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# VAV Systems And Outdoor Air

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HVAC system outdoor airflow rates are usually measured and set at the air-handling unit. The effectiveness of an HVAC system at delivering the outdoor air to the occupied spaces of a building is varied and often disputed. To investigate the delivery of outdoor air to the occupied spaces of a variable-air-volume system, ASHRAE Technical Committee 9.1, *Large Building Air Conditioning Systems*, funded Project 687-TRP, *Minimum Ventilation Airflow Rates with VAV Systems*. This article presents some of the information collected during that project.

## Background

For office spaces, ANSI/ASHRAE Standard 62-1989, *Ventilation for Acceptable Indoor Air Quality*, generally prescribes 20 cfm (9.4 L/s) of outdoor air per person to meet ventilation requirements. This requirement is for the 20 cfm (9.4 L/s) to be delivered to the occupied zone, not just brought in at the air-handling unit.

For example, assume that there is a multizone system that serves an area occupied by 40 people. If the system was treated as one big zone with a perfect mixing of room air and supply air, it would require 800 cfm (376 L/s) of outdoor air to be brought in at the air-handling unit for ventilation requirements. If the system had a total supply airflow rate of 8,000 cfm (3773 L/s), the percentage of outdoor air in the supply air to each room would be 10%. Since it is a multizone system, the zone airflow rates would not all be the same. Therefore, the system cannot be treated like a single zone for ventilation purposes.



For example, if one of the zones in the system had a supply airflow rate of 300 cfm (141 L/s), the amount of outdoor air delivered to the zone would be 30 cfm (14 L/s). If the zone was occupied by two people, the ventilation requirements would be 40 cfm (18.8 L/s) of outdoor air, and thus the zone would be underventilated. At least, the zone appears to be underventilated according to these calculations.

Next, consider a VAV system that has a minimum supply airflow rate of 8,000 cfm (3773 L/s), a maximum supply airflow rate of 12,000 cfm (5660 L/s), and the area that it is ventilating has an occupancy of 40 people. Taking a simplified approach where the system is treated as a large single zone, at 20 cfm (9.4 L/s) per person, the system minimum outdoor air requirement would be 800 cfm (377 L/s). If the minimum outdoor air setting is made when the total system supply airflow rate is at the minimum of 8,000 cfm (3773 L/s), then there would be 10% outdoor air in the supply air.

The VAV system has several VAV boxes and the box with the lowest minimum supply airflow rate is 200 cfm (94.3 L/s). The space supplied by the zone is occupied by one person, which means that 20 cfm (9.4 L/s) of outdoor air is required for the space, and the air supplied to the room will require 10% outdoor air. The system appears to be set up so that it is supplying sufficient outdoor air.

If the system supply air increases to 10,000 cfm (4717 L/s), and the system outdoor air is maintained at 800 cfm (377 L/s), the percentage of outdoor air in the supply air for each room would only be 8%. If some VAV boxes were at some stage of fully open, but the previously mentioned box was still operating at a minimum airflow of 200 cfm (94.3 L/s), the outdoor air delivered to the zone would be only 16 cfm (7.5 L/s), and the zone would be underventilated. It would appear that the system minimum outdoor air would need to be set at 1,000 cfm (471.7 L/s), or 10% outdoor air, when the system supply air is at 10,000 cfm (4717 L/s), so that the critical zone would be assured of receiving proper ventilation.

When the system decreases back down to minimum supply airflow of 8,000 cfm (3773 L/s) with the minimum outdoor air

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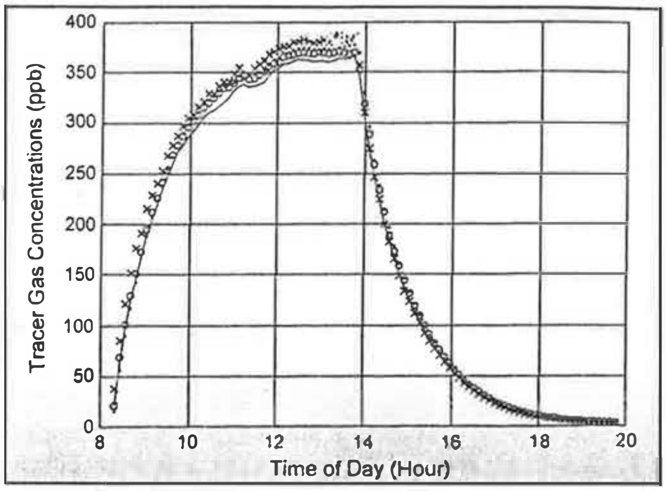


*Figure 1: Typical results of tracer gas tests for age of air.*

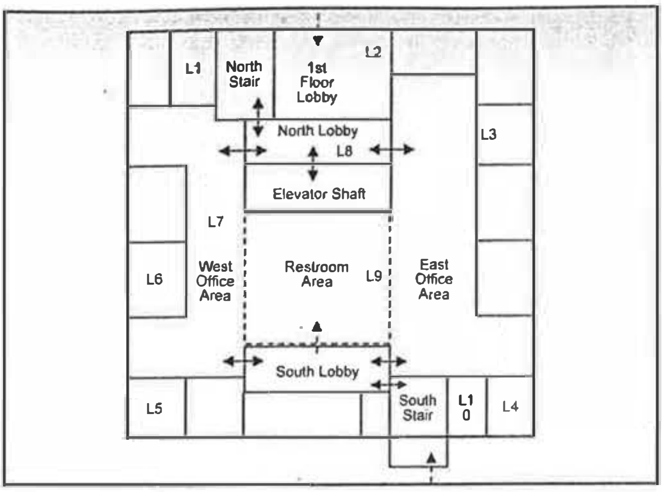


*Figure 2: Typical floor layout.*

set at 1,000 cfm (471.7 L/s), the percentage of outdoor air would be 12.5%. The previously mentioned room with a VAV box operating at a minimum airflow of 200 cfm (94.3 L/s) would have 25 cfm (11.8 L/s) of outdoor air, and would be over-ventilated. There are many other scenarios like this that would change the total outdoor air requirements of the system because of the needs of one particular zone, and they usually increase the energy usage.

In summary, outdoor air quantities are usually measured and set at the air-handling unit, and the previous examples show that what appears to be the correct setting at the air-handling unit does not necessarily mean that the required amount of outdoor air is delivered to a particular space.

## Measuring Ventilation Rates at the Occupied Zones

Because of the questions concerning the actual ventilation rates of HVAC systems, numerous techniques, both experimental and theoretical, have been proposed and tested to measure and predict the delivery of outdoor air to the occupied spaces.

This article presents the results of the "air change effectiveness" studies done during this project, and to discuss the implications of the results to the design and operation of VAV systems. The theory and details of the test methods have been discussed in numerous articles, reports, guidelines and standards and only a basic, simplified summary of the test method used in this project is presented here. Additional information can be found in ASHRAE Standard 129P, *Standard Method of Measuring Air Change Effectiveness,* the *ASHRAE Handbook—Fundamentals,* and the bibliography at the end of this article.

In this project, the experimental method used to measure delivery of outdoor air to the occupied space was based on the Age of Air theory. The age of air (AA) is the period of time that has elapsed since a particle of outside air has entered a space. The older the AA, the longer the air has been in the space. Direct AA measurements require the injection of a tracer gas into the outside air duct of the HVAC system which is ventilating the space. The concentration of the tracer gas is then monitored and the values are used to determine the AA. A lower AA value means that the air is "fresher." The outdoor air delivered to the room can be determined from the AA for the room, which is explained later.

Several injection methods are commonly used, but only the step-up and decay methods were used for this project. *Figure 1* shows a graph of the tracer gas concentration typically seen in an AA test. For step-up, the initial tracer gas concentration is zero, then tracer gas is injected into the air-handling unit and the process follows a curve approaching a steady state concentration that depends upon the ventilation characteristics of the system and space. For decay, the tracer gas injection is halted, the initial concentration is the value at steady state, and the process follows a curve approaching zero.

The AA for the step-up process is calculated from the expression:

$$AA = (t_{end} - t_{ini})\,[1 - (C_{avg}/C_{end})] \quad (1)$$

where

$(t_{end} - t_{ini})$ = the time, in hours, elapsed from when the tracer gas injections began and when the last sample was taken.

$C_{avg}$ = the time averaged concentration of tracer gas measured in the test zone from when the tracer gas injections began to when the last sample was taken.

$C_{end}$ = the tracer gas concentration when the last sample was taken at time equals $t_{end}$.

The AA for the decay process is calculated from the expression:

$$AA = (t_{stop} - t_{start})\,(C_{avg}/C_{start}) \quad (2)$$

where

$(t_{stop} - t_{start})$ = the time, in hours, elapsed from when the tracer gas injections stopped and when the last sample was taken.

$C_{avg}$ = the time averaged concentration of tracer gas measured in the test zone from when the tracer gas injections stopped to when the last sample was taken.

$C_{start}$ = the tracer gas concentration when the first sample was taken at time equals $t_{start}$.

## Building and System Description

The building studied during the project was a six-story office building that had a brick exterior and small operable windows. A basement contained a mechanical room with an HVAC system for the bottom three floors. The sixth floor was about half the size of the typical floor and housed a mechanical room

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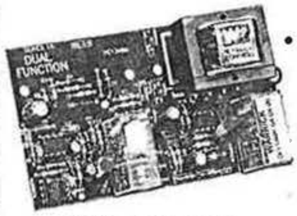

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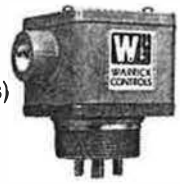

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AJ

| Test | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| Supply Air (cfm) | 7,350 | 7,450 | 8,500 | 8,650 | 8,800 | 9,150 | 11,800 | 12,000 | 12,000 | 13,000 |
| Outside Air (cfm) | 1,800 | 1,900 | 1,975 | 1,150 | 1,975 | 1,300 | 2,000 | 2,000 | 2,100 | 2,100 |
| Location 1 (Hrs) | 1.11 | 1.09 | 1.02 | 0.98 | 0.95 | 0.88 | 0.84 | 0.75 | 0.74 | 0.71 |
| Location 2 (Hrs) | 1.15 | 1.02 | 0.97 | 1.05 | 0.97 | 0.85 | 0.82 | 0.77 | 0.74 | 0.75 |
| Location 3 (Hrs) | 1.12 | 1.04 | 1.04 | 1.00 | 0.92 | 0.87 | 0.82 | 0.76 | 0.75 | 0.74 |
| Location 4 (Hrs) | 1.12 | 1.12 | 1.07 | 0.97 | 0.96 | 0.90 | 0.81 | 0.75 | 0.73 | 0.71 |
| Location 5 (Hrs) | 1.11 | 1.07 | 1.02 | 0.97 | 0.94 | 0.91 | 0.82 | 0.77 | 0.76 | 0.72 |
| Location 6 (Hrs) | 1.12 | 1.06 | 1.05 | 0.92 | 0.91 | 0.88 | 0.83 | 0.76 | 0.76 | 0.74 |
| Location 7 (Hrs) | 1.10 | 1.05 | 1.02 | 0.98 | 0.93 | 0.90 | 0.81 | 0.77 | 0.75 | 0.74 |
| Location 9 (Hrs) | 1.11 | 1.08 | 1.10 | 0.94 | 0.93 | 0.89 | 0.80 | 0.72 | 0.74 | 0.72 |
| Location 10 (Hrs) | 1.14 | 1.11 | 1.05 | 0.99 | 0.95 | 0.88 | 0.82 | 0.74 | 0.75 | 0.74 |
| Average Age of Air (Hrs) | 1.12 | 1.07 | 1.04 | 0.98 | 0.94 | 0.88 | 0.82 | 0.75 | 0.75 | 0.73 |
| Standard Deviation Age Air (Hrs) | 0.01 | 0.03 | 0.04 | 0.04 | 0.02 | 0.02 | 0.01 | 0.02 | 0.01 | 0.01 |
| Elevator Location 8 (Hrs) | 1.15 | 1.76 | 1.15 | 0.85 | 1.01 | 1.18 | 0.83 | 0.73 | 0.72 | 0.68 |

***Table 1: Age of air test results for office locations on fourth floor.***

and break room. The lower three floors were supplied by a VAV system with an unducted return. The upper three floors were supplied by a VAV system with ducted returns and was the subject of the ventilation studies.

*Figure 2* shows the typical floor plan in the building. Floors 1 to 5 were each about 5,200 ft$^2$ (483 m$^2$) and consisted of enclosed offices around the perimeter, and open interior office spaces. A pair of elevators and the north stairwell ran from the basement to the sixth floor, and a south stairwell ran from the first floor to the sixth floor. Restrooms were located in the area just south of the elevators on the first, third and fifth floors.

The HVAC system that supplied the fourth, fifth, and sixth floors was a VAV system that could provide up to 13,000 cfm (6137 L/s) of air. The supply fan speed was regulated by maintaining the supply duct static pressure at setpoint. The supply fan control signal was also sent to the return fan to regulate the return airflow. Inlet guide vanes were used on both fans for airflow regulation. Pneumatic controls were used throughout the system including the pressure independent VAV boxes. The 26 VAV boxes ranged in airflow from a minimum of 100 cfm (47.2 L/s) to a maximum of 1,600 cfm (755 L/s).

## Age of Air Test Results

For this project, sampling was performed through the use of a gas chromatograph with an electron capture detector. Sampling tubes were run to 10 locations on the fourth floor. They are shown in *Figure 2* by the designations L1, L2, etc. The continuously purged sampling tubes were connected to a sequential-valve arrangement which would allow the gas chromatograph to periodically analyze the tracer gas concentration in each space.

The outdoor airflow rate into the air-handling unit was monitored using a thermistor-type airflow array, and the outdoor air, return air and relief air dampers were controlled such that the outdoor airflow rate was maintained at a fixed amount.

*Table 1* presents the results of the AA studies conducted during the project. Several airflow conditions, from minimum to maximum total system airflow, were studied to investigate the effects on the AA.

By looking down a column for a particular test, for Locations 1 to 7, 9 and 10, the data shows that the AA for all of the zones varied very little from zone to zone. This would indicate that the air was well mixed throughout the floor even though some zones had a lower zone-supply airflow than others. This implies that the outdoor air was being distributed throughout the floor in a uniform manner and that no spaces were receiving significantly less outdoor air than other spaces, regardless of whether the VAV box supplying the area was at low or high airflow. Location 8 was in the elevator lobby area and experienced larger variations due to the operation of the elevators.

## Effect of Common Return Air

This even distribution of outdoor air on the floor can be explained by the effect that the common return air ducting has on mixing of building air. The effect of the common return ducting can be illustrated in terms of age of air as follows for a simplified two-room system.

Rooms A and B are of identical volume and each is ventilated by a dedicated HVAC system. It is assumed that good mixing of the air occurs in each room, and no air enters or leaves the room from other areas. From each room, 80% of the room return air is recirculated, and 20% of the room air is exhausted. The system supply airflow contains 80% recirculated air and 20% outdoor air.

At this point, a measure of ventilation performance is required. The *Handbook—Fundamentals* defines the space air exchange rate ($I_S$) for a zone or building served by an air-handling unit as the supply airflow rate ($Q_{SA}$) entering a building or

zone divided by the volume of the room ($V_R$):

$$I_S = Q_{SA}/V_R \qquad (3)$$

When the time unit is in hours, the air exchange rate is also called air changes per hour (ACH).

Returning to the example, the supply air to Room A is always twice that to Room B such that the space air exchange rate ($I_S$) is 5.0 ACH for Room A and is 2.5 ACH for Room B.

Another measure of ventilation is the nominal time constant ($T_N$) which is the duration that the air stays in a room. The $T_N$ equals the volume of the room divided by outdoor airflow rate ($Q_{OA}$):

$$T_N = V_R/Q_{OA} \qquad (4)$$

The mean age of air ($AA_E$) for air exiting a zone on a dedicated system is equal to $T_N$ for that zone. The outside airflow rate is the outside air fraction ($X_{OA}$) multiplied by the supply airflow:

$$Q_{OA} = X_{OA} \times Q_{SA} = 0.2Q_{SA} \qquad (5)$$

Substituting for $Q_{OA}$ from *Equation 4*, for Rooms A and B:

$$AA_E = T_N = V_R/0.2Q_{SA} \qquad (6)$$

Substituting for $V_R$ from *Equation 3* gives a calculated age of air exiting Room A ($I_S$ = 5.0 ACH) of:

$$AA_E = 0.2Q_{SA}/0.2Q_{SA} = 1 \text{ hour} \qquad (7)$$

$AA_E$ for Room B is 2 hours.

The supply air for Room A is 80% recirculated air at an age of air of 1 hour, plus 20% outside air at an age of air of 0 hours, giving a mean age of supply air ($AA_S$) of 0.8 hours. The $AA_S$ for Room B would be 1.6 hours.

When the two rooms are supplied by a common system, the common recirculated air would be 2/3 of Room A air at $AA_E$ = 1 hour, and 1/3 Room B air at $AA_E$ = 2 hours. The age of air for the common return/recirculated air would be $AA_E$ = 1.33 hours. The age of air for the common supply would now be $AA_S = (0.8 \times 1.33 \text{ hr}) + (0.2 \times 0 \text{ hr}) = 1.06$ hours.

The *Handbook—Fundamentals* defines the mean age of air ($AA_M$) of a space equals the space time constant ($T_S$) which is the inverse of the space air exchange rate:

$$AA_M = T_S = V_R/Q_{SA} = 1/I_S \qquad (8)$$

Using the value of $I_S$ given earlier, $AA_M$ is 0.2 hours for Room A and is 0.4 hours for Room B.

The mean age of air at the return of Room A, for the common supply and return system (since good mixing of the air is assumed in the room) would be a combination of the age of air for the supply air and the room air:

$$AA_E = AA_S + AA_M = 1.26 \text{ hours} \qquad (9)$$

The mean age of air at the return of Room B would be 1.46 hours.

The effect of the common return ducting has increased the age of air exiting Room A from 1 to 1.26 hours, and dehad an effect on the AA values. *Figure 3* is a plot of the standard deviations of the mean AA for the nine office area locations on the fourth floor, versus the total supply airflow rate.

The graph shows a tendency of the standard deviation of the AA to decrease as the supply airflow rate increased. The values varied from 0.01 to 0.08 when the supply airflow was below 9,000 cfm (4245 L/s), and only varied from 0.01 to 0.04 when the supply airflow was above 11,000 cfm (5189 L/s). This appears to confirm the generally accepted theory from laboratory results and field experiences that the air in a room mixes better as the supply airflow rate to the room increases.

If a ventilation effectiveness value of less than one was used for calculating the outside air requirements, the data suggests that the outside air requirements for a room could be reduced as the supply airflow to the room increases, since the mixing of outdoor air with room air would be increased.

For instance, assume the ventilation effectiveness used to calculate the outdoor air requirements for the critical room was 0.8 when the supply airflow rate to the room was 100 cfm (47.2 L/s), and the ventilation effectiveness was 1.0 when the supply airflow rate to the room was 400 cfm (188.7 L/s). With one person in the room, the outdoor airflow rate requirement at the low supply airflow rate would be 20 cfm (9.4 L/s) divided by 0.8, or 25 cfm (11.8 L/s). But, at the higher supply airflow rate, the outdoor airflow rate would only be 20 cfm (9.4 L/s) since the ventilation effectiveness is 1.0. Furthermore, the supply air to the room would require 25% outdoor air at the low airflow condition, but only about 5% at the higher rate.

Next, assume that the multiple room theory of mixing reduced the outdoor air volume requirements for the total system to 20% at minimum total supply airflow, and 4% at maximum total supply airflow. If the whole VAV system had a minimum total supply airflow rate of 6,000 cfm (2830 L/s), the minimum outdoor airflow rate requirement would be 1,200 cfm (566 L/s). At the maximum system supply airflow rate of 12,000 cfm (5660 L/s), the outdoor air required would only be 480 cfm (226 L/s).

Many VAV systems use a fixed minimum outdoor air damper position to bring in a constant percentage of outdoor air over the full range of supply airflows. (Actually, the percentage of outdoor air may vary over the range of supply airflows depending on the interaction of supply and return fans, damper characteristics, and other system and control factors.) For a system that has been set up with 20% outdoor air, at a supply airflow of 6,000 cfm (2830 L/s), the outdoor airflow would be 1,200 cfm (566 cfm). At a supply airflow of 9,000 cfm (4245 L/s), the outdoor airflow would be 1,800 cfm (849 L/s). At a supply airflow of 12,000 cfm (5660 L/s), the outdoor airflow would be 2,400 cfm (1132 L/s).

As mentioned earlier, an hour by hour analysis of airflow conditions should be conducted to determine what the minimum outdoor airflow should be for the actual occupancy requirements, and under what conditions it occurs so that the dampers can be properly set. It is possible that the system might still require 20% outdoor air when the system supply airflow is at 9,000 cfm (4245 L/s). Optimal system performance would probably best be accomplished by continuous measurement of system and zone airflows and control of the actual outdoor airflow rate based upon the actual requirements.

creased that of Room B from 2 to 1.46 hours. The common return ducting mixes the two airstreams, reducing the difference in the mean AA between the two rooms. The same analysis could be extrapolated to a system with many rooms.

If the VAV system were set up with the minimum outdoor airflow rate set according to the needs of the room that has the highest percentage of outdoor air requirement, more outdoor air than required would be brought into the air-handling unit than was needed to meet the ventilation needs of all the zones.

The *Handbook—Fundamentals* recommends using the multiple space calculation process from Standard 62-1989 for calculating the system minimum outdoor air requirements for simple VAV systems. The designer must use an hour-by-hour building energy analysis computer program to calculate the hourly cooling and heating loads for each space, and then the airflow requirements. Then *Equation 10* can be applied in each hour, and the minimum outdoor airflow rate requirement for each hour can be found.

$$Y = X/[1 + X - Z] \qquad (10)$$

where

$Y$ = corrected total outdoor airflow rate divided by total supply airflow rate of system.

$X$ = sum of outdoor airflow rate required for each zone divided by total supply airflow rate of system.

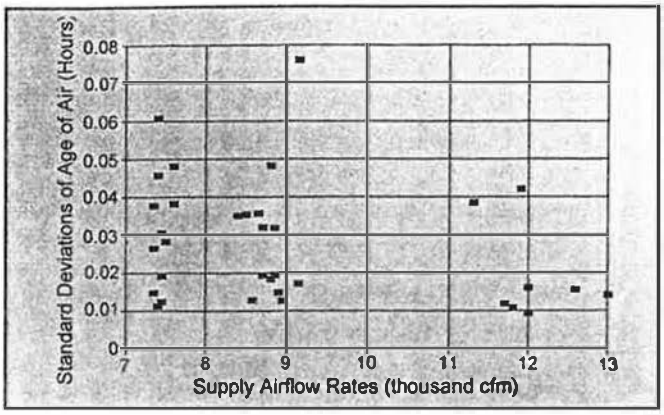


***Figure 3: Supply airflow rate effects on age of air.***

$Z$ = outdoor airflow rate of critical zone divided by supply airflow rate for the critical zone.

VAV systems with fan-powered boxes and other more complex VAV systems would require a more complex analysis as explained in the *Handbook—Fundamentals*.

## Supply Air Effects on Age of Air

The first part of this article discussed how the common return air ducting affected the AA on the fourth floor. The data that were collected showed that the total supply airflow rate

All of these minimum outdoor airflow rate requirements are dependent upon providing enough outdoor air to make up for exhausted air and to provide building pressurization, if it is desired. But, it is probably true that many VAV systems could reduce the amount of outdoor air brought in when the system is above 75% of the maximum because of increased ventilation effectiveness. The higher system supply airflow rates generally will occur when the outside air is the hottest and most humid. By cutting back on the outdoor air intake at the higher supply airflow rates, energy consumption can be reduced.

## Conclusion

The test results showed that a common return for a VAV system has a significant influence upon distributing outdoor air throughout the zones serviced by the air-handling unit. The common return mixes the air from separate zones and causes the AA in all of the zones to be similar, regardless of the zone-supply airflow rate. Following Standard 62-1989 guidance on calculating ventilation for multiple spaces can reduce the outdoor air requirements for many systems.

The test results also showed that increasing the supply airflow to a zone can improve the ventilation effectiveness of a zone such that the outdoor air requirements could be reduced for some zones. Innovative control strategies could be incorporated in some situations to reduce the outdoor air brought into the air-handling unit as the supply airflow rate increases.

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