Experimental Validation of the Multiple-Zone System Ventilation Efficiency Equation of ANSI/ASHRAE Standard 62.1 (1276-RP)

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ABSTRACT
This article describes an experiment that was carried out on an existing building to test the validity of the system ventilation efficiency equation for multiple-zone recirculating systems of ANSI/ASHRAE Standard 62.1. The system ventilation efficiency equation (SVEE) can be applied to buildings that use a recirculating air distribution system. It accounts for the fact that the return air carries some “unused” outdoor air, so that the amount of new outdoor air introduced at the air handler can be reduced. The SVEE is based on a mass balance but infiltration and interzonal mixing are not included in the formulation. Since infiltration is unpredictable it can’t be relied upon to ventilate a space, so the validation focuses on interzonal mixing. The experiment uses tracer gas techniques to study the air distribution in an existing office building, with four zones being treated as nominal critical zones. The tests are conducted with constant flow rates under a range of conditions. The SVEE is found to be a very good predictor of ventilation distribution in the building.

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INTRODUCTION

*ANSI/ASHRAE Standard 62.1 – 2010 Ventilation for Acceptable Indoor Air Quality* specifies minimum ventilation rates and other measures to provide indoor air quality that will be acceptable to occupants of buildings, and to minimize the potential for adverse health effects (ASHRAE 2010a). Standard 62 was first published in 1973 and has undergone many revisions (Persily 2002), including substantial changes to the amount of ventilation air that must be provided to occupied areas, and to the procedure for calculating these amounts.

One of these revisions was the introduction of the system ventilation efficiency equation for multiple-zone recirculating systems (SVEE), shown in Equation 1, below. The SVEE can be applied to buildings that use a recirculating system – one which takes return air from the occupied zones, mixes it with outdoor air, and redistributes it to multiple occupied zones. Each zone has a required flow rate of outdoor air, normally based on the zone’s usage, occupancy and area. The zone that requires the greatest fraction of outdoor air in its primary air supply is defined as the *critical zone*. The SVEE accounts for the fact that all non-critical zones receive more outdoor air than required, and some of this “unused” outdoor air is recirculated (Ke and Mumma 1996, Yuill et al. 2008). Therefore, the quantity of outdoor air introduced into the air handler can be reduced while still sufficiently ventilating the critical zone. In most climates such a reduction in outdoor air intake can save a substantial amount of energy and reduce peak demand, thereby reducing required system capacity, and hence first cost (Eto and Meyer 1988, Warden 1995).

\[ E_v = 1 + X_s - Z_d \]  

(1)
where:

\( E_v \) is the system ventilation efficiency when analyzed with respect to the critical zone

\( X_s \) is the uncorrected outdoor air intake fraction at the air handler, which is equal to the average fraction of outdoor air needed in the primary air for all zones in the system

\( Z_d \) is the outdoor air fraction required in the air discharged into the critical zone under the condition being analyzed (typically the ventilation design condition)

The SVEE is based on a mass balance. The theory behind the equation needs no validation. However, in a practical application there are several factors that are not included in the derivation of the SVEE that could nevertheless affect the quantity of ventilation air delivered to an occupant of a building. These factors include a) imperfect mixing within a zone; b) uncontrolled flows such as infiltration and exfiltration; and c) mixing between zones.

The first of these three factors is accounted for by considering zone air distribution effectiveness. Sections 6.2.2.2 and 6.2.2.3 of the standard address this issue by presenting a means of adjusting the value of \( Z_d \) (ASHRAE 2010a).

The second factor, b) uncontrolled flows, can’t cause the SVEE to be invalid. Exfiltration from a zone does not ventilate that zone because it does not dilute the concentration of pollutants. Although infiltration to a zone introduces outdoor air to the zone, the definition of ventilation air from the standard is: “that portion of supply air that is outdoor air plus any recirculated air that has been treated for the purpose of maintaining acceptable indoor air quality” (ASHRAE 2010a). Therefore, even though it may dilute contaminants, infiltration is not considered to ventilate a
zone because it is not part of the supply air. This makes sense for two reasons. First, infiltration does not produce a reliable and steady flow of outdoor air, because it is a function of wind, stack effect, envelope tightness, and zone pressurization caused by the operation of building heating, ventilation and air conditioning equipment (ASHRAE 2009); these factors are normally outside the control of the designer or operator of an HVAC system. Second, infiltration can cause damage to structure and envelope systems through moisture transport (Gudmundsson 2003) and can cause local thermal comfort and air quality problems (Yuill et al. 2003), so buildings are normally pressurized in an effort to prevent infiltration (ASHRAE 2009).

The only remaining factor that could affect the validity of the SVEE is interzonal mixing.

**MOTIVATION**

The validity of the SVEE has been called into question (Taylor et al. 2003). It has also been criticized as being too difficult and laborious to use when designing buildings, often by those who question its validity (Persily 2002). It is commonly ignored or misapplied (Persily et al. 2007), resulting in an existing building stock with a wide range of ventilation rates (Persily and Gorfain 2008). If the equation were ignored, this would increase the outdoor air required in multiple zone systems because the required outdoor air fraction at the air handler would equal the fraction required in the critical zone, with no credit given for the recirculation of unused outdoor air. Consequently the energy consumption of these systems would increase but the effort of designing HVAC systems would decrease. Or, if the equation were not valid because interzonal mixing was found to be sufficient to ventilate the whole building equally, the outdoor air required at the air handler could be reduced to the average outdoor air fraction required in the zones, saving energy and design effort. Some critics cited previous research as an indicator that
interzonal mixing does produce a well-mixed building, such as the statement in Chamberlin et al. (1999): “air was well mixed throughout the floor even though some zones had a lower zone-supply airflow than others.”

Determining the validity of the SVEE and studying interzonal mixing are important and directly related goals. The experiment reported here was designed to determine the validity of the SVEE in an existing building, and to provide insight into interzonal mixing.

**METHODOLOGY**

The experimental validation was carried out in a building that was selected to address the needs of this study: representative of common types of buildings currently being built, sufficiently large for statistical validity, having a controls and automation system that can be manipulated to meet the experimental requirements, an envelope that is sufficiently tight that infiltration can be eliminated during testing, and an air distribution system that is designed to meet diverse flow requirements in the zones of the building.

To quantify the interzonal mixing that takes place, tracer gas was released into the central air-handling unit and measurements of tracer gas concentration were made at several locations, following established tracer gas testing methods (Fisk and Faulkner 1992, Lagus and Persily 1985, Christianson et al. 1995, Fisk et al. 1988).

**Test site description:**

The test building had the following characteristics germane to the study:
• 130,000 ft² (12,077 m²), five-story office building in Omaha, Nebraska, built in 1997
• Two single-duct variable-air-volume (VAV) air handling units (AHU), each with a design capacity 65,000 CFM [30,677 L/s] (Figure 1)
• 134 pressure-independent air terminal units; 87 are parallel fan-powered induction units with reheat, 47 with no fan and no reheat
• A common ceiling space is used as a return air plenum on each floor
• Average maximum flow rate divided by the area served is 1.4 CFM/ft² [7.1 L/s/m²], although the overall system is sized for 1.0 CFM/ft² [5.1 L/s/m²] due to load diversity
• Some exterior zones have partitions from floor to structure (with transfer boots to carry return air across partitions) while others have partitions to ceiling height only

During the tests the air handlers were configured to run in typical recirculation mode, with the economizer dampers closed but the minimum outdoor air dampers open. The fan and damper

Figure 1: AHU Schematic Diagram
controls were overridden to pressurize the building to 0.1 i.w.c. [25 Pa] to reduce infiltration. The air terminal units were controlled to conduct three tests of conditions that were of interest with respect to interzonal mixing in typically operating buildings. These tests are

- Test 1: zones at minimum primary flow with fan-powered air terminal unit fans on
- Test 2: zones at minimum primary flow with fan-powered box fans off
- Test 3: zones at 70% of design primary flow and fans off (due to design for load diversity, the AHUs are not capable of supplying 100% of design flow in all zones simultaneously).

With the building controlled to these conditions a tracer gas, sulfur hexafluoride (SF$_6$), was released at a constant mass flow rate into the AHU. This tracer is intended to track outdoor air. It was outside the scope of this project to study the mixing of outdoor air with return air. Therefore it was assumed that perfect mixing occurred. To simulate this condition a tracer gas diffusion system was built across the Return Air (recirculation) dampers and the Minimum Outdoor Air dampers (Figure ), rather than simply injecting it into the outdoor air intake (Fisk et al. 1988).

The tracer gas was distributed throughout the building with the supply air, then returned to the air handler where some was discharged from the building with the relief air (or equivalently, exfiltrated through the envelope of the building), and some recirculated into the supply air and mixed with newly-injected tracer gas. Therefore, the concentration of tracer gas at any location
is expected to increase asymptotically toward the ratio of tracer injection rate to outdoor air flow rate.

To quantify the effects of interzonal mixing four test zones were selected: two conference rooms and two offices, each comprising a zone. These four zones were controlled to have very different discharge air flow rates than the remainder of the building. The doors to these rooms were kept closed during the testing. These rooms were not adjacent to one another; direct mixing couldn’t occur from one test zone to another. The fan-powered air terminal unit fans for these four zones were off during all tests (These fans promote interzonal mixing, most significantly to the critical zone. This effect is accounted for in ANSI/ASHRAE Standard 62.1 - 2010 and has previously been described [Warden 1995, Taylor 1996, Ke 1997] and measured [Yuill et al. 2008]).

The four zones’ discharge air flow rates ranged from very high (25 ACH or 3.7 CFM/ft² [17 L/s/m²]) to very low (0.8 ACH or 0.1 CFM/ft² [0.5 L/s/m²]). A description of the zones is shown in Table 1. The central idea to the test method is the following: If the building were well mixed, these zones’ tracer gas concentrations would all rise together; they would match the well-mixed return air (measured in the air handler’s relief air). This would indicate that the SVEE does not accurately describe the distribution of ventilation air in a real building, because it does not account for interzonal mixing.
A gas chromatograph with an electron capture detector and a data acquisition system was used to measure the tracer gas concentrations. The system has a nine-port sample valve system to draw samples sequentially over an 18-minute time period. The manufacturer’s stated accuracy for this device is ± 3%. Field tests showed repeatability of ± 1%. The tracer gas system meets the requirements of ANSI/ASHRAE Standard 129-1997.

Experimental research using tracer gas has shown that obtaining well-mixed samples is of critical importance, but can be difficult in field tests (Fisk and Faulkner 1992, Lagus and Persily 1985, Christianson et al. 1995). To address the requirement for good mixing, the four test zones were each mixed with several powerful mixing fans during testing. A confounding factor was discovered while confirming the zone air mixing: the ceiling-mounted supply and return system allowed short-circuiting of the air, even with the mixing fans running. To eliminate this effect polyethylene skirts were attached to each test zone’s diffusers, forcing the air to flow vertically down into the zone where it could be fully mixed before passing through the return grille. Measurements then confirmed that these zones were well-mixed.

Samples were taken from each zone, from the building’s return air (at the relief dampers), from outdoors (to indicate sensor drift, if present), from the supply air of each AHU, and from the

<table>
<thead>
<tr>
<th>Zone</th>
<th>Terminal Unit ID</th>
<th>Use</th>
<th>Area (sq ft) (m²)</th>
<th>Volume¹ (ft³) (m³)</th>
<th>Floor</th>
<th>Location</th>
<th>Return Path</th>
<th>Flow Rate (CFM)</th>
<th>Flow Rate (L/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>3-1-6</td>
<td>Office</td>
<td>198</td>
<td>1731</td>
<td>4ᵗʰ</td>
<td>SE corner</td>
<td>Open plenum</td>
<td>650</td>
<td>150</td>
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<td></td>
<td></td>
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<td>540</td>
<td>307</td>
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<td></td>
<td>255</td>
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</tr>
<tr>
<td>B</td>
<td>3-1-10</td>
<td>Office</td>
<td>194</td>
<td>1677</td>
<td>4ᵗʰ</td>
<td>NW corner</td>
<td>Open plenum</td>
<td>675</td>
<td>150</td>
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<td></td>
<td>290</td>
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<tr>
<td>C</td>
<td>4-1-10</td>
<td>Conf. Room</td>
<td>204</td>
<td>1835</td>
<td>5ᵗʰ</td>
<td>South wall</td>
<td>Transfer boot</td>
<td>700</td>
<td>150</td>
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<td></td>
<td></td>
<td></td>
<td>453</td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>4-1-12</td>
<td>Conf. Room</td>
<td>202</td>
<td>1819</td>
<td>5ᵗʰ</td>
<td>South wall</td>
<td>Transfer boot</td>
<td>700</td>
<td>150</td>
</tr>
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<td></td>
<td></td>
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<td></td>
<td>640</td>
<td>330</td>
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<td></td>
<td>302</td>
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</tbody>
</table>
discharge (supply) air to each test zone. The discharge air measurements would match the AHU supply measurements and would be redundant if the supply air was perfectly mixed. However, despite efforts to ensure well-mixed supply air, significant stratification took place. This is discussed later under “Uncertainty”. The gas analyzer was field-calibrated at the beginning of each test and checked for drift at the conclusion of each test, using a bottle of reference gas.

A number of other data were gathered during the experiment, to be used to investigate unexpected results or problems, and to further understand and quantify the air distribution and mixing in the building. These data include high-frequency pressure differential measurements between the test zones and adjacent zones, building pressure relative to outdoors, temperature and humidity of each air stream, and climatic conditions. These data indicate that no infiltration of outdoor air occurred in the test zones, negligible infiltration took place into the building, and that flow and pressures were relatively steady during the tests.

RESULTS

Measurement data for the concentrations in the zones and building average during Test 1 are plotted in Figure 2. This figure shows SF₆ concentration versus time for the duration of the test. The measurement data points are connected by lines to make the plot more easily read.
A visual inspection of Figure 2 (showing Test 1: non-test zones at minimum flow with fan-powered box fans on) shows that the concentration in zones C and D rises faster than the relief air (the relief air, a dashed grey line, is a proxy for building average concentration). This is not surprising, since these two zones have a higher air change rate than the building average. Similarly, in zones A and B the concentrations rise more slowly than the relief air. The air change rate in these zones is lower than the building average. This figure shows that the building is *not* well mixed. However, it does not tell us quantitatively how well the SVEE prediction matches the measured data.
To address this question we have created simulations of the SVEE predictions. These simulations use measured flow rate, room volume, and concentration data to predict what the time-dependent concentration in the zones should be if there is no interzonal mixing (the SVEE assumption). We then compare the simulations with zone concentration measurements to assess the SVEE’s accuracy.

**SIMULATION**

The simulation for each zone is generated by solving equation 2 for each time step, \( i \). Equation 2 is derived by applying a tracer gas mass balance in the zone.

\[
C_{\text{zone}}(i) = C_{\text{zone}}(i-1) \cdot \left(1 - \frac{V_{dz} + V_{dm}}{Vol_{zone}}\right) + C_d(i-1) \cdot \left(\frac{V_{dz}}{Vol_{zone}}\right) + C_{\text{ret}}(i-1) \cdot \left(\frac{V_{dm}}{Vol_{zone}}\right)
\]  

(2)

With the following notation:

- \( C_{\text{zone}} \): zone concentration
- \( C_d \): zone discharge air concentration
- \( C_{\text{ret}} \): building return concentration (measured in relief air)
- \( V_{dz} \): zone discharge flow rate
- \( V_{dm} \): mixing flow rate (i.e. rate of interzonal airflow)
- \( Vol_{zone} \): zone volume

Data for the zone discharge air concentration, \( C_d \), are fitted from the measured data using a second-order polynomial least squares regression analysis (the initial zero measurement is not included in the regression). Figure 3 shows an example plot with this regression, a similarly
regressed relief air measurement, measured data from the zone, and the simulated zone concentration of equation 2. This plot represents data for Test 1 in Zone C.

![Figure 3: Simulated and measured concentration data for Zone C in Test 1](image)

The zone’s concentration measurements (the plotted series “Zone C”, represented by circles) almost match the discharge air (“Discharge C”). This is because this zone has a very high flow rate (22.3 ACH). The question of validity of the SVEE hinges on the question: do the Zone C measured data better match the building average (“Relief”) or the SVEE-based simulation (“Sim Zone C”)? In Figure 3 these measured data appear to match the SVEE simulation exactly. This suggests that the building is not well mixed and in this zone the SVEE is an excellent predictor of ventilation distribution. However, a zone with an unusually high flow rate will tend to be pressurized relative to adjacent zones, and therefore will not have any interzonal air influx.
A similar plot for Zone B (with a more typical 5.4 ACH) during Test 2 shows that some interzonal mixing does take place (Figure 4). The amount of interzonal mixing is indicated by the distance from the measured data (circles) to the simulated line (Sim Zone B) versus the distance to the relief air line (Relief).

![Simulation and measurement data for Zone B in Test 2](image)

**Figure 4. Simulated and measured concentration data for Zone B in Test 2**

The term $V_{dm}$ in equation 2 is the mixing flow rate. This represents a flow of air from a fully mixed building space into the zone being analyzed. Such a flow will increase the tracer gas concentration in zones with air change rates below the building average, and decrease the concentration in zones with air change rates above the building average. (“Air change rate” refers to the zone discharge air flow rate divided by zone volume, and does not include the interzonal flow rate, which is unknown). This is because the discharge air is the source of the tracer gas into a given zone. A greater than average air change rate means a more rapid increase of tracer gas
concentration, so that a transfer from an average-concentration area will dilute the tracer gas in the zone, and vice versa. The term $V_{dm}$ is used to calculate how much interzonal flow is necessary to cause the measured results. In this way the accuracy of the SVEE can be assessed quantitatively.

$V_{dm}$ values are iteratively assigned until the average value of the residuals is zero (ASHRAE 2010b). This is done for each zone in each test. Figure 5 shows the residuals for Zone B in Test 2 (the case shown in Figure 4) with an assumption of no interzonal mixing (SVEE assumption) and with an interzonal mixing rate of 38 CFM [18 L/s], the value that gives zero average residuals.
DISCUSSION

The apparent mixing value for Zone B in Test 2, above – 38 CFM [18 L/s] – seems quite reasonable. However, not all of the values calculated in this manner seem as reasonable. Table
shows a summary of the flow rates that were required to bring the average of the residuals to zero. These flow rates are also expressed as a percentage of the zone’s discharge air flow rate.

Table 2. Interzonal flow rates calculated and as a percentage of zone discharge

<table>
<thead>
<tr>
<th>Zone</th>
<th>Test 1 CFM</th>
<th>Test 1 L/s</th>
<th>Test 1 %</th>
<th>Test 2 CFM</th>
<th>Test 2 L/s</th>
<th>Test 2 %</th>
<th>Test 3 CFM</th>
<th>Test 3 L/s</th>
<th>Test 3 %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zone A</td>
<td>42</td>
<td>20</td>
<td>191%</td>
<td>29</td>
<td>14</td>
<td>112%</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Zone B</td>
<td>70</td>
<td>33</td>
<td>146%</td>
<td>38</td>
<td>18</td>
<td>25%</td>
<td>44</td>
<td>21</td>
<td>29%</td>
</tr>
<tr>
<td>Zone C</td>
<td>40</td>
<td>19</td>
<td>6%</td>
<td>50</td>
<td>24</td>
<td>7%</td>
<td>10</td>
<td>5</td>
<td>1%</td>
</tr>
<tr>
<td>Zone D</td>
<td>30</td>
<td>14</td>
<td>18%</td>
<td>150</td>
<td>71</td>
<td>20%</td>
<td>177</td>
<td>84</td>
<td>24%</td>
</tr>
</tbody>
</table>

The high percentages for Zones A and B are a result of the low supply air flow rates that these zones receive; the actual interzonal flow rates are not particularly high. As discussed earlier, zones with air change rates below the building average can be expected to have elevated interzonal flow to them because of the pressure differential set up by the lower supply air flow. Conversely, zones with high air change rates should have low mixing flow rates because they likely have flows outward, not inward. Therefore, the high mixing flow rates, such as Zone D in Test 2 and 3 are surprising considering the high supply flow rates to these rooms.

In Test 3, Zone A produces a seemingly impossible result. The simulation predicts a concentration lower than the average building concentration, but the data show a concentration higher than the average building concentration. This cannot be explained by assuming that well-mixed building air is mixing into the zone, because that would tend to bring the measured concentration closer to the average building concentration, not above it. A reasonable explanation is that Zone A, which is likely depressurized relative to adjacent zones, is getting
interzonal mixing air from a higher-than-average concentration zone; i.e. an adjacent zone with a high discharge rate, hence a high concentration and high relative pressure, is leaking air into Zone A.

ERROR AND UNCERTAINTY
As previously mentioned, stratification (i.e. inadequate mixing) tends to cause problems in field tests involving tracer gas sampling. In the current experiment a problem was encountered with mixing of the tracer gas at the injection site with the recirculated air from the building. An investigation showed the supply duct’s tracer gas concentration to vary across its cross section. (This stratification occurred despite the presence of air blenders, parallel plenum-type supply fans, and 90° duct bends, all located downstream of the tracer injection site). Therefore the discharge concentration for each test zone was measured, instead of using a single value for all zones.

The stratification in the distribution system means that the concentration in the non-test zones was not uniform. The simulation results above (that determined the interzonal mixing rates of Table 2) use discharge concentration to predict the concentration in the zone, but they also use an assumption of average building concentration in the interzonal mixing air ($C_{ret}$ of Equation 2). This is a source of uncertainty in the values of Table 2.

A source of possible bias error is the presence of the mixing fans in the test zones. Wherever the discharge stream from a mixing fan impinges on a partition surface at a location having leakage paths, an artificially high interzonal mixing rate may occur. Another source of possible bias error is the low flow rates used in some test zones. As discussed above, high flow rates will not
affect a test zone’s SF₆ concentration, but a very low flow rate will normally cause a room to be depressurized, thus increasing the concentration by drawing air from adjacent zones (since low flow rooms have lower concentration than the building average).

Other possible sources of uncertainty include: error in calculation of room volume, and unsteady control of the VAV damper controller. The VAV damper is controlled by a PID feedback control loop that is tuned at a typical flow rate. At higher and lower flows, oscillation is likely. This effect was anticipated and guarded against by re-tuning each controller, making periodic checks of the discharge flow rate, and by allowing a great deal of settling time during the experiments. However, the VAV controllers for the test zones were typically operating outside of their recommended flow ranges, and may have experienced some oscillation.

For each room and each test a calculation of the total propagated uncertainty of the time-dependent concentrations was made (Figliola and Beasley 1991, ASHRAE 2010b), using manufacturer’s data for sensors, and estimates for other sources of uncertainty. Examples of these calculations are shown in Figures 6 and 7.
Figure 6: Uncertainty in Test 2, Zone C Concentrations
Figure 7: Uncertainty in Test 2, Zone A Concentrations

The shaded area represents the uncertainty range of the simulation values (with the simulated values on the bold line). The circles are the measured values. Each has an error bar on it.

In these error calculations, the assumed interzonal mixing flow rate is zero. For the 12 plots (four zones in three tests) there are six in which the data are well within the uncertainty range, as in Figure 6, three in which the data are mainly inside the certainty range, and three in which the data are mainly outside the uncertainty range, as in Figure 7. We can conclude that for the latter three, and perhaps the latter six, that some interzonal mixing is occurring.
CONCLUSIONS

The testing approach and results presented in this paper are complex. However, a simple conclusion of the experiment is: *the multiple spaces equation is valid; i.e. it predicts ventilation air distribution in buildings very well.*

Three tests are of particular interest in considering the validity of the SVEE: (1) Test 1 – Zone D; (2) Test 2 – Zone B; (3) Test 3 – Zone B. These three tests have flow rates that can be found in normally operating typical buildings – between 5 and 6 ACH (see Table 1). In these three zones the calculated interzonal mixing rates range from 30 CFM (14 L/s) to 44 CFM (21 L/s). The ventilating effect of this flow mimics the effect of a fan-powered-box or transfer fan bringing air from the adjacent zones. Since fan-powered air terminal units typically have much higher airflows than this, the magnitude of the effect as measured is considered very small. In the test building, for example, accounting for interzonal mixing would reduce the outdoor air requirement in the supply air by 2 - 3% if the test zone were the critical zone.

However, as with infiltration, interzonal mixing is beyond the control of the designer and cannot be relied upon in a ventilation calculation. Furthermore, in half of the 12 tests in this study, the interzonal mixing effect is too small to be measured. In these cases the SVEE is an excellent predictor of ventilation air distribution.

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