LBNL 56292

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Efficacy of Intermittent Ventilation for Providing Acceptable Indoor Air Quality

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Technologies Division**

October 2004

This work was supported by the Assistant Secretary for Energy Efficiency and Renewable Energy, Building Technologies Program, of the U.S. Department of Energy under contract No. DE-AC03-76SF00098.

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ABSTRACT

Ventilation standards and guidelines typically treat ventilation as a constant and specify its value. In many circumstances a designer wishes to use intermittent ventilation, rather than constant ventilation, but there are no easy equivalencies available. This report develops a model of efficacy that allows one to calculate how much intermittent ventilation one needs to get the same indoor air quality as a the continuous value specified. We have found that there is a simple relationship between three dimensionless quantities: the temporal ventilation effectiveness (which we call the efficacy), the nominal turn-over and the under-ventilation fraction. This relationship allows the calculation of intermittent ventilation for a wide variety of parameters and conditions. We can use the relationship to define a critical time that separates the regime in which ventilation variations can be averaged over from the regime in which variable ventilation is of low effectiveness. We have found that ventilation load-shifting, temporary protection against poor outdoor air quality and dynamic ventilation strategies can be quite effective in low-density buildings such as single-family houses or office spaces. The results of this work enable ventilation standards and guidelines to allow this extra flexibility and still provide acceptable indoor air quality.

Keywords: Ventilation, Air Exchange Rate, Indoor Air Quality, Ventilation Standards

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INTRODUCTION

A key step in designing a building is determining the correct amount of ventilation and the optimal system with which to provide it. There is no shortage of guidance on how much ventilation to use. The standard of care for ventilation system design is probably the 62 series of ASHRAE standards (62.1-2004 for non-residential buildings and 62.2-2004 for residential buildings). One can find a variety of books and other publications with recommendations including from ASHRAE (http://www.ashrae.org)

When ventilation rates are stated in terms of airflow rate per person or airflow rate per floor area, we generally assume a constant airflow during the entire period of interest. There are, however, a variety of reasons why one might want to design and operate the ventilation system with variable amounts of ventilation airflow. For example:

- There may be periods of the day when the outdoor air quality is poor and one wishes to reduce the amount of outdoor air entering the building;
- Economizer operation can over-ventilate a space from the point of view of indoor air quality; energy savings can be achieved by lower ventilation rates at other times by taking account of the over ventilation;
- Demand charges or utility peak loads may make it advantageous to reduce ventilation for certain periods of the day; and
- Some HVAC equipment may make cyclic operation more attractive than steady-state operation such as residential or small commercial systems that tie ventilation to heating and cooling system operation.

Regardless of the reason, the designer or decision-maker needs a method to determine how intermittent ventilation compares to continuous ventilation for the purposes of providing acceptable indoor air quality. ASHRAE Standard 62.1-2004 does not directly address these issues; 62.2-2004 does address intermittent ventilation in a limited way.

The purpose of this report is to develop approaches for determining the equivalency of intermittent ventilation based on fundamental principles, and to demonstrate these approaches using a few representative cases of interest in both residential and non-residential buildings.

Background

Ventilation is principally used to maintain acceptable indoor air quality by controlling indoor contaminant concentrations and minimizing occupant exposures to the contaminants. Whole-building ventilation dilutes contaminants in the indoor air with air that does not contain those contaminants, and is normally used for controlling unavoidable, generic or non-specific contaminants. When specific contaminant sources can be identified, they are best dealt with directly through source control methods including local exhaust. For example, bathroom and cooking contaminants (including water vapor) are best addressed by exhaust fans in those spaces. Volatile Organic Compounds (VOC) are often best addressed by changes in composition or use of specific materials.

If ventilation rate and contaminant concentration were linearly related, the average concentration would be proportional to the average ventilation and straightforward methods could be used to determine the effectiveness of intermittent ventilation. Unfortunately, ventilation and concentration are dynamically and inversely related through the mass continuity equation, which leads to a typically non-linear relationship between ventilation and concentration.

Solutions to the continuity equation always involve an air change rate appropriate to the problem at hand. Although we are often more accustomed to dealing with ventilation in terms of specific airflow rates, the efficacy of intermittent ventilation will depend on the air change rate, so it is important to keep typical rates in mind for some specific, but common occupancies. A related parameter of interest is the *turn-over time*, which is the inverse of the air change rate. It is the characteristic time in which the concentration of a contaminant responds to a change in ventilation rate.

One can derive typical air change rates and turn-over times from literature and from standards such as ASHRAE 62 using specific ventilation rates, typical occupant densities, and typical geometry of the space in question.

Table 1: Prototypical Air Change Rates (ACH)[1] and Turn-Over Times

ACH (1/h)	***Turn-over time (h)***	***DESCRIPTION***
0.15	6.67	Infiltration rate of new homes from 62.2 (2004)
0.25	4.00	Infiltration rate of commercial buildings from Persily (1999)
0.3	3.33	Ventilation requirement of almost empty commercial buildings from 62.1 (2004)
0.5	2.00	Office space requirement from 62.1 (2004); also large home from 62.2 (2004)
0.7	1.43	Ventilation requirement for small homes from 62.2 (2004)
1	1	Infiltration rate of older home from Sherman and Matson (1997)
2	0.50	Conference room requirement from 62.1 (2004)
4	0.25	High density space (e.g. theater lobby) from 62.1 (2004)

The inverse of the air change rates in Table 1 vary from 15 minutes to 6 hours, indicating that different occupancies will behave quite differently at a variety of configurations. The use of such quantities to explore the spatial dependency of ventilation is also important for large spaces, but will not be discussed here. Sandberg and Sjoberg (1984) developed much of the nomenclature used in this field to deal principally with spatial variation.

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[1] The term "air change rate" does not discriminate between, infiltration, natural ventilation, or mechanical ventilation. It simply denotes that air is being exchanged between indoors and outdoors—somehow.

Sherman and Wilson (1986) followed by Yuill (1986, 1991) have already solved the continuity equation for the general case and defined (temporal) ventilation effectiveness,[2] ε, as a measure of how good a given, time-varying, ventilation pattern is at providing acceptable IAQ. As in those cases, we limit our analysis to contaminants with a linear dose-response and no other loss mechanism (e.g. sorption or deposition). ASHRAE Standard 136 (1993) uses this kind of approach to convert time-varying envelope air leakage into an effective seasonal ventilation rate.

To ventilate intermittently, the rate of ventilation when the system is operating (or operating on "high") must be larger than if it were operating continuously. If there was no *non-linearity problem* to contend with, we would only need to make the total number of air changes the same in the continuous and intermittent ventilation cases. For example, if one wanted to ventilate only 8 hours per day, the ventilation rate would need to be tripled during those 8 hours compared to what was needed in steady-state, just to get the same number of air changes during the day.

As will be shown, it would be an unusual case if one "only" had to triple the ventilation rate to ventilate 8 hours out of 24. The non-linearities caused by the continuity equation often require that the ventilation rate be increased substantially above the level necessary to maintain the same total turn-over.

MATHEMATICAL DESCRIPTION

The temporal ventilation effectiveness, i.e. efficacy—*ε*, is the ratio of the ventilation one would need if the rate were constant to the actual ventilation; for our simple case it links the equivalent (or desired) steady-state ventilation rate (A_{eq}), the actual (or needed) rates of over-ventilation and under-ventilation (A_{high} and A_{low}) and the fraction of time that the space is under-ventilated (f_{low}):

$$1 \qquad \varepsilon = \frac{A_{eq}}{f_{low} A_{low} + (1 - f_{low}) A_{high}}$$

If we have an independent measure of the efficacy, we can use it and Equation 1 to determine the range of acceptable design parameters. We have developed a simplified physical expression of the process that gives us a closed form expression for the efficacy in the appendix. Our solution is expressed in dimensionless terms involving the efficacy and two other parameters:

$$2 \qquad \varepsilon = \frac{1 - f_{low}^2 \mathrm{N} \cdot \coth(\mathrm{N} / \varepsilon)}{1 - f_{low}^2}$$

where the nominal turn-over, N, is defined as follows:

$$3 \qquad \mathrm{N} \equiv \frac{(A_{eq} - A_{low}) \cdot T_{cycle}}{2}$$

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[2] We will also use the term *efficacy* as a synonym for (temporal) ventilation effectiveness.

Equation 2 is recursive; i.e. it refers to the efficacy in order to calculate the efficacy. In certain parameter limits, the equation can be further simplified and recursion can be removed. For example, if one were to use Equation 1 to solve for the under-ventilation fraction given the other parameters, it can be solved without recursion. For the rest of the cases, however, the equation must be solved numerically, which is what we have done.

Figure 1 displays the relationship between the dimensionless parameters and we can draw some general conclusions. When the nominal turn-over is less than unity the efficacy is always high; that is, close to unity. So, if the cycle time is short compared to the turn-over time, almost any pattern of ventilation will work temporally efficiently. For higher air changes, the effectiveness depends strongly on the fraction of time the space is under-ventilated. Especially for the larger under-ventilation fractions (e.g. 50 and 75%), the effectiveness drops to zero at some point and certain combinations are simply not possible (i.e. one cannot always find an on-cycle air change rate that can be used intermittently to provide ventilation equivalent to the continuous ventilation case).

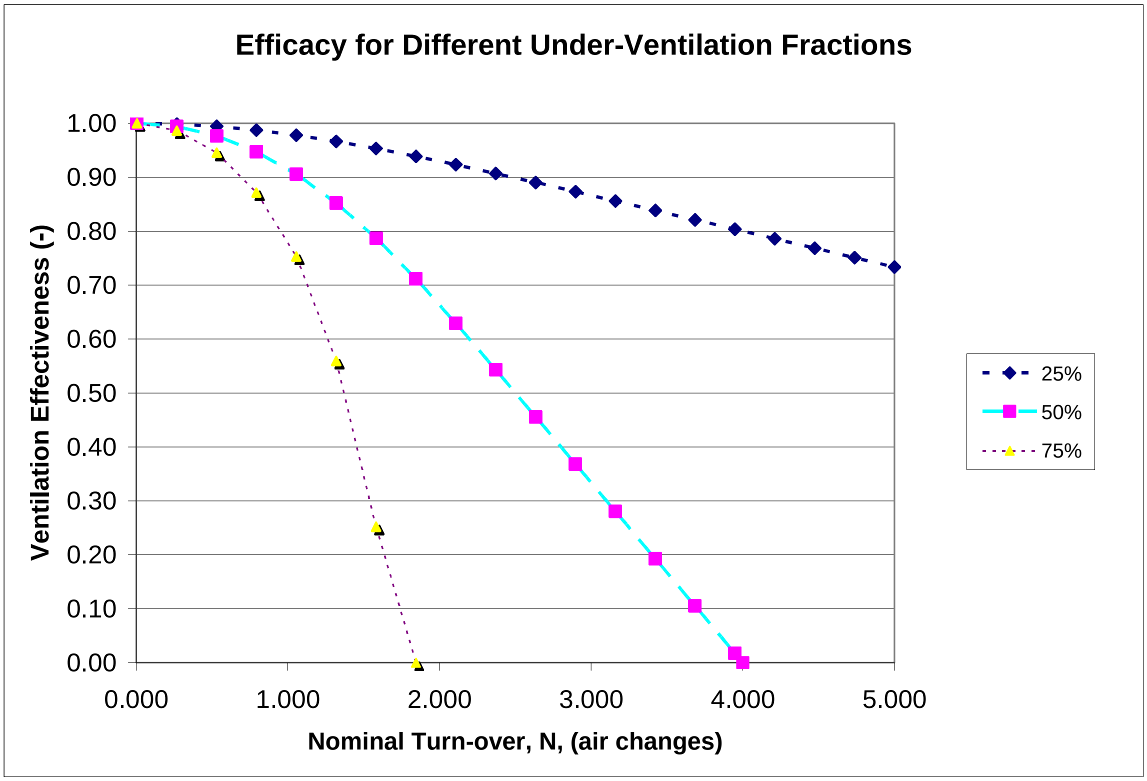

FIGURE 1: Efficacy for three different under-ventilation time fractions as a function of nominal turn over.

Critical Time

Figure 1 shows that the efficacy curve changes its behavior when the nominal turn-over is unity. When the nominal turn-over is well below this critical value, the efficacy is quite high and stable and is relatively independent of the under-ventilation fraction. Above this critical value, however, the efficacy drops off almost linearly and depends strongly on the under-ventilation fraction.

The nominal turn-over is dimensionless, but we can use it to define a critical time. This critical time is twice the equilibrium turn-over time (or 2 divided by the net equilibrium air change rate).

$$4 \qquad \tau_{critical} \equiv 2/(A_{eq} - A_{low})$$

As can be seen through the specifics below, variations in ventilation that happen in cycle times that are short compared to this critical time are effectively averaged out, but cycles that are longer than the critical time may be quite inefficient.

Linear Regime (N<1)
When the critical time is long compared to the cycle time (i.e. the nominal turn-over is small), the efficacy approaches unity approximately linearly as can be seen by taking that limit of Eq. 2:

$$5 \qquad \varepsilon \simeq 1 - f_{low}^2 \mathrm{N}^2$$

Non-Linear Regime (N>1)
When the critical time is short compared to the cycle time (i.e. the nominal turn-over is large), the non-linearities cannot be ignored. Eq. 2 can be approximated in this regime as follows:

$$6 \qquad \varepsilon \simeq \frac{1 - f_{low}^2 \mathrm{N}}{1 - f_{low}^2}$$

When there is signification under ventilation, neither of these approximate expressions works very well in the critical regime near N=1.

APPLICATIONS

While the previous section is quite general, we need to look at the implications for specific applications. We will apply Eqs. 1 through 3 to find out how specific cases of interest perform.

As we consider these applications, we will be looking to find the size of the ventilation system needed to provide the desired level of IAQ under a specific intermittent ventilation scenario. We will show our results as a *Ventilation Multiplier*, which is how much larger the ventilation system has to be made compared to the one that would be needed in steady-state. Part of this increase will just be due to the fact that the system is running part of the time, but some of this increase will be due to working in the non-linear regime and having lowered efficacy.

Notch Ventilation

Consider the case where we often want to be able to shut down the main ventilation system for one period of time during the day to coast through some period of high cost or high outdoor pollution. (See for example, Figure 2a.) We need to figure out how much larger the ventilation should be the rest of the time.

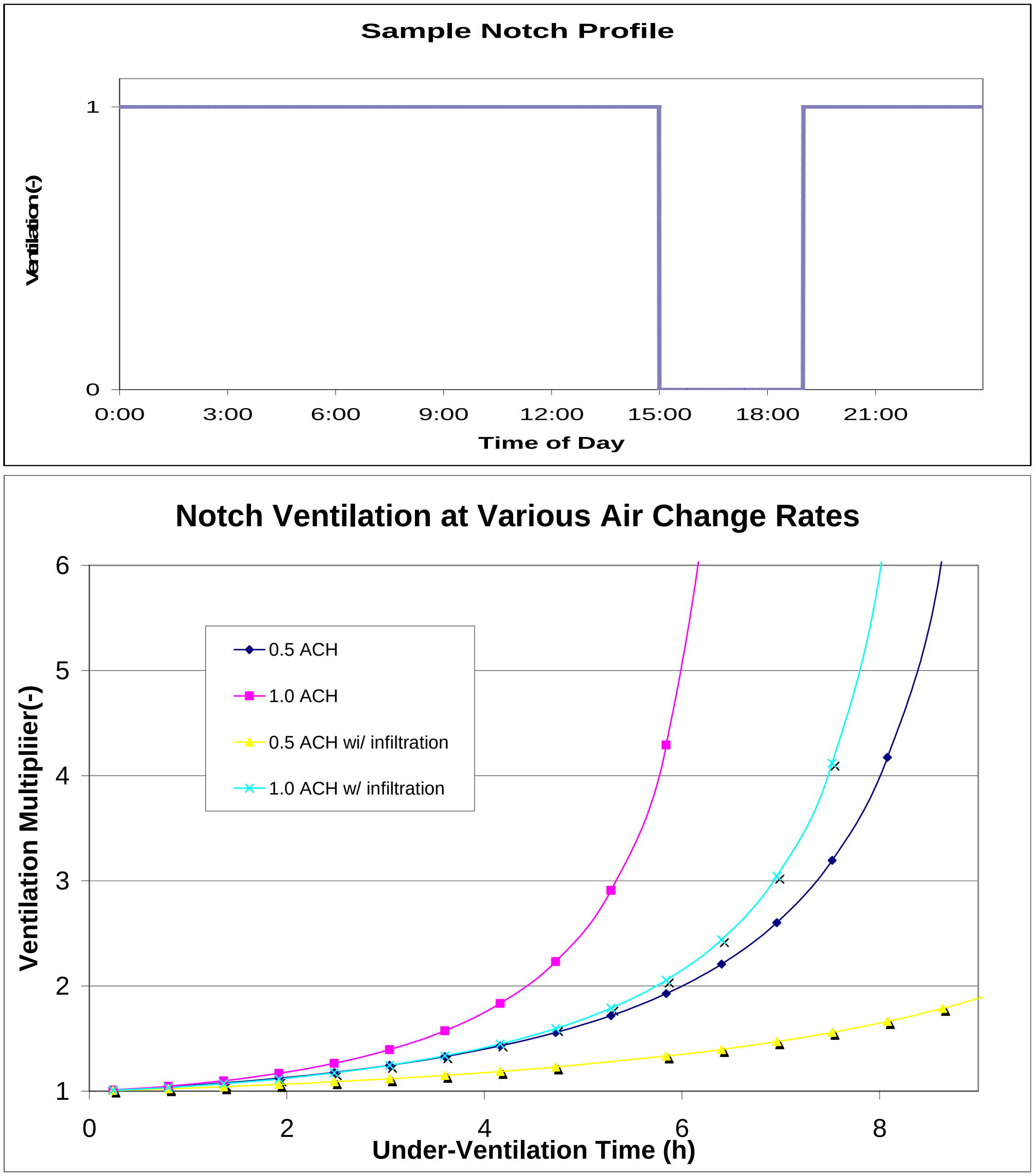

FIGURE 2: 2a: Example under-ventilation pattern (4 hour notch). 2b: Fractional increase in ventilation capacity necessary to accommodate an under-ventilation (notch) period, with and without 0.2 ACH of infiltration.

Figure 2b was generated using the exact (numerical) calculation. This chart plots the fractional increase in ventilation equipment size that is necessary to accommodate a notch of various sizes. The calculations were done for two air change rates (1 ACH and 0.5 ACH) and for the case where there was no infiltration during the off period and the case for which there was 0.2 ACH of infiltration during the off period. (See first two rows of Table 1.)

If the objective is to get a substantial period with the ventilation system off (e.g. at least 6 hours) and not have to radically increase the size of the ventilation system (e.g. ventilation multiplier of 2), then the ventilation requirement of the space should not be more than about 0.5 ACH. ach. For low-density spaces like offices and large homes, we can achieve this, but for high density spaces we may not.

Figure 2 also shows that the presence of infiltration during the notch when the ventilation system is off can be quite helpful. For example, if the ventilation requirement is 0.5 ach and there is 0.2 ach when the ventilation system is off, one can have a notch that is almost 8 hours long for only a 50% increase in ventilation system capacity.

Pulse Ventilation

In air distribution systems, the heating and cooling is often interconnected with the ventilation in such a way that it is not always possible to automatically get the right amount of ventilation for any heating or cooling demand. In commercial buildings, this appears in the form of minimum stops for Variable Air Volume (VAV) systems. In residential systems, this appears in the form of extra controls on systems with outside air inlets into return plenums.

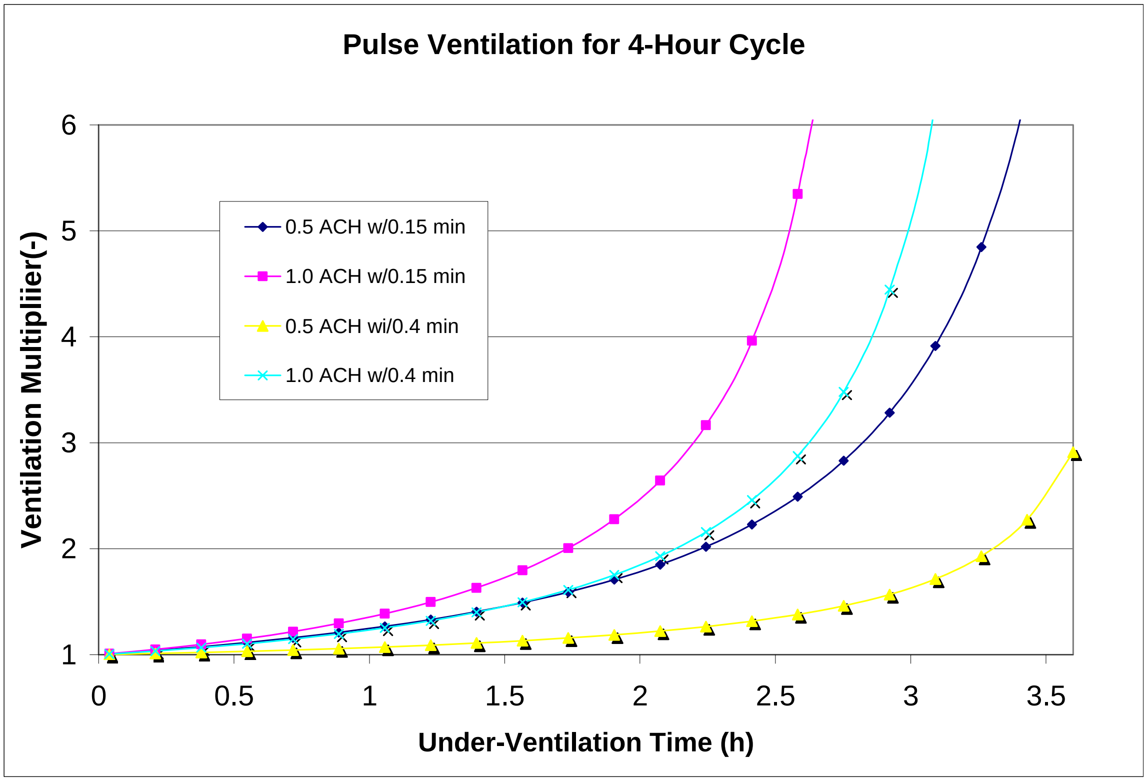

FIGURE 3: Pulse ventilation rate necessary to accommodate low ventilation rates for remainder of (4-hour) period.

Conversely, a nominally fully-recirculating system can "accidentally" induce air exchange either through duct leakage or by differentially pressurizing various spaces and thereby inducing extra infiltration. If, for a period of time, one allows the HVAC system to only provide this accidental ventilation, one could make up for any under ventilation by adding a pulse of ventilation for a while to provide acceptable indoor air quality.

Figure 3 is an example of such a design. We have assumed, somewhat arbitrarily, that the cycle time is 4 hours. We consider two cases, one in which the “accidental” ventilation is 0.15 ach and another assuming it is 0.4 ach. We assumed the same 0.5 and 1.0 ACH requirements used earlier. We then look to see what the pulse ventilation must be in the remainder of the period to provide the necessary dilution

If one is considering a pulse ventilation strategy, one must have the ventilation capacity to go beyond the steady state ventilation rate. Factors of 3 for excess ventilation capacity are common in residential buildings and are not unreasonable in commercial buildings, if diversity is adequately taken into account. A pulse ventilation strategy can have advantages for HVAC systems that cannot fully and independently control the ventilation and thermal conditioning such as VAV systems or a supply air inlet system. Additional controls and extra ventilation capacity may, however, be required.

DISCUSSION

As can be inferred from the examples above, various intermittent ventilation strategies can be employed effectively, but most will quickly become impractical once the efficacy begins to drop. We can use our model of efficacy to show what combinations of parameters are likely to work and which are not.

Figure 4 displays contour lines of efficacy as a function of the two key dimensionless parameters: under-ventilation fraction and nominal turnover:

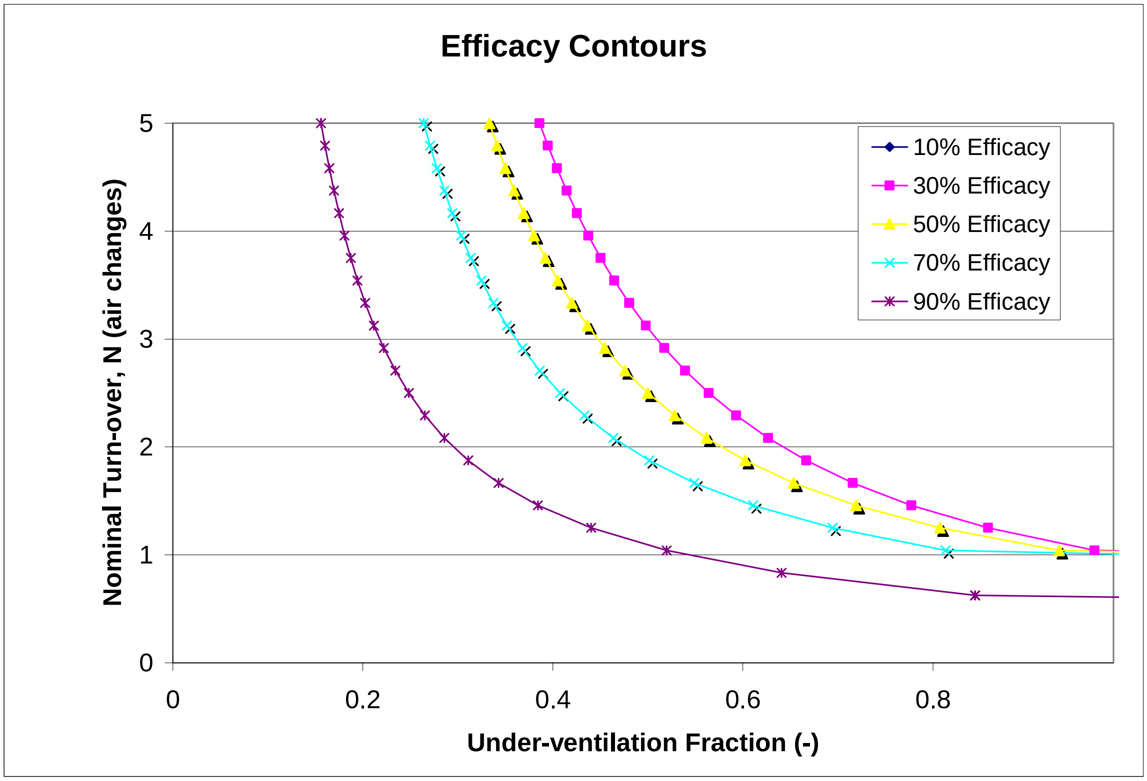

FIGURE 4: Ventilation effectiveness (efficacy) contours for dimensionless quantities under-ventilation fraction and nominal turn-over.

Figure 4 helps identify the range of nominal turn-over and under-ventilation fraction that one should normally work toward. The left-most curve in the figure is the 90% efficacy contour. Anything to the left (or below) of that curve operates at a sufficiently high efficacy that the non-linearities inherent in the problem are minimal.

If the efficacy is high, the average ventilation over the period will be close to the equilibrium ventilation and there will be minimal energy or sizing penalty for operating in that regime. There may be circumstances where the penalties associated with operating below 90% efficacy may be worth the additional costs necessary to provide the increased ventilation, but outside that range of parameters, the efficacy drops off so quickly that it will only be a desirable operating range for very special situations.

Assuming that the 90% efficacy level is the delineator between those strategies that are reasonably efficient and those that will require an excessive amount of extra air, we can use our model to generate the locus of points for different air change rates that will provide 90% efficacy.

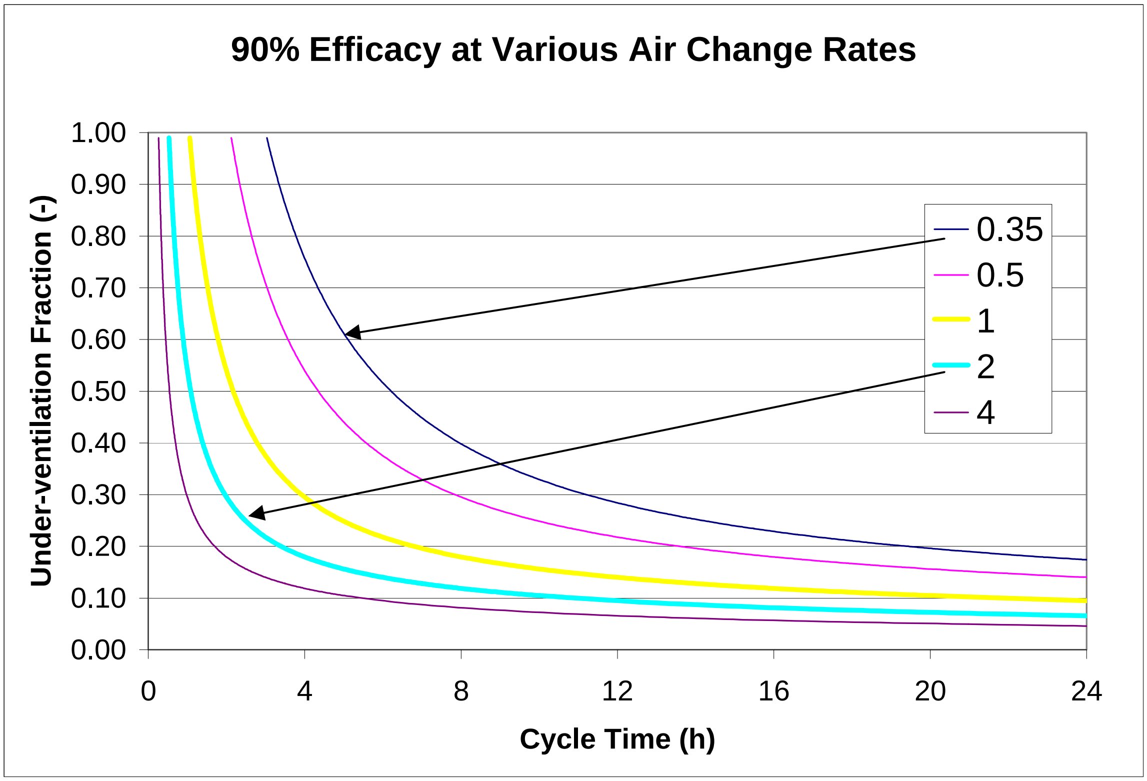

FIGURE 5: Maximum under-ventilation fraction possible to achieve 90% efficacy for various cycle times and air change rates.

Figure 5 shows the 90% efficacy curves for five different air change rates as a function of the cycle time and the under-ventilation fraction. Any point that falls below the curve indicates an efficacy above 90%. Note that for cycle times on the order of a day (24 hours), one cannot get much above a 10% under-ventilation fraction for the range of air change rates given, but at lower cycle times (e.g. 4 hours) the under-ventilation fraction can get quite high regardless of the air change rate.

For long cycle times, one might be willing to accept lower efficacies in exchange for flexibility, especially across an entire day. Figure 6 shows the efficacies one can achieve with a 24-hour cycle time.

For the 24 hour cycles shown in Figure 6, it is impossible to have above a 50% under-ventilation fraction (i.e., an under-ventilation period greater than 12 out of 24 hours) for any air change rate. The steep drop off implies that few strategies that need to be spread over the entire day could be reasonably effective, unless they involve only quite short periods of under ventilation.

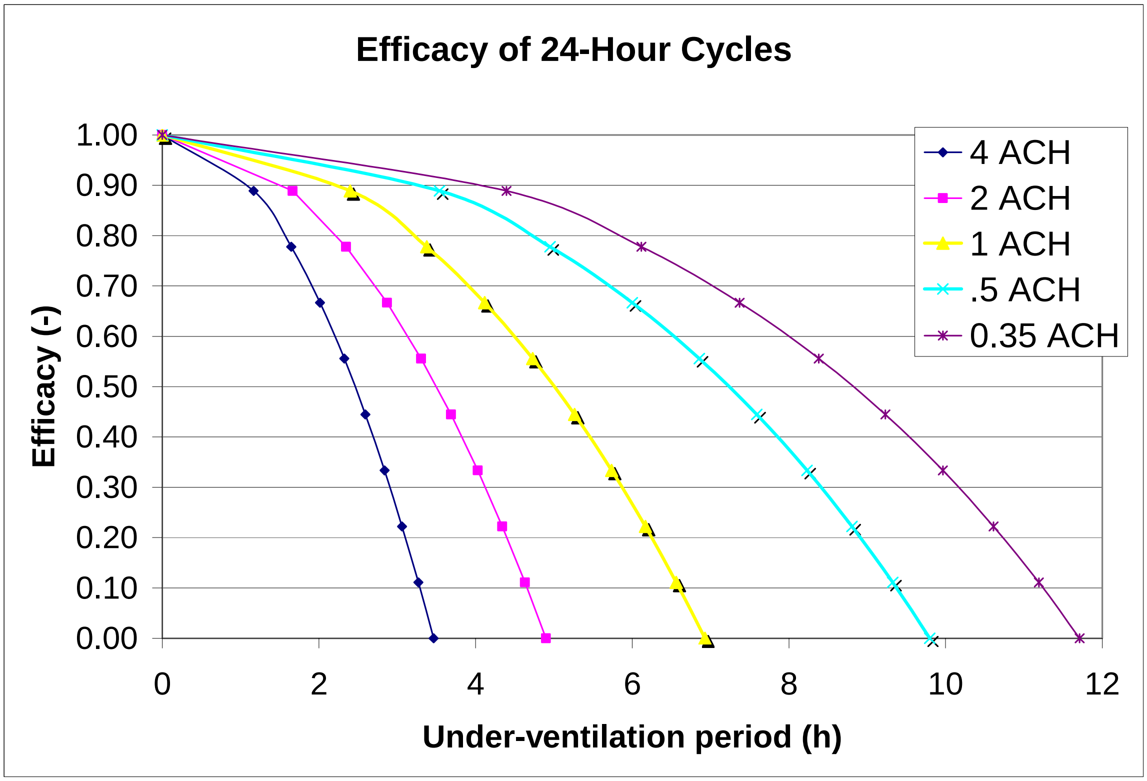

FIGURE 6: Efficacy of 24-hour cycles as a function of under-ventilation fraction.

For many applications, however, shorter cycle times are appropriate. For example, occupancy may change in 8-hour shifts or fan cyclers may work on a 3-hr cycle time. As one moves to shorter cycle times, there is a larger range of acceptable under-ventilation fractions and a higher overall efficacy, which indicates that there will be more reasonable design options to consider. The shape of the curves may also be slightly different, but the general rule of more flexibility at lower air change rates still applies. The spread between different air changes would continue until the efficacy approaches its upper limit of unity.

At the opposite limit, the efficacy will approach zero when the under-ventilation time gets long enough. Figure 7 shows this maximum under-ventilation as a function of cycle-time for different air change rates.

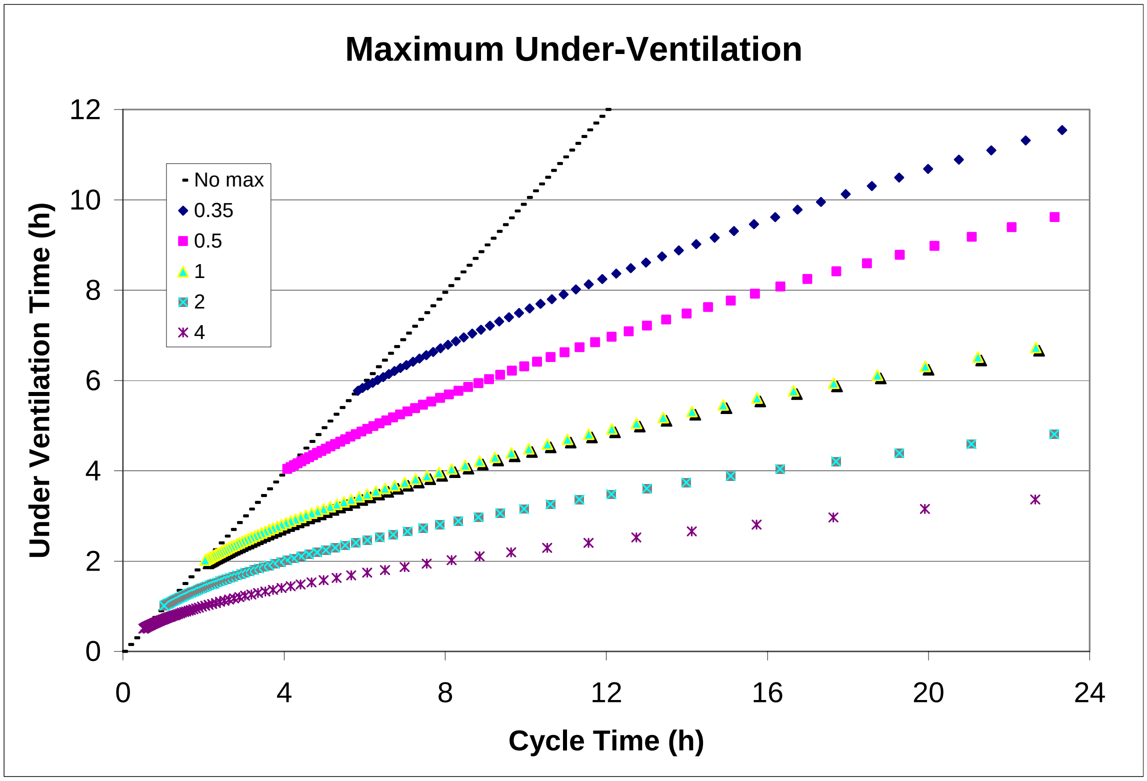

FIGURE 7: Maximum possible under-ventilation for different air change rates as a function of cycle time.

The straight line on the left represents the point at which the maximum under-ventilation time is equal to the cycle-time and thus there is no limit (although the efficacy may still be low).

Low-Density Residential Buildings

Single-family homes have quite moderate ventilation requirements compared to higher occupant density or more highly polluted buildings. Standard 62 typically requires approximately 0.35 ACH. Figure 8 shows the size that an intermittently operating mechanical ventilation system must be to provide the necessary indoor air quality.

Figure 8 displays the information as a function of under-ventilation time for different cycle times. If these data were plotted as a function of cycle time, the curve would be very similar in shape to that of Figure 9 (which is based on 1 ACH instead of 0.35 ACH), but the limits would be shifted accordingly.

The upward curvature of system capacity in Figure 8 for increasing under-ventilation time is caused by the drop in efficacy as the cycle time gets longer and non-linearities begin. The low cycle-time limits are those required to deliver the same number of air changes as the continuous system. When the under-ventilation fraction is low (e.g. 25% of cycle time), there is no significant curvature out to the full 24 hours (e.g. to use notch ventilation). Thus, for low cycle times, one need only deliver the right amount of total air changes in any configuration (i.e. any under-ventilation fraction works).

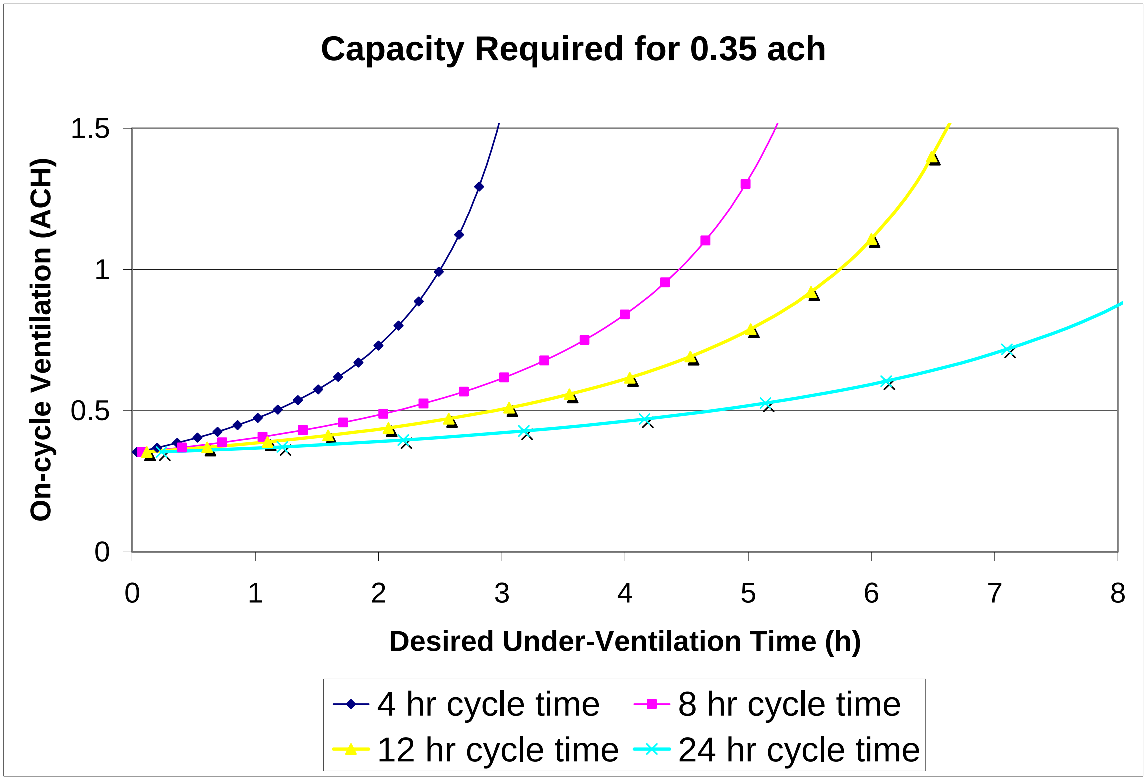

FIGURE 8: Capacity of intermittently operating mechanical ventilation system necessary to provide 0.35 equivalent air changes.

As a specific example of when curvature matters: if one wants to have the system on for 3 hours and off for 6 hours, the system must be able to provide roughly 10 ten times the steady-state value (i.e. 3.5 ACH), when it is operating. Because of the increased fan size and associated operational costs such a situation is not usually going to be attractive when looking at ventilation alone, but might be attractive when considered in a whole-house context. Such a situation might, for example, make sense if one were operating an economizer or very large exhaust fans for kitchen ventilation on a predictable schedule.

High-Density Residential Buildings

In high-occupant-density residential buildings, the necessary mechanical ventilation may be closer to 1 ACH than to 0.35 ACH. The 0.35 ACH value for lower-density dwellings was developed assuming some default infiltration values. If one does not have this infiltration, 1 ACH of mechanical ventilation might also be a reasonable value for moderately sized homes with high occupancies, as one can calculated from 62.2. Figure 9 shows the required ventilation system capacity for 1 ACH as a function of cycle time. If it were plotted as a function of desired under-ventilation time, it would look similar to that of Figure 8 with limits shifted accordingly.

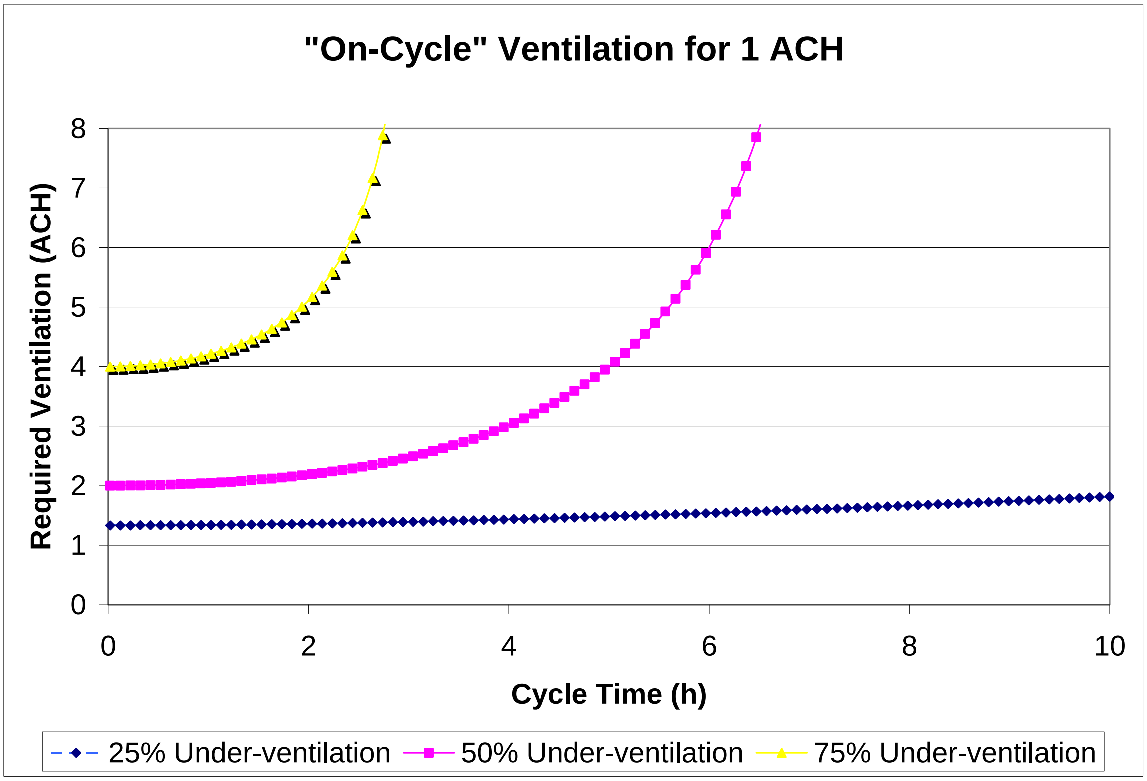

FIGURE 9: Capacity of intermittently operating mechanical ventilation system necessary to provide 1 equivalent air changes.

Intermittent ventilation is much less attractive in high-density residential buildings than in low-density ones. In a large single-family home, one could, for example, use a 6-hour notch-ventilation strategy quite effectively, but in a high-density case, one would only want to use a 2 or 3 hour notch before decreased efficacy would require impractically large ventilation.

As a specific example, consider doing a 2-hour on and 2-hour off strategy (50% under-ventilation fraction) to match to some heating system cycle. In such a case, Figure 9 shows that one would need 3 air changes during the on-cycle, which has about a 50% energy penalty (compared to steady-state ventilation) for conditioning the ventilation air. (Fan power is not usually a major factor in homes, but could vary as well, in principle)

Low-Density Commercial and Institutional Buildings

In office spaces and other low-density commercial occupancies, the required air change rate can often be similar to that of single-family homes, so the curves for low-density residential buildings are applicable. Some low density commercial spaces have slightly higher requirements because of increased contaminant sources, so an increase to 0.5 ACH might be a more reasonable value to use. The shapes of Figures 8 and 9 would be representative of low-density commercial buildings as long as the limits were shifted to account for the different air change rate.

High-Density Commercial and Institutional Buildings

As we move to larger required ventilation rates, Figure 7 shows that the longest useful cycle length and longest useful under-ventilation period become necessarily shorter, which in turn limits design options for intermittent ventilation.

In high density spaces such as class-rooms and theaters, this constraint can be quite apparent. For 4 ACH, intermittent ventilation may be useful as long as the under-ventilation time, or the cycle time is kept short. Thus it might be useful during transient events like changing classes or showings, but will not be useful for more extended periods or as part of a lead/lag ventilation calculation.

SUMMARY AND CONCLUSIONS

We have developed, from first principles, a simplified physical model that allows one to determine what intermittent ventilation pattern is equivalent to a constant ventilation level. The model relates three dimensionless parameters: the efficacy, the nominal turnover, and the under-ventilation fraction, which in turn can be calculated from the air change rate, the ventilation target, and system operating parameters.

Ventilation standards and guidelines rarely address the topic of intermittent ventilation, so it is not always clear when one is allowed to average out variable ventilation rates and over what period of time one can do this. The model developed in this report can directly be used to address that issue and we have explored several prototypical applications.

Our analysis indicates that there is a critical time for averaging the effects of intermittent ventilation. Any variations that happen faster than that critical time are essentially averaged out; things that happen slower than that critical time do not get averaged out and can lead to poor performance, which means increased costs to provide acceptable ventilation.

Low-density spaces such as houses and offices typically have critical times of much more than an hour so that there is a great deal of flexibility that a designer can use in selecting intermittent ventilation systems to minimize energy use, protect against poor outdoor air, reduce peak demand, or optimize interactions with the thermal distribution system (e.g., minimum stops on VAV systems in commercial buildings or fan cyclers in residential buildings.)

Ventilation codes and standards, such as ASHRAE's 62 series, could be made more flexible by incorporating the results of this work. Future efforts should focus on non-steady-state and/or multilevel modeling as well as specific application development and experimental verification.

ACKNOWLEDGEMENTS

This work was supported by the Assistant Secretary for Energy Efficiency and Renewable Energy, Building Technologies Program, of the U.S. Department of Energy under contract No. DE-AC03-76SF00098.

This report was also supported in part by work sponsored by the California Energy Commission (Energy Commission). It does not necessarily represent the views of the Energy Commission, its employees, or the State of California. The Energy Commission, the State of California, its employees, contractors, and subcontractors make no warranty, express or implied, and assume no legal liability for the information in this report, nor does any party represent that the use of this information will not infringe upon privately owned rights. This report has not been approved or disapproved by the Energy Commission nor has the Energy Commission passed upon the accuracy or adequacy of the information in this report.

Finally, special thanks to Craig Wray whose expert spreadsheet abilities enabled the many numerical simulations that were required for the figures and plots of this paper..

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APPENDIX: Defining Equations and Simplified Physical Modeling

We wish to be able to compare a time-varying ventilation rate with an equivalent steady state one. To make this comparison we follow the convention, used by Sherman and Wilson (1986) and others, that two ventilation strategies are equivalent if they lead to the same contaminant exposure. We do not need to know what the contaminant of concern is; for a constant air change rate of A_{eq}, we will get a steady state concentration of C_{eq}. When the concentration is not in steady state, we can use the continuity equation to relate the instantaneous concentration time to the instantaneous change rate:

7 $$\dot{C}(t) + A(t) \cdot C(t) = A_{eq} \cdot C_{eq}$$

where the concentration and air change rate are shown as functions of time, *t*, but source strength (i.e. product of the equilibrium concentration and air change rate) is constant.

If we assume that for some period of time the air change rate is roughly constant, we can integrate Eq. 7 to get an equation that determines the concentration, *C*, at any time:

8 $$C(t) = C_{t=0} e^{-A \cdot t} + C_{eq} \frac{A_{eq}}{A} (1 - e^{-A \cdot t})$$

Consider the situation in which we ventilate at a pseudo-constant, low air change rate, A_{low}, for a time, t_{low}, followed by a pseudo-constant high rate, A_{high}, for a time, t_{high}. During each of the periods, Eq. 8 will be followed with the appropriate air change rate. At the end of the low ventilation rate period, the concentration will be a new value:

9 $$C_{max} = C_{start} e^{-A_{low} \cdot t_{low}} + C_{eq} \frac{A_{eq}}{A_{low}} (1 - e^{-A_{low} \cdot t_{low}}) \qquad \text{At end of low ventilation period}$$

Then, the air change rate will switch to high and the concentration will come down to its end value:

10 $$C_{end} = C_{max} e^{-A_{high} \cdot t_{high}} + C_{eq} \frac{A_{eq}}{A_{high}} (1 - e^{-A_{high} \cdot t_{high}}) \qquad \text{At end of high ventilation period.}$$

In general, we are concerned about what the concentrations will be over the long term, which means we are interested in a steady-state condition, such as that when the ventilation rate follows a repeating pattern. (We will not consider transient cases such as those in which the system starts out of equilibrium.) We can thus apply cyclic boundary conditions, which requires that the initial and final concentrations be the same:

11 $$C_{end} = C_{start} = C_{eq} \frac{\frac{A_{eq}}{A_{low}} (1 - e^{-A_{low} \cdot t_{low}}) e^{-A_{high} \cdot t_{high}} + \frac{A_{eq}}{A_{high}} (1 - e^{-A_{high} \cdot t_{high}})}{1 - e^{-A_{low} \cdot t_{low}} e^{-A_{high} \cdot t_{high}}}$$

If this particular pattern of ventilation is equivalent to the constant ventilation case, the exposure (i.e. integrated concentration) during the period must be equal. This would imply:

$$12 \quad T_{cycle} = \frac{A_{eq}t_{high} + (\frac{C_{max}}{C_{eq}} - \frac{A_{eq}}{A_{high}})(1 - e^{-A_{high} \cdot t_{high}})}{A_{high}} + \frac{A_{eq}t_{low} + (\frac{C_{start}}{C_{eq}} - \frac{A_{eq}}{A_{low}})(1 - e^{-A_{low} \cdot t_{low}})}{A_{low}}$$

where the cycle time, T_{cycle}, is defined as

$$13 \quad T_{cycle} = t_{high} + t_{low}$$

The equations above represent a consistent description that relates the parameters and can be used to solve for any of them given the others. The purpose of this description is to quantify the relationship between these parameters so that one can estimate impacts or design the right ventilation system by adjusting appropriate times and ventilation rates. The temporal ventilation effectiveness (or efficacy), ε, is the primary quantification of this process and can be defined as follows using the parameters that satisfy the previous equations:

$$14 \quad \varepsilon \equiv \frac{A_{eq} \cdot T_{cycle}}{A_{low}t_{low} + A_{high}t_{high}}$$

Once the efficacy has been calculated, however, there is no need to refer to concentrations again. Unfortunately, the solution of these equations must often be done numerically, depending on which parameters ones knows and which parameters one needs to determine. While for some extremely detailed problems, it might be necessary to use the above equations, we shall consider a simplified but robust approach that leads to a closed-form solution

Zero "Off-cycle" Ventilation

Consider the case in which the ventilation can be assumed to be zero for the "low" period of time and then is at some constant rate for the rest (i.e. "high" part) of the time. Under such a circumstance it is possible find a solution for the efficacy by carefully taking the limit of "low" ventilation going to zero[3].

The minimum and maximum concentrations can be calculated as follows:

$$15 \quad C_{max} - C_{eq} \cdot A_{eq}t_{low} = C_{start} = C_{end} = C_{eq}\left(\frac{A_{eq}}{A_{high}} + \frac{A_{eq}t_{low}e^{-A_{high}t_{high}}}{1 - e^{-A_{high}t_{high}}}\right)$$

with the equivalence equation as

$$16 \quad T_{cycle} = \frac{A_{eq}t_{low}^2}{2} + \frac{C_{start}}{C_{eq}}t_{low} + \frac{A_{eq}}{A_{\backslash high}}T_{cycle}$$

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[3] The limiting process and subsequent manipulations are too lengthy to be reproduced here.

The efficacy is then

$$17 \quad \varepsilon = \frac{A_{eq} \cdot T_{cycle}}{A_{high} \cdot t_{high}} = \frac{1-(t_{low}/T_{cycle})^2 \mathrm{N} \cdot \coth(\mathrm{N}/\varepsilon)}{1-(t_{low}/T_{cycle})^2}$$

where we have defined the effective turn-over, N, as follows:

$$18 \quad \mathrm{N} \equiv \frac{A_{eq} T_{cycle}}{2}$$

The form of these two expressions makes it clear that the effectiveness is a function only of the nominal turnover and the fractional time that the ventilation is in low mode, t_{low}/T_{cycle}. The main text explores the form of this equation in some detail. The efficacy itself can never be larger than unity so that the "high" ventilation rate is always higher than the equilibrium rate.

Non- Zero "Off-cycle" Ventilation

The equations developed above assume that there is no ventilation rate during the "low" ventilation period. In many instances there will be some non-negligible ventilation, such as infiltration or accidental ventilation and its presence can make a non-trivial difference; and we wish our general model to be able to deal with these situations.

Let us separate the air change rate into two parts: a "low" part that is pseudo-constant for the entire period and another part that follows the pattern of the previous section (i.e. is high for a period of time, but zero otherwise.) Thus we subtract a term from both sides of the continuity equation to make the left side look the case from the previous section.

Most of the time when the ventilation rate is "low" it is significantly below the equilibrium ventilation rate, A_{eq}, and we shall assume that is the case here. We thus treat the "low" part of the ventilation as a perturbation on the system. Instead of considering that new right hand term as a function of time, we take its expectation value over the period In any solution to the problem the expectation value of the concentration is the target concentration, C_{eq}. The continuity equation then becomes the following:

$$19 \quad \dot{C}(t) + \left(A(t) - A_{low}\right) \cdot C(t) = A_{eq} \cdot C_{eq} - A_{low} \cdot C(t) \simeq \left(A_{eq} - A_{low}\right) \cdot C_{eq}$$

This looks just like our original continuity equation with a transformed set of coordinates. Thus our earlier solution for the zero off-cycle ventilation still holds as long as we use the transformed set of ventilation rates that have all had the "low" ventilation rate subtracted from them. Specifically, we can use our dimensionless solution for the efficacy as long as we used a modified definition for the effective turn-over:

$$20 \quad \mathrm{N} \equiv \frac{(A_{eq} - A_{low}) T_{cycle}}{2}$$

Once the value of the efficacy is determined, whatever set of coordinates that is convenient may be used so we have chosen to use Eqs. 1-3 as our fundamental description in the body of the text.