10 zone CERV2 with Wireless Distributed IAQ Sensors and Actuators Preparing to Ship

PREVENTILATION – Part 2

Smart Air Distribution

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FOREWORD

Preventilation. Try Web searching “preventilation”. Few web matches are likely to turn up. To us, it is a fascinating term we invented to describe new possibilities for beneficially managing our indoor environment. Preventilation sounds oddly familiar, and yet unfamiliar. Build Equinox is making preventilation a reality. Preventilation improves our health and well-being. The power of “Big Data”, “AI” (Artificial Intelligence), and ever-increasing improvements in technology for seamless monitoring and controlling the indoor environment are all important pieces of our preventilation concept.

We emphasize two aspects of “preventilation”:

1) **PRE**ventilation anticipates the need for ventilation before undesirable thresholds of poor air quality and energy usage occur
2) **PREVENT**ilation is a prescient ability, a meta-based awareness of the interaction of seemingly unrelated factors that impact our health and feeling of well-being

Smart ventilation and smart air distribution are two essential features of preventilation. As expressed by Florence Nightingale more than 150 years ago, without proper ventilation, all else is for naught.

Our Part 1 - Preventilation report concentrates on smart ventilation, describing how automated sensing and control of residential indoor air quality improves both air quality and energy efficiency beyond that of today’s ventilation systems. Part 2 – Preventilation focuses on smart air distribution and the concept of “ventilation efficiency”, the fraction of fresh air that benefits a home’s occupants.

Join us on this journey to improve the health and well-being of yourself and those around you!

Executive Summary

Smart air distribution requires air recirculation with local zone sensing and control for larger and more complex homes. Several aspects of effective smart air distribution are discussed:

1) Homes with house volume recirculation <2 hours are generally small enough to not require zone air flow management, while homes with >2 hours for house volume recirculation can improve air quality management with zone sensors and damper flow control
2) A zone efficiency parameter can be defined for homes without recirculation by dividing the ventilation air flow in an occupied room by the total ventilation air flow.
    a. A home with 5 zones, no recirculation, and equally divided ventilation air flow has a ventilation efficiency of 20% when all occupants are in one zone
    b. Recirculation increases ventilation efficiency to 100%
    c. Zone sensing and flow control layers an additional level of ventilation efficiency to large and complex homes without requiring excessive recirculation air flow rates
3) Air quality comparisons of field data for a smart ventilated home with recirculation and two homes without smart air distribution
    a. A conventional (leaky) home without recirculation with very high carbon dioxide levels in children’s bedroom
    b. A high performance (<0.6ACH50) Passive House with constant flow ventilation with poor air quality when occupied
    c. Smart ventilated home with air recirculation maintains good air quality throughout home during periods of varying occupancy
4) Simulation modeling comparisons of a high performance (0.6ACH50) home with a high efficiency (90%) HRV with ASHRAE 62.2-2016 constant ventilation and a smart ventilated home with recirculation at varying occupancy and occupant activity levels
    a. Smart ventilated home with recirculation automatically maintains good air quality throughout home under occupied and unoccupied periods
    b. Constant flow ventilation often has poor air quality in occupied rooms
        i. A room with a continuously ill person with airborne contagion (colds, flu) is more likely to transmit the disease to susceptible house occupants
    c. CERV2 smart ventilated home is more energy efficient than constant ventilated home
5) Supply and return zone control can be integrated with recirculation for larger, more complex homes in which the occupants and occupant activities require precise ventilation
    a. Air quality, manual switches, electric circuit sensors, and occupancy sensors can be used to determine local ventilation demand
    b. Wired and wireless dampers can be used to shuttle fresh air where needed and to exhaust polluted air
        i. Ducts and dampers should be designed for negligible pressure drop
        ii. No region of a house should have air flow completely closed
    c. Zone control can be integrated with local exhaust control (kitchen, bath exhaust) in a seamless manner

Introduction

Smart ventilated homes must have smart air distribution, too. Current ASHRAE 62.2-2016 residential ventilation standards do not prescribe air distribution. One could supply a home's ventilation air at ASHRAE 62.2-2016 levels into a closet and meet the standard. Effective air distribution is essential for air quality control and energy efficient air quality management. Two important aspects of smart air distribution, recirculation and zoning, are the subjects of this report.

It is incredible that we pay so little attention to fresh air ventilation in homes. Historically, fresh air distribution and air exhaust were integral to building design (1). Today, commercial and institutional buildings spend more than \$100 per ft^2 for HVAC systems, while ventilation of our homes is still largely left to poor rules-of-thumb, construction flaws and the wind (literally). People spend much more time in their homes than anywhere else. It is time for us to elevate the importance of our health and well-being above that of everything else in the extensive list of home design topics. As expressed by Florence Nightingale more than a century ago (2), if architects and builders were responsible for paying the health costs of their buildings' occupants, buildings would be very different!

Part 1 of our Preventilation reports focused on delivering fresh air to a home at a rate required to keep occupants healthy in an energy efficient manner. Delivering fresh air into a home is the first step, followed by the equally important step of delivering fresh air to where occupants need it. Air distribution within residences has traditionally centered around air flow needed for comfort conditioning rather than air quality. In today's high performance homes, air quality may dominate duct design criteria.

An unfortunate, but popular design practice among today's high performance home designers has been elimination of air recirculation. Instead, a constant flow of fresh air is divided among various zones within the house. This "one-and-done" ventilation design philosophy (sometimes euphemistically referred to as "cascading" ventilation by its promoters, but it is not!) leads to unhealthy air quality in the occupied regions of a home, wasted fresh air in unoccupied zones, and an uncontrolled buildup of particulates. Recirculation provides the opportunity to filter indoor air and increases ventilation efficiency by using fresh air that is "stored" in the unoccupied areas of a home. Our health benefit from recirculation is worth much more than the \$5 per year per home occupant for continuous operation of a solar powered, 15W fan.

"Large" homes are ones in which occupant activities are limited to a small portion of the home. Zone control provides an additional level healthy home management in addition to recirculation in large homes. Prediction of zone air movement is complex (3), but with modern sensors and controls, we can shepherd air through a house in an efficient manner with dampers. Zone dampers on supply and return ducts are operated such that fresh air is directed to occupied regions of a home, and areas with higher pollutant concentrations are exhausted.

Two parameters characterize smart air distribution. First, the time required to mix a home's volume of air through recirculation. As this time length parameter increases above 1 to 2 hours, a home is large enough to consider "zone" air control. A second parameter is ventilation efficiency parameter, or the fraction of fresh air that benefits a home's occupants. Home's without recirculation and zone control, today's one-and-done ventilation homes may have ventilation efficiency below 25% with a majority of ventilation air never passing over the home's occupants.

Local, or “triggered” ventilation in which periodic, focused ventilation (exhaust and/or supply) is desired is the final topic discussed. Kitchen venting and bathroom venting are two common examples of local venting. We discuss some methods for managing local exhaust with smart ventilation systems.

The residential environment is much more complex than the commercial and institutional buildings in which temporal occupancy, spatial occupancy, and activities are predictable. A home environment is a combination of a restaurant, hotel, business, exercise center, movie theater, hobby shop, library, and much more. Residential occupant density is much lower (1000ft^2 per occupant) than a commercial building (100ft^2 per occupant), further increasing the need to be able to sense where and when pollutant generating activities are occurring. And, we spend most of our lives in our homes. Smart air distribution is essential for keeping a home’s occupants healthy wherever they are, whatever their activities, and whenever fresh air is needed.

Background

Smart ventilation introduces fresh air into a home when it is needed (4, 5, 6), while smart air distribution is the efficient use of the fresh air once it is delivered to a home's interior. Yesterday's leaky homes often have an excessive wind driven infiltration coupled with a central HVAC system's recirculation moving air throughout the house volume. Unfortunately, as discussed in our Part 1 Preventilation report, even the leakiest of homes suffer from poor air quality when the wind doesn't blow. And, even when it is windy, there are times when a central HVAC is not operating, resulting in stagnant zones with poor air quality.

Today's well-sealed and highly insulated homes cannot rely on happenstance and wishful thinking for good air quality. Ventilation based on odor to keep dissatisfaction below 20% is not healthy air. Why do we continue to use the 20% dissatisfaction level as the primary metric for ventilation design? Even when sufficient fresh air is delivered to a home, local spaces may have poor air quality (7,8).

Figure 1 is a schematic of a house with constant ventilation air flow (aka, "one-and-done" ventilation) divided among a home's spaces. Three common types of constant air flow systems are exhaust ventilation, supply ventilation, and balanced ventilation systems. In exhaust ventilation systems, as a fan exhausts air from a house, infiltration air enters a home in an uncontrolled manner from construction flaws, flue vents, dryer vents, cooking vents, dry plumbing vents, and other openings. Sometimes, passive supply vents are added in the hope that these passageways will enhance air flow distribution, however, studies have shown this strategy is ineffective. Supply ventilation is the opposite of exhaust ventilation in which a fan blows air into a home, with house air exiting through uncontrolled air leakage pathways.

Balanced ventilation reduces uncontrolled infiltration air flow with supply and exhaust fans operated to keep a home at neutral pressure relative to the outdoor environment. One should note that pressure distribution over a house exterior is very dynamic and geometrically complex, such that a uniform "neutral" pressure does not exist.

Referring to Figure 1, assume we have a required ventilation flow of 100cfm based on the ASHRAE 62.2 2016 standard (for example, a 2500ft^2 home with 3 bedrooms). On "average", the home receives 25cfm per occupant for the ASHRAE 62.2 estimated occupancy of 4 (occupants equal number of bedrooms plus 1). Evenly distributing ventilation air to Figure 1's 5 rooms results in 20 cfm per room. Although the house is receiving 50cfm of air flow per occupant based on 2 occupants, only 10 cfm per occupant is delivered to where they are located. On average, the house should have a carbon dioxide and associated VOC concentration that is less than 700ppm, however, the occupied room will exceed 1500ppm of carbon dioxide with constant ventilation!

Figure 2 shows field data for 3 weeks from the living room of a high performance home (super-insulated, <0.6ACH50 construction) with constant ventilation flow divided among its rooms. The home has two occupants who were absent for approximately 1 week. The data indicates the living room has excessively high carbon dioxide and VOCs when the occupants are in that space, and is overventilated when they are absent.

Figure 3 is data for a 3 week period from another high performance home (super-insulated, <0.6ACH50 construction) that has smart ventilation and air distribution. The smart ventilation system pollutant threshold is set at 850ppm of either carbon dioxide or equivalent total VOC concentration levels. The vertical green bars indicate active fresh air ventilation periods triggered by either carbon dioxide or total VOCs. Pollutant levels are much more effectively controlled and the integrated exposure of occupants to pollutants are lower.

We can define a simple efficiency term related to Figure 1's use of fresh air to benefit its occupants. Assuming a constant, evenly divided ventilation air flow without recirculation or zone control, the home in Figure 1 has a ventilation efficiency 20%. That is, only 20% of the 100cfm of fresh air flow benefits the home's occupants while the other 80% is exhausted without benefitting the occupants. We will examine more field data and computer simulation results that illustrate the buildup of poor air quality in homes with poor ventilation efficiency. Improving ventilation efficiency can be accomplished in two manners: recirculation and zone control. At high enough recirculation levels, ventilation efficiency reaches 100%. Second, in larger or more complex homes, ventilation efficiency can be increased with zone control (in addition to recirculation).

Polluted rooms degrade our health (9-17)! Figure 4 shows the trend of home infiltration. "Normal" or "natural" leakage is roughly 1/20th of blower door ACH50 measurement; eg, a home with 10ACH50 has a normal leakage of 0.5, and is representative of homes constructed in 1980 (18). Since 2010, builders regularly construct homes reaching the IRC (International Residential Code) level of 3ACH50 (0.15 normal leakage), with many progressive builders achieving 0.6ACH50 (0.03 normal leakage) and lower (19).

Since 1950, pollutant buildup in our homes has steadily increased with improved home sealing. Figure 5 shows the concentration of indoor pollutants relative to a home constructed in 1894. A home built in 1990 with 8ACH50 (normal leakage of 0.4) has nearly 5 times the pollutant concentration as the 1894 home. The 1990 era home is even worse because the soup of pollutants in today's homes are much more complex than the simpler home furnishing materials of yesteryear's homes. Infiltration leaks in modern homes are not evenly divided around the house, but instead are concentrated at flue vents, dryer vents, and basements, while occupied spaces such as bedrooms are very well-sealed.

Figure 5 shows the increase of asthma in the US populace over time, with very strong correlation to the increase of indoor pollutant concentration. Infiltration air flow through a home historically has kept odors below olfactory detection for most humans (20). Correlation does not mean causation, and it is very difficult to pinpoint specific factors causing increased asthma. Phthalates (plasticizers that soften rubber duckies and other polymer materials) exhibit hormonal effects (21) and show strong linkage to increased asthma, but are they a part of the cause of increased asthma? We must work to reduce the sources of pollutants and freshen the air we spend most of our lives breathing.

Figures 6 and 7 show how likely you are to "catch" a cold or the flu by spending time in a room with an infected person using Rudnick and Miltons' airborne disease transmission model based on carbon dioxide concentration (14). A home without good fresh air distribution is much more likely to transmit illness than a home with high ventilation efficiency that dilutes contagions in occupied spaces. Note that the influenza virus is much more contagious than the cold, as represented by the probabilities in Figures 6 (cold virus) and 7 (flu virus).

Figure 8 shows trends of indoor particulate concentration for an unventilated home, a constant flow ventilated home, and a smart ventilated home with recirculation air. Particulates of various composition, size and shape trigger respiratory attacks, heart attacks, and stroke and are factors in cancers and dementia. Particulates in today's homes are primarily generated indoors from skin shedding, cooking, textile abrasion, dirt on feet, etc (22). It is a myth that highly sealed homes have no dust! Super-sealed homes have dust, and recirculation is an effective and efficient method for controlling indoor particulates. A constant ventilated home will have significantly higher particulate levels than a smart ventilated home with recirculation where indoor particulates can be continuously filtered.

Finally, elevated pollutant levels of carbon dioxide and VOCs impair cognition, our ability to think. Figure 9 shows the energy cost related to a home's air quality and an estimated value of our improved productivity. Our productivity is 100 times more valuable than the cost of energy associated with improved air quality! Fresh air clears our heads, allows us to concentrate, to be creative, to make better decisions, and overall to feel good. The impact of poor air quality is immediate. When we are immersed in a high pollutant levels, the impact is fast as blood circulates pollutants through our bodies. Bedrooms frequently have high pollutant levels in homes, causing degraded sleep and a sleep deficit "hangover" impacting our next day's productivity and feeling of well-being (12).

Maintaining excellent air quality in our homes, schools, and buildings is more than just a nice thing to do. Energy cost for improved ventilation are minor compared to the value of improving our health, productivity and feeling of well-being. In the case of smart ventilation and smart air distribution, we can have our cake and eat it too, with fresh air introduced to our homes when needed and distributed to where we need it, often in a more energy efficient manner than constant flow, one-and-done ventilation systems.

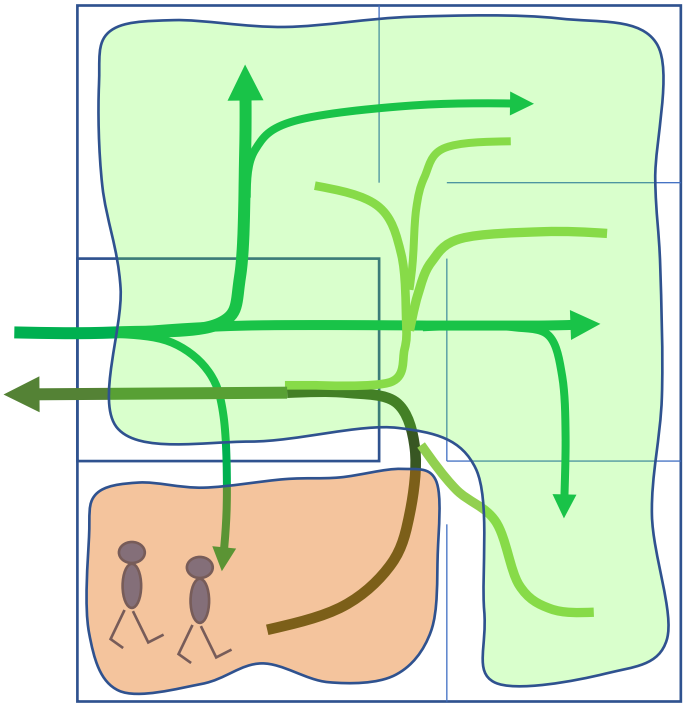

Figure 1 Constant (one-and-done), non-recirculation air distribution.

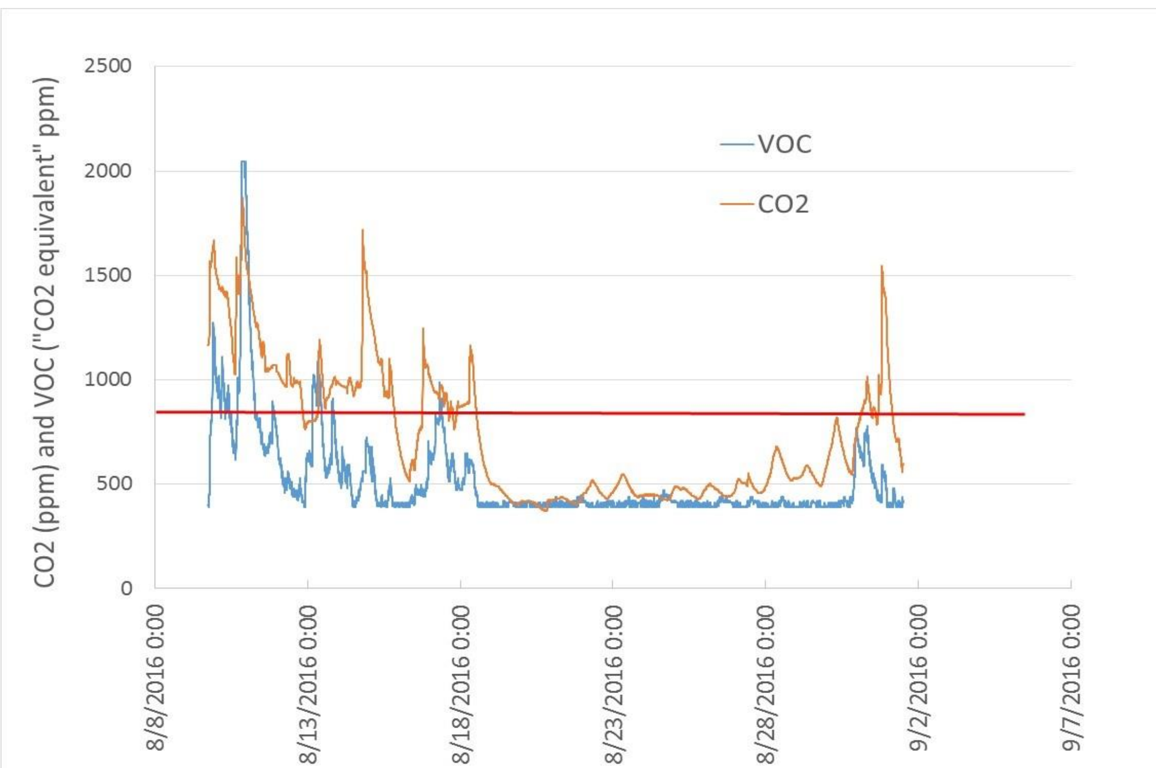

Figure 2 Sample data from a high performance (<0.6ACH50) home with constant flow ventilation.

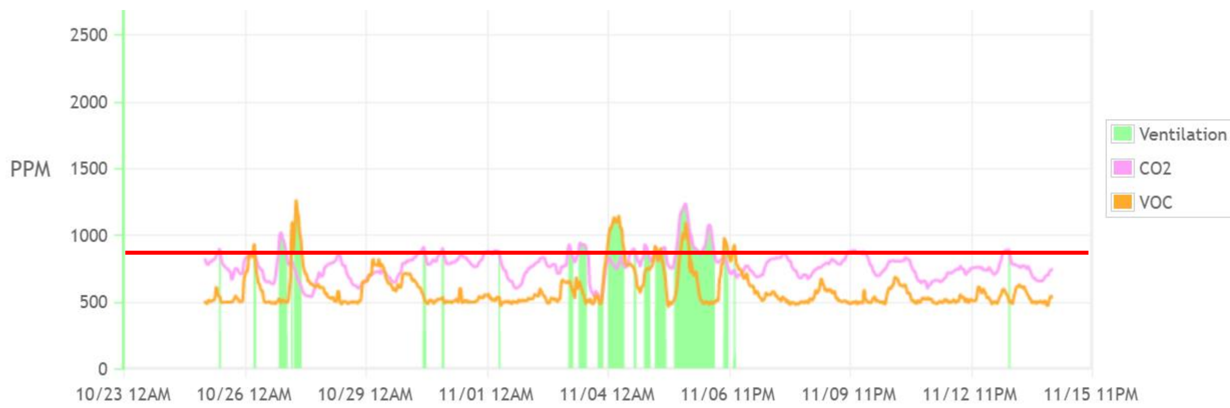

Figure 3 Sample data from a high performance (<0.6ACH50) home with smart ventilation and recirculation.

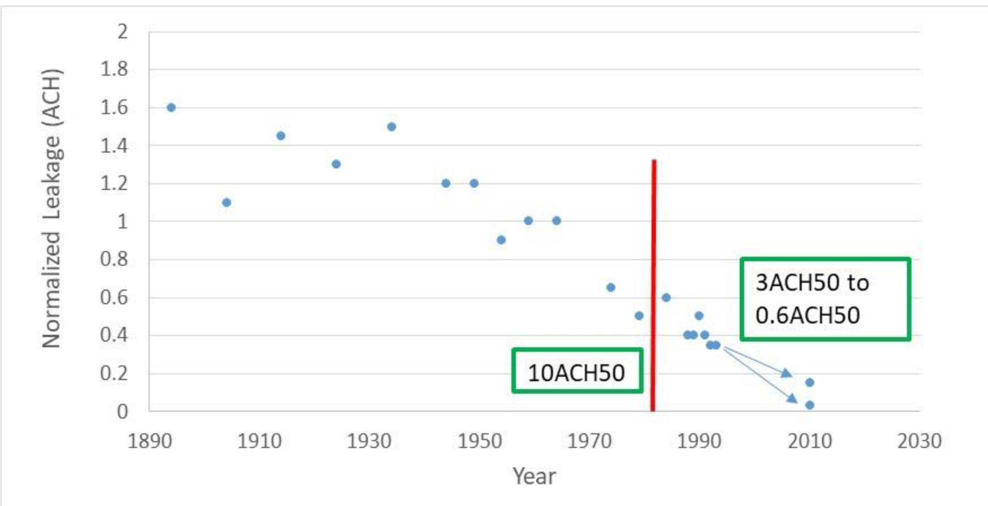

Figure 4 Trends in home sealing(normalized leakage) since 1894.

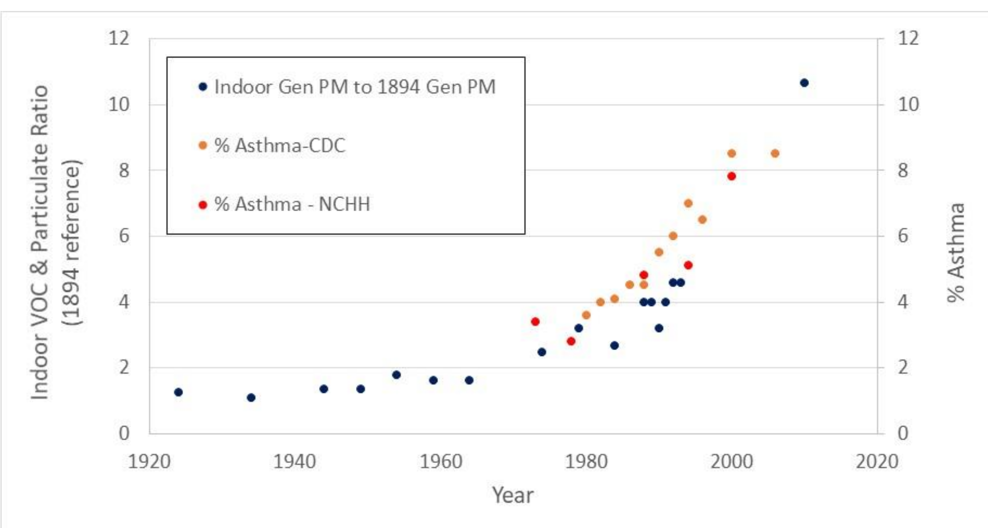

Figure 5 Correlation of asthma and relative increase (1894 reference) of indoor pollutants.

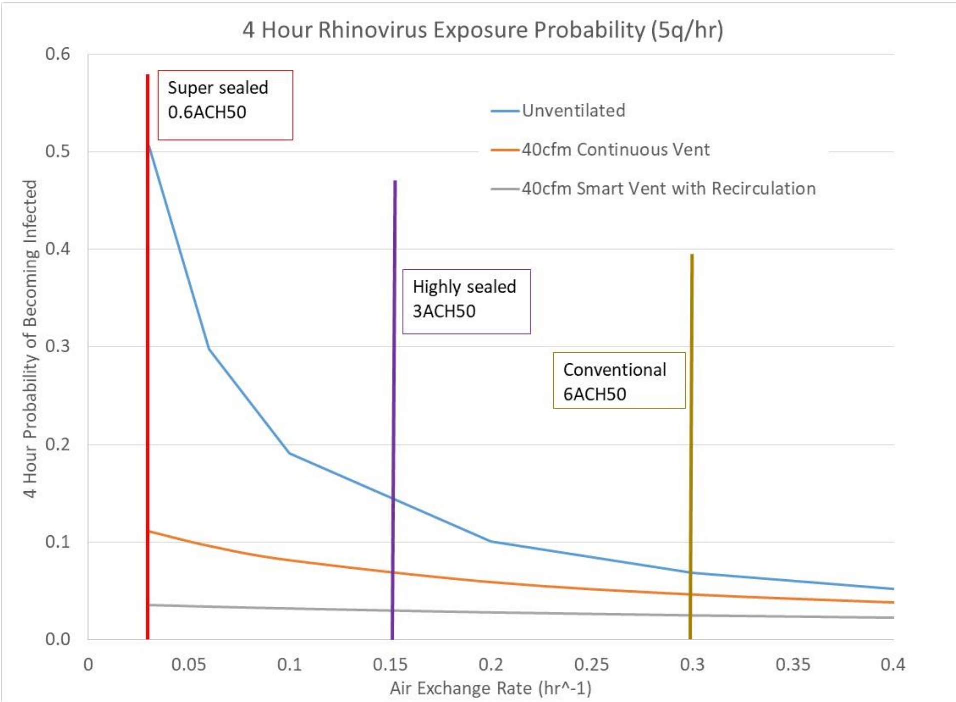

Figure 6 Four hour probability of rhinovirus (cold) transmission in unventilated, constant flow ventilated, and smart ventilated with recirculation homes.

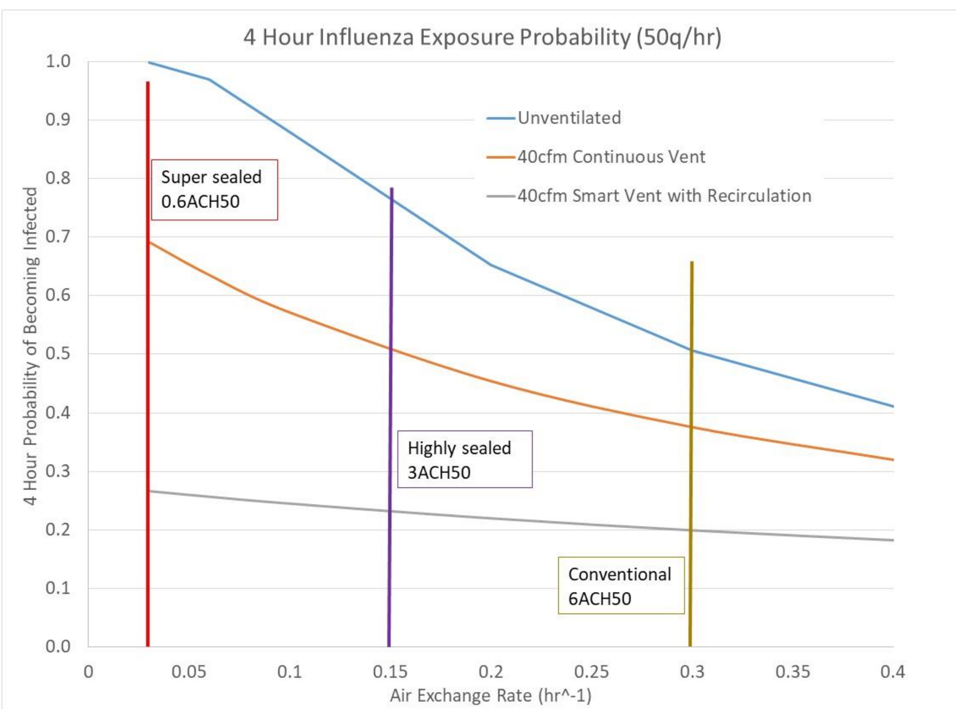

Figure 7 Four hour probability of influenza transmission in unventilated, ventilated, and smart ventilated with recirculation homes.

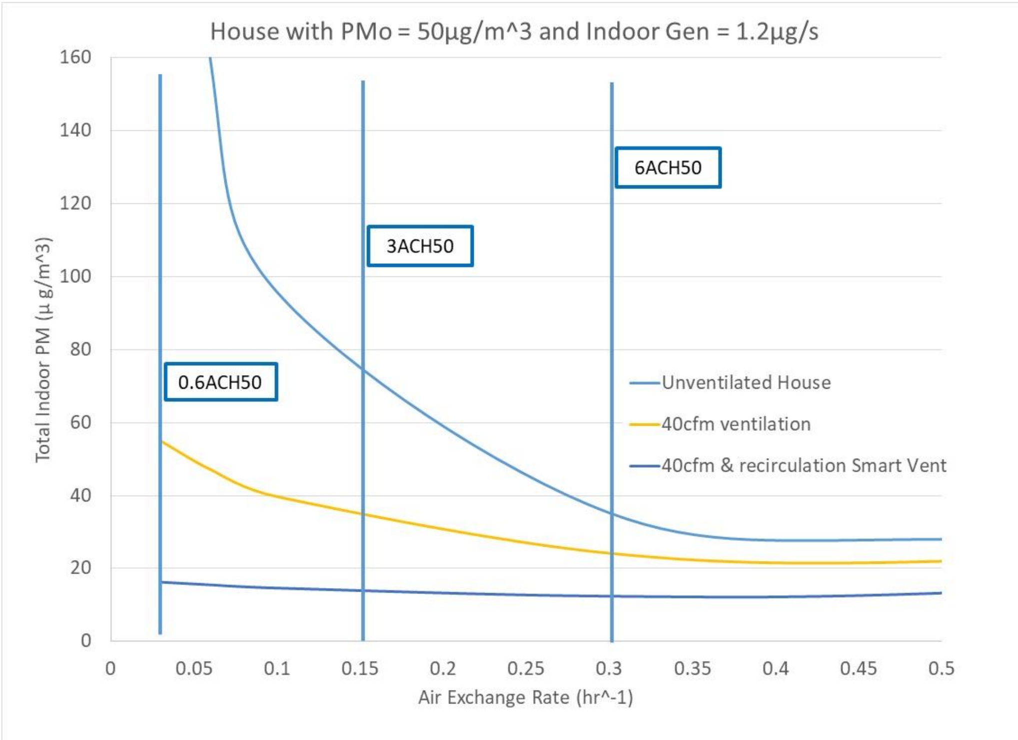

Figure 8 Indoor particulate concentrations in unventilated, ventilated, and smart ventilated with recirculation homes.

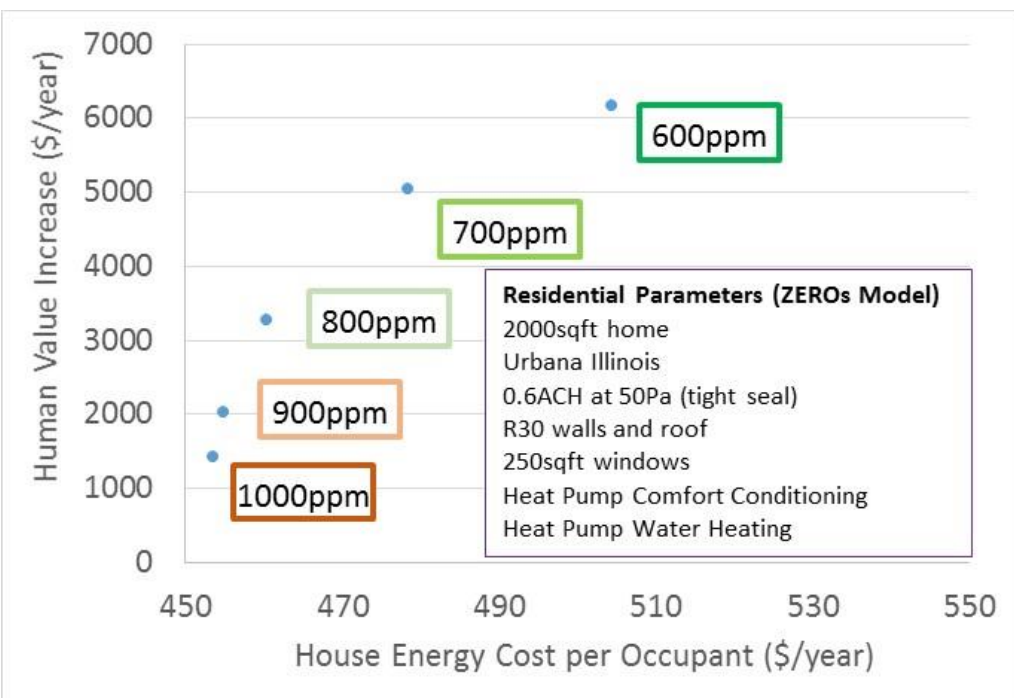

Figure 9 Cognitive improvement value relative to home energy cost per occupant increase for improved indoor air quality.

Pollutant Characteristics of Well-Mixed and Unmixed Homes

Moving air throughout a home is important for efficient utilization of fresh air brought into a home. Figure 10 shows a home with one room. The air in a home with only one room will be well-mixed from the natural movement of air driven by ventilation and infiltration air flow into and out of the space, along with air movement from buoyancy due to temperature variations, occupant movement, ceiling fans, etc.

Figure 11 is a schematic of a house with two rooms. Walls form barriers that prevent mixing of air from one room to another. Air recirculation is effective for stirring and mixing air among rooms in a house. Recirculation air flow that overturns the house volume within 1 to 2 hours is sufficient for mixing air throughout a house. When recirculation air flow requires more than 2 hours to recirculate a home's air volume, zone control should be added to recirculation for managing room air quality.

Figure 12 shows simulated pollutant (carbon dioxide) concentration variations in two, perfectly mixed houses with smart ventilation control. Pollutant concentrations are shown for a larger home (20,000ft^3) and smaller home (10,000ft^3) with two occupants. The smart ventilation system switches to fresh air venting mode whenever the indoor air quality reaches 1000ppm carbon dioxide concentration, and switches to an air recirculation mode when fresh air venting has reduced carbon dioxide to 900ppm. The home analyses for Figure 12 assumed 200cfm of fresh air ventilation and air recirculation flow rates. Modeling relations for Figure 12 are included in Appendix B.

The larger home in Figure 12 requires twice as much time as the smaller home to reduce the pollutant level 100ppm. Likewise, the larger home takes twice as long to increase to 1000ppm as the smaller home. The important concept to understand from Figures 10, 11 and 12 for a single room home or a well-mixed home is that the fraction of time (and amount of fresh air) required to maintain air quality in smaller and larger homes is exactly the same for the same pollutant generation level. The results in Figure 12 neglects the impact of infiltration. A larger home has greater infiltration air flow rates than a smaller home with similar infiltration characteristics (eg, 1ACH50). A smart ventilation system senses this difference and alters the ventilation air flow accordingly. Preventilation – Part 1 discusses the impact of infiltration in detail.

The air flow (200cfm) used for the example homes in Figure 12 is greater than that need to steadily maintain the home at 1000ppm of carbon dioxide for the assumed occupancy conditions. One could reduce the fresh air flow rate until it exactly matches the level to steadily hold the room at 1000ppm without periodically adding fresh air. Two reasons why it is important to use a higher air flow rate than the steady air flow rate are:

1) The time between fresh air periods can be used for recirculation of house air which provides an opportunity for removing particulates
2) Recirculation time periods help mix air between separated rooms, utilizing fresh air "stored" in unoccupied areas of a home

The 200cfm ventilation air flow rate used for the Figure 12 example is typical of the air flow used in a CERV2 smart ventilation system. Air flow at this level is sufficient for maintaining air quality in homes with up to 5 to 8 occupants, depending on occupancy time periods, occupant metabolic characteristics (age, gender), and occupant activities (cooking, cleaning, exercising, sleeping, etc). Additionally, air flow at this level is sufficient for mixing house air among zones within 1 to 2 hours for homes up to 2000ft^2.

Figures 13 and 14 show carbon dioxide concentrations in Equinox House (Urbana Illinois) over a 4 week period and 5 day period within the 4 week data collection period. Equinox House has a first generation CERV (installed in 2010) smart ventilation system that operates in recirculation mode whenever carbon dioxide is below a user selected setpoint (850ppm). Whenever carbon dioxide or total VOCs exceed the pollutant threshold level, fresh air is delivered until pollutant concentrations are 100ppm below the setpoint level. Equinox House is 2100ft^2 with 2 occupants who are typically out of the house for 8 to 10 hours per day during weekdays. Air flow and air recirculation rates for the first generation CERV is approximately 150cfm with reasonably clean, MERV 13 filters.

Three carbon dioxide monitoring stations were placed in Equinox House in the family/dining/kitchen room area, an unused bedroom, and the master bedroom. The CERV monitors carbon dioxide concentration in the return air from the house, which is a bulk mixture of Equinox House air. The data was collected over the winter holiday season that included very active occupancy levels and a 4 day period with no occupancy. The 5 day monitoring period shown in Figure 14 is taken from the Figure 13 data and shows the complexity and dynamic variation of air quality typical in a home environment. Whenever the CERV's pollutant sensors exceeded the 850ppm threshold, a sharp drop in pollutant concentrations are observed until the CERV senses a 100ppm drop of pollutant concentration in its return air.

Comments are included in Figure 14 showing a period with the highest pollutant levels in the main living area prior to 10pm, followed by higher pollutant concentrations in the master bedroom after 10pm. The spatial and temporal variation of pollutant concentrations with Equinox House are not large, and the bulk CERV pollutant concentration measurement reasonably represents the air quality of the home due to recirculation mixing of house air.

Figures 15 and 16 are data collected over a 4 week period from a 3 bedroom home without fresh air ventilation and without air recirculation. The home is approximately 1800ft^2 with 5 occupants (2 adults and 3 small children). The home was constructed in the 1950s and has not been retrofitted with additional insulation or improved infiltration leak sealing. Radiant ceilings provide heat during the winter rather than forced air circulation from a furnace. Three carbon dioxide monitoring stations were placed in the family room, living room and a bedroom for 2 children. Children bedtime was 7pm. The parents would open the bedroom door at 9pm, allowing better air communication with the living room through the rest of the night.

No blower door infiltration data has been collected for the home, however, normal leakage of 0.23/hr (~4-5ACH50) is estimated using Figure 16 data during a 6 hour, no occupancy period on December 23, 2016. Overall air quality shown in Figure 15 is poor and in need of improvement with active fresh air ventilation. Examination of data during the 5 day period shown in Figure 16 illustrates how a lack of recirculation of indoor air causes significant segregation of air quality between occupied regions of the home and unoccupied locations. The children bedroom volume rapidly increases in carbon dioxide concentration for two hours with a closed door until the parents open the bedroom door at 9pm. Carbon dioxide concentration remains high in the bedroom even with an open door. The family room tends to be where the family spends most of their time in the house. The family room, dining room and living room are connected by broad openings, such that the two larger rooms track each other closely.

Comparison of a highly sealed home (Equinox House) with smart ventilation and recirculation to the reasonably well-sealed home without active ventilation and recirculation illustrates the benefits of automated ventilation control. The next section examines and compares constant ventilation systems in detail.

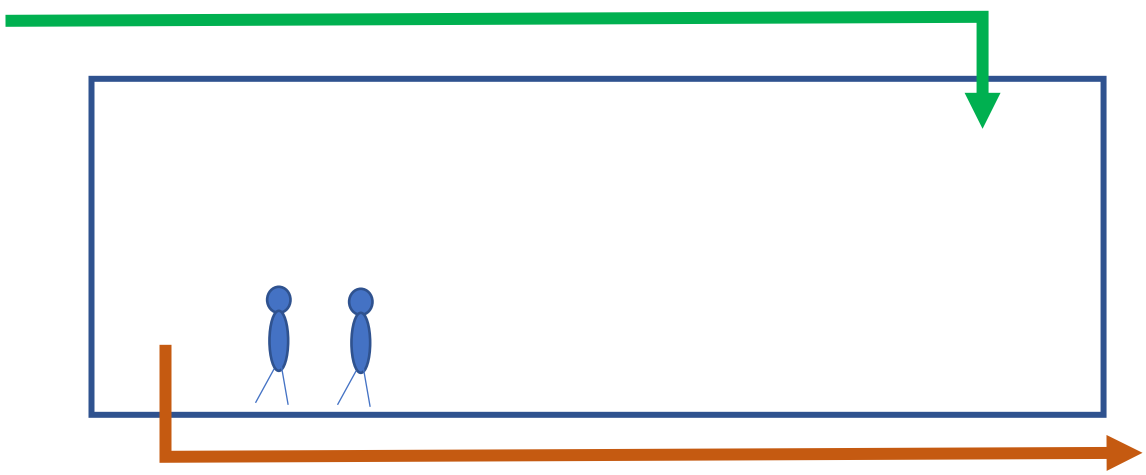

Figure 10 Single room house with well-mixed air.

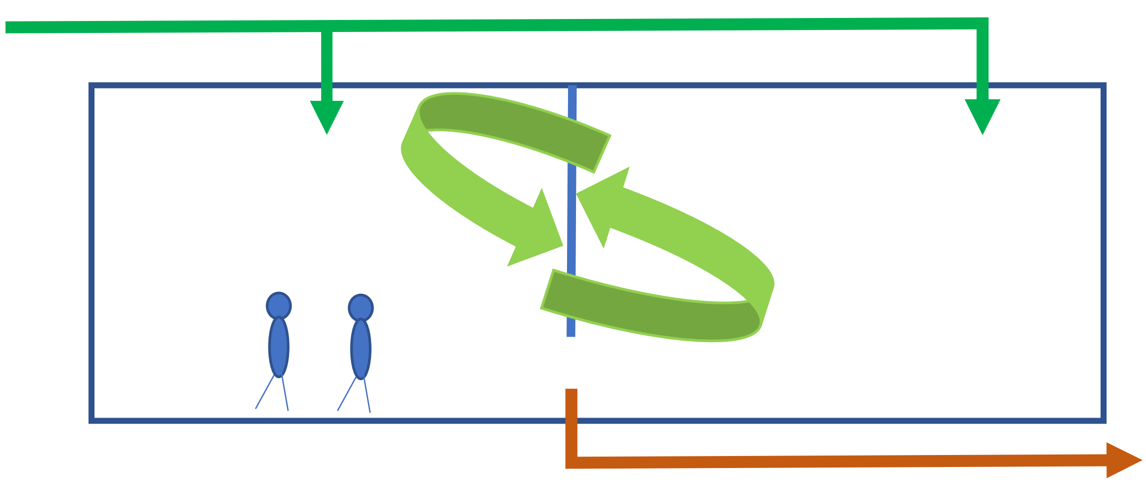

Figure 11 Well-mixed air in a house with two rooms and air recirculation.

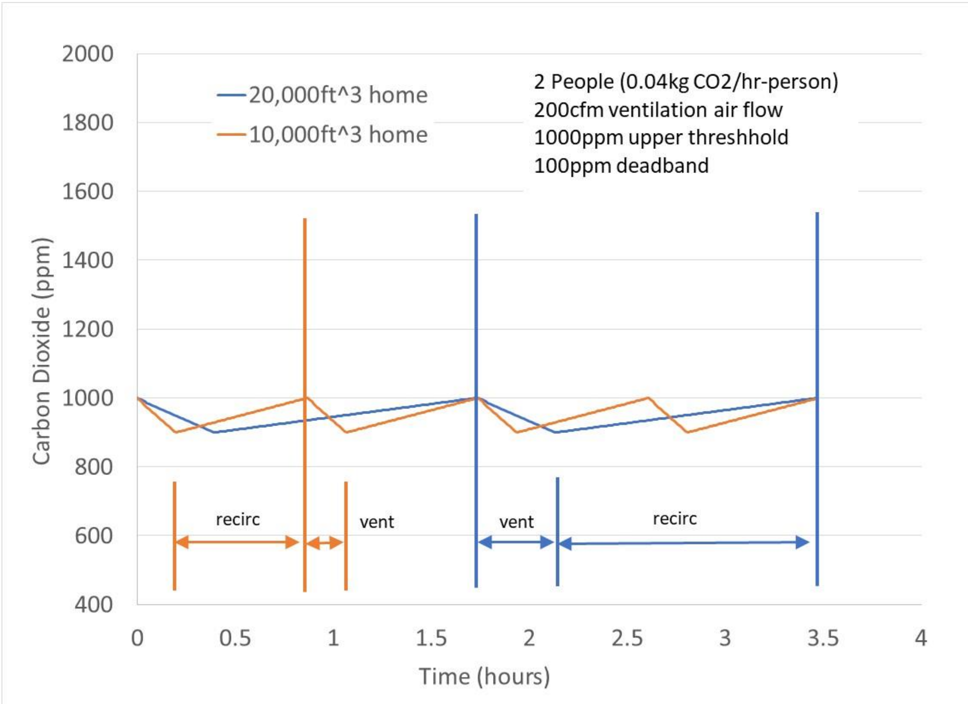

Figure 12 Indoor pollutant variation during fresh air ventilation and recirculation time periods for two homes with the same occupancy (2 occupants) and different indoor volumes (10,000ft^3 and 20,000ft^3). Upper CO_2 pollutant control setpoint is 1000ppm with a deaband of 100ppm.

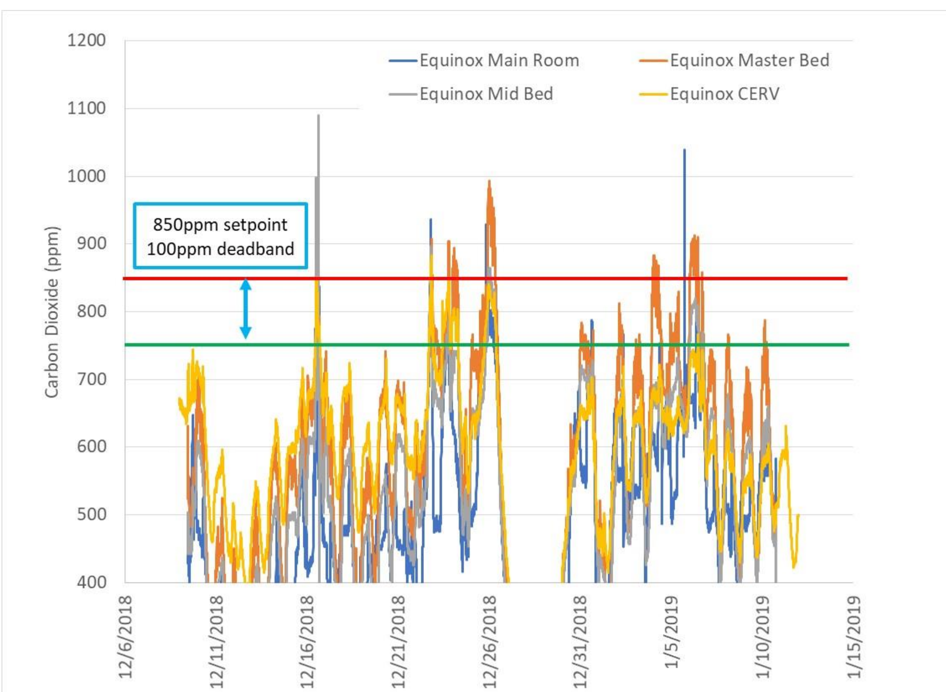

Figure 13 Equinox House carbon dioxide concentrations during a four week period.

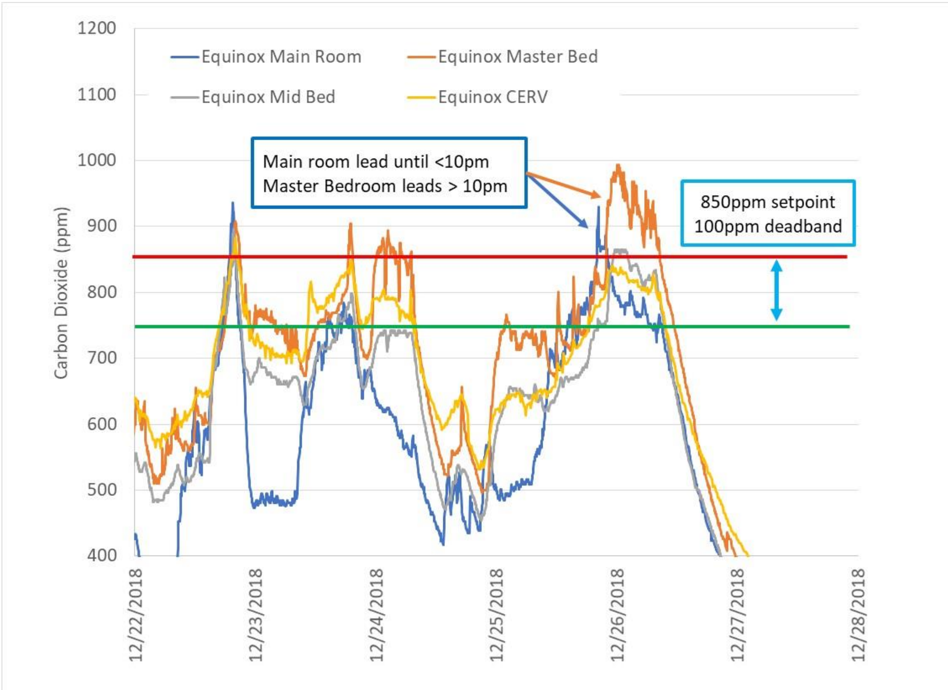

Figure 14 Carbon dioxide concentrations in Equinox House with smart CERV2 ventilation over a 5 day period.

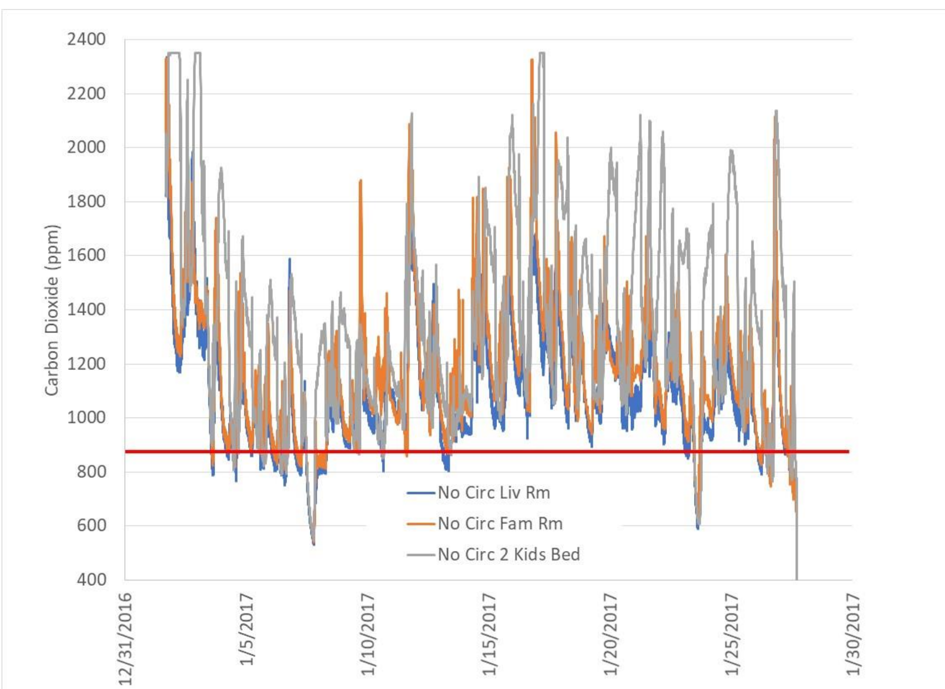

Figure 15 Carbon dioxide concentrations in 3 locations in a home with 5 occupants and minimal air recirculation over a 4 week period.

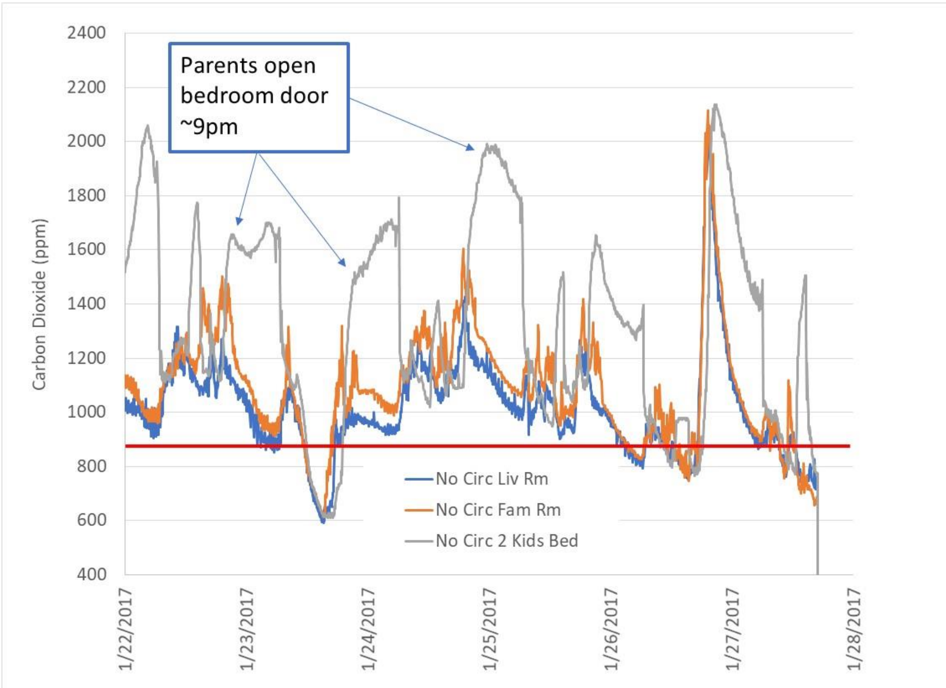

Figure 16 Variation of carbon dioxide in 3 locations during a 5 day period in a home with minimal air recirculation.

One-and-Done (Constant Flow) Ventilation Distribution Characteristics:

A house with no ventilation and no recirculation will have poor air quality. In a home with constant ventilation without recirculation (aka, "one-and-done" ventilation), air flow may be sufficient to keep "average" air quality conditions acceptable, but air quality is often poor where occupants reside, and excellent in unoccupied areas of the home. It is essential to maintain excellent air quality where a home's occupants reside.

We examine localized air quality within a highly sealed, ventilated example home in this section. The home has a high efficiency (90%) energy recovery ventilator operating at ASHRAE 62.2-2016 ventilation levels. As discussed in our "Preventilation – Part 1 Smart Ventilation" report, constant ventilation supplies too much or too little ventilation air. Smart ventilation systems outperform constant ventilation systems in both air quality management and energy efficiency by automatically adjusting air flow as needed.

We explore the characteristics of a home using our 5 minute time interval, concentration and energy simulation model. Our example home is an industry average 2700ft^2, 4 bedroom home with 5 occupants. The home has a master bedroom (2 occupants), 3 smaller bedrooms (1 occupant each), an office, and an open living room, dining room and kitchen area. We model air quality (carbon dioxide concentration) and energy usage with the same January 2010 hourly data file used for Preventilation – Part 1 smart ventilation report.

Human carbon dioxide output, and associated human generated VOCs, are related to our activity level (23). Table 1 lists representative human metabolic rates for different levels of activity and exertion. Note that metabolic rates are dependent on human gender, age and size as well as an individual's specific characteristics. Appendix A contains additional details on human metabolism and carbon dioxide output for females and males based on these factors. Appendix B includes several relations based on human activity level that allow one to determine the time required for an unventilated room to increase a specified carbon dioxide concentration, and the time required for a ventilated room to decrease a specified carbon dioxide concentration level.

Table 2 is an activity (metabolic rate) schedule used for our example home. Everyone in the household is assumed to have the same activity pattern and associated metabolic output.

We divide the ASHRAE 62.2-2016 constant ventilation air flow (120cfm) among the rooms as:

- Living/Dining/Kitchen zone (1350ft^2) = 60cfm
- Master bedroom (450ft^2) = 20cfm
- 3 Bedrooms (225ft^2) = 10cfm per bedroom
- Office (225ft^2) = 10cfm

Infiltration (0.6ACH50) is assumed to be uniformly leaked into each space based on floor area. Note that this is a very simple home with only six zones while a home of this size might have 8 or more zones in reality. Also note that infiltration leaks are not uniformly distributed around a house. Even with uniformly distributed leakage holes, the speed and direction of wind will impact infiltration and exfiltration flow patterns and magnitudes around a home.

Figures 17 and 18 show the air quality for the month of January 2010, and for a 5 day period within the month, respectively. For the month as a whole, poor air quality in the main room is a daily occurrence. The bedrooms have peak carbon dioxide concentrations that regularly exceed 1000ppm. During unoccupied time periods, the ventilation system reduces carbon dioxide to low levels.

Figure 18 also shows the house average carbon dioxide concentration, which is the house carbon dioxide concentration of a well-mixed house. If the house were well-mixed with recirculation, air quality would be much better. Basically, the house has poor air quality in occupied areas, and good air quality in unoccupied regions and during time periods when the house is vacant.

Figure 19 shows results for the same example house with the same occupant and occupant activity levels, but with the allotted ventilation air (120cfm) divided up differently. In Figure 19, the more polluted main room ventilation air flow is increased from 60cfm to 90cfm. The master bedroom is decreased from 20cfm to 10cfm and the office and small bedrooms are reduced from 10cfm to 5cfm air flow. The main living area air quality is improved relative to Figure 18 conditions, however air quality is still poor during much of the occupied time. The bedroom areas all increase in carbon dioxide concentration. On a practical basis, note that adjusting room air flow in the 5 to 10cfm range is very difficult, and never stays at this level as due to changing infiltration levels as well as air filter condition.

Figures 17 and 18 also show the carbon dioxide concentration in a continuously occupied bedroom, such as when someone is ill. The continuously occupied bedroom has 1800 to 2000ppm carbon dioxide during continuous occupancy. Fluctuations in carbon dioxide concentration in the bedroom are due to wind speed variations impacting infiltration. Figures 20 and 21 show the probabilities associated with transmission of the cold virus and flu virus, respectively. The disease transmission charts are based on the Wells-Riley relation in which an airborne contagion's transmission effectiveness is related to carbon dioxide concentration (14).

Carbon dioxide concentration is a measure of the fraction of air in a room that has been in an infected person's lungs. Figures 20 and 21 are based on two people in a room, one infected and one susceptible to infection. The room air quality simulation conditions have higher disease transmission probability because the room with the sick person is primarily filled with carbon dioxide from that person rather than a 50/50 mix of carbon dioxide from a sick occupant and an uninfected occupant. Therefore, the actual probabilities of getting sick are higher than estimated from Figures 20 and 21.

Figure 20, with 2000ppm of carbon dioxide generated by one sick and one uninfected person, indicates the uninfected person to have a chance of 35% to 60% of catching a cold with 4 to 8 hours of exposure to the bedroom air. Influenza transmission efficiency is 10 times greater than that of the cold virus, resulting in nearly 100% transmission probability for a room with 2000ppm with exposure times greater than 4 hours, and over 60% chance of transmission with only 1 hour of exposure time (Figure 21).

Effective ventilation that reduces room carbon dioxide concentrations significantly reduces the probability of transmitting cold and flu viruses. As discussed in our Preventilation – Part 1 report, a large field study (11) found increased building ventilation from 20cfm per person to 40cfm per person reduced employee sick days by the same amount (~35%) as the flu vaccine.

Figure 22 includes a plot of a smart ventilation system with recirculation that unifies air quality throughout the example home. The smart ventilation system's carbon dioxide control setpoint is

1000ppm, which switches the smart ventilator to fresh air ventilation mode at 200cfm. When indoor carbon dioxide is reduced by 100ppm (to 900ppm), the smart ventilator switches to a recirculation mode with sufficient recirculation to keep the house reasonably well-mixed as previously discussed.

Smart ventilation systems are superior to constant flow ventilation by automatically maintaining excellent air quality throughout a home. As discussed for the ventilation case comparisons in Preventilation – Part 1, this smart ventilation system is more energy efficient than a constant ventilation flow home with a high efficiency HRV (90%) using ASHRAE 62.2-2016, requiring 385kWh versus 413kWh for the January 2010 month.

Table 1 Representative activity level Metabolic Units (Met) (ASHRAE 55-2010).

Activity	Met
Sleeping	0.7
Seated, quiet	1.0
Standing, relaxed	1.2
Walking about	1.7
Cooking	1.8
House Cleaning	2.0-3.4
Exercise	3.0-4.0
Heavy exertion	7.0-9.0

Table 2 Met schedule level for 2700ft^2, 4 bedroom home with 5 occupants.

Time Period	Met
0am to 6am	0.7
6am to 8am	2.0
8am to 4pm	0.0
4pm to 7pm	2.0
7pm to 10pm	1.3
10pm to 12pm	0.7

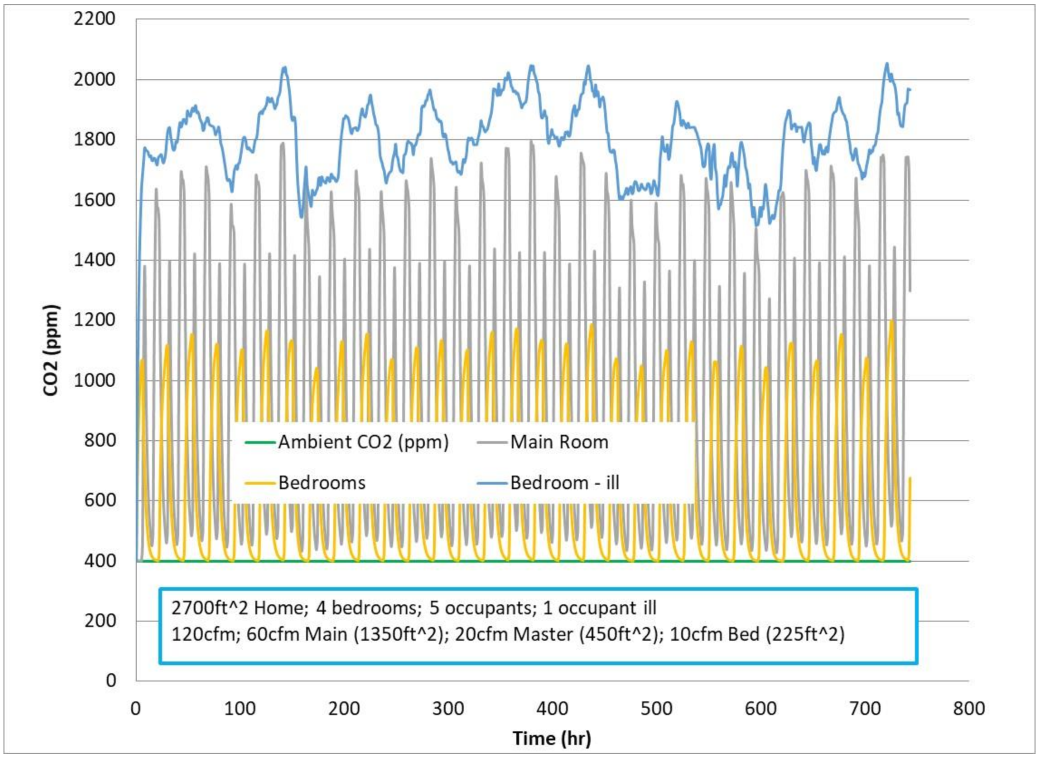

Figure 17 Carbon dioxide variations in a home with constant flow ventilation distributed to 4 bedrooms, an office and an open living room, dining room and kitchen using January 2010 Urbana Illinois weather.

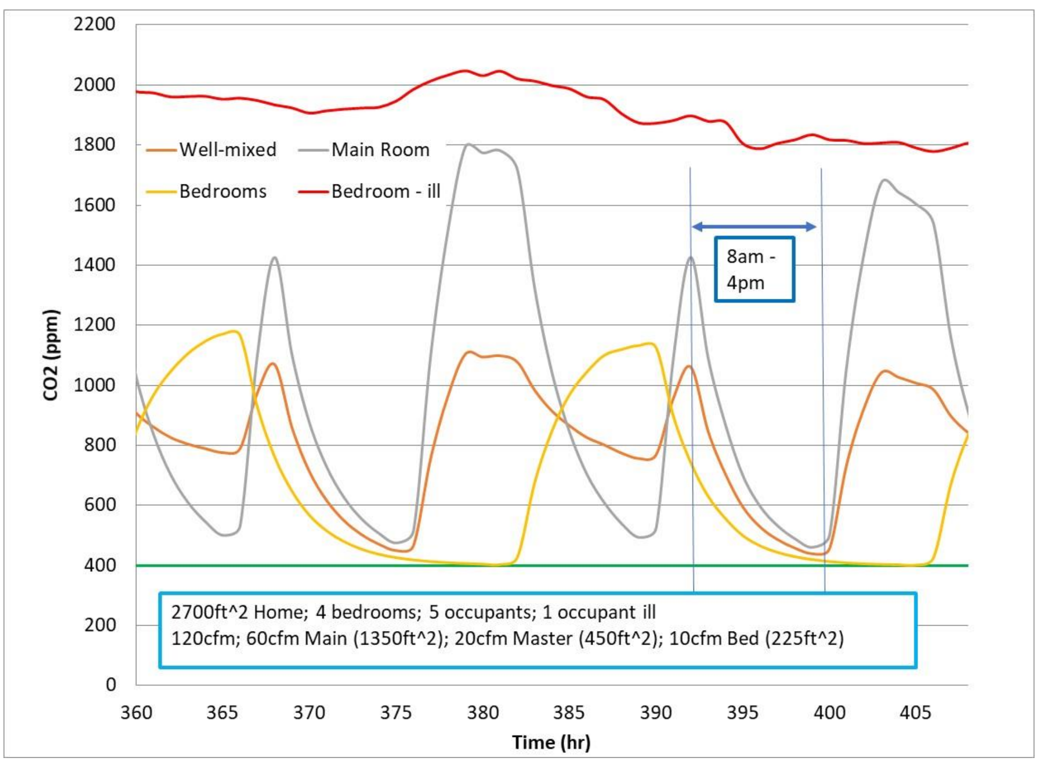

Figure 18 Carbon dioxide variations over a 4 day period during January 2010 Urbana Illinois weather.

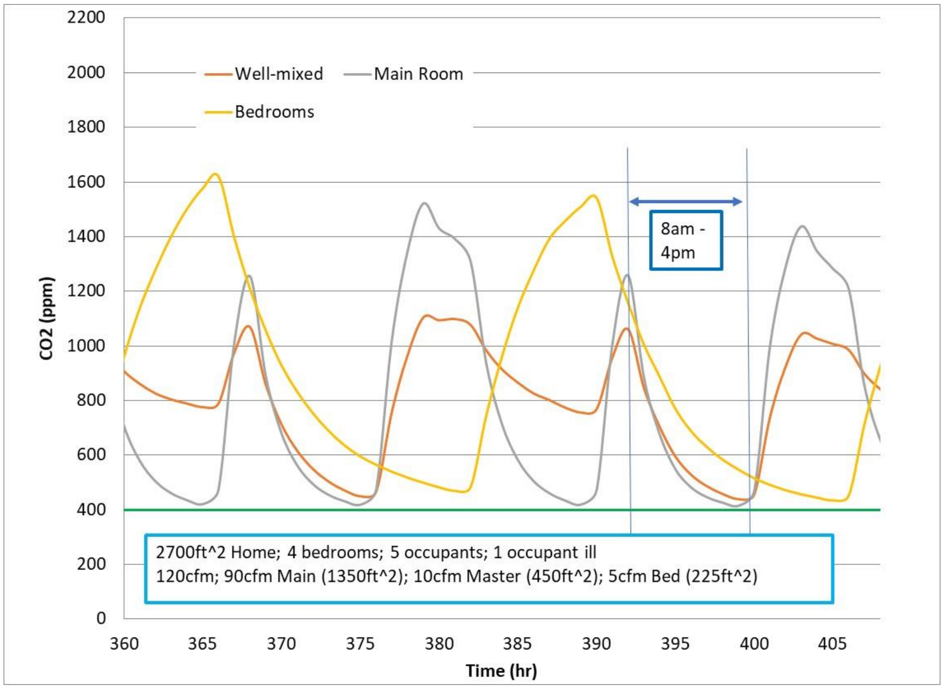

Figure 19 Carbon dioxide variations during 4 day period with January 2010 Urbana Illinois weather data with adjustment to constant air flow distribution.

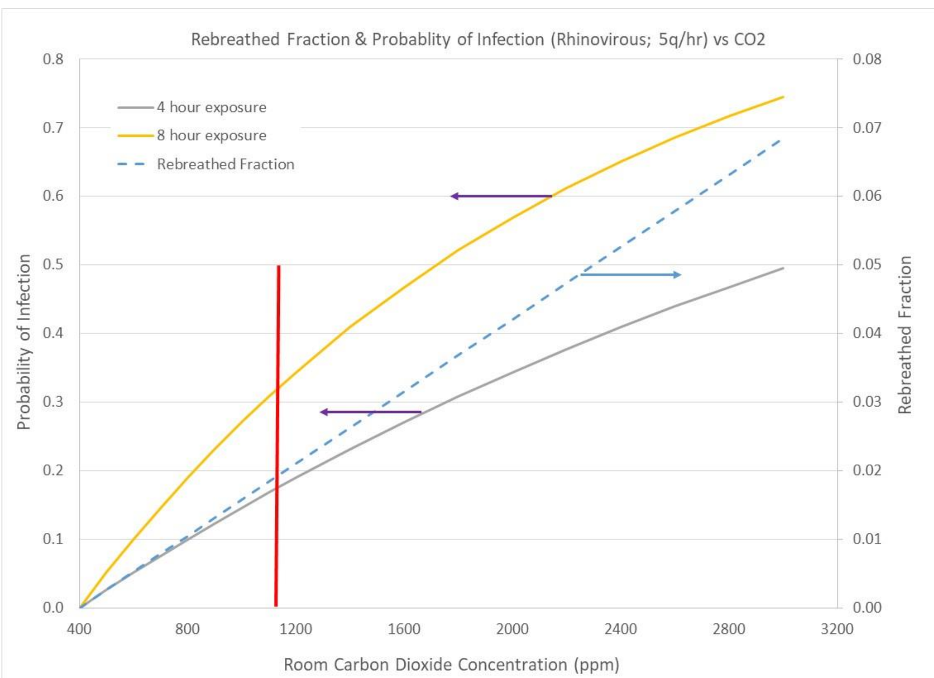

Figure20 Probability of cold virus transmission in a room with one uninfected person and one infected person.

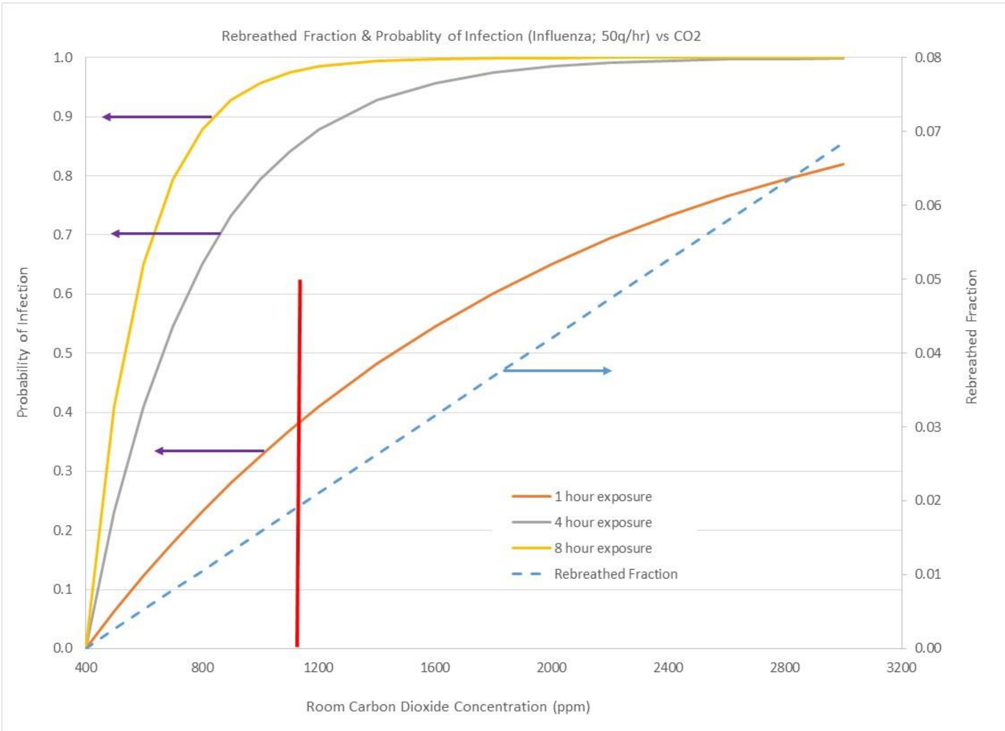

Figure21 Probability of influenza virus transmission in a room with one uninfected person and one infected person.

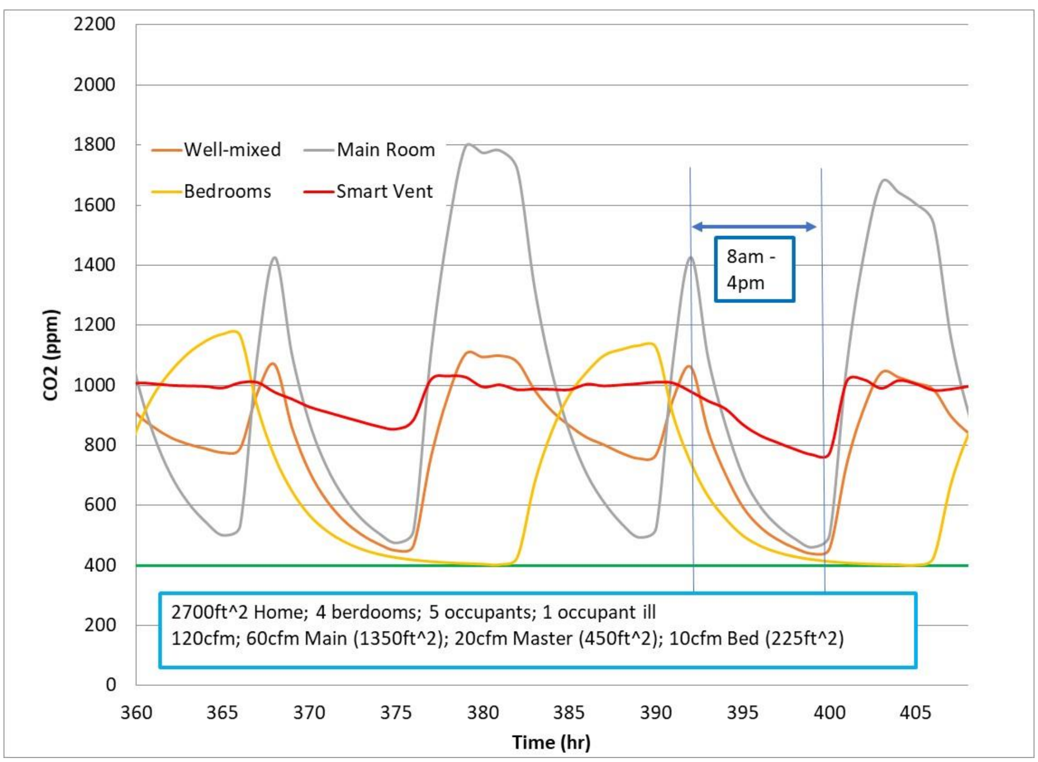

Figure 22 Comparison of indoor air quality (carbon dioxide concentration) between smart ventilation with recirculation and constant ventilation with no recirculation (one-and-done ventilation).

Zone Ventilation Control

Zone ventilation increases the ability to locally control air quality in a building. Dampers manage supply and exhaust air flows from various regions of a home. Zones can be activated automatically or manually. Ideally, damper controlled zones are designed such that minimal damper pressure drop occurs, keeping ventilation fan power and noise at low levels.

Automated zone control sensors determine where pollution is generated and targets those areas for fresh air ventilation and exhaust. Recirculation works to keep a home perfectly mixed, such that all building air is used to maintain air quality before needing to bring in fresh air. Integrating recirculation and zone damper control capabilities further increases ventilation efficiency and effective utilization of fresh air.

We view recirculation as essential in all homes in order to manage particulates. In smaller homes (a small home is defined as one that recirculates the house volume within 1 to 2 hours), recirculation also provides a mechanism for efficient utilization of fresh air. As a home increases in size and room complexity, increasing air recirculation air flow increases fan power and ventilation noise to undesirable levels. Adding zone control capability provides an additional degree of freedom to control air quality in larger homes while maintaining the ability to filter indoor particulates.

Figure 23 is a schematic showing a two zone house with an array of zone sensors and switches that signal a smart ventilation system to favor one zone or another. In the Figure 23 schematic, a damper for the occupied zone is open while the damper of the unoccupied region is partially closed. No zone should ever fully closed as it is important that air movement to some degree continues in all zones.

Figure 24 shows photos of CERV2 dampers and CERV2 wireless temperature, humidity and carbon dioxide concentration sensors, wireless switches, active circuit sensors, and occupancy sensor. CERV2 dampers can be operated by combinations of wired and wireless communications. CERV2's enOcean wireless protocol allows most sensors to be "ambient" powered (battery free).

A single sensor or switch, or multiple sensors and switches can wirelessly communicate with the CERV2 unit to activate fresh air venting or an enhanced recirculation event. For example, local carbon dioxide concentration sensors distributed throughout house zones will detect a local pollutant increase that exceeds a zone's setpoint threshold, causing dampers to move to positions that enhance fresh air to the zone(s) requiring additional fresh air. Fan speed may also be automatically increased for additional fresh air flow to those regions. Occupancy sensors automatically trigger enhanced fresh air distribution to occupied areas. Note that sensors can overlap zones. For example, if two supply zones have the same exhaust zone, the appropriate dampers respond accordingly.

Figures 25, 26, and 28 are illustrations of two zones with supply and return dampers. One zone consists of the living room and kitchen, and the second zone consists of a bedroom and a bathroom. In Figure 25, normal operation is shown with dampers in both zones fully open. Figure 26 shows a triggered (wireless switch activated) event for enhanced air flow to the living room and kitchen and reduced (partially closed) air flow to the bedroom and bathroom. Figure 27 shows the opposite with a switched ventilation event for the bedroom and bathroom. Note that any of the other sensors shown in Figure 24 can be utilized in parallel with switches. For example, the bathroom may be triggered by an occupancy sensor and/or humidity sensor while a local carbon dioxide sensor in the living room and/or an active circuit sensor connected to the vent hood in the kitchen could call for enhanced venting. Note that fan speed can also be adjusted during calls for enhanced or multiple zone venting.

Figure 28 is a plot of the "C value" of a 6 inch diameter CERV2 damper versus damper position. Our Ductology Part 1 and Part 2 reports describe the C value, which is a parameter that relates pressure drop across a section of duct to the air flow through the duct section. Energy efficient zone control requires good duct design. As described in Ductology Part1 and Part2, economically optimized ducts will have C values greater than 1000, with duct velocities in the 300 to 400fpm (feet per minute) range.

A duct distribution system with multiple dampers can use the C values to determine how air flow rates are shifted among different zones in a similar manner. The duct system's C values are important for this analysis and the interested reader should refer to appropriate resources such as the ASHRAE Handbook of Fundamentals as well as our Ductology Part 1 and Part 2 reports. For the present discussion, we assume that the duct distribution system has a high C value, indicating low pressure drop and negligible impact on air flow among the zone dampers. When a duct distribution has low C values, duct sections control flow distribution requiring greater zone damper closures for adjusting flow causing increased pressure drop, fan power and noise generation.

As an example, assume a CERV2 distribution system with 5 zones (5 supply and 5 return, see Figure 29). For a CERV2 operating at 200cfm, when all 5 dampers are fully open with the same C values (and negligible connecting duct pressure drop), each zone has 40cfm of supply and return air. During a situation when more air flow is required for one zone (eg, a wireless local carbon dioxide sensor signals high concentration in a zone) while other zones do not require increased flow, the supply and return dampers in the enhanced zone remain fully open while the supply and return zone dampers are closed to 45 degrees. Assuming negligible pressure drop between dampers as air flow changes, damper C values can be from Figure 28. C values are independent of air flow, and for a fully open, 6 inch diameter damper, the C value is 1500 and the partially closed dampers have C values of 250 (see Figure 30). Zone 1 would have 120cfm air flow while the Zones 2-5 have 20cfm of air flow. The pressure drop across the dampers, which can also be determined from the C value information, is 0.014"H_2O.

Note that many combinations of air flow proportioning can be achieved with dampers, such as multiple zones requiring enhanced flow or a triggered exhaust event such as a switch or occupancy sensor in a bathroom. Fan speeds in the CERV2 can be adjusted in addition to damper control, providing an additional degree of freedom.

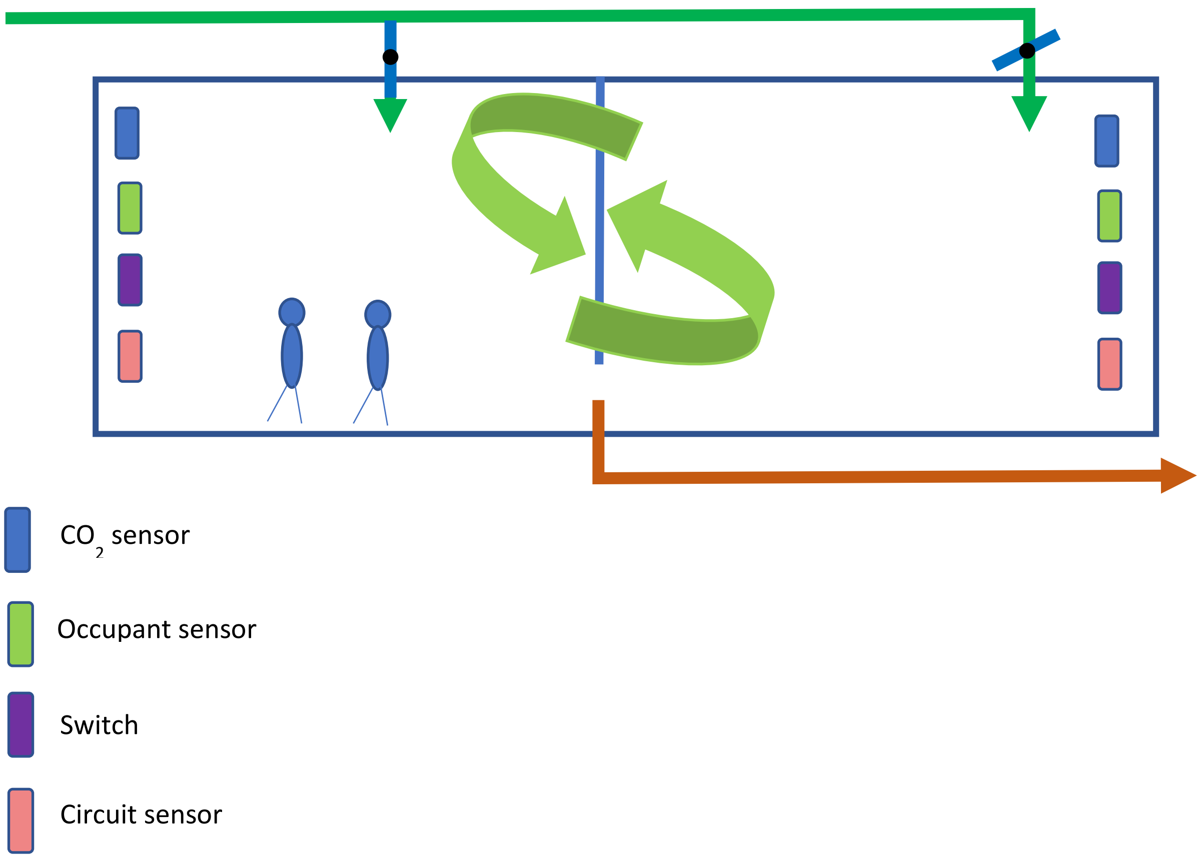

Figure 23 Schematic of zone control of two rooms with combination of occupancy, air quality, active circuit sensing and manual zone control capabilities.

Figure 24 Photos of CERV2 zone control dampers with battery-free wireless air quality sensor, wireless switch, active circuit transmitters (high and low voltage), and wireless occupancy sensor.

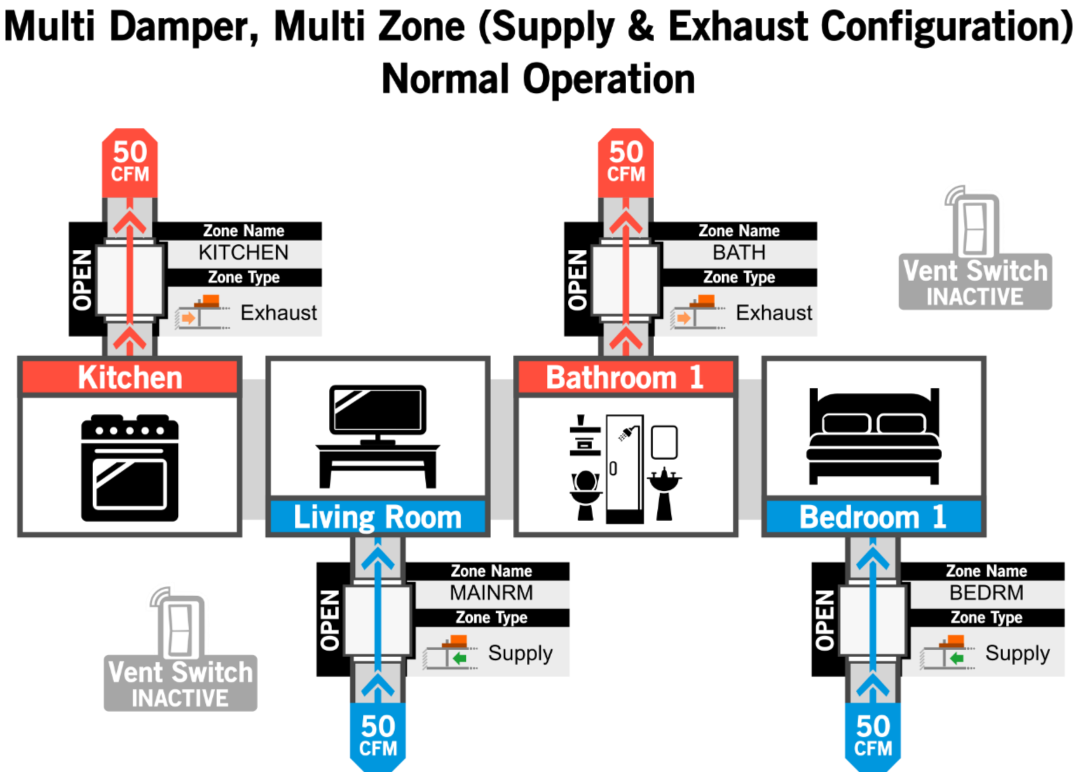

Figure 25 Two zone control with supply and return damper control with dampers fully opened.

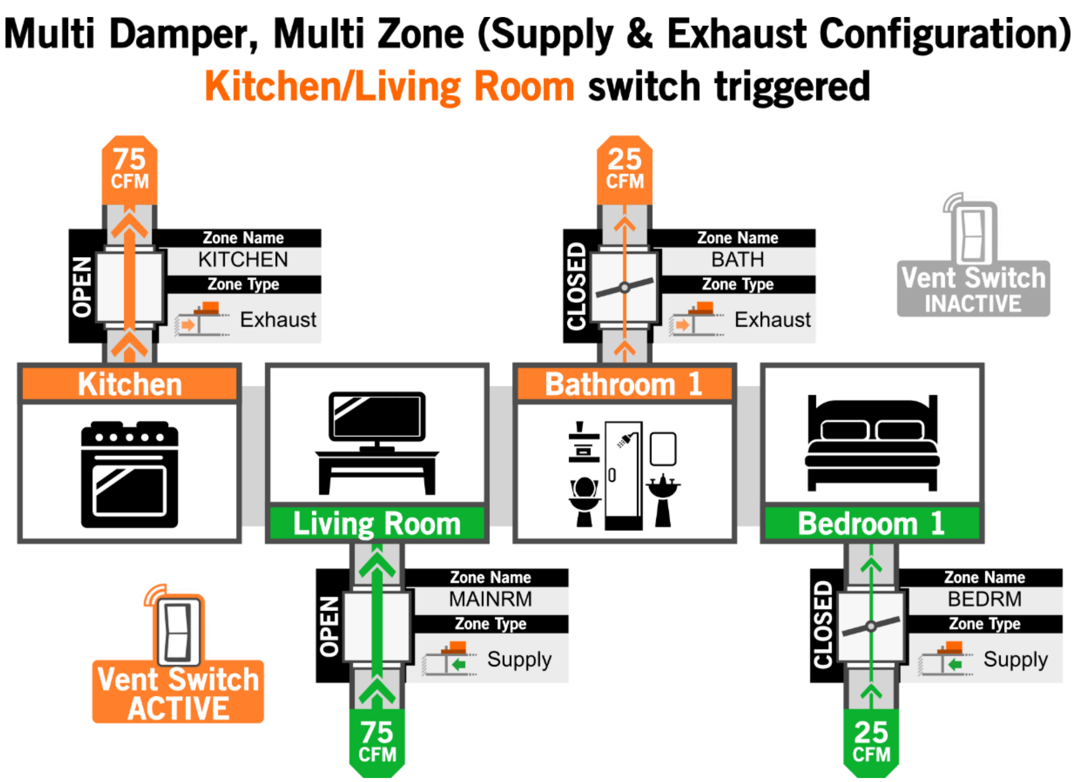

Figure 26 Two zone control with living room (supply) and kitchen (exhaust) dampers open and bedroom 1 (supply) and bathroom 1 exhaust partially closed due to living room/kitchen vent trigger.

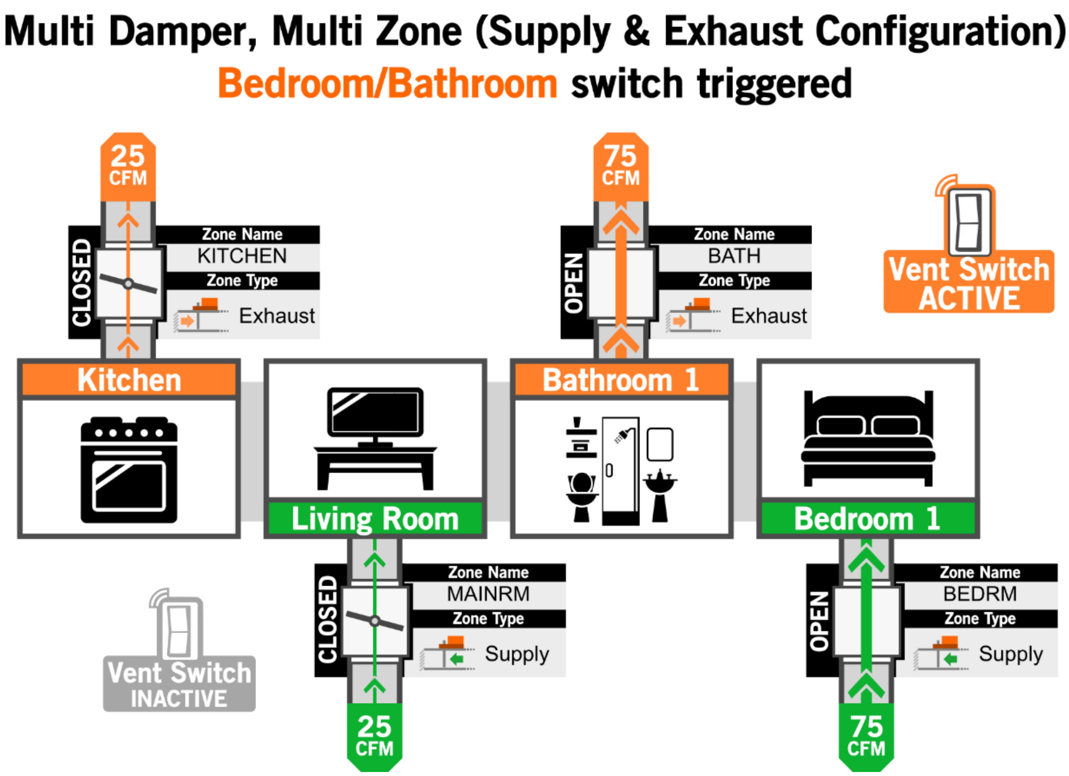

Figure 27 Two zone control with living room (supply) and kitchen (exhaust) dampers open and bedroom 1 (supply) and bathroom 1 exhaust partially closed due to bedroom/bathroom vent trigger.

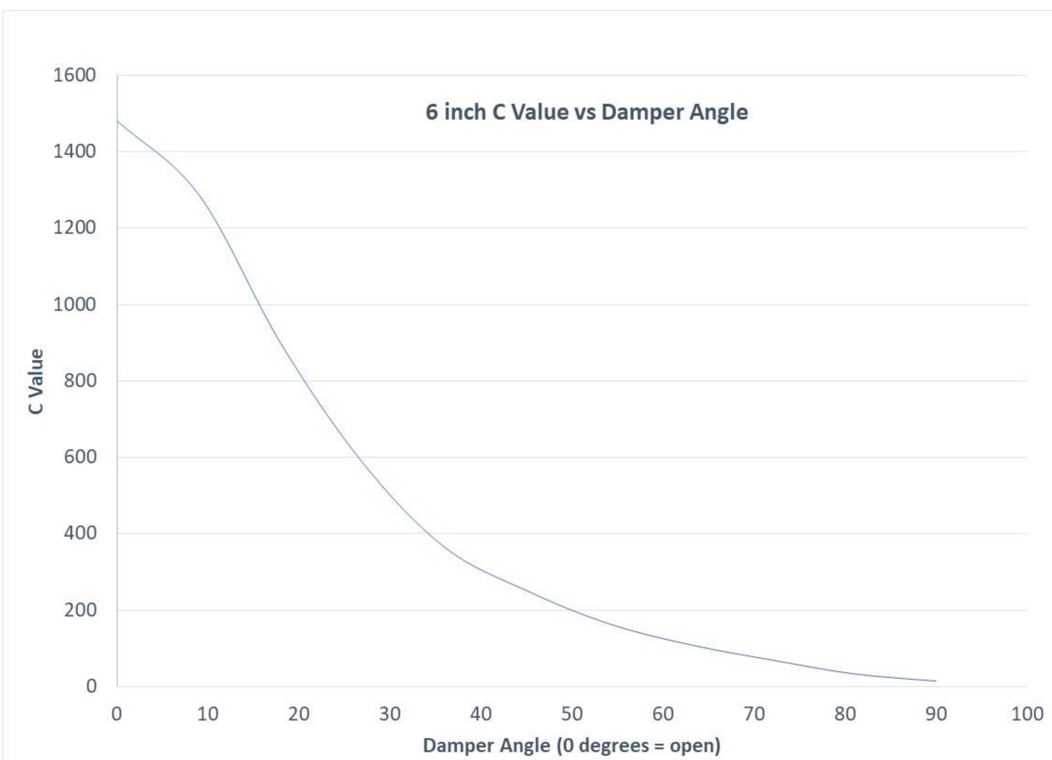

Figure 28 C value characteristics for a 6 inch diameter CERV zone damper.

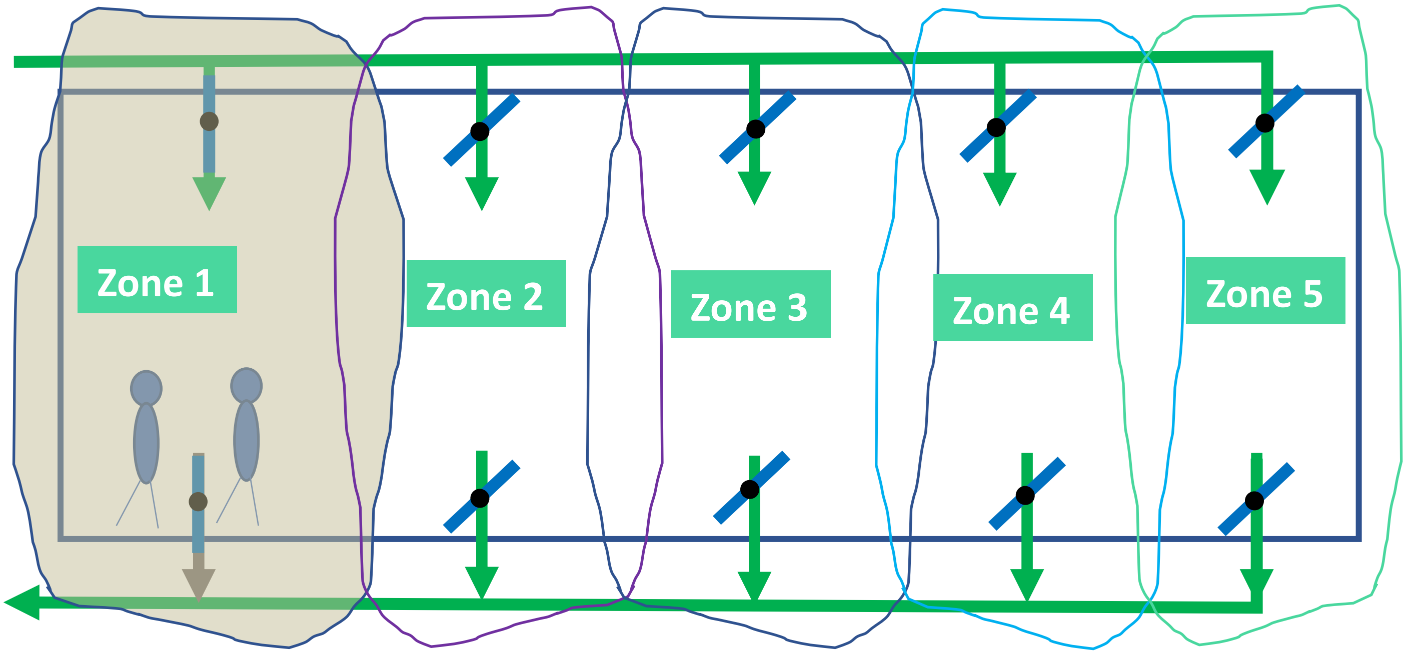

Figure 29 Five zone supply and return schematic with one occupied zone requiring enhanced flow.

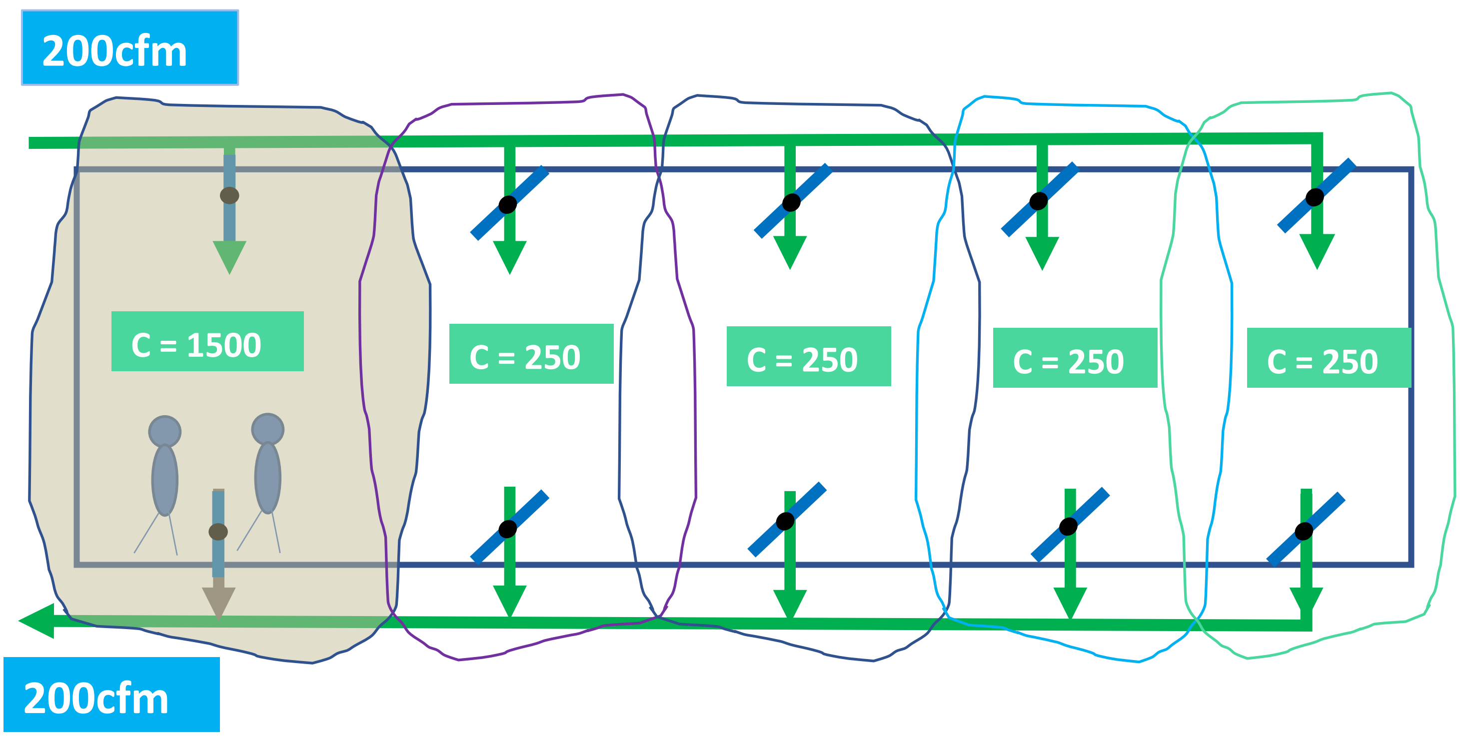

Figure 30 C-values 6 inch diameter damper (Figure 28) for Zone 1 (open) and Zones 2-5 (45 degree damper closure). Zone 1 has 120cfm while Zones 2-5 have 20cfm.

Local (Triggered) Venting

Local exhaust enhancement is desirable for events such as cooking or showering. Rather than waiting for air quality sensors to pick up elevated pollutant levels, a local exhaust event can be triggered directly through manual switches or circuit sensors. During a local exhaust event, a user selected exhaust time period is chosen and a triggered exhaust fan speed is chosen. For high pollutant generation events such as cooking, enhanced local exhaust provides additional protection for occupants (eg, cooks) in the local pollutant generation zone. Smart ventilation ensures that “excess” fresh air introduced to a home during a triggered exhaust will be utilized efficiently by sensing the addition of fresh air. High pollutant generation periods with local exhaust removal of pollutants allow higher pollutant concentrations to be removed before they can be diluted with indoor air, further improving ventilation efficiency.

Figure 31 shows an example of enhanced kitchen exhaust for a CERV2 smart ventilation system. Kitchen exhausting is commonly triggered with a manual wireless switch and/or active circuit transmitter (installed in recirculating kitchen vent hood wiring). For wired damper operation, a single auxiliary relay (included with the CERV2 controller) operates dampers without an additional relay expansion board. When enhanced kitchen exhaust is triggered, dampers in other return branches are reduced, causing kitchen exhaust ventilation air flow to increase. The trigger signal additionally adjusts the CERV2’s supply and exhaust fan speeds to a user selected level. The enhanced venting operates until user selected time period or active circuit sensing ceases.

During a triggered ventilation period, fresh air flow distributed throughout the house will be re-directed toward the open kitchen exhaust with reduced (but never fully closed) exhausts from other zones. Beyond this simple example, layers of control occur with the CERV2’s algorithms managing multiple zone control needs as well as simultaneous local triggered events (eg, local air quality sensor requiring increased fresh air for a zone coupled with a triggered exhaust event for a different region).

Larger, more complex home environments use multiple CERV2 units that seamlessly overlap. Multiple CERV2 units may be ducted in independent manners, with some zones managed by one of the CERV2 units. In other cases, a single duct distribution system with multiple CERV2 units distributed throughout the duct network can work interactively with each other to manage local air quality and triggered exhausting.

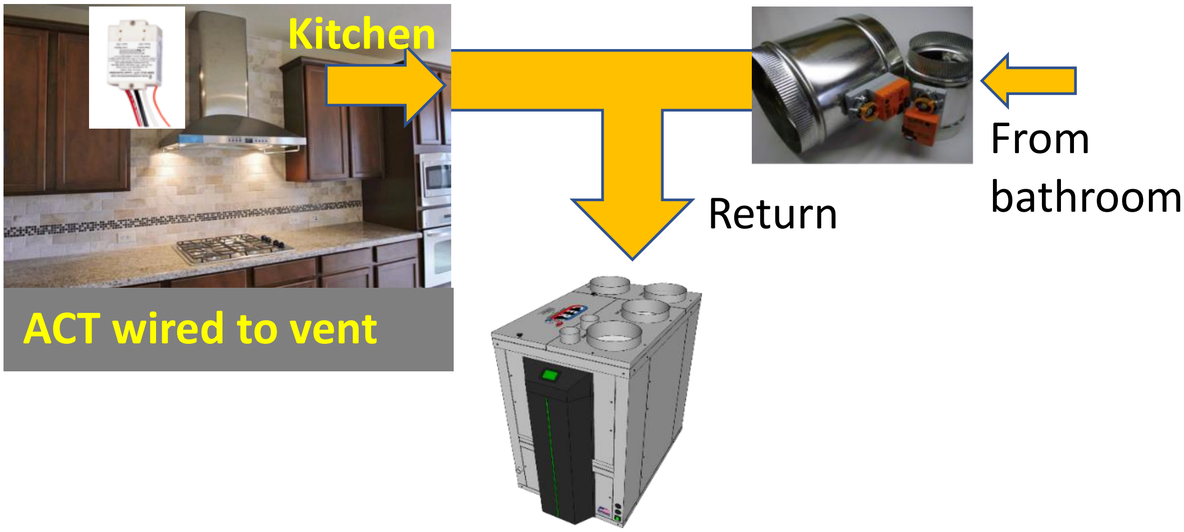

Figure 31 Simple example of local exhaust zoning with kitchen exhaust enhanced by reducing other house return flow.

Summary

Smart air distribution is an essential feature of smart ventilation systems. Constant ventilation without effective fresh air distribution results in inefficient use of fresh air and poor air quality in occupied rooms. Recirculation should always be part of smart air distribution, with precision zone air flow added when needed for additional air quality management.

Recirculation promotes utilization of fresh air stored in unoccupied regions of a home and for particulate filtering. As homes become larger (greater than 1-2 hours for house volume recirculation) and more complex, precision ventilation with zone sensor monitoring and damper control can be layered on recirculation.

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Appendix A – Human Pollutant Generation

We define “effective” carbon dioxide concentration as a combination of the average human (female and male) carbon dioxide output combined with human expelled VOCs. Figures below provide a description of female and male carbon dioxide output based on body mass and metabolic activity.

In addition to human carbon dioxide output, humans offgas various chemical compounds in our respiration, exuded through our skin, and from the microbiome living on us. At a high enough concentration level, human VOCs become offensive odors. The 20cfm per person ventilation rule-of-thumb was developed in the 1930’s by Harvard researchers who found that a recently showered human wearing clean clothing and performing office work level activity (sedentary) offended 20% of the general population (21).

A human subject was placed in a sealed room with a control flow of fresh air through the room. Experiment participants were recruited who smelled the air exhausted from the room. Only recently have we learned that carbon dioxide at these ventilation levels (~1000ppm) impair cognition. We have known that VOCs, such as emitted by offgassing from furnishings (carpeting, paints, polymers of various sorts), cleansers, adhesives, cosmetics, and many other sources also impair cognition and productivity as well as detrimentally impacting on our health.

A 30 to 40 year old female weighing 165 pounds (74.5kg) at sedentary conditions (1.2 Met) produces 0.0035liters per second of carbon dioxide. A 30 to 40 year old male weighing 191 pounds (87kg) at sedentary conditions produces 0.0046liters per second, or 0.0046liters per second of carbon dioxide. The average female and male carbon dioxide output is 0.00405liters per second, or 0.0275kg/hour.

We do not know the specific impact of differ VOCs, as well as the combined effects of carbon dioxide and VOCs on our health and cognition, but we do know the combination of both affects our health and performance. In order to account for an “average” VOC impact, we assume a unit of human VOC output correlated to human carbon dioxide output as an additional effect to the pollution loading affecting building occupants. That is, an average human (female and male average) at sedentary conditions outputs a VOC loading equivalent to 0.0275kg/hour of carbon dioxide.

We assume the combination of carbon dioxide and VOC loading to be a vector addition rather than a direct sum, although we have no basis at this time for a rational method for combining the effects. Future research on carbon dioxide combined with common VOCs will help guide the best method for determining how health is impaired and cognition degraded. Based on a vector addition of effects, we find an effective average human carbon dioxide production rate of:

$$\text{Carbon dioxide generation (kg/hour)} = (0.0275^2 + 0.0275^2)^{1/2} = 0.04\text{kg/hour}$$

The analyses conducted in this report use a reference average human carbon dioxide generation rate of 0.04kg/hour. Note that very small increases in metabolic activity (walking, cooking, etc) will result in human carbon dioxide outputs exceeding this assumed value. In fact, a human’s carbon dioxide output can vary by almost a factor of 10 from sleep to vigorous exercise. Therefore, the air quality in a home with 4 sedentary occupants can be the same as a home with one very active occupant.

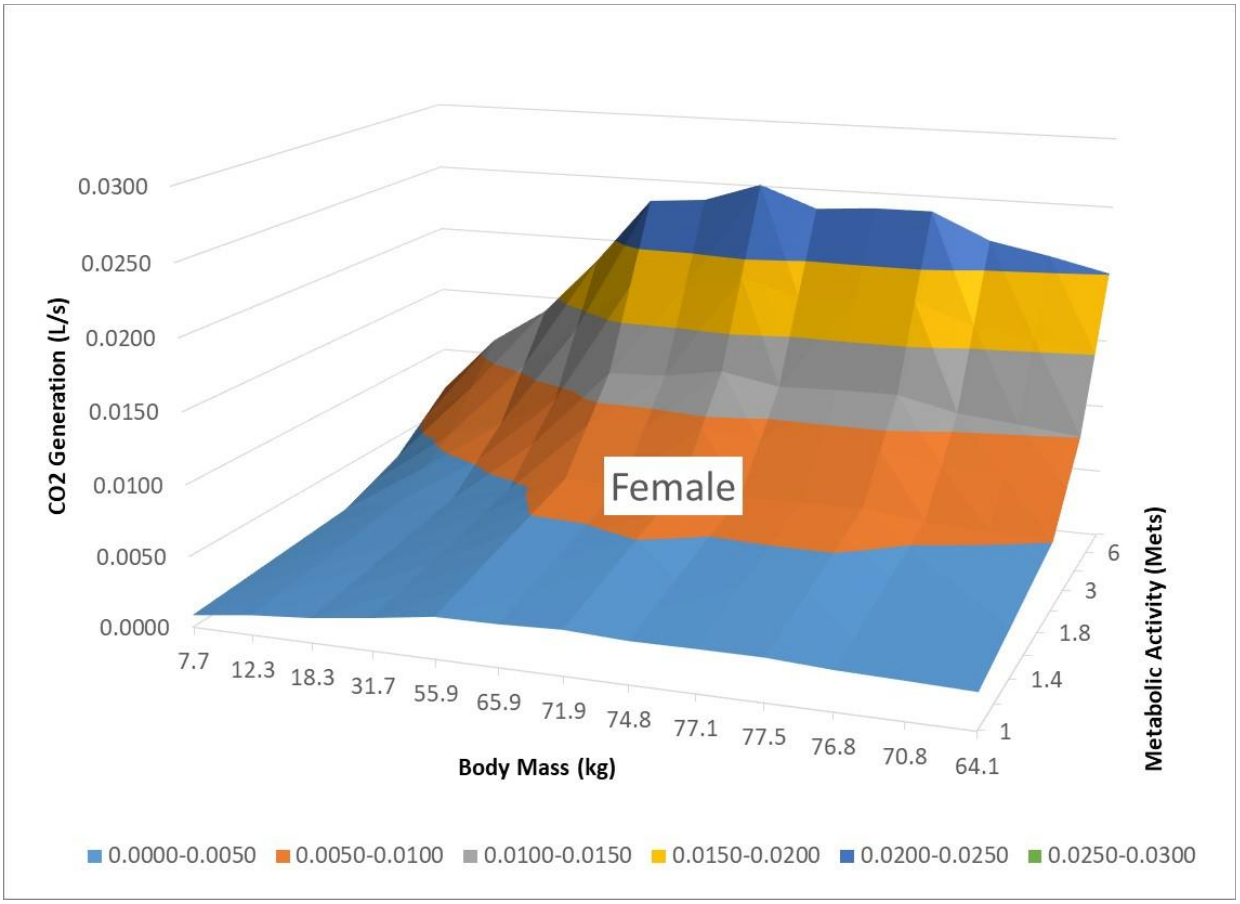

Figure 10 Female carbon dioxide output based on body mass and metabolic activity.

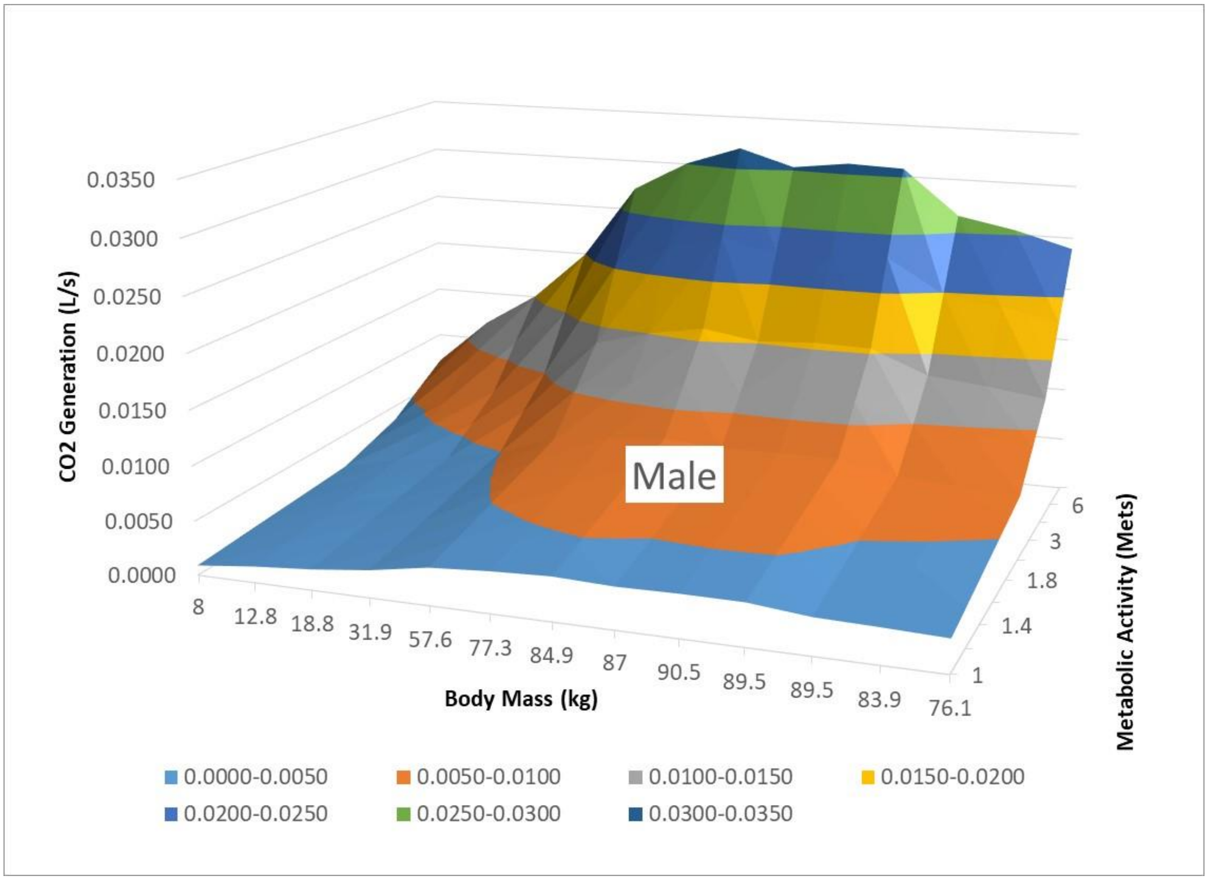

Figure 11 Male carbon dioxide output based on body mass and metabolic activity.

Appendix B Ventilation Performance Parameters for a Well-Mixed (non-zoned) Building

Several parameters quantify the performance characteristics of ventilation systems during recirculation, fresh air ventilation. We list these parameter relations for a non-zoned (well-mixed) building in a format that is directly useable with commonly used units. Although the hybrid units we use may be upsetting to some who would prefer purely SI unit consistency, the units selected allow those in North America to use directly in spreadsheets for their own analyses.

Recirculation Time Constant:

The recirculation time constant characterizes the time required to "turn over" the air within a building. Buildings with recirculation time constants less than 1 to 2 hours should mix air within the building in a reasonable manner as well as filter indoor particulates effectively. As building recirculation time constant exceeds two hours, active zone control becomes desirable.

$Ƭ = V/Å_r$

Where $Ƭ$ = time constant (minutes)

V = building volume (ft^3)

$Å_r$ = building recirculation air flow rate (cfm)

Steady Airflow Rate to Maintain Steady Carbon Dioxide Concentration (well-mixed building):

The fresh airflow required to maintain carbon dioxide at a steady level above ambient (outdoor) carbon dioxide in a building with steady occupancy can be determined as:

$Å_{f\text{-}steady}$ = steady fresh air flow rate to building (cfm) = $P \times M \times 10{,}000 / (C_B - C_{amb})$

Where P = number of building occupants

M = occupant activity level (Metabolic units or Mets; 1.3Met for sedentary activity)

C_B = steady building carbon dioxide concentration (ppm)

C_{amb} = outdoor carbon dioxide concentration (ppm)

Example: A building with 2 sedentary people requires an airflow of 37cfm to maintain indoor carbon dioxide concentration of 1100ppm with an outdoor carbon dioxide concentration of 400ppm.

No Vent Time Length (well-mixed building):

The time length for a room or well-mixed building volume to change a specified carbon dioxide concentration amount can be determined as:

$t_{no\ vent}$ = time length (minutes) with no fresh air = $V_z \times DC /(10{,}000 \times P \times M)$

Where V_z = building or zone volume (ft^3)

DC = building or zone carbon dioxide change (ppm)

P = number of building occupants

M = occupant activity level (Metabolic units or Mets; 1.3Met for sedentary activity)

Example: A 10,000ft^3 building with 2 sedentary people will increase 200ppm in carbon dioxide level in 77 minutes.

Vent Time Length (well-mixed building):

The time length required to reduce a well-mixed building by a specified carbon dioxide concentration with a given number of occupants with a specified activity level is determined as:

t_{vent} = time length (minutes) to reduce carbon dioxide concentration

$$= (V_z / Å_f) \times \ln[(C_i – C_{amb} – 10{,}000 \times P \times M / Å_f)/ (C_i – DC - C_{amb} – 10{,}000 \times P \times M / Å_f)$$

Where V_z = building or zone volume (ft^3)

$Å_f$ = fresh air flow rate (cfm)

DC = desired building or zone carbon dioxide decrease (ppm)

P = number of building occupants

M = occupant activity level (Metabolic units or Mets; 1.3Met for sedentary activity)

C_i = initial building carbon dioxide concentration (ppm)

C_{amb} = outdoor carbon dioxide concentration (ppm)

The ventilation time is subject to a constraint that requires the fresh air ventilation flow rate is sufficient to reduce the carbon dioxide concentration by the specified amount:

$Å_{f\text{-}min}$ = minimum fresh air flow rate (cfm) > 10,000 x P x M / (C_i – DC - C_{amb})

Example: Can 200cfm of fresh air flow reduce a 10,000ft^3 building by 100ppm from 1000ppm of carbon dioxide with 2 sedentary people, and if so, how long is required for fresh air venting? Ambient carbon dioxide is 400ppm.

A minimum fresh airflow of 52cfm is required to reduce the building's carbon dioxide by 100ppm, less than the 200cfm ventilation air flow rate. 12 minutes is required to reduce the room carbon dioxide concentration by 100ppm with 200cfm air flow.

Fraction of Time in Fresh Air Venting (well-mixed building):

A building with a sufficiently high fresh air flow rate for reducing a building's carbon dioxide concentration a desired amount can be determined by dividing the ventilation time length by the sum of the ventilation time length period and the no-ventilation time length period.

$f_{vent} = t_{vent} / (t_{vent} + t_{no\ vent})$ = fraction of time required for fresh air venting

$$= \frac{10{,}000 \ln[(C_i - C_{amb} - 10{,}000 \times P \times M / Å_f)/ (C_i - DC - C_{amb} - 10{,}000 \times P \times M / Å_f)}{V_z x DC /(PxM)+10{,}000 \ln[(C_i - C_{amb} - 10{,}000 \times P \times M / Å_f)/ (C_i - DC - C_{amb} - 10{,}000 \times P \times M / Å_f)}$$

The fresh air venting fraction is subject to the same constraint that the fresh air flow rate is sufficient for reducing the building carbon dioxide by the desired amount:

$Å_{f\text{-}min}$ = minimum fresh air flow rate (cfm) > $10{,}000 \times P \times M / (C_i - DC - C_{amb})$

Appendix C Zoned Building Ventilation Performance Parameters

A building with zones and no recirculation suffers from inefficient distribution of fresh air to occupied rooms and waste of fresh air delivered to unoccupied rooms. The ventilation parameters for vent and no-vent time lengths are extensions of the well-mixed parameters with the addition of a zone fraction parameter and ventilation efficiency parameter. The following describe a zoned building's ventilation characteristics.

Zone Fraction Parameter:

The Zone Fraction parameter is the fraction of a building's volume defined as a zone.

$\beta_v = V_z/V$

Where β_v = zone volume fraction

V_z = zone volume (ft^3)

V = building volume (ft^3)

Ventilation Efficiency:

The Ventilation Efficiency parameter is the fraction of fresh ventilation air that benefits a building's occupants. High recirculation air flows (low building time constants) result in high ventilation efficiency. Zone control to move fresh air where occupants are located within a building also increases the ventilation efficiency. Ideal ventilation efficiency limit is 1.

$\beta_z = \text{Å}_{fz}/\text{Å}_f$

Where β_z = fraction of fresh air benefiting occupants

Å_{fz} = fresh air flow rate to building zone (cfm)

Å_f = total fresh air flow rate to building (cfm)

For buildings with no recirculation and fresh air flow evenly divided among zones, the ventilation efficiency is:

$\beta_z = 1/Z$

where Z = number of zones

No Vent Time Length (zoned building):

The time length for a room or building zone volume to increase a specified carbon dioxide concentration amount with no fresh air ventilation can be determined as:

$t_{no\ vent}$ = time length (minutes) with no fresh air = β_v x V_z x DC /(10,000 x P x M)

Where V_z = building or zone volume (ft^3)

β_v = zone volume fraction

DC = building or zone carbon dioxide change (ppm)

P = number of building occupants

M = occupant activity level (Metabolic units or Mets; 1.3Met for sedentary activity)

Example: A 1000ft^3 room in a 10,000ft^3 building with 2 sedentary people will increase 200ppm in carbon dioxide level in 7.7 minutes without fresh air flow.

Vent Time Length (zoned building):

The time length required to reduce a zoned building space by a specified carbon dioxide concentration with a given number of occupants with a specified activity level.

t_{vent} = time length (minutes) to reduce carbon dioxide concentration

$= (\beta_v x V_z)/(\beta_z x Å_f) \text{ x } \ln[(C_i - C_{amb} - (10{,}000xPxM)/(\beta_z x Å_f)/(C_i - DC - C_{amb} - (10{,}000xPxM)/(\beta_z x Å_f)$

Where V_z = building or zone volume (ft^3)

$Å_f$ = fresh air flow rate (cfm)

β_v = zone volume fraction

β_z = fraction of fresh air benefiting occupants

DC = desired building or zone carbon dioxide decrease (ppm)

P = number of building occupants

M = occupant activity level (Metabolic units or Mets; 1.3Met for sedentary activity)

C_i = initial building carbon dioxide concentration (ppm)

C_{amb} = outdoor carbon dioxide concentration (ppm)

The ventilation time is subject to a constraint that requires the fresh air ventilation flow rate is sufficient to reduce the carbon dioxide concentration by the specified amount:

$Å_{f\text{-}min}$ = minimum fresh air flow rate (cfm) > 10,000 x P x M / (β_z x(C_i – DC - C_{amb}))

Example: Can 200cfm of fresh air flow reduce a 10,000ft^3 building by 100ppm from 1000ppm of carbon dioxide with 2 sedentary people, and if so, how long is required for fresh air venting? Ambient carbon dioxide is 400ppm.

A minimum fresh airflow of 52cfm is required to reduce the building's carbon dioxide by 100ppm, less than the 200cfm ventilation air flow rate. 12 minutes is required to reduce the room carbon dioxide concentration by 100ppm with 200cfm air flow.

Fraction of Time in Fresh Air Venting (well-mixed building):

A building with a sufficiently high fresh air flow rate for reducing a building's carbon dioxide concentration a desired amount can be determined by dividing the ventilation time length by the sum of the ventilation time length period and the no-ventilation time length period.

$$f_{vent} = t_{vent} / (t_{vent} + t_{no\ vent}) = \text{fraction of time required for fresh air venting}$$

$$= \frac{10{,}000 \ln[(C_i - C_{amb} - 10{,}000 \times P \times M / (\beta_z x Å_f) / (C_i - DC - C_{amb} - 10{,}000 \times P \times M / (\beta_z x Å_f)}{\beta_z x V_z x DC/(PxM) + 10{,}000 \ln[(C_i - C_{amb} - 10{,}000 x P x M/(\beta_z x Å_f)/(C_i - DC - C_{amb} - 10{,}000 x P x M/(\beta_z x Å_f)}$$

The fresh air venting fraction is subject to the same constraint that the fresh air flow rate is sufficient for reducing the building carbon dioxide by the desired amount:

$$Å_{f\text{-}min} = \text{minimum fresh air flow rate (cfm)} > 10{,}000 \times P \times M / (\beta_z x(C_i - DC - C_{amb}))$$