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TECHNOLOGIES FOR MEASURING FLOW RATES OF OUTDOOR AIR INTO HVAC SYSTEMS: SOME CAUSES AND SUGGESTED CURES FOR MEASUREMENT ERRORS

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TECHNOLOGIES FOR MEASURING FLOW RATES OF OUTDOOR AIR INTO HVAC SYSTEMS: SOME CAUSES AND CURES FOR MEASUREMENT ERRORS

ABSTRACT

Although the rate of outdoor air (OA) ventilation has a substantial influence on building energy consumption and occupant health, the available data indicate the outdoor air ventilation rates are poorly controlled in many buildings. Technologies being marketed for real time measurement of the flow rates of outdoor air into HVAC systems should enable better control of OA ventilation. In laboratory research we have studied the performance of these technologies. Sources of measurement errors identified during conduct of this research include: low air speeds; high spatial variability in air speed and direction; large eddies downstream of outdoor air intake louvers; and backwards airflow through a portion of outdoor air dampers. Several suggestions for overcoming these sources of errors were developed including: design and control of the outdoor air intake system to avoid low, hard-to measure, air speeds; use of highly sensitive pressure and velocity sensors; measuring air speeds between blades of louvers, rather than downstream of louvers; smoothing out the airflow between the outdoor air louver and damper through proper louver selection and insertion of components to straighten air flow; and maintaining a pressure drop across the outdoor air damper that exceeds approximately 0.04 IWG (10 Pa).

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. We estimate that roughly 1 Quad (1 EJ) of energy is used annually thermally condition the outdoor air provided to service sector buildings in the US (Fisk et al. 2004) and that approximately 0.3 Quad (0.3 EJ) of energy would be saved if the average minimum rate of OA supply was reduced to bring rates in alignment with the current standards. However, ventilation rates should not be reduced indiscriminately because low ventilation rates, particularly those below the specifications in current minimum ventilation standards, are associated with adverse health effects (Seppanen et al. 1999).

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. The limited data available indicate that most buildings have minimum ventilation rates substantially exceeding code requirements; however, the available data also indicate that many buildings also provide less ventilation than specified in codes. These data indicate the need to better control building ventilation rates. In response to this need, manufacturers have started to market technologies for direct real-time measurement of airflow through the OA intake using a sensor system located at the OA intake. In a separate document (Fisk et al. 2004), we report on a evaluation of some of these commercially available outdoor airflow measurement technologies (OAMTs). When assessing technology performance, we identified several causes of measurement errors. This document summarizes our thoughts about the causes of these errors and suggests some approaches of overcoming these errors.

APPROACH

Figure 1 illustrates the main features of a laboratory-based test apparatus that we have used to evaluate technologies for measuring flow rates of outdoor air into HVAC systems. Typically, the OAMTs are installed between the OA intake louver and the OA damper. These OAMTs determine OA flow rates as follows:

- The air speed is measured at several locations in a cross section of the duct located between the OA louver and the OA damper and the OA flow rate is calculated as the average measured air speed multiplied by the cross-sectional area of the duct.
- One system measures the speed of air exiting the channel between a sample of adjacent pairs of louver blades. This average air speed is related to the OA flow rate via a calibration curve provided by the manufacturer.
- One system uses a set of special probes to measure the pressure drop across the OA louver. The OA flow can them be determined from the louver manufacturer's data on the pressure drop of air as it flows through the louver.

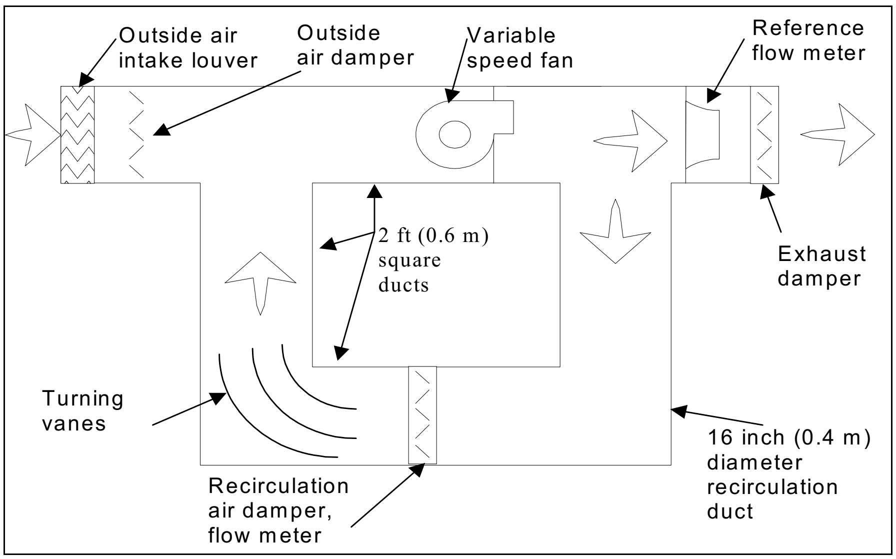

Figure 1. Schematic diagram of test system.

Because the test system has minimal air leakage, the rate of OA flow into the system through the OA intake louver equals the rate of flow exhausted from the test system through the highly accurate reference air flow meter. Therefore, the accuracy of OAMTs can be assessed by comparing the OA flow rates indicated with an OAMT to the flow rate measured with the reference flow meter.

During the studies of OAMT performance, several sources of measurement errors were identified. Some sources of error, such as low air velocities near detection limits, were obvious. Other sources of errors related to the nature of the airflow profiles between the OA intake louver and the OA damper. To learn about the airflow profiles, a hot wire anemometer was used to measure the air speed at multiple locations. In addition, we replaced one duct wall with a sheet of transparent plexiglass and injected chemical smoke into the duct at various locations. Observation of the smoke transport provided a qualitative indication of the directions of airflow. We also placed static pressure taps at numerous locations downstream of the louver and determined how the measured static pressure, relative to the pressure outside of the test system, varied with probe location. Finally, we experimented with changes in hardware and with damper control strategies for overcoming some of the sources of errors.

The evaluations of OAMTs and of the causes of measurement errors were performed for a broad range in OA flow rates, with various rates of air recirculation, and – in one case – with three different types of OA intake louvers, designated louver 1 (L1), louver 2 (L2), and louver 3 (L3). Figure 2 provides simplified schematics of the cross sections of each louver. The nominal cross sectional dimensions of each louver were 24 inch by 24 inch (61 cm by 61 cm).

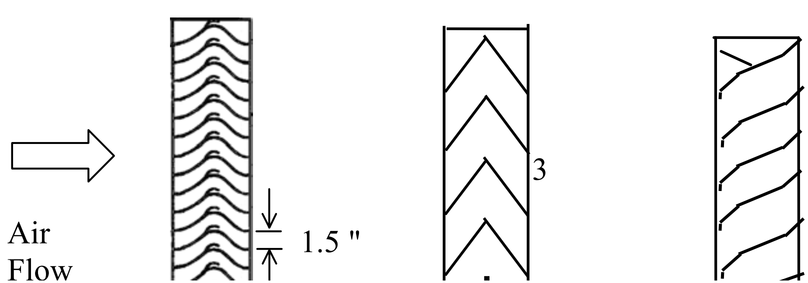

Figure 2. Simplified illustrations of cross sections of louvers used during tests with Louver 1 viewed from the top and Louvers 2 and 3 are viewed from the side. The illustrations of Louver 2 and Louver 3 do not show the full number of louver blades in the actual louvers.

CAUSES AND CURES FOR MEASUREMENT ERRORS

Low air speeds near sensor detection limits.

OA intake velocities are intentionally kept low to minimize rain and snow from being drawn into the air handler. Based on a review of specifications of louvers, the maximum recommended air velocity within the "free area[1]" of an intake louver is usually 700 to 2500 fpm (3.5 to 13 m s^{-1}) to minimize entrainment of rain and snow, and are sometimes lower. If the HVAC system has an economizer control system, these maximum velocities occur with the maximum flow at the OA intake during economizer operation with 100% outdoor air. The minimum OA supply may be only 20% of the full supply air flow rate; hence, 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.

Table 1 provides the maximum air velocities recommended with the three louvers (L1, L2, and L3) used in our research, the minimum air velocities assuming that the minimum outdoor air flow rate is 20% of the maximum, and the corresponding velocity pressures. The velocity pressures are relevant because most OAMTs use the velocity pressure to sense air velocity. It is clear from this table that the air velocities vary considerably, i.e., by more than a factor of three, among the louvers, and that the velocity pressures downstream of the louver at minimum outdoor air conditions are less than 0.001 IWG (0.25 Pa) which is too small for accurate measurements using the pressure transducers typically used in buildings.

Table 1.

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

Air velocities inside and upstream and downstream of intake louvers and corresponding velocity pressures.

Parameter	Louver 1	Louver 2	Louver 3
Free area of louver as a percentage of nominal louver area[2]	31%	31%	44%
Maximum recommended free area velocity in fpm (m/s)	1856 (9.43)	500 (2.54)	696 (3.54)
Corresponding velocity pressure in IWG (Pa)	0.21 (53)	0.015 (3.87)	0.030 (7.50)
Velocity upstream and downstream of louver with maximum velocity in free area of louver -- fpm (m/s)	575 (2.92)	155 (0.78)	306 (1.56)
Corresponding velocity pressure in IWG (Pa)	0.021 (5.13)	0.001 (0.37)	0.006 (1.45)
Minimum* free area velocity in louver in fpm (m/s)	371 (1.89)	100 (0.51)	139 (0.71)
Corresponding velocity pressure in IWG (Pa)	0.009 (2.13)	0.0006 (0.15)	0.001 (0.30)
Velocity upstream and downstream of louver with minimum velocity* in free area of louver -- fpm (m/s)	115 (0.58)	31 (0.16)	61 (0.31)
Corresponding velocity pressure in IWG (Pa)	0.0008 (0.21)	0.00006 (0.01)	0.0002 (0.06)

*Assumed equal to 20% of maximum velocity, i.e., assuming that the minimum percentage of outdoor air in the supply airstream is 20%.

There are five relatively obvious approaches to reduce errors in OA flow rate measurement that are caused by the low air velocities in OA intake systems.

1. In HVAC systems with economizer control systems, the air-handling unit (AHU) can have two sets of OA intake louvers and dampers installed in parallel. One louver for the minimum outdoor air supply may have a damper that remains open at all times. This louver should be sized to have the maximum recommended air velocity in the louver when the AHU is providing minimum outdoor air. An OAMT is used in this portion of the OA intake system. The second louver and corresponding damper is maintained closed when minimum OA is supplied by the AHU. This second damper opens as needed when the economizer controls call for more than the minimum amount of outdoor air. An OAMT may be used in this section of the OA intake system if it desired to measure total OA flow rates when they exceed the minimum. This approach is not new -- separate OA intake sections are already often used in large AHUs, but they do increase costs.

2. The designer of the HVAC system can select a louver with a high value of maximum recommended air velocity. For example, among the three louvers in Table 2, L1 would be the clear choice.

3. The OAMT can determine OA flow rates from measurements of air velocities at locations between the blades of louvers, which can exceed the velocities downstream of louvers by a factor of three.

4. A highly sensitive and accurate pressure transducer can be selected for use in conjunction with the OAMT. To maximize accuracy, the full-scale pressure range of the transducer should be no greater than necessary. Regular calibrations of the pressure transducer may be needed to assure accurate measurements of OA flow rates.

5. Electronic velocity sensors can be used in place of pressure-based velocity sensors because electronic sensors often remain accurate at lower air velocities[3].

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

[3] The long-term sensor stability of electronic or pressure-based velocity sensors when used in the unfiltered air in OA intakes was not investigated in our research.

Two or more of the approaches listed above can be employed simultaneously to reduce or eliminate errors associated with low velocities in OA intakes.

Uneven air velocities and eddies

The air velocity profile in a cross section of the duct between the OA intake louver and the OA damper can be spatially very non-uniform. In some cases, large eddies can develop between the louver and damper. The spatial variability in air speed and direction can make it difficult to accurately determine the OA flow rate using air speed sensors placed between the louver and damper. The eddies and non-uniform velocities also make it more difficult to measure the static pressure drop of air flowing through OA intake louvers.

Figure 3 provides some of the evidence of non-uniform air velocities. The dashed lines in this figure illustrate the airflow patterns observed downstream of L3 under some operating conditions. This illustration is based on our visual observation of the direction of flow of chemical smoke injected at various locations downstream of the louver. Observations of smoke transport provide only an indication of the airflow pattern, thus, the dashed lines in figure 3 represent our estimation of the airflow patterns consistent with the observed smoke transport. Due to the design of L3, the air exiting the louver has a strong upward trajectory. There appears to be a large eddy near the lower section of the duct and smaller eddies behind the edges of the louver, because airflow is blocked around the periphery of the louver. When the OA damper is substantially closed, the airflow near the damper has a downward velocity component – at least near the top of the damper. In general, there were more pronounced eddies when the OA damper was nearly closed; however, OA flow rate measurements are most critical when dampers are mostly closed and the minimum amount of outdoor air is being supplied to a building.

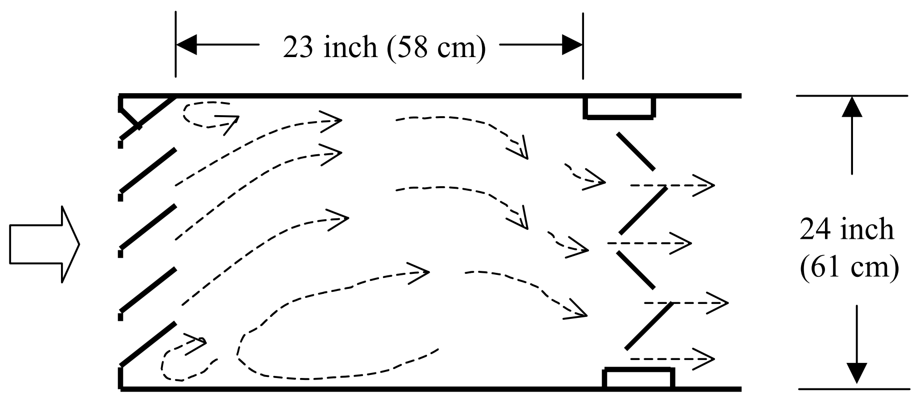

Figure 3. Illustration of the airflow pattern downstream of L2 based on a visual observation of the direction of flow of injected chemical smoke.

Tests with smoke suggest a similar but inverted airflow profile downstream of L2, from which air exits with a downward trajectory. The airflow direction downstream of L1, relative to that downstream of L2 and L3, was more consistently toward the OA damper, which coincides with expectations given the louver's geometry. However, there was still evidence of the development of eddies downstream of the edges of L1 which block the airflow.

Further evidence of highly non-uniform air velocities between louvers and OA dampers is provided in Table 2. This table portrays the results of measurements of air speeds downstream of L2 made with a hot wire anemometer. The hot wire anemometer only indicates air speed – not direction of flow. The table shows the measured air speeds, normalized by the average speed, in a vertical plane (normal to the intended direction of air flow) located 15.5 inches (39 cm) downstream of the downstream face of L2, with the fully open OA damper located 7.5 inch (19 cm) further downstream. The measurement plane downstream of the louver represents a plane where the air speed sensors of an OAMT might be placed. During the measurements, the OA flow rate was approximately 680 cfm (320 L/s). The air speeds in the measurement plane were highly non-uniform, with air speeds at individual measurement locations ranging from 36% to 416% of the average speed. The air speed is far from symmetrical about the vertical axis, with higher speeds near the bottom of the duct, which is consistent with expectations given the geometry of L2. Tests with smoke indicated that air was actually flowing backwards toward the louver near the top of the duct, presumably due to the presence of a large airflow eddy. Air speed sensors within an OAMT installed in this plane would not indicate that the flow was backwards at this location.

Table 2
Air speeds measured in a vertical plane located 15.5 inch (39 cm) downstream of L2, normalized by the average air speed.

Inch* (cm)	2 (5.1)	4 (10.2)	6 (15.2)	8 (20.3)	10 (25.4)	12 (30.5)	14 (35.6)	16 (40.6)	18 (45.7)	20[#] (50.8)	22[#] (55.9)
1 (2.5)	0.73	0.72	1.05	1.17	1.10	1.22	1.20	1.08	0.76	0.72	0.73
3 (7.6)	0.47	0.42	0.50	0.49	0.49	0.73	0.63	0.45	0.41	0.42	0.47
5 (12.7)	0.43	0.42	0.39	0.39	0.39	0.39	0.50	0.40	0.44	0.42	0.43
7 (17.8)	0.40	0.39	0.39	0.40	0.40	0.40	0.39	0.42	0.46	0.39	0.40
9 (22.9)	0.59	0.41	0.39	0.39	0.39	0.37	0.36	0.34	0.43	0.41	0.59
11(27.9)	0.69	0.42	0.42	0.42	0.41	0.37	0.36	0.38	0.38	0.42	0.69
13 (33.0)	0.76	0.48	0.39	0.37	0.37	0.36	0.36	0.37	0.36	0.48	0.76
15 (38.1)	1.13	0.38	0.35	0.37	0.36	0.38	0.38	0.39	0.40	0.38	1.13
17 (43.2)	1.12	0.62	0.64	0.46	0.45	0.46	0.43	0.36	0.48	0.62	1.12
19 (48.3)	1.44	0.87	1.38	0.99	0.68	0.67	0.81	0.65	0.42	0.87	1.44
21 (53.3)	2.54	2.83	2.86	2.83	2.29	2.27	2.17	1.78	2.14	2.83	2.54
23 (58.4)	4.16	3.88	3.88	4.01	3.98	3.87	3.78	3.93	3.09	3.88	4.16

*From top left corner of measurement plane viewed looking downstream.
[#]Air speeds in this column were not measures, they were assumed from symmetry.

Airspeeds were also measured inside of L1[4] at locations centered between the vertical louver blades and 0.25 inch (0.64 cm) upstream of the downstream edge of the louver blades. The resulting air speeds, normalized by the average air speed are shown in Table 3. The spatial variability in air speed at these locations centered between the blades of L1 is far less than the spatial variability in air speed measured 15.5 inches (39 cm) downstream of L2 as depicted in Table 2. The ratio of maximum to minimum air speeds measured between the louver blades of L1 is 1.4, while ratio of maximum to minimum air speeds measured down stream of L2 is 12.2. Thus, OA flow rates based on measurements of air speeds between louver blades might be more reliable than measurements of OA flow rates based on air speeds measured in a section of ductwork downstream of louvers. One of the commercially available measurement technologies (Fisk et al. 2004) uses a similar approach -- it has air speed sensor blades centered between selected blades of L1 and located at the downstream plane of the louver.

[4] Actually, we used a version of L1 with airflow monitoring blades located immediately downstream of two of the vertical airflow passages (See Fisk et al. 2004).

Table 3
Air speeds between the louver blades of L1, normalized by the average air speed.

inch (cm) from top of airflow passage	Passage Number[5] from Left Side				
	2	5	7	9	12
1 (2.5)	0.75	0.88	0.86	0.92	0.87
2 (5.1)	0.86	0.98	1.04	0.99	0.88
3 (7.7)	1.03	1.00	1.06	0.96	0.97
4 (10.2)	1.02	0.98	1.08	0.97	0.98
5 (12.8)	1.03	1.00	1.06	1.05	1.01
6 (15.3)	1.03	0.99	1.03	1.04	1.03
7 (17.9)	1.04	1.01	1.07	0.98	1.02
8 (20.4)	1.03	1.07	1.08	1.03	1.00
9 (23.0)	1.05	1.08	1.05	0.97	1.01
10 (25.5)	1.04	1.13	0.98	0.96	1.03
11 (28.1)	1.03	1.01	0.90	0.88	1.05
12 (30.6)	1.04	1.14	1.02	1.02	1.04
13 (33.2)	0.98	1.09	1.08	1.03	1.05
14 (35.7)	0.89	1.11	0.97	0.75	0.93

*While the nominal louver height was 24 inch (61 cm), metal plates obstructed the top 4 inch (10 cm) and bottom 5 in (13 cm) of the louver, resulting in 15 inch (38 cm) high air flow passages.

Based on these findings, we can suggest five general approaches for reducing the errors in measurements of OA flow rates that are caused by uneven air velocities and the development of eddies in the airflow between louvers OA dampers.

1. The OA intake louver can be one that directs air predominately toward the OA damper without out a strong velocity component toward any duct wall. Directing air toward the OA damper should inhibit the development of eddies and diminish the spatial variability in air velocity[6]. Thus, L1 would generally be preferable to L2 or L3.

2. An airflow straightening device can be installed downstream of the louver but upstream of the air speed sensors. For example, one of the OAMTs evaluated by Fisk et al (2004) uses an aluminum honeycomb airflow straightener upstream of the air speed sensors.

3. OAMTs can be integrated with specific packages of louvers and OA dampers with calibration curves provided that are specific to the package. In this case, the airflow profile does not need to be spatially uniform -- one only needs a consistent relationship between the OA flow rate and the output signal of the sensor system.

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[5] There are 14 air flow passages between the vertical blades of L1 and the air speed was measured at 14 heights between the 2nd, 5th, 7th, 9th, and 12th airflow passage from either side of the louver. Airflow passage numbers were designated 1 through 14 with passage 1 on the left when the louver is viewed from its downstream face
[6] Selecting such a louver may not eliminate the development of uneven airspeeds upstream of a partially closed OA damper.

4. The air speed sensors can be placed between louver blades where the air speed is less spatially variable compared to downstream of the of the louver (see Table 3 compared to Table 2). Again, a calibration curve specific to the package will be required.

5. Abrupt contractions and expansions in the cross section of the airflow path between the louver and OA damper can be reduced through selection of louvers and dampers that do not have large frames that obstruct airflow. Alternately, as shown in Figure 4, sheet metal inserts can smooth out the airflow path. We found that these inserts reduced or eliminated the eddies normally found downstream of the periphery of L1.

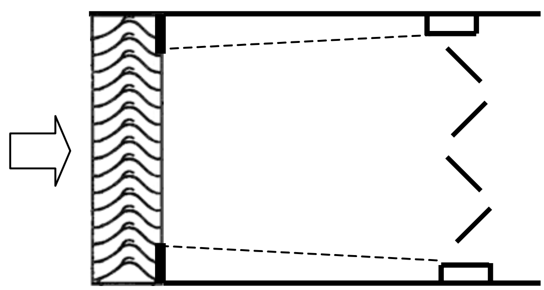

Figure 4. Illustration of an OA intake system using L1, viewed from the top. For illustrative purposes, we show plates blocking the sides of the louver, while the largest plates at the actual louver outlet are located at the top and bottom of the louver. The dashed lines represent sheet metal plates installed between the louver and the frame of the OA damper to reduce the development of eddies downstream of the periphery of the louver.

Airflow backwards through the OA damper

When the OA damper was fully or substantially open, OA sometimes flowed backward, i.e., toward the louver, through the lower section of the damper, even through airflow through the OA intake louver was entirely in the intended direction. This backwards flow was detected by injecting chemical smoke just "downstream" of the damper and observing smoke transport through the damper. The tendency to have this backward flow through the OA damper was much more pronounced when there was a large ratio of recirculation flow to outdoor air flow. Figure 5 illustrates this backward flow through the lower sections of an OA damper with a horizontal dashed arrow. We suspect that one cause of backward flow may be the redirection of the jet of the recirculation airstream when this jet reaches the bottom of the duct. However, in some cases we detected a small amount of backwards flow through the OA damper even when there was no recirculation airflow in the test system; thus, turbulent eddies that cause pressure differences may also sometimes be a cause of this backward airflow.

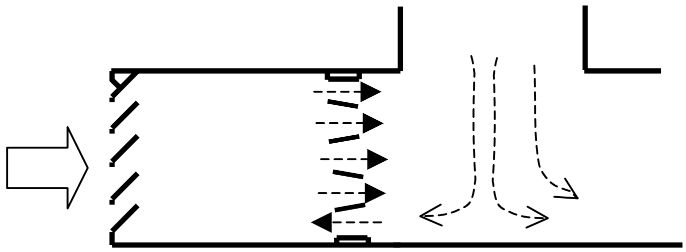

Figure 5. Illustration of OA intake section with the horizontal dashed lines representing the airflow direction through the OA damper that is reversed at the bottom of the damper. The curved dashed lines illustrate a recirculation airflow pattern hypothesized to contribute to backward flow through OA dampers.

When there is considerable backwards airflow through the OA damper, the velocity profiles that occur at OAMTs located upstream of this damper may be distorted, reducing the accuracy of the OA flow rate measurement. In tests of OAMTs (Fisk et al. 2004), we found that maintaining a pressure drop across the OA damper greater than approximately 0.04 IWG (10 Pa) eliminated reversed airflow through OA dampers and improved the accuracy of OAMTs under some operating conditions[7]. Figure 6 shows an example of the benefits of maintaining such a pressure drop. The error in measurement of OA flow rate with measurement technology number 4 and L1 (see Fisk et al., 2004) is plotted versus the pressure drop across the OA damper. This measurement technology has a honeycomb airflow straightener located downstream of the OA louver and air speed sensor blades located downstream of the flow straightener but upstream of the OA damper. In the figure, when the pressure drop across the OA damper is greater than approximately 0.05 IWG (12 Pa), measurement errors tend to be small.

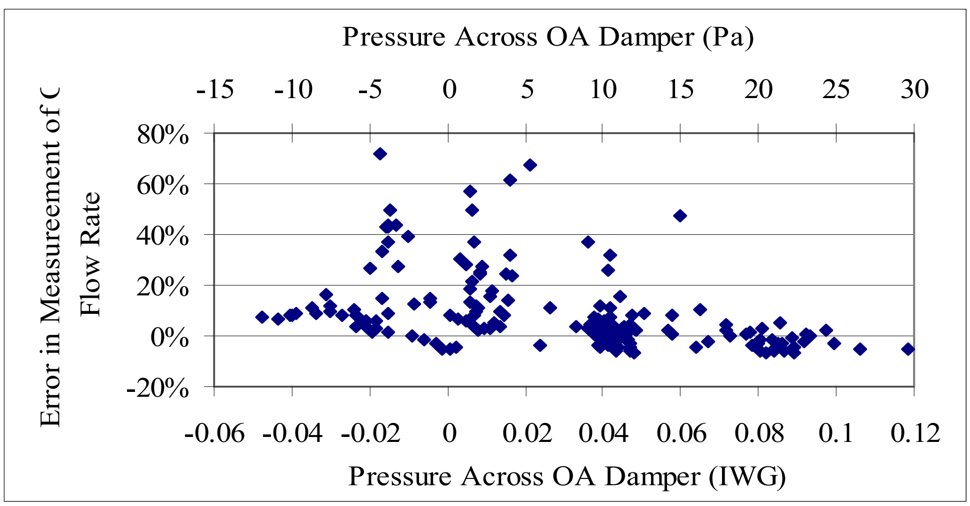

Figure 6. Example of error in measurement of OA flow rates through an HVAC system intake plotted versus the pressure drop across the OA damper.

[7] In practice, the pressure drop measured across OA dampers will vary with the type and locations of pressure probes, presumably because there is a large amount of turbulence upstream and downstream of the damper. Maintaining a pressure drop greater than zero across all portions of the damper may be sufficient to prevent reverse airflow; however, in practice one will normally use only single upstream and downstream pressure taps, thus a "measured" pressure drop significantly greater than zero, e.g., 10 Pa, is needed to assure no reverse direction flow.

CONCLUSIONS

This research identified the following causes of errors in measuring the flow rates of outdoor air through outdoor air intakes of HVAC systems:

- Low air speeds near the detection limit of sensors;
- High spatial variability in air speed and direction and the presence of large eddies downstream of outdoor air intake louvers;
- Backwards airflow through a portion of the outdoor air damper.

Suggested general approaches for reducing the errors in measuring flow rates of outdoor air include the following:

- Design and control of the outdoor air intake system to avoid small, hard-to-measure, air speeds;
- Use of highly sensitive pressure and velocity sensors;
- Measuring air speeds between blades of louvers, rather than downstream of louvers;
- Smoothing out the airflow between the outdoor air louver and damper through proper louver selection and insertion of components to straighten air flow;
- Maintaining a pressure drop across the outdoor air damper that exceeds approximately 0.04 IWG (10 Pa).

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