimum outdoor air supply, although OA supply rates should be higher during economizer operation.

Within the past few years, manufacturers have pursued another option -- the direct real-time measurement of airflow through the OA intake using a sensor system located at the OA intake. A handful of related measurement technologies have emerged on the market within the last few years. The primary objective of the research discussed in this paper was to evaluate the accuracy of these direct measurement technologies. A separate paper being prepared will review the causes of measurement errors and describe some approaches for overcoming these sources of error.

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[5] Use of a the same CO_2 sensor to measure the concentrations in outdoor, return, and supply air is recommended to reduce errors.

Approach

Test system description

The laboratory test system constructed for this research and illustrated diagrammatically in Figure 1, has a changeable OA intake louver and damper system, air recirculation ductwork, a variable speed fan, recirculation and exhaust dampers, and a precision "reference" airflow meter upstream of the location of air exhaust. The reference airflow meter has a built-in airflow straightener, a nozzle, a Pitot-static tube like velocity sensor, and a manufacturer's rated accuracy of ± 0.5%. Based on our evaluations of this type of flow meter using the Pitot tube traverse method, errors in measuring the flow meter's pressure signal are the largest source of flow rate measurement error. Two different sizes of reference flow meters are used for accurate measurements over a wide range of airflow. Accounting for the drift in the calibration of our pressure transducer, for reference flow rates exceeding 250 cfm (118 L s^{-1}), we estimate that the accuracy of the reference flow rate measurements is approximately ±7% or better. The recirculation flow rates are measured with less accuracy (estimated ±20%) based on the pressure drop across an iris-style damper, relying on the manufacturer's calibration of flow versus pressure drop. Highly accurate measurements of recirculation air flow rates are not important for our tests.

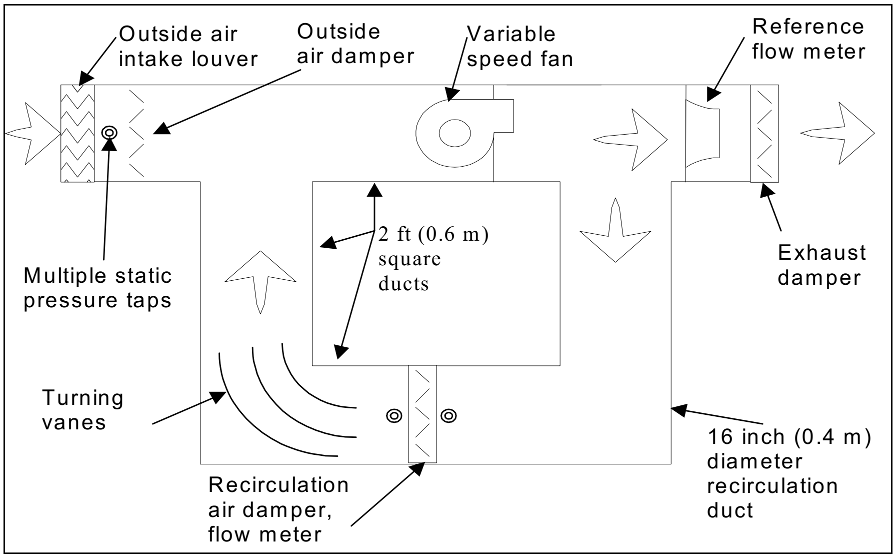

Figure 1. Illustrative diagram of test system. In practice, there are three** diameters of straight duct upstream and downstream of the reference flow meter.

In the test system, technologies for measuring OA flow can be installed per manufacturers' specifications. Independent control of the OA and recirculation air flow rates can be accomplished by adjusting the position of the three dampers[6].

Because the system is sealed to reduce air leakage to a negligible level[7], the flow of OA into the test system equals the exhaust airflow rate, which is measured with the reference airflow meter. Thus, the

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[6] Flow rates were not stable if the fan speed was reduced below full speed, thus, we used only the dampers to modulate flow rates.

[7] All joints were carefully caulked and smoke tubes were used to check for leaks and the system was pressure tested at the maximum operating pressure to assure negligible leakage.

accuracy of the OA measurement technology being tested is determined by comparison to the reference airflow meter, and the percentage measurement error (*%error*) is calculated from the following equation:

$$\%error = 100\% \left(Q_{mt} - Q_{ref}\right) / Q_{ref} \qquad (1)$$

where Q_{mt} and Q_{ref} are the OA flow rates from the measurement technology being evaluated and the reference flow meter, respectively.

Static pressure taps are installed at a number of locations to enable measurements of pressure drops across the measurement systems. Per specifications in ANSI/ASHRAE standards (ASHRAE 1999a, ASHRAE 1999b), the taps are 0.07 inch (1.8 mm) diameter holes in the duct wall with a smooth inner face.

The output signals of pressure transducers are logged with a data acquisition system. Instrumentation specifications and our estimates of accuracy during the tests are provided in Table 1. The calibration of the eight-channel pressure transducer system was checked using a micro-manometer that has a micrometer and electrical circuit for precisely measuring the height of the fluid column. A skilled user of the micro-manometer can obtain measurements repeatable within 0.0005 inch water (0.1 Pa). However, after accounting for instrument drift, the errors in pressure measurements may be as high as ±2 Pa.

Table 1. Instrumentation used with the test system

Parameter Measured	**Type of Instrument**	**Measurement range**	**Manufacturer's Rated Accuracy [estimated accuracy in use]**
Exhaust (reference) flow rate	18" (46 cm) and 10" (25 cm) flow meters flow meters have a flow straightener and converging nozzle, with Pitot-static type sensor centered at outlet of nozzle	Large 18" (46 cm) flow meter: 690 to 3700 cfm (0.33 to 1.75 $m^3 s^{-1}$) with pressure signal of 0.4 to 1.2 inch water (10 to 290 Pa). Small 10" (25 cm) flow meter: 330 to 1160 cfm (0.16 to 0.55 $m^3 s^{-1}$) with pressure signal of 0.1 to 1.3 inch water (26 to 330 Pa)	0.5 % of reading [±7% or better for reference flow exceeding 250 cfm (0.09 $m^3 s^{-1}$)]
Recirculation flow rate	16" (41 cm) Iris Damper with integral differential pressure flow meter	150 to 4000 cfm (0.07 to 1.9 $m^3 s^{-1}$) for differential pressure range of 0.1 to 2.0 inch water (25 to 500 Pa)	±7% of reading [± 20%]
Pressure difference	Eight channel electronic differential pressure transducer	±1.6 inch water (± 400 Pa)	Larger of ±0.001 inch water (± 0.2 Pa) or ± 1% of reading [±2 Pa or better]

The velocity profile of air entering an OA intake may be affected by winds. Our limited tests (described in Fisk et al. 2003) have indicated that winds can affect the accuracy of OA measurement technologies. Fisk et al. (2003) describes laboratory-based methods for preliminary investigations of the influence of winds and surfaces on the accuracy of the measurement technologies; however, the remainder of this paper focuses on conditions without winds.

Test protocol

The protocol for evaluating measurement technologies was straightforward. By adjusting dampers, OA flow rates were varied over the desired range. Recirculation air flow rates were adjusted so that the percentage of outdoor air (%OA), [i.e., outdoor air flow rate divided by outdoor plus recirculation flow rate, expressed as a percentage] ranged from approximately 10% to 100%.

In tests of the first measurement technology, we set the OA damper at ¼, ½, ¾, and fully open positions and used the exhaust and recirculation damper to obtain the desired flow rates. In subsequent tests of a second measurement technology, it became apparent that the air recirculation process could, under some circumstances, disturb the velocity or pressure profiles upstream of the OA damper and increase errors in measurements of OA flow rate. Therefore, in the subsequent testing we either a) varied the rate of OA flow by adjusting the OA air damper and maintaining the exhaust damper fully open; or b) varied the rate of OA flow by adjusting the exhaust air damper opening while maintaining the OA damper sufficiently closed so that the pressure drop across this damper was approximately 0.04 IWG (10 Pa). Maintaining this pressure drop across the OA damper largely eliminated the measurement errors associated with recirculation downstream of the OA damper.

Louvers used during tests

Experiments took place using three different types of louvers and the OA inlet that span over a wide range of louver designs. Figure 2 illustrates a cross section of a part of each louver.

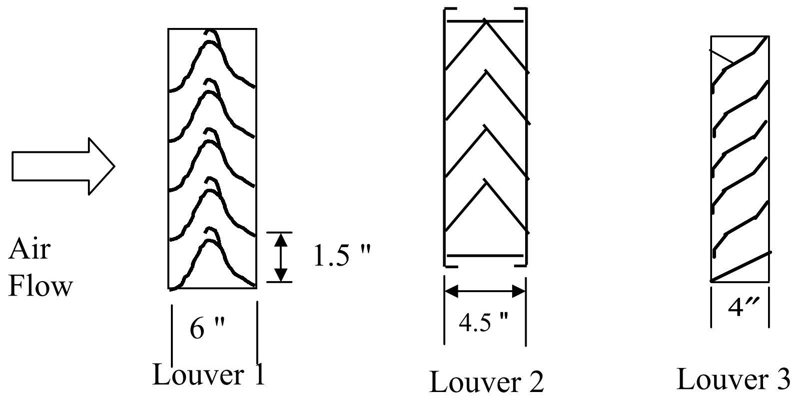

Figure 2.Schematic illustration of cross sections of louvers used during tests with Louver 1 viewed from the top and Louvers 2 and 3 are viewed from the side. The actual louvers have more blades than shown in the drawings.

Table 2 summarized characteristics of the louvers including the maximum recommended air velocities and the corresponding air flow rates for the nominal 2 ft by 2 ft (0.6 m by 0.6 m) louvers used in the tests. The table also provides the air velocities and flow rates at 20% of the maximum recommendations. These numbers indicate the minimum velocities and flow rates expected in an HVAC system with an economizer that has a minimum OA flow rate equally to 20% of the maximum OA flow rate

Table 2. Characteristics of the louvers

Parameter	**Louver 1**	**Louver 2**	**Louver 3**
Free area of louver[8]			
ft2	1.24	1.23	1.75
m2	0.115	0.114	0.163
Max recommended free area velocity			
fpm	1856	500	696
m/s	9.43	2.54	3.54
Flow rate at maximim free area velocity			
cfm	2301	615	1218
L/s	1086	290	575
Maximum velocity upstream and downstream of louver			
fpm	575	154	305
m/s	2.92	0.78	1.55
Flow rate at 20% of maximum recommended			
cfm	460	123	244
L/s	217	58	115
Velocity upstream and downstream of louver at 20% of maximum recommended			
fpm	115	31	61
m/s	0.58	0.16	0.31

<u>Measurement technologies</u>

This report summarizes results of our evaluations of three OA measurement technologies under conditions without winds at the OA intake. In all cases, the overall cross sectional dimensions of the OA inlet section was 2 ft by 2 ft (0.6 m by 0.6 m).

Measurement technology number 1 (MT1), illustrated in Figure 3, integrates a set of closely spaced (1.5 inch [3.8 cm]) vertical louver blades, identical to those identified as Louver 1, with a set of downstream airflow sensing blades that extend over the height of the louver system and that are centered between adjacent blades of the louver. The manufacturer provides a calibration curve in terms of average air velocity through the free-area of the louver system versus pressure signal from the airflow sensing blades. The airflow sensing blades appear to be designed to provide a pressure signal proportional to the average velocity along a vertical path centered between adjacent louvers. Compared to many louver systems, the MT1 louver system also has a relatively high recommended maximum free area velocity which helps to maintain a measurable pressure signal. The shape of the airflow-sensing blade should also yield a larger pressure signal than a standard Pitot-static tube.

The manufacturer's minimum "velocity requirement" for MT1 was 345 fpm (1.8 m s^{-1}) in the free area of the louver. The corresponding OA flow is 430 cfm (0.20 m^3 s^{-1}). Manufacturer's data indicate that the pressure drop across the louver system (without a bird screen) ranges nonlinearly from 0.01 inch water (2.5 Pa) with an air velocity through the free area of 470 fpm (2.4 m s^{-1}) to 3 inch water (747 Pa) with a velocity of 7300 fpm (37 m s^{-1}). MT1 was installed with 27.5 inch (70 cm) of straight duct located between the downstream edge of the louver and the upstream edge of the fully open OA damper.

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[8] The velocity at which the results of a moisture entrainment test meet certain criteria

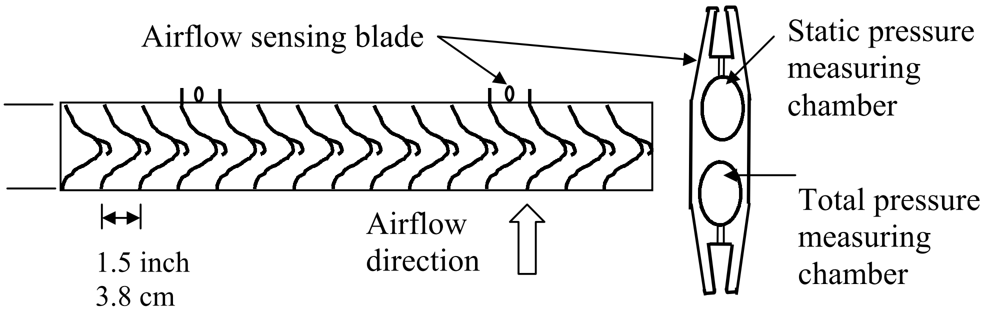

Figure 3. Illustration of outdoor airflow measurement technology number 1 (MT1). Top views of cross section of the louvers and airflow sensing blades are shown. The airflow sensing blades extend vertically nearly the full height of the louver system.

In this paper, we do not report results of an evaluation of Measurement Technology number 2 because we believe our evaluation was not sufficiently extensive for conclusions about performance. To maintain our numbering system, the next technology described in this paper is designated Measurement Technology 3 (MT3) which is illustrated in Figure 4. MT3 uses special static pressure tap at the outdoor face of the OA inlet and another type of static pressure tap downstream of the OA louver to sense the pressure drop across the louver. The outdoor pressure tap, mounted on the inlet face of the louver system appears to be designed to provide a pressure signal unaffected by wind direction. The pressure tap placed downstream of the louver, called an “inlet airflow sensor” is a 0.5 inch (1.3 cm) diameter 5 inch (13 cm) long cylinder with a 0.8 inch (2 cm) long sintered metal end that is inserted through a duct wall into the airstream. We presume that this tap is designed to provide a reliable measure of static pressure in the turbulent airstream located downstream of a louver. The full MT3 system comes with a pressure transducer, temperature sensor to enable control for air density, electronics, and a digital display. The system is designed for OA velocity ranges of either 150 to 600 fpm (0.8 to 3.0 m s^{-1}) or 250 to 1000 fpm (1.3 to 5.1 m s^{-1}) and has a rated accuracy of ±5% of the reading. The relationship of measured pressure drop to OA flow rate will vary with the design of the louver and must therefore be determined via a factory or field-based determination of this relationship. We did not use the manufacturer’s electronics or pressure sensor -- we used our research grade pressure transducer to measure the pressure difference. Thus, our tests only determined whether the OA flow rate could be determined by measuring the pressure difference across an OA inlet louver using the pressure taps provided. Because field based measurements of OA flow-pressure drop relationship may be impractical, we assumed that in practice a user would estimate OA flow rates from the measured pressure drops across the louvers and the pressure drop –velocity data provided by the louver manufacturers. We installed the “inlet airflow sensor” through the duct side wall

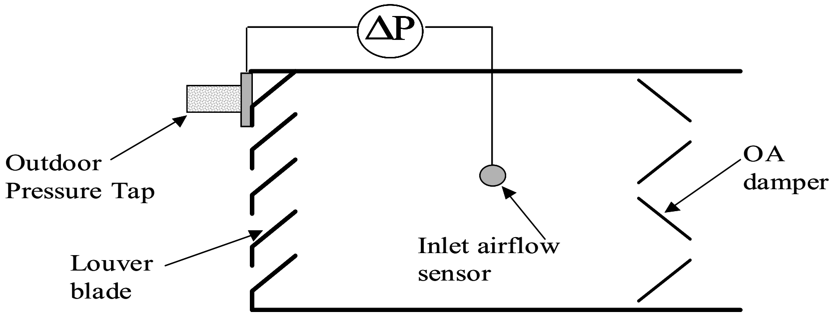

Figure 4. Schematic illustration of MT3

at various locations. For some tests, in place of the inlet airflow sensor we used static pressure taps in the walls of the duct downstream of the louvers or the static taps of Pitot-static tubes installed downstream of the louver. MT3 was tested using all three types of louvers placed upstream.

Measurement technology number 4 (MT4), illustrated in Figure 5, contains an airflow straightener upsteam of a set of airflow monitoring blades, followed by a section of straight ductwork and then an OA damper. The airflow straightener is constructed of 3/8 in (0.95 cm) aluminum honeycomb. The airflow monitoring blades are identical[9] to those used in MT1. The basic measurement concept appears to be to straighten and condition the airflow with the airflow straightener, determine an average velocity from a pressure signal obtained from the airflow monitoring blades, and provide some straight duct downstream of the airflow monitoring blades to isolate the blades from airflow disturbances at the OA damper. The manufacturers recommended velocity range is 400 to 5000 fpm (2 to 25 m/s) which correspond to 1600 to 20,000 cfm (760 to 9,400 L/s) for a 2 ft by 2 ft (0.6 m by 0.6 m) duct. The rated accuracy is ± 3% for a set of standard test conditions that include an upstream section of straight duct. In our tests, the unit was installed immediately downstream of L1. However, we modified Louver 1 slightly by removing some plates that blocked the periphery of the outlet plane, so that the air passage at the outlet of the louver better matched dimensions of the duct system and airflow straightener. The unit can be supplied with a pressure transducer, actuators, and controls; however, we evaluated none of these elements. We used our research grade pressure transducer and manipulated the damper position manually.

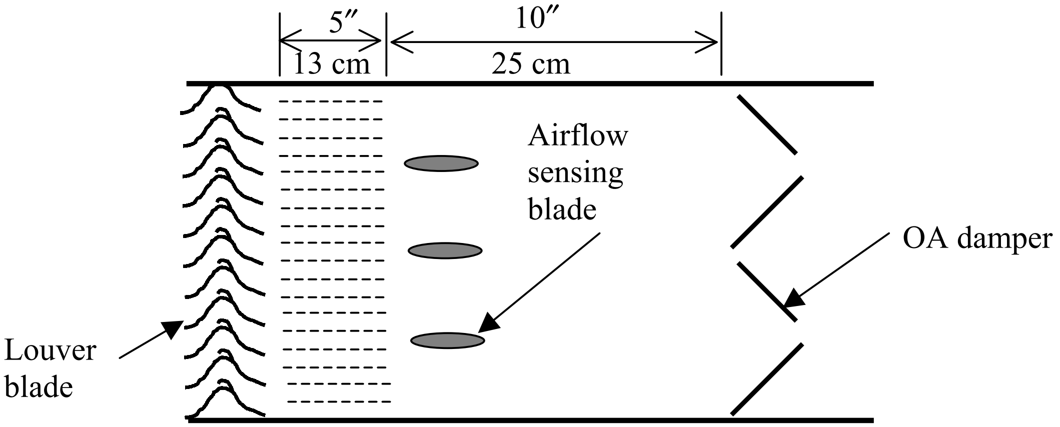

Figure 5. Schematic illustration of MT4 installed in the OA inlet section of a HVAC system.

The pressure drop imposed by MT4 as a function of air flow rate was measured without the upstream louver, using the static taps of Pitot-static tubes to measure the static pressure at locations between the airflow sensing blades and the OA damper.

Results

Figure 6 shows the accuracy (%error*)* of MT1 plotted versus the reference (i.e., “true”) OA flow rate. The figure includes results of tests with a range of %OA (from 10% to 100%) and with a range of OA damper positions. Figure 7 provides the measured pressure signal from the airflow sensor blades of MT1. With our research-grade pressure transducer used to measure this pressure difference, MT1 is accurate within approximately ± 20% for outdoor air flow rates[10] exceeding approximately 250 cfm (0.12 $m^3 s^{-1}$).

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[9] The same manufacturer produces MT1 and MT4.

[10] To convert the flow rates to the nominal air velocities downstream of louvers divide cfm values by 4 ft^2 or L/s values by 0.37 m^2.

In actual applications, the pressure transducer normally used in conjunction with MT1 will be less accurate (and also less expensive) than our research-grade pressure transducer. Therefore, for three OA flow rates, Figure 6 includes sets of error bars illustrating the expected errors in OA flow rates measured with MT1 with errors in differential pressure measurement of ±0.004 and ±0.01 inch water (± 1 Pa and ± 2 Pa), which are assumed to be more typical of the errors that occur with the electronic pressure transducers commonly used in field settings. With an error in pressure measurement of ± 0.01 IWG Pa (± 2 Pa), the corresponding error in OA flow rate is as high as 100% at 20% of the manufacturer's recommended maximum rate of flow through the louver. If pressure measurement errors can be limited to ±0.004 inch water (± 1 Pa), the maximum error in outdoor air flow rate measurement is about -20% to + 30% with a flow rate equal to 20% the manufacturers maximum recommended flow rate. As OA flow rates increase, the errors from inaccurate pressure measurements will decrease dramatically. Based on a more detailed examination of the test data, the accuracy of MT1 appeared to be nearly independent of both %OA (i.e., the rate of air recirculation) and the degree of opening of the OA damper.

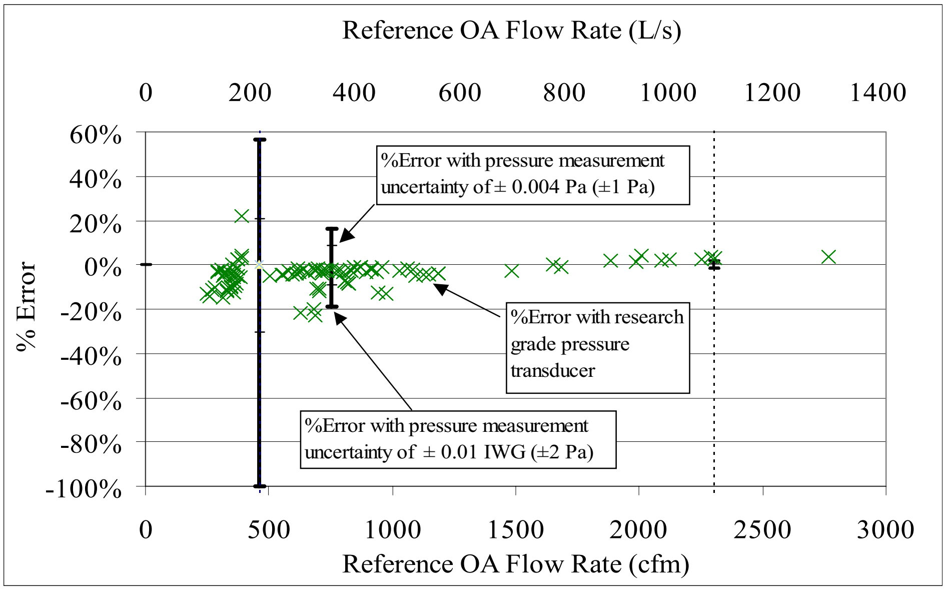

Figure 6. Accuracy of MT1 versus reference OA flow rate. The dashed vertical line marks 100% of the manufacturer's recommended rate of flow through the louver and the left-most set of error bars is positioned at 20% of the manufacturer's recommended rate of flow through the louver.

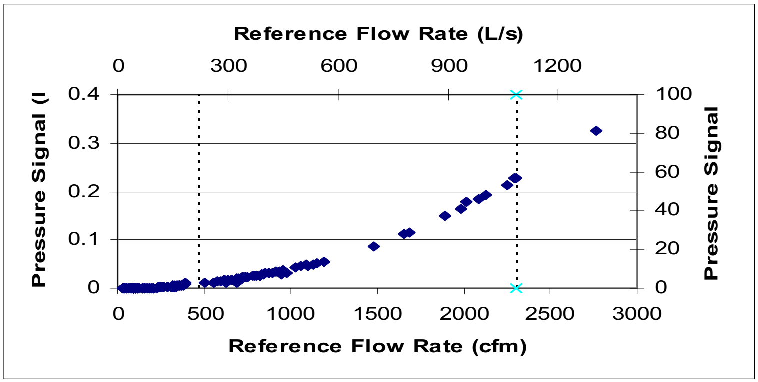

Figure 7. Pressure signal of MT1 versus reference OA flow rate.

Figure 8 shows the results of using MT3 in conjunction with L1. The horizontal axis is the reference OA flow rate and the vertical axis is the OA flow rate predicted based on the measured pressure drop across L1 and the louver manufacturer's pressures versus flow rate data[11] for L1. The figure shows results with the inlet airflow sensor of MT3 installed at two locations downstream of L1. The first location was 7.5 inch (19 cm) downstream of the downstream edge of L1, 12 inch (30.5 cm) from the top of the duct, inserted through a vertical duct wall. The second location was 20 inch (51 cm) further downstream from L1 and 8 inch (20 cm) from the top of the duct, inserted through the same duct wall. With these two tap locations, the predicted flow rates were 1.20 and 1.24 times the reference flow rates, respectively, and the predicted and reference flow rates were well correlated (R^2 = 0.99 to 1.00). Thus, without reliance on a field-based calibration, MT3 used with L1 should yield OA flow rates accurate within approximately 20% when the pressure signal is large enough to be measured accurately. For comparison, Figure 8 also shows results obtained with the pressure downstream of L1 based on the average of downstream pressures from three static pressure taps located on the duct top wall and two side walls downstream of L1. In this case, the predicted flow rate was 1.05 times the reference flow rate; however, the improvement in accuracy may be fortuitous because the measured pressure drop varied substantially among the three locations.

The results depicted in Figure 8 were obtained using our research grade pressure transducer. At 20% of the maximum recommended air flow rates through the L1, i.e., at a flow rate of 460 cfm (270 L/s), the measured pressure drops across L1 was only about 0.01 inch water (2.5 Pa). With this low OA flow rate, the errors in determination of OA flow rate could easily exceed 50% unless a very accurate pressure transducer was used to make the pressure measurements.

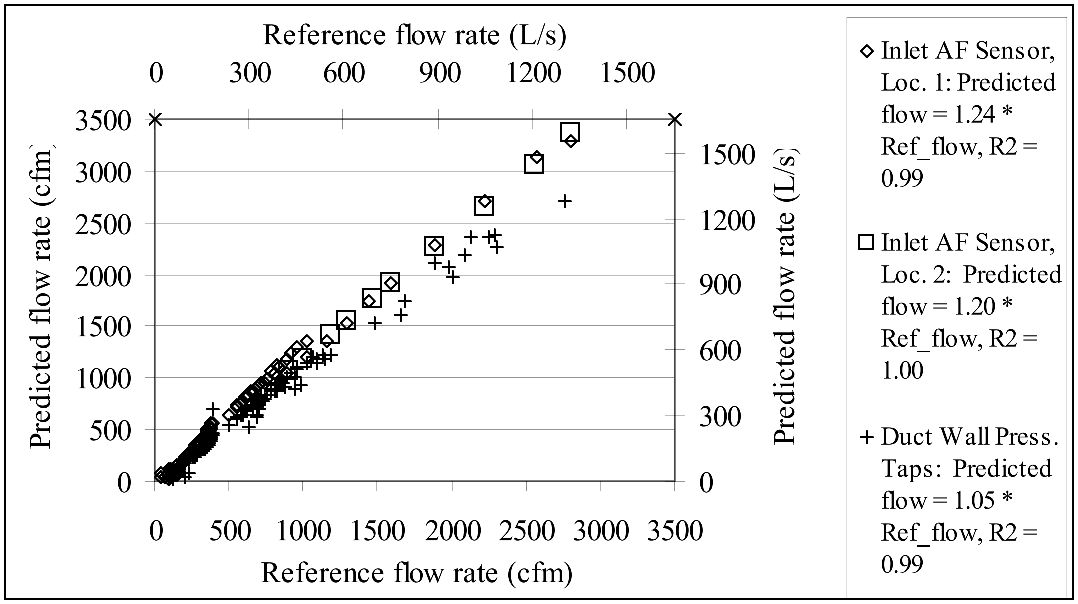

Figure 8. Relationship of reference flow rate to flow rate predicted using MT3 plus the manufacturer's pressure versus flow rate data for L1. Two of the data series represent data collected with an inlet airflow sensor of MT3 located downstream of L1 at two different locations. The third data series represents data collected with the pressure downstream of L1 based on the average from pressure taps in three duct walls.

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[11] Actually, the louver manufacturer provides data graphically on pressure drop versus free-area velocity. We multiplied the free area velocity by the free area of L1 and curve fit the data with a power equation. The resulting equation was cfm = 311 (IWG *250) ^0.4978), with an R^2 = 1.00.

The results of using MT3 in conjunction with L2 are shown in Figure 9. The measured data for L2 reflect conditions with 5% to 100% OA. To perform the measurements with L2, we used the "inlet airflow sensors" of MT3 located at two positions downstream of the louver. The first location was 4.5 in (11.4 cm) downstream of the downstream edge of the louver and 12 in (30.5 cm) from the top of the duct, inserted through a side duct wall. The second location was 20 in (51 cm) further downstream from the louver and 8 in (20 cm) from the top of the duct. The data points from these two probe locations fall on the same curve and are not distinguished on the figure. The predicted flow rate[12] was 1.28 times the reference flow rate, and the predicted and reference flow rates are well correlated ($R^2 = 1.00$). Thus, without reliance on a field-based calibration, MT3 used with L2 should yield OA flow rates accurate within approximately 28% when the pressure signal can be accurately measured. At 20% of the maximum recommended airflow through the louver, the pressure signal for determining OA flow rate is only about 0.005 IWG (1 Pa), which is too small for accurate measurements with the pressure transducers and procedures used in buildings.

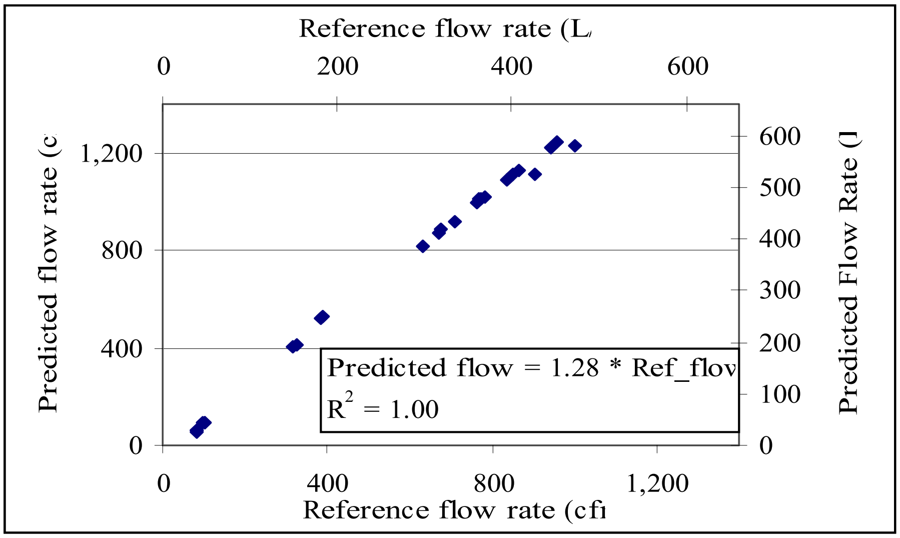

Figure 9. Relationship of reference flow rate to flow rate predicted using MT3 plus the louver manufacturer's pressure versus flow rate data for L2.

The tests of MT3 with L3 were performed without any recirculation and with a set of three Pitot-static tubes used in place of the inlet airflow sensor as the static pressure sensor located downstream of L3. The distance between the downstream edge of the louver and the upstream edge of fully open blades of the OA damper was 2 ft (0.6 m) and the Pitot-static tubes were installed halfway between the louver and the damper. The predicted flow rates[13] were 1.2 times the reference flow rates (Figure 10) and again the predicted and reference flow rates were very well correlated ($R^2 = 1.00$). Thus, without reliance on a field-based calibration, MT3 in conjunction with L3 should yield OA flow rates accurate within approximately 20% when the pressure signal is large enough to be measured accurately. At 20% of the maximum recommended airflow through the louver, the pressure signal for determining OA flow rate is less than 0.01 IWG (2.5 Pa), which again is too small for accurate measurement[14].

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[12] The predicted flow rate was based on a curve fit to manufacturer's pressure drop versus velocity data for L2. The resulting equation was cfm = 130 * (IWG * 250)^0.4729.

[13] The predicted flow rate was based on a curve fit to manufacturer's pressure drop versus velocity data for L3. The resulting equation was cfm = 219 * (IWG * 250)^0.515.

[14] With our estimated uncertainty in pressure measurements of 2 Pa, errors could be 100%

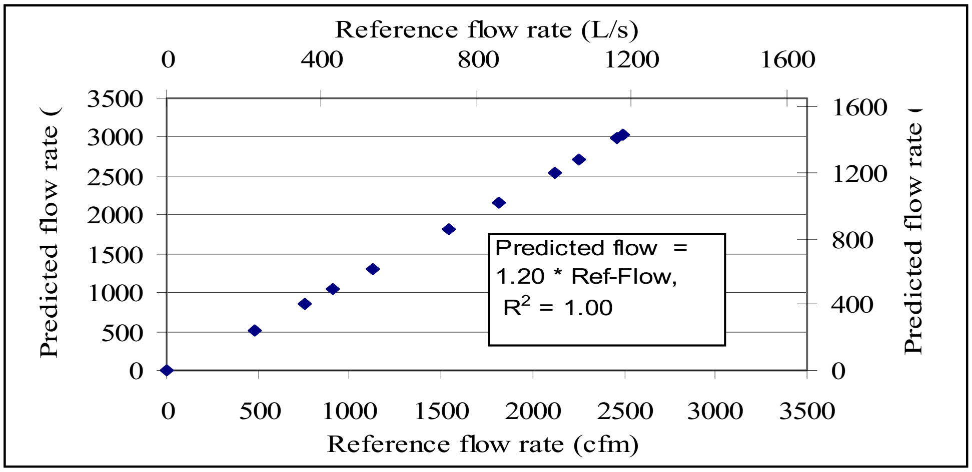

Figure 10. Relationship of reference flow rate to flow rate predicted from the measured pressure drop across L3 plus the louver manufacturer's pressure versus flow rate data for L3.

The relationship of pressure signal with reference flow rate for MT4 when placed downstream of L1 is shown in Figure 11. There is a smooth well-defined relationship of pressure signal with flow rate. The pressure signal becomes very small, less than approximately 0.01 IWG (2.5 Pa), when the flow rate is less than 1000 cfm (470 L/s). Therefore accurate measurements of flow rate will only be possible when the rates of airflow through the L1 are above approximately 50% of the maximum recommenced flow rate through L1. Figure 12 shows the %error in the flow rate measurement versus reference flow rate. Using our research grade pressure transducer to measure the pressure signal, the error is less than ±10% for flow rates exceeding 1000 cfm, (470 L/s). All of the data points indicating an error larger than ±10% are from tests with a pressure signal smaller than 0.01 IWG (2.5 Pa). The tests conditions included values of %OA ranging from 5% to 100% and an examination of test data indicates that the measurement error was unrelated to %OA. The manufacturer's minimum recommended flow rate for MT4 is 1600 cfm (760 L/s); thus, for flow rates in the manufacturer's recommended range the %error using our research grade pressure transducer was less than 10%. At 1600 cfm, the pressure signal was approximately 0.03 IWG (7.5 Pa). If the pressure measurement uncertainty with a practical pressure transducer was 0.01 IWG (2 Pa), the associated uncertainty range in the measurement of OA flow rate would be –10% to +16%.

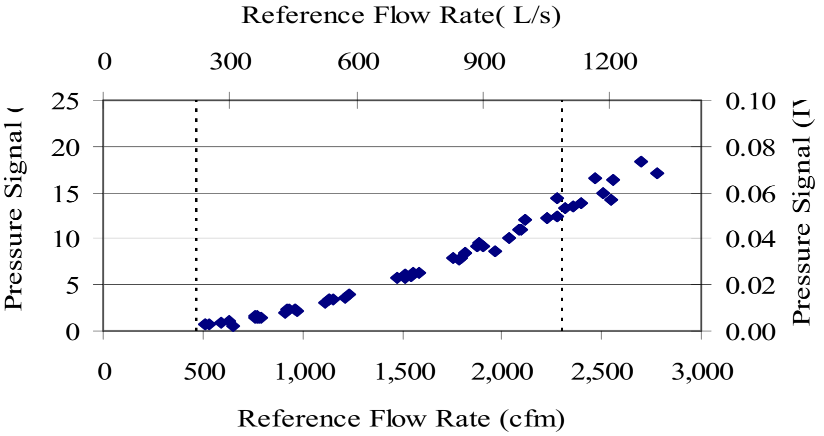

Figure 11. Pressure signal of MT4 versus reference air flow rate, with MT4 installed downstream of L1. The dashed vertical lines mark 100% and 20% of the maximum recommended rate of flow through L1.

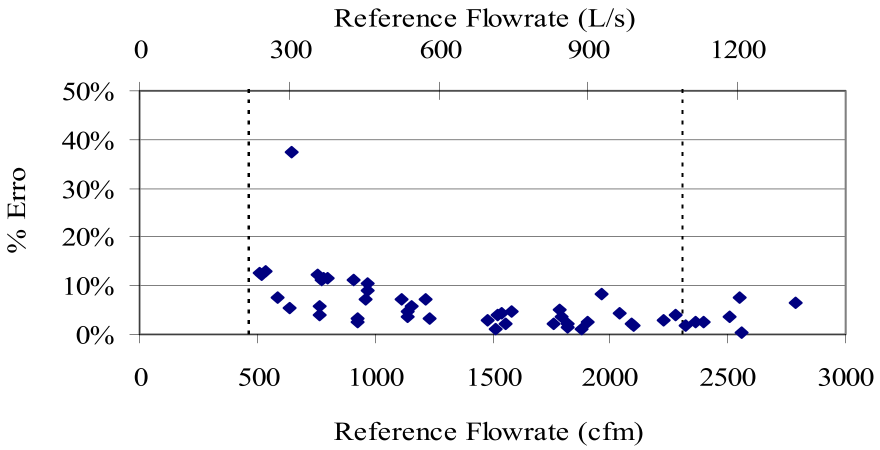

Figure 12. Percent error in measurements of flow rate with MT4 installed downstream of L1 versus reference flow rate. The dashed vertical lines mark 100% and 20% of the maximum recommended rate of flow through L1. All of the data points indicating an error larger than ±10% are from tests with a pressure signal smaller than 0.01 IWG (2.5 Pa).

Table 3 compares the performance of the three measurement technologies. Each technology should be usable at the maximum recommended rates of OA flow through louvers, although the errors with MT3, used with data from the louver manufacturer, were as high as 28% even with a research grade pressure transducer employed to measure the pressure signal that indicates OA flow[15]. MT4 has the smallest pressure signal, thus, it requires the highest velocities.

Table 3. Comparison of performance of measurement technologies.

		Max. Flow Through Louver				20% of Max Flow Through Louver*		
Meas. Technology	Louver	Flow Rate CFM (L/s)	Press. Signal IWG (Pa)	Press. Drop IWG (Pa)	Calibration Error (Bias)	Flow Rate CFM (L/s)	Press. Signal IWG (Pa)	±0.01 IWG (±2Pa) Error#
1	1	2300 (1090)	0.23 (57)	~0 (~0)	< 5%	460 (220)	0.007 (1.9)	-100% to +54%
3	1	2300 (1090)	0.224 (56)	~0 (~0)	+24%	460 (220)	~0.01 (~2)	~ - 70% to ~ +40%
3	2	615 (290)	0.108 (27)	~0 (~0)	+28%	120 (58)	~0.001 (~0.2)	-100% to +200%
3	3	1220 (580)	0.148 (37)	~0 (~0)	+20%	240 (110)	<0.01 (<2.5)	-100% to >100%
4	1	2300 (1090)	0.053 (13)	0.092 (23)	< 10%	460 (220)	~0.002 (~0.5)	-100% to +120%

*Expected minimum OA flow rate if HVAC system has an economizer control system
#Estimated errors resulting solely from a ±0.01 IWG (± 2Pa) error in pressure signal measurement.

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[15] The errors reported in this paper forMT3 can not be assigned specifically to the measurement technology. As we have applied the technology, the accuracy of the OA flow rates also depend on the accuracy of the pressure drop versus flow rate data for the louver.

We did not measure the pressure drop of MT1, due to the airflow measurement blades in flow path, and also did not measure the pressure drop of MT3 due to the pressure measurement probes in the flow path; however these pressure drops are likely to be negligible. The maximum pressure drop of MT4 was only 0.09 IWG (23 Pa). Thus, all of the measurement devices have pressure drops that are likely to be judged acceptable.

If a building has an economizer control system, during periods of minimum OA supply to the building, the flow rates of OA through the measurement technology may be reduced to 20% of the maximum recommended rate of flow through the upstream louver. Under these conditions, the pressure signals of MT1, MT3, and MT4 are very small and very difficult to measure accurately. With 20% of the maximum recommended flow rate, errors of only ±0.01 IWG (±2Pa) in measuring pressure differences will lead to errors in measurement of OA flow rates that sometimes exceed 100%. For MT3, we can estimate the minimum air flow rates needed to limit errors to 20% if the uncertainty in measuring pressure difference is ±0.01 IWG (±2Pa). The required air flow rates are 27%, 42% and 37% of the recommended maximum flow rates for use of MT3 with L1, L2, and L3, respectively.

MT1, MT3, and MT4 could be used in buildings with economizer control systems; however, to maintain accurate measurements of OA flow rate it will be necessary to divide the OA intake into two sections, each with a separate OA damper system. The economizer control system and associated controls must be designed and programmed to maintain rates of OA flow through the measurement technologies that are sufficient to produce a accurately measured pressure signals when rates of OA supply are minimized.

Discussion

Testing methods

The test system and protocol developed for this project provided a convenient and accurate method of evaluating the accuracy of the measurement technologies under conditions without wind. Individual data points could be obtained rapidly (e.g., within one minute) after flow rates were adjusted to obtain the desired conditions. If large numbers of tests were required, a computer control system could be developed to automatically adjust damper positions and fan speeds. Replacing the large reference flow meter with the smaller reference flow meter (or vice versa) required approximately 15 minutes of labor. Removing and replacing the OA flow measurement technology in the experimental system may require up to several hours of labor, depending upon the technology. The main limitation of the test apparatus and protocol is that they do not evaluate the influence of winds on measurement system accuracy. Preliminary testing with simulated winds indicates that winds can reduce accuracy, presumably by causing uneven airflow through the OA intake louvers. To confirm the reliability of data obtained with simulated winds we believe that limited testing should be performed with the systems exposed to real winds.

Performance of Measurement Technologies

We have not surveyed potential users of OA measurement technologies to assess their accuracy requirements. However, considering the complete lack of an OA air flow rate measurement technology in most buildings and the imprecise knowledge of the relationship of OA ventilation rates with health, we anticipate that systems with an accuracy on the order of ±20% will be considered valuable by users.

Our test data indicate that the three commercially available measurement technologies can provide reasonably accurate measurements of OA flow rates as long as air velocities are maintained high enough to produce accurately measurable pressure signals. In practice, this can be accomplished by dividing the OA intake into two sections, each with a separate OA damper system. The economizer control system and associated controls must be designed and programmed to maintain rates of OA flow through the measurement technologies that are sufficient to produce a accurately measured pressure signals when rates of OA supply are minimized.

MT3, in combination with manufacturer's data on pressure drops across louvers, was tested with three different louver systems. When flow rates were maintained sufficiently high for accurate pressure difference measurements, the measurement errors were ± 20% to ±30 percent. If an accurate calibration was performed in the field, errors could be further reduced; however, inaccurate field based calibrations might lead to larger errors. While these results are encouraging, we cannot be confident that a similar level of measurement accuracy will occur with other types or sizes of louvers. Our confidence in this measurement method would be improved if MT3 were supplied integrated with a louver and damper system, with a factory calibration.

The performance of MT4 may also depend on the type of louver used upstream. We placed MT4 downstream of L1. The configuration of L1 causes air to enter the airflow straightener with a fairly uniform velocity, which, in turn, should improve the accuracy of MT4. In contrast, L2 would direct air preferentially toward the bottom of the airflow straightener and L3 would direct air toward the top of the airflow straightener. Thus, it is possible that MT4 would be considerably less accurate if placed downstream of L1 or L3.

To better assess the accuracy of these OA measurement devices in practice, we need improved information on the accuracy of pressure difference measurements made in real building HVAC systems. To produce Table 3, we have assumed, based on our experience, that ± 0.01 IWG (±2 Pa) is a typical level of uncertainty. However, the manufacturer's accuracy specifications for some pressure transducers marketed for use in HVAC systems imply better accuracy. For example, one manufacturer's specifications imply that uncertainties are as low as ± 0.001 IWG (±0.25 Pa) for a pressure transducer with a full scale range of 0.1 IWG (25 Pa) and as low as 0.0025 IWG (0.6 Pa) for a transducer with a full scale range of 0.25 IWG (62 Pa). Calibrations to confirm such a high level of accuracy are very difficult. If pressure transducers are indeed as accurate in actual use as indicated by manufacturers, MT1 and MT3 may be useable for measuring the minimum rate of OA supply in HVAC systems with economizer controls, without providing a separate OA damper system for minimum OA.

None of the measurement technologies have large pressure drops that are likely to be judged unacceptable. Thus, pressure drop limitations do not appear to be a barrier to measurement of OA flow rates into HVAC systems.

Most of the measurement systems do require that the OA damper is located a significant distance downstream of the OA louver. The recommended or required distance between the downstream edge of louver and upstream edge of the fully open OA damper is approximately 4, and 15 inch (10 and 38 cm) for MT1 and MT4 respectively. No guidance was identified for MT3.

Costs are another consideration and we don't know what level of costs will be deemed acceptable. We paid $800 for MT1, $450 for MT3[16], and $1100 for MT4, all without any associated pressure sensors or controls. MT1 included an integral louver and MT4 included an integral OA damper, so the net costs of the measurement technologies are less than indicated above. HVAC equipment manufacturers who purchase large numbers of products might be able to obtain systems a lower cost. Given the potential energy cost savings and health benefits of providing better control of OA supply rates, we suspect that these product costs will be acceptable.

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[16] With a single downstream pressure probe which is called an inlet airflow sensor by the manufacturer. If multiple probes are used the cost per probe is $75.

Conclusions

The test system and protocol developed for this project provides a convenient and accurate method of evaluating the accuracy of technologies for measuring outdoor airflows into air handling systems. Further research is needed to develop systems and protocols for assessing the influence of winds on measurement accuracy.

The series of tests performed for this research identified three commercially available measurement technologies that should provide reasonably accurate measurements of OA flow rates (i.e., 10% to 30% errors) as long as air velocities are maintained high enough to produce accurately measurable pressure signals. In practice, these conditions can be achieved by dividing the OA intake into two sections, each with a separate OA damper system. The economizer control system and associated controls must be designed and programmed to maintain rates of OA flow through the measurement technologies that are sufficient to produce a accurately measured pressure signals when rates of OA supply are minimized.

All of the measurement devices have pressure drops that are likely to be judged acceptable. Thus, pressure drop limitations do not appear to be a barrier to measurement of OA flow rates into HVAC systems.

Acknowledgements

This work was supported by the assistant Secretary for Energy Efficiency and Renewable Energy, Building Technologies Program of the U.S. Department of Energy under contract DE-AC03-76SF00098. The authors thank Woody Delp and Steve Taylor for their reviews of a draft of the report on which this paper was based.

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