Measuring OA Intake Rates

By **William J. Fisk,** Fellow ASHRAE; **David Faulkner, P.E.;** and **Douglas P. Sullivan**

Approximately 1 quad (1 EJ) of energy, costing $7.2 billion, is used annually for conditioning the OA ventilation air supplied to U.S. commercial, institutional, and government, buildings.[1] The rate of OA ventilation also affects occupant health.[2] In cross-sectional studies of buildings with various rates of OA ventilation, lower ventilation rates have been associated with increased respiratory illnesses (e.g., common colds), increased sick building syndrome symptoms, and diminished satisfaction with IAQ.[2] Recent data indicate that lower OA ventilation rates also are associated with small decrements in work performance.[3] Clearly, a need exists to strike a balance between the benefits of increased OA ventilation and the beneficial energy savings from reduced OA ventilation.

Design of the OA intake systems to avoid low pressure signals and the use of accurate pressure transducers are keys to accurate measurements of OA flow rate. With real-time data on OA flows, substantial improvements in our control of OA supply to buildings should be possible.

Despite the substantial influences of OA ventilation on energy use, health and performance, most U.S. buildings do not have a system for measuring the OA intake rates of HVAC systems continuously or even periodically. Given the absence of measurement systems, it is not surprising that minimum OA ventilation rates measured in surveys vary widely and often differ substantially from the ventilation rates specified in codes and in design documents.[4,5]

Available data indicate that average OA ventilation rates in office buildings substantially exceed code requirements, implying an opportunity for energy savings.[4,5] However, a significant fraction of office buildings still provide less OA than specified in codes.[4,5] Based on high measured CO_2 concentrations in classrooms, a majority of classrooms have less OA ventilation than specified in codes.[6,7]

Accurate measurements of OA intake rates are challenging because OA intake velocities are kept low to minimize the amount of rain and snow drawn into the air handler. When the OA inlet is sized for the entire OA intake flow during economizer operation, the result is particularly low OA intake velocities, near or below the detection limits of many velocity sensors, during periods of minimum OA intake when measurements are most important. The geometry of the OA intake and its impact on velocity profiles, and limited accessibility of the OA intake in some HVAC systems, further complicates the measurements.

The outdoor air passes through a bird screen, a set of louvers, and an OA damper. Downstream of the louvers or OA dampers the speed and direction of airflow will normally vary markedly across the flow cross section.[8] Thus, averaging of velocity measurements made at a few locations in the cross section can lead to large measurement errors. Although these challenges and the need for better measurement and control of OA intake rates have long been recognized, until recently there has been only moderate progress toward meeting this need. A recent review article[9] summarizes much of the recent research.

To address this problem, several manufacturers now offer technologies for direct real-time measurement of the rate of airflow through the OA intake. This article describes results of tests of three technologies that performed reasonably well (e.g., errors of a few percent to 25% in laboratory studies) and provides guidance on how these technologies should be used. More details are available in two papers recently published in *ASHRAE Transactions.*[4,8]

Evaluation Methods

The accuracy of measurement technologies (MTs) marketed for measuring rates of OA intake was assessed for a range of OA intake rates and air recirculation rates in a laboratory test system with a 2 ft by 2 ft (0.61 m by 0.61 m) OA intake louver and duct. Highly accurate reference flow meters (rated ±0.5% of flow) that contain an airflow straightener, a nozzle, and an array of pitot-like sensors were used to determine the "true" OA flow rates for comparison to the flow rates indicated by the MTs being evaluated. A calibrated research grade self-zeroing pressure transducer that is more accurate but more expensive than transducers normally used in buildings, with rated accuracy of ±0.001 in. of water (± 0.2 Pa) or ± 1% of reading, was used to measure the pressure signals from the MTs.

Accuracy of Three Measurement Technologies

Measurement technology 1 (MT1), depicted in *Figure 1*, integrates a set of vertical louver blades with downstream airflow sensing blades that extend the height of the louver system and that are centered between adjacent blades of the louver. No additional intake louver is required. The manufacturer's calibration curve relates the average air velocity through the free-area of the louver with the pressure signal from the airflow sensing blades.

Figure 2 shows the accuracy of MT1 plotted vs. the reference OA flow rate. The figure includes results of tests with 10% OA to 100% OA. With our research-grade pressure transducer used to measure the pressure signal, MT1 was accurate within approxi-

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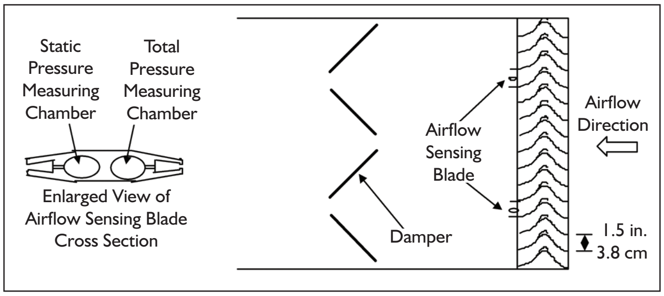

Figure 1: Illustration of MT1. Top views of cross section of the louvers and airflow sensing blades, and a side view of the OA damper are shown. The bird screen present upstream of the louver is not shown.

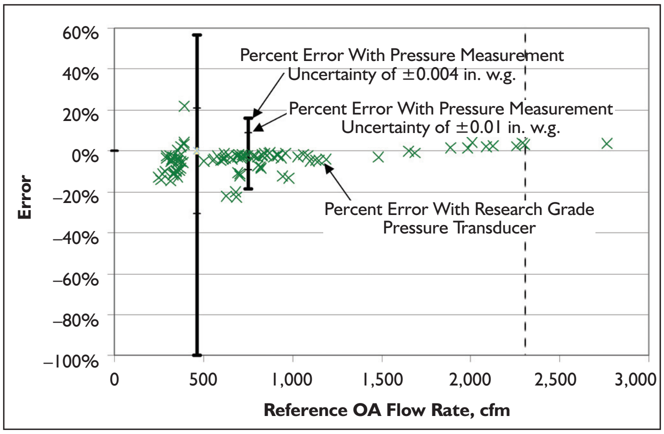

Figure 2: Accuracy of MT1 vs. reference OA flow rate. The dashed vertical line marks 100% of the recommended maximum rate of flow through the louver (to prevent excessive moisture intake) and the left-most set of error bars is positioned at 20% of the recommended rate of flow through the louver.

mately ±20% for outdoor airflow rates* exceeding approximately 250 cfm (118 L/s), corresponding to nominal intake velocities exceeding 62 fpm (0.31 m/s). The pressure signal from MT1 was 0.23 in. of water (58 Pa) with the maximum recommended air velocity in the louver. Such a pressure difference can be measured accurately with commercial pressure transducers.

However, at 20% of the maximum recommended velocity in the louver, which would be expected in an HVAC system with an economizer that had only one OA damper, the pressure signal was only 0.007 in. of water (1.75 Pa), which is difficult to measure accurately with the pressure transducers marketed for HVAC applications.

Therefore, for two OA flow rates, *Figure 2* includes error bars illustrating the expected errors in OA flow rates with errors in

* To convert the flow rates to the nominal air velocities downstream of louvers divide cfm values by 4 ft^2 to obtain velocities in fpm or divide L/s values by 0.372 m^2 to obtain velocities in m/s.

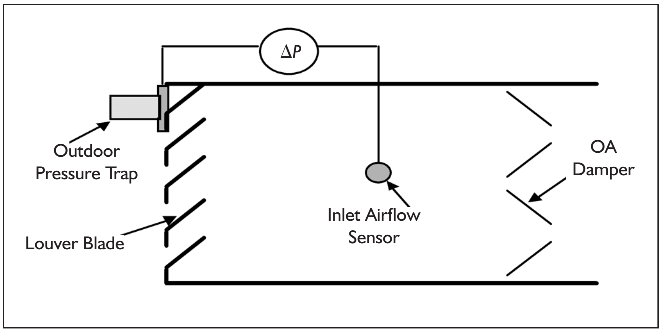

Figure 3: Schematic illustration of MT3.

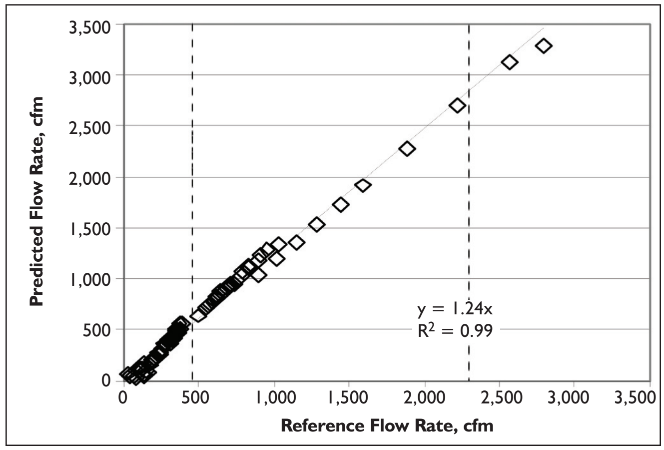

Figure 4: Results of tests of MT3 used in conjunction with Louver 1. The dashed vertical lines mark 100% and 20% of the recommended maximum flow rate through the louver.

differential pressure measurement of ±0.004 and ±0.01 in. of water (±1 Pa and ±2.5 Pa), which are assumed to be more typical of the errors that occur with the electronic pressure transducers commonly used HVAC systems. With an error in pressure measurement of ± 0.01 in. of water (±2.5 Pa), the corresponding error in OA flow rate is as large as –100% at 20% of the recommended maximum rate of flow through the louver.

Under the same conditions, if pressure measurement errors can be limited to ±0.004 in. of water (±1 Pa), the maximum error in OA flow rate measurement is about –30% to +20%. As OA flow rates increase, the percentage errors from inaccurate pressure measurements decrease dramatically because the pressure signal becomes larger and is more accurately measured. Also, the low-pressure signals can be avoided by using two OA dampers in parallel—one for the minimum OA intake and a second damper, which must have low leakage when closed, for the increased OA intake during economizer operation. Based on an examination of the test data, the ac-

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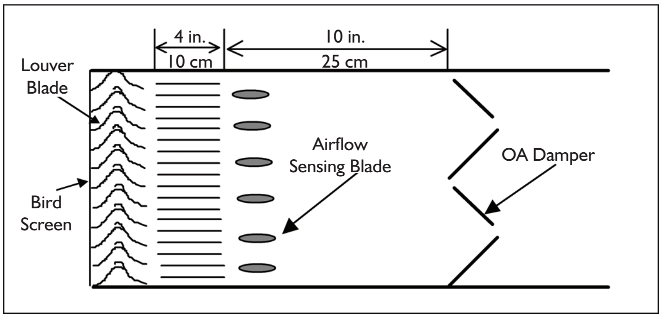

Figure 5: Illustration of MT4. For illustrative purposes, a top view cross section of the louver is shown, while a side view cross section is depicted for all other components of MT4.

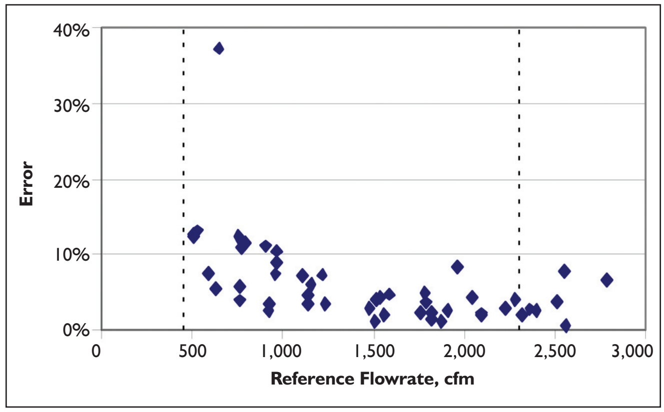

Figure 6: Percent error in measurements of flow rate with MT4 installed downstream of L1 vs. reference flow rate. The dashed vertical lines mark 100% and 20% of the manufacturer's maximum recommended rate of flow through L1, respectively.

curacy of MT1 was nearly independent of percent OA (i.e., the amount of air recirculation), with the rate of OA intake held constant. Summary data on the performance of MT1 is provided in *Table 1*.

MT3** (*Figure 3*) uses a special static pressure tap at the outdoor face of the OA inlet and another type of static pressure tap, called an "inlet airflow sensor" downstream of the OA louver to sense the pressure drop across the louver. The outdoor pressure tap, mounted on or near the inlet face of the louver system, appears to be designed to provide a pressure signal unaffected by wind direction. The inlet airflow sensor is a 0.5 in. (1.3 cm) diameter, 5 in. (13 cm) long cylinder with a 0.8 in. (2 cm) long sintered metal end that is inserted through a duct wall. We presume that this sensor 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 has a manufacturer's rated accuracy of ±5% of the reading. The relationship of measured pressure drop to OA flow rate varies 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. Thus, our tests only determined whether the OA flow rate could be determined by measuring the pressure difference across an OA intake louver using the pressure taps provided. Because an accurate field-based calibration may be impractical, we assumed that a user would estimate OA flow rates from the pressure drops measured with MT3 and the pressure drop-velocity data provided by louver manufacturers. Although recognizing that the manufacturer's data on pressure drops across louvers is not perfect, our goal was to evaluate this practical approach.

MT3 was tested using three types of louvers placed upstream. Louver 1 (L1) is identical to the louver depicted in *Figure 1,* but has no airflow measurement blades. The air exits L1 directed predominately parallel to the duct walls. L2 is a traditional horizontal blade louver from which the outlet air has an upward trajectory, and L3 is a horizontal blade sight-proof louver from which the outlet air has a downward trajectory.

** This article does not include results of tests of MT2, for which we have insufficient test data.

Measurement Technology	Louver	Maximum Flow Through Louver				20% of Maximum Flow Through Louver*		
		Flow Rate, cfm	Pressure Signal, in. w.g.	Pressure Drop,** in. w.g.	Calibration Error,†† bias	Flow Rate, cfm	Pressure Signal, in. w.g.	±0.01 in. w.g. Error†
1	1	2,300	0.23	~0	<5%	460	0.007	–100% to 54%
3	1	2,300	0.224	~0	+24%	460	~0.01	~ –70% to ~ 40%
3	2	615	0.108	~0	+28%	120	~0.001	–100% to 200%
3	3	1,220	0.148	~0	+20%	240	<0.01	–100% to >100%
4	1	2,300	0.053	0.092	<10%	460	~0.002	–100% to 120%

* Expected minimum OA flow rate if HVAC system has an economizer control system. These low flow rates and associated large errors can be avoided using two OA dampers in parallel, one for minimum OA supply.
** Incremental pressure drop in the OA intake from the addition of the measurement technology.
† Estimated errors resulting solely from a ±0.01 in. of water (±2.5 Pa) error in pressure signal measurement.
†† Random error was very small and will vary primarily with the signal noise from the pressure transducer.

Table 1: Summary of performance of measurement technologies.

Figure 4 shows an example of how the OA flow rates predicted using MT3 relate to the reference OA flow rates. The data shown were collected using L1. The predicted flow rate, based on the pressure signal of MT3, was well correlated with the reference flow rate ($R^2 = 0.99$) and, on average, the predicted flow rate was 24% high.

When we repeated tests with the inlet airflow sensor at a different location downstream of L1, the predicted flow rate was high by 20% and the correlation remained high ($R^2 = 1.00$). In tests with L2, the predicted flow rate was 28% high ($R^2 = 1.00$). In tests with L3, we used the static taps of three pitot-static tubes placed downstream of L3 in place of the inlet airflow sensor. The correlation between predicted and reference flow rate remained very high ($R^2 = 1.00$) and the predicted flow rate was 20% higher than the reference flow rate. While better accuracy in measurements of OA flow rates may be desired, OA flow rate data with 20% to 30% errors are preferable to having no real-time data on OA flow, which is the typical situation. If an accurate field-based calibration could be performed, measurement errors would be smaller.

Data in *Table 1* indicate that the pressure signals provided by MT3 with the maximum recommended rates of airflow through the three louvers ranged from 0.22 to 0.11 in. of water (55 to 28 Pa). Given the magnitude of these pressure signals, accurate measurements should be possible with at least some of the pressure sensors marketed for HVAC applications. However, at 20% of the maximum recommended flow rates, the pressure signal of MT3 was always less than 0.01 in. of water (2.5 Pa), which is less than our estimated errors in pressure measurements with many of the pressure transducers marketed for use with HVAC systems.

MT4 (*Figure 5*) contains a honeycomb airflow straightener upstream of a set of airflow monitoring blades, followed by a section of straight ductwork and then an OA damper. The airflow monitoring blades are identical to those used in MT1. The measurement concept appears to be to straighten the airflow, 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 manufacturer's recommended velocity range is 400 to 5,000 fpm (2 to 25.4 m/s), which corresponds to 1,600 to 20,000 cfm (755 to 9440 L/s) for a 2 ft by 2 ft (0.61 m by 0.61 m) duct. The manufacturer's rated accuracy is ±3% for standard test conditions with an upstream section of straight duct. In our tests, MT4 was installed downstream of L1. The unit can be supplied with a pressure transducer, actuators, and controls. However, we evaluated none of these elements.

Figure 6 shows the error in the flow rate measurement vs. reference flow rate. Using our research grade pressure transducer to measure the pressure signal, the error is less than ±10% for flow rates exceeding 1,000 cfm (472 L/s). All data points indicating an error larger than ±10% are from tests with a pressure signal smaller than 0.01 in of water (2.5 Pa). The tests conditions included 5% OA to 100% OA and the measurement error was unrelated to percent OA, with OA flow rate held constant. The manufacturer's minimum recommended flow rate for MT4 is 1,600 cfm (755 L/s).

Thus, for flow rates in the recommended range the error using our research grade pressure transducer was less than 10%. At 1,600 cfm (755 L/s), the pressure signal was approximately 0.03 in. of water (7.5 Pa). If the pressure measurement uncertainty with a practical pressure transducer was 0.01 in. of water (2.5 Pa), the associated uncertainty range in the measurement of OA flow rate would be –10% to +16%.

Data from our field testing[10] indicate that the OA flow rates measured with MT4 have substantially larger errors when MT4 is used with an upstream horizontal-blade louver from which air exits with an upward trajectory. Thus, to maintain high measurement accuracy with MT4, it may be necessary to use L1 or some other louver with an outlet airflow that is predominately parallel to the duct walls.

The pressure signal from MT4 is relatively small (0.053 in. of water [13.2 Pa]) even with the maximum recommended rate of flow through L1. At 20% of the maximum recommended flow rate, the pressure signal is very small (*Table 1*) and consequently difficult to measure accurately with the pressure sensors marketed for HVAC applications.

None of the MTs tested create large pressure drops that are likely to be judged unacceptable with respect to fan capacity and fan energy use.[4] Thus, pressure drop limitations do not appear to be a barrier to measurement of OA flow rates into HVAC systems.

Effective Application of These Technologies

The small pressure signals provided by these technologies seem to be the main factor limiting the accuracy of the measurements of OA flow rates. To maintain measurement accuracy, it will be necessary to use a pressure transducer with a full-scale range not much larger than the maximum anticipated pressure signal. Our calculations indicate that percentage error in flow rate, due solely to a pressure measurement error, is roughly half of the percentage error in the pressure signal measurement, e.g., a 20% error in pressure measurement, leads to a 10% error in flow rate. Thus, one might design for a 20% error in the smallest anticipated pressure signal, and benefit

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from smaller errors when the pressure signal is larger.

If the HVAC system has an economizer, to maintain a sufficient pressure signal, the OA intake can be divided into two sections, each with a separate OA damper. The damper that is closed during minimum OA intake must have a low rate of air leakage. The economizer control system and associated controls must be designed 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.

To measure accurately with MT4 when placed immediately downstream of the OA intake louver, it may be necessary to use a louver with an outlet airflow that is predominately parallel to the duct walls. Our research also indicates that maintaining a pressure drop of at least 0.04 in. of water (10 Pa) across the OA damper can help to maintain a high measurement accuracy.[8]

In a limited program of field research,[10] we evaluated whether measurement accuracy is maintained when the OA intake is subject to winds. In these studies, neither wind speed nor wind direction appreciably affected measurement accuracy of the three MTs discussed in this article. Also, this research showed that some of the pressure transducers marketed for use with commercial HVAC systems were sufficiently accurate for this application. Maintenance requirements and the required frequency of pressure transducer calibration were not studied.

Conclusions

Rates of OA ventilation should be monitored and well controlled because prior research indicates these rates substantially affect building energy use and occupant health. The available data indicates that OA supply rates are often poorly controlled. Some of the commercially available systems, when used properly, can measure the rate of outdoor air intake with errors of 20% or less. Design of the OA intake systems to avoid low pressure signals and the use of accurate pressure transducers are keys to accurate measurements of OA flow rate. With real-time data on OA flows, substantial improvements in our control of OA supply to buildings should be possible.

Acknowledgments

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