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IAQ Based Design of an Efficient DCV System

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DISCLAIMER

SUMMARY

The principle of air quality equivalency is a cornerstone when developing energy efficient ventilation systems. In this paper we introduce the concept of applying demand controlled ventilation (DCV) to buildings in a way that accounts for time of occupancy and how occupants change pollutant emission rates. The reason for using DCV is to reduce the total air volume required to ventilate the building while maintaining indoor air quality. Indoor air quality will be evaluated by the use of occupant dose – the integrated exposure. The key concept is to take advantage of allowing pollutant levels to be higher when the building is unoccupied because people will not be exposed to these levels of pollutants as they are absent. Ventilation rates are lowered during unoccupied hours and raised during occupied hours. The parameters that govern the use of DCV are: occupancy pattern, pollutant generation for occupied vs. unoccupied times, and the constant ventilation rate that usually is mandated by standards. The constant ventilation rate determines the occupant dose and is thereby the target for equivalent indoor air quality. An analytical solution to the mass continuity equations is used to relate these parameters to the required high and low ventilation rates for occupied and unoccupied times, respectively. We will show some example results for typical occupancy, pollutant generation, and ventilation rates in a residential building. Because energy consumption is related to the total volume of air, these results will be used to provide design guidance for minimizing the total air volume used to ventilate a residence while maintaining the same indoor air quality. We discus discuss energy related issues, fan sizing and potential for future work.

INTRODUCTION

Ventilation is used to provide an acceptable air quality by controlling the concentration of pollutants in a space. The concentration can be controlled by dilution or by source control methods. When specific pollutants can be identified they are best dealt with through source control methods or, if possible, by directly removing them from the space. Any remaining pollutants must be diluted by whole-house ventilation. The ventilation required in buildings today is often given by a constant rate in standards and buildings codes. When specifying requirements for ventilation one must consider the emission of pollutants in the space. In most buildings the pollutant emission rates depend on occupancy, and are higher when occupants are present due to biological processes and occupant activities. These emissions are added to the emissions from materials within the building that occur independent of occupancy. A constant ventilation rate may lead to periods with poor indoor air quality and/or unnecessary energy consumption during unoccupied times. A potential strategy in the development of energy efficient ventilation systems that do not jeopardize the indoor air quality involves changing the ventilation rate from being constant to being controlled by the demand. Such a system can provide acceptable indoor air quality without being wasteful with energy. A first step towards the development of an energy efficient ventilation system is to show that it provides acceptable air quality or to show that the provided air quality is equivalent with that obtained when ventilating at the rates required by standards or building codes. The first approach is complex because thorough knowledge of all pollutants health effects on people is needed, therefore we use the concept of air quality equivalency. The principle of air quality equivalency has been studied for intermittent ventilation systems by Sherman (2006). He investigated how much the ventilation rate in an intermittent system should be raised to provide an air quality equivalent to that of a constant air volume system (CAV). The air quality was evaluated independent of occupancy, and pollutants were generated at a constant rate. The results of the study have been included in ASHARE standard 62.2 by allowing intermittent ventilation provided that the ventilation rate is raised outside the off period. The concept used by Sherman and repeated here, is to calculate occupant dose, which is the exposure to a pollutant integrated over time. The exposure and thus dose is assumed to be linearly proportional to the pollutant concentration. The vast majority of indoor air quality issues examined for ventilation standards, are usually limited to chronic, long term exposure and do not address short term exposures to highly toxic substances with non-linear dose response for human health. Therefore dose is used as the metric for equivalent air quality in this study. A key concept in this study is to limit exposure and dose calculations to times when occupants are present. We can thus take advantage of allowing pollutant levels to be higher when the building is unoccupied because people will not be exposed to these levels of pollutants because they are absent. This paper presents an analytical study of the ventilation effectiveness of a residential demand controlled ventilation (DCV) system compared to a CAV system to provide equivalent air quality during occupied hours. Because energy consumption is related to the total volume of air, these results will be used to provide design guidance for minimizing the total air volume used to ventilate the residence while maintaining the same indoor air quality. We discus discuss energy related issues, fan sizing and potential for future work.

METHODS

We seek to evaluate the performance of a DCV system with a CAV system given that the air quality in the two systems is equivalent. The dose is the quantity we wish to hold constant to show air quality equivalency. The dose cannot be calculated in a straightforward manner because ventilation and concentration are dynamically and inversely related through the mass continuity equation. The mass continuity equation is solved for a DCV system with variable ventilation and emission rates, but in cyclic equilibrium on a daily basis. We use an analytical approach to determine the high and low air flow rates that solves the continuity equation for equivalent dose. The emission of pollutants is comprised of a constant part associated with the building and an intermittent part associated with the occupants. Pollutants with shorter emission profiles (e.g., showering) are assumed to be dealt with by source control methods, although they may be considered to be part of the background emission over long term. The pollutants are assumed to be additive resulting in a step-wise emission profile. The profile can be described by the emission ratio (ER) relating the emission during occupied hours to unoccupied hours.

$$ER = \frac{S_{constant} + S_{intermittent}}{S_{constant}} \quad (1)$$

Where $S_{constant}$ is the constant pollutant emission and $S_{intermittent}$ is the intermittent pollutant emission.

Pollutants are assumed to be removed by ventilation and not by other mechanisms such as filtration or, sorption on surfaces. The ventilation rate of the DCV system is controlled by occupancy and the building is ventilated at a high rate during occupied hours and at a low rate during unoccupied hours. The range of possible DCV systems is restricted by the low ventilation rate that never can be less than zero and never higher than the ventilation rate of the CAV system. Each DCV system can thereby be identified by its ‘ventilation index’ expressing the low ventilation rate of the DCV system to the ventilation rate of the CAV system. At a ‘ventilation index’ of 1 the low and high ventilation rates are identical. The low and high ventilation rates that solve the mass continuity equation for equivalent dose are used to express the effectiveness of the test system. The effectiveness is a measure of how good the

DCV system is at providing an air quality equivalent to the CAV case. The effectiveness only considers the time variation of the ventilation and not local inefficiencies associated with imperfect mixing. Furthermore, it does not include dilution due to infiltration. The effectiveness is defined by the volume of air one would need in the reference system to that needed in the DCV system throughout the cyclic period. Based on the DCV systems occupancy controlled ventilation profile the effectiveness is calculated by:

$$\varepsilon = \frac{A}{A_{low} \cdot f_{low} + A_{high} \cdot (1 - f_{low})} \qquad (2)$$

Where ε is the ventilation effectiveness of the system, A is the constant ventilation rate in the CAV system, A_{high} is the high ventilation in the DCV system, A_{low} is the low ventilation rate in the DCV system and f_{low} is the daily fractional off time.

Example calculations

Example calculations using typical values are used to illustrate the effects of the various parameters on residential DCV operation. The effectiveness of an occupancy controlled DCV system is compared to a CAV system for an apartment of $70m^2$ occupied by 2 persons. The occupants spend 16 hours a day in the apartment corresponding to the time people in general spend in their home (Brasche, Bischof 2005, Leech et al. 2002). An estimate of the emission ratio is obtained from ASHRAE standard 62.2 and EN15251, where ventilation rates are calculated based on the number of occupants and the floor area of the space. The pollutant emission rates are assumed to be proportional to the air flow rates in the standards. This leads to the emission ratios given in Table 1. Based on these values, we use emission ratios of 1.0, 1.6 and 4.0 in our example calculations. The emission ratio of 1 corresponds to occupants making no contribution to pollutant emission and it is thereby the minimum generation of pollutants that can occur.

Table 1: Emission ratios based on air flow rates in ASHRAE standard 62.2 and EN15251

Standard	*Emission Ratio (ER)*
ASHRAE 62.2	4.0
15251, very low polluting building	1.6
15251, low polluting building	1.3
15251, non-low polluting building	1.2

When selecting the CAV flow rates we refer to residential ventilation requirements. The ventilation required in residential buildings in Denmark (BR 2008) corresponds to $0.5h^{-1}$ whereas the required mechanical ventilation in ASHRAE 62.2 is $0.22h^{-1}$ for the specific apartment. For these example calculations we will use the 0.22 and 0.5 air change (ACH) levels for the CAV system together with an increased ACH level of 1.0 to examine the CAV rates impact on the ventilation effectiveness.

RESULTS

At a constant air change rate of $0.5h^{-1}$ and emission ratios of 1.0, 1.6 and 4.0 the effectiveness is given as a function of the ventilation index in Figure 1.

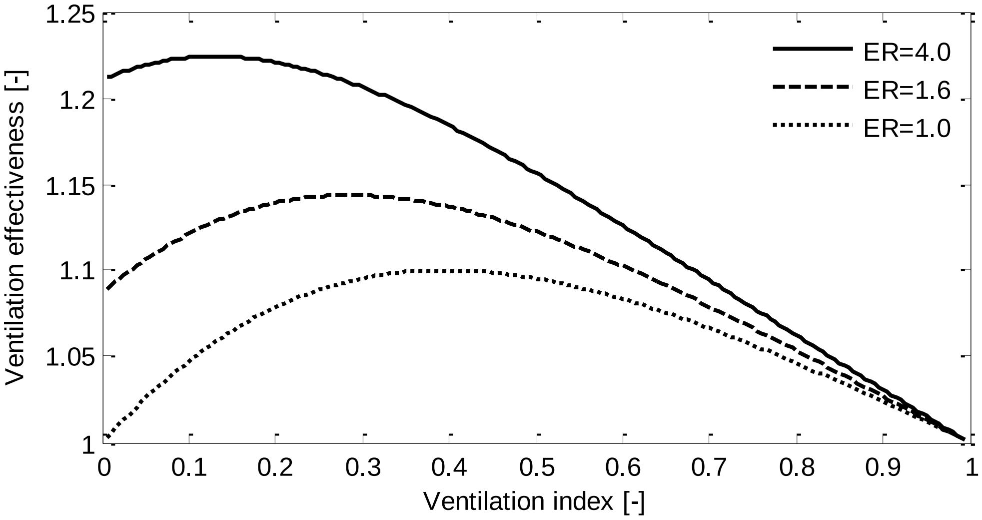

Figure 1: Ventilation effectiveness as a function of the DCV system's ventilation index at a constant air change rate of $0.5h^{-1}$.

The minimum benefit that can be obtained by ventilation more during occupied hours is when the emission of pollutants is the same during occupied and unoccupied hours, i.e., ER =1. Increasing the emission ratio increases the peak effectiveness. At ER=1 the peak effectiveness is 1.10 which occurs when the low air flow rate is 40% of the CAV rate. Knowing the effectiveness and the low ventilation rate we us use equation 2 to calculate the high air flow rate to be 117% of the CAV rate. At the emission ratio of 1.6 deduced from standard 15251 the peak effectiveness is 1.14 and the low and high air flow rates are 28% and 117% of the CAV rate, respectively. At ER=4.0 the peak effectiveness is 1.22 and the low and high air flow rates are 13% and 116% of the CAV rate, respectively. At the ventilation index's upper limit of 1 (i.e. constant ventilation rate) the results show, as expected, that the effectiveness is always 1. At the ventilation index's lower limit of 0 (i.e. the ventilation system is completely off during unoccupied hours) the effectiveness is 1 when ER=1 and pollutant generation does not change. The greater the occupant contribution to emissions, the greater the effectiveness and thus, the lower the total air volume needs to be to obtain equivalent dose.

Figure 2 shows the ventilation effectiveness of DCV systems for an emission ratio of 1.0 at CAV air changes of $0.22h^{-1}$, $0.5\ h^{-1}$ and $1.0\ h^{-1}$.

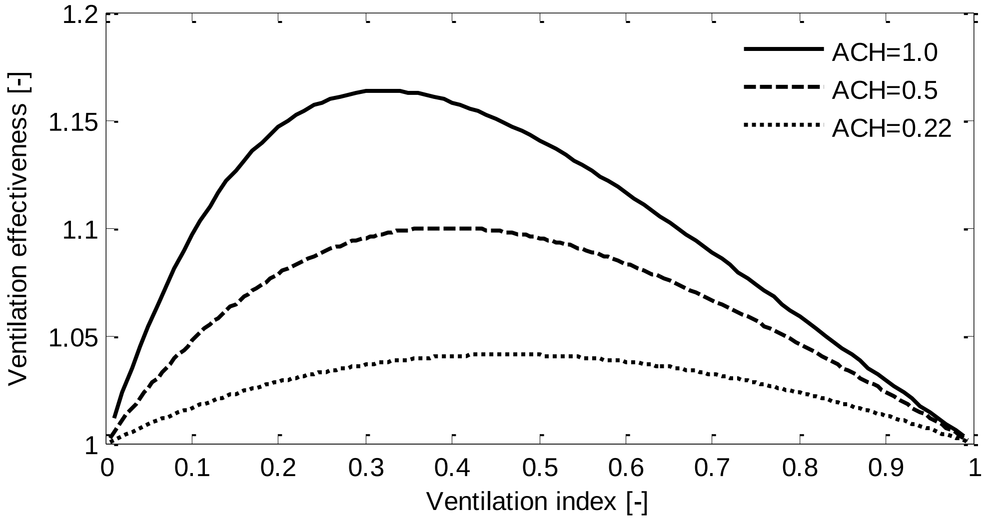

Figure 2: Ventilation effectiveness as a function of the DCV system's ventilation index at an emission ratio of 1 and varying CAV air change rates.

Varying the CAV air flow does not change the effectiveness at the upper and lower limits of the ventilation index for an emission ratio of 1 – instead it changes the magnitude and the ventilation index at which peak effectiveness occurs: the higher CAV air flow; the higher effectiveness can be obtained, but at the cost of a larger total air volume per day. Because the CAV air flow in the three cases varies the target for equivalent dose differs among the three cases. The lowest dose occurs in the case with highest CAV air flow rate i.e. also the system using largest total air volume per day. The peak ventilation effectiveness ranges between 1.04-1.16 at low ventilation rates of 32-46% of the CAV air flows.

Figure 3 expands on figure 2 with the addition of ventilation effectiveness profiles for pollutant emission ratios of 1.6 and 4.0. The solid line is for an emission ratio of 1.0, the dashed line is ER=1.6 and dotted line is ER=4.0.

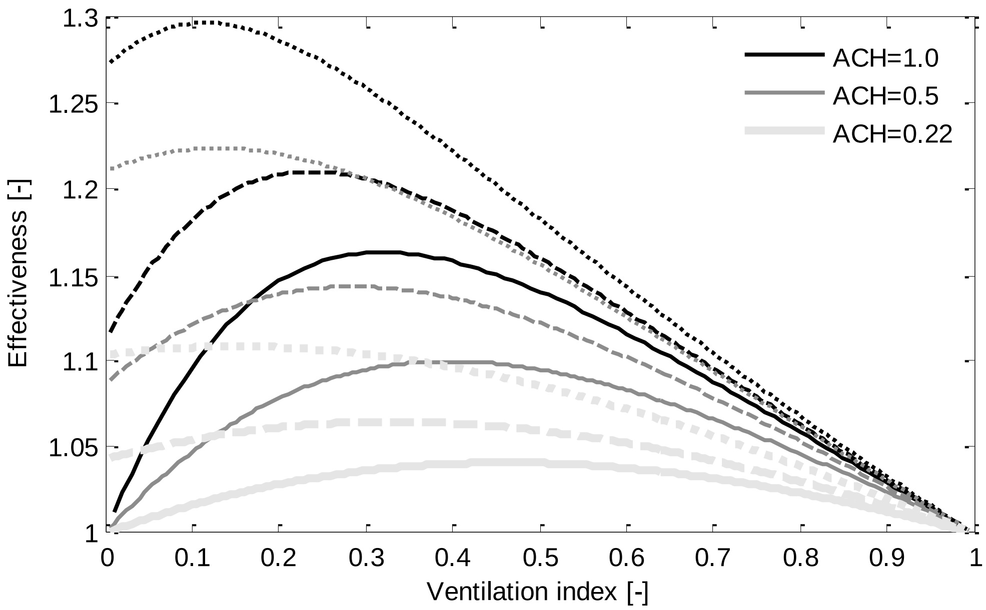

Figure 3: Ventilation effectiveness as a function of ventilation index at CAV air flow of 0.22, 0.5 and 1.0 and at emission ratios of 1.0, 1.6 and 4.0. The solid line is ER=1.0, dashed line is ER=1.6 and dotted line is ER=4.0.

Figure 3 shows the trend of greater peak effectiveness at higher CAV air flows and also greater peak effectiveness at higher occupant contribution to emissions. This indicates a higher potential for total air volume reduction at higher ventilation rates and higher emission ratios. Furthermore it is seen that greater peak ventilation effectiveness occurs at lower ventilation indexes. Table 2 summarizes low and high air flows at which peak ventilation effectiveness occurs.

Table 2: Low and high air flows in pct. of the CAV flow at which peak effectiveness occurs

CAV air flow	A_{low} in pct. of CAV flow	A_{high} in pct. of CAV flow	Peak ventilation effectiveness
$0.22 h^{-1}$	15-46%	121-128%	1.04-1.11
$0.5\ h^{-1}$	13-40%	116-117%	1.10-1.22
$1.0\ h^{-1}$	11-32%	110-113%	1.16-1.30

DISCUSSION

An occupancy controlled DCV system can be designed to provide equivalent indoor air quality as a CAV system during occupied hours using the algorithms shown in this paper. The peak ventilation effectiveness ranges from 1.04 to 1.30 with highest value at greater emission ratios and greater CAV air flow. This means that this type of occupancy controlled DCV system will be most useful/cost effective in residences with high occupant density and high required constant ventilation rates. The emission ratio and ventilation rate deduced from ASHRAE has a high emission ratio but low CAV flow and these effects tend to cancel out. The net effect is a peak effectiveness of 1.11 (at 0.22 ACH and ER=4). The peak effectiveness occurs at low and high air flow rates of 15% and 128% of the CAV flow rate respectively. For the European standard 15251 (at 0.5 ACH and ER= 1.6) the net effect is a peak effectiveness of 1.14. The peak effectiveness occurs at low and high air flow rates of 28% and 117% of the CAV flow rate respectively. The results for peak effectiveness are used to set guideline values for the high and low ventilation rates in an occupancy controlled DCV system. The ventilation rate during unoccupied and occupied hours should be 11-46% and 110-128% of the CAV flow respectively to obtain highest ventilation effectiveness. These guideline rates apply when the home is occupied 16 hours a day and other occupancy patters may lead to considerably different rates.

No matter how you chose to redistribute the CAV air flow in an occupancy controlled DCV system the ventilation effectiveness is increased or remains unchanged. This is because we allow pollutant levels to be higher when the residence is unoccupied. The greatest redistribution we can make is when the fan is turned off during unoccupied hours. In this DCV system we find that the higher emission ratio the less is given away in peak effectiveness by controlling the fan in an on/off mode. At the emission ratio of 4.0 deduced from ASHRAE standard 62.2 the on/off control strategy gives away less than 2 percentage points in peak effectiveness resulting independent of the CAV air flow. The on/off control strategy gives away more in effectiveness at lower emission ratios but the effectiveness will never be lower than that of the CAV system. On/off operation of the fan is an appealing control strategy because it is simple and requires little installation effort.

The energy consumption related to mechanical ventilation is used to transport and condition the air. Increasing the flow rate increases the energy used to transport the air. The fan in the investigated DCV system equivalent to a CAV system with an air change of 0.5 and ER=1.6 must be able to operate at air flows 17% greater and 72% less than the air flow in the CAV system. Assuming the efficiency of the motor remains unchanged when varying the air flow and assuming the same duct system is used in all cases, the fan power is increased by 60% (using the fan power law equation) during occupied hours. During unoccupied hours the fan power is reduced to 2% of the CAV consumption. The total energy consumption for transportation of the air is thereby increased by increased 8%. This could be reduced by optimizing the fan and duct systems to better match the increased air flow rates. Larger fan and larger ducting as well as any controls used to detect occupancy imply higher first costs for the DCV system. Estimating these costs is beyond the scope of this study – but would be required in a detailed design analysis. However, in most cases the energy saved by conditioning less air will be greater than these fan power changes. Assuming that energy to condition the air scales with total air flow, an effectiveness>1.08 is needed to offset the fan power increase calculated above, and this must be taken into consideration when designing the DCV system. For a better estimate of energy savings we would need to convolve the changing ventilation rates with changing outdoor temperatures.

This study represents a preliminary investigation into the use of DCV in residences and has revealed potential for future work. This work needs to be expanded to look at the effects of changing occupancy patterns and improved estimates of the potential energy savings that include the effect of changing indoor-outdoor conditions with time. Another aspect of DCV is the capacity to respond to signals from utilities to avoid operation at the utility peak load where the costs of energy are higher. This represents a potential for energy cost savings and will be become more important in the future as utilities switch to time of use rates. Lastly, there is the possibility of using the effectiveness calculation in a control algorithm so that extra ventilation could be provided before and after the period of low ventilation rate to maintain acceptable indoor air quality, e.g., combining with the control algorithm by Sherman, Walker and Dickerhoff (2010).

CONCLUSION

This paper presents an analytical study of the total volume of air required on a daily basis to obtain equivalent dose during occupied hours in a DCV system as in a CAV system. The results indicate there is potential to lower total air volume for ventilation systems and that the high and low air flows in a DCV system can be optimized to minimize this total air volume without compromising indoor air quality. The results and discussion in this paper is a first step towards the develop design guidelines for residential DCV system.

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