A study of demand-controlled ventilation (DCV) and constant air volume (CAV) systems

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ABSTRACT

One of the most common measures of IAQ (indoor air quality) is carbon dioxide, CO_2, generated by human respiration, in particular, where the main source of pollutions are occupants. In this report, the occupancy-related pollutants are considered as the main pollutant source. However, other type of sources may also be removed satisfactory when governing the ventilation system for removal of occupancy-related pollutants. In this article, the ventilation system in a room is modelled by a simple dynamic differential equation. The model has then been used for simulations. Simulations of demand controlled ventilation (DCV) systems have been carried out and DCV systems have been compared with constant air volume (CAV). Comparisons based on good air quality (a CO_2 concentration less than 1000 ppm) show that DCV using feedback system requires less integrated outdoor air flow than base/forced ventilation no matter which controller is used. In our simulations the highest difference between CAV-system with a constant outdoor airflow rate on 0.9 m^3/s and DCV with variable outdoor airflow rate is 1664 m^3 during 45 min. The potential of energy savings by going from a traditional system to the DCV system is high as it is shown by an example in this article.

INDEX TERMS

DCV (demand controlled ventilation); CAV (constant air volume); VAV (variable air volume); Control systems; Feedback; Energy savings

INTRODUCTION

There are many factors which affect the indoor air quality (IAQ). The generation of air pollutants inside the building as well as pollutants which enter with outside air affect the IAQ. Building material, home furnishing and occupants may be some examples of sources to indoor-generated pollutants. Pollutant sources are some times divided into two categories, continuous pollutant sources and non-continuous pollutant sources. Continuous pollutant sources are characterized by the fact that they are not directly related to the presence of people and their activities. Examples are emissions from building materials and furniture. One of the most common measures of IAQ is carbon dioxide, CO_2, generated by human respiration, in particular where the main source of pollutions are occupants. In difference from the continuous pollutant sources, the occupancy-related pollutants, called also non-continuous pollutant sources, are related to the presence and the activity of persons. In this report, the occupancy-related pollutants are considered as the main pollutant source. However, other type of sources may also be removed satisfactory when governing the ventilation system for removal of occupancy-related pollutants. The outdoor CO_2 concentration is approximately between 350 and 450 ppm and at this concentration CO_2 does not cause any health damage. However, CO_2 is often used as an indicator of

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IAQ. Though CO_2 itself is not a pollutant at normal indoor levels, it is used as an indicator for human-originated pollutants (bioeffluents) and as a result it can be used as an indicator of IAQ. According to recommendations of acceptable IAQ by the World Health Organization (WHO), the CO_2 concentration should not exceed 1000 ppm. CO_2 levels higher than 1000 ppm mean that the outside air supply per occupant is not enough to maintain an accepted IAQ. CO_2 is easily measured and gives a measure of other occupant-generated pollutants (1). Since human health and effectiveness are strongly affected by IAQ and since the demands on energy saving has been increasing during last decades, many investigations have been carried out in ventilation systems striving to achieve a good IAQ and save energy. One of the most important measures in ventilation system in order to achieve these goals has been *Demand Controlled Ventilation* (DCV). A DCV system is defined by the International Energy Agency (IEA) as a ventilation system where the air flow rate is governed by a sensor detecting humidity or airborne pollutants, in order to keep the concentration level of the detected substance(s) below a preset value (2). In this article, CO_2 is the detected substance in order to keep it below a certain value. Such DCV system works based on measuring CO_2 concentration by a sensor and allowing a feedback control loop to control the rate of outside air supply in order to maintain an acceptable IAQ with minimum amount of outside air supply. The benefits of a DCV system depends on many factors and above all depends on the unpredictability and variability both in time and concentration of occupancy profile and hence CO_2. A DCV system provides a good IAQ and offers a more energy-efficient solution than conventional ventilating systems.

In this article, DCV systems have been compared with CAV (constant air volume). The ventilation system in a room is modelled by a simple dynamic differential equation. The model has then been used for simulations.

MODELLING OF VENTILATION IN AN AUDITORIUM

A dynamic balance equation for CO_2 concentration in a room can be written as:

$$\dot{V} \cdot C_{\mathrm{out}} + G - \dot{V} C_{\mathrm{e}} = V \frac{\mathrm{d}C}{\mathrm{d}t} \qquad (1)$$

where $\dot{V}$ is the rate of outside air flow, C_{out}, C_{e} and C are outdoor concentration, exhaust concentration and indoor concentration of CO_2, respectively, V is the volume of the building and G is the indoor pollutant generation rate. The outside concentration of CO_2 (C_{out}) is normally about 350–450 ppm. C_{out} and G (CO_2 generation rate) of 400 ppm and 18 l h^{-1} per person, respectively are assumed in the simulations in this article. In a one-zone model C represents the indoor concentration of CO_2 and C_{e} which denotes CO_2-concentration in the exhaust air is equal to C. Assuming $C_{\mathrm{e}} = C$ and stationary state when the equilibrium is reached, Eqn (1) can be written as:

$$C = C_{\mathrm{out}} + \frac{G}{\dot{V}} \qquad (2)$$

By rearranging, Eqn (2) can also be written as:

$$\dot{V} = \frac{G}{(C - C_{\mathrm{out}}) \times 10^{-6}} \qquad (3)$$

Note: 10^{-6} is multiplied in (C–C_{out}) in denominator to ensure that $\dot{V}$ is obtained in $m^3\ s^{-1}$ if C and C_{out} are in ppm.

A room can also be divided in several zones and a balance equation for CO_2 concentration can be written for each zone (multi-zone modelling).

SIMULATIONS OF THE MODELL

Equation (1) can be simulated in the software program Matlab-Simulink and the dynamic characteristics of the model can be investigated. Figure 1 shows the Simulink model of (Eqn 1) where C is assumed to be equal to C_e (i.e. the indoor air is perfectly mixed).

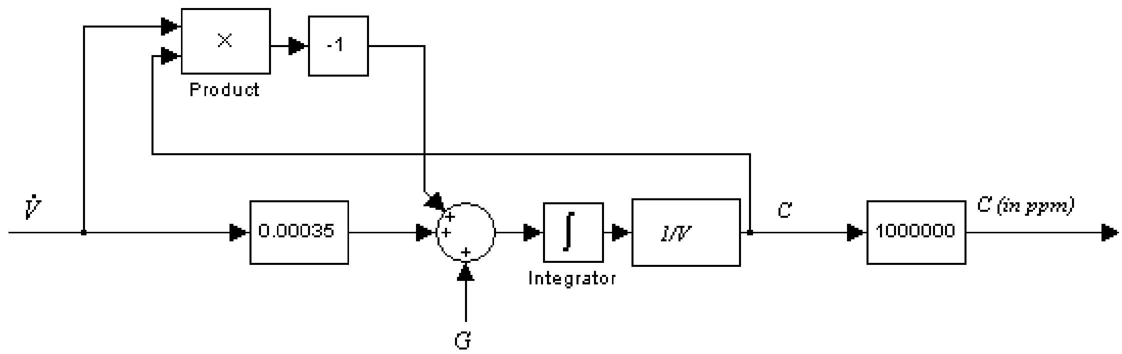

Figure 1 A Simulink model of Eqn (1) where C_{out} is assumed to be 350 ppm. Output signal is the CO_2 concentration of indoor air in ppm and input signals are $\dot{V}$ ($m^3\ s^{-1}$) and G ($m^3\ CO_2/s$). It is assumed that $C = C_e$.

DIFFERENT CONTROL STRATEGIES FOR DCV SYSTEMS

In this section, different control strategies for a DCV system are investigated. The results of different control strategies on outdoor air flow rate and CO_2 concentrations are compared. The goal and the base for comparisons is to keep CO_2 concentrations below a certain value (1000 ppm) with a minimum amount of outdoor air flow rate. In this article the outdoor air is not directly used for warming and/or cooling and hence the sizing of outdoor air flow rate is made only based on CO_2 concentrations. However, the outdoor air may be handled by for example warming and/or cooling to maintain an acceptable indoor climate. By minimizing the outdoor air flow rate and still not exceeding the maximum allowed value for CO_2 concentration the energy for driving the fans, warming and/or cooling the outdoor air when the outside air is very cold or warm will be reduced. The same auditorium using one-zone model is simulated for different strategies. Following control strategies are investigated: ON–OFF controller, ON–OFF controller with dead zones, P-controller and CAV (constant air volume).

Demand-controlled Ventilation Using an ON–OFF Controller

Figure 2 shows a block diagram for a DCV system using an ON–OFF controller.

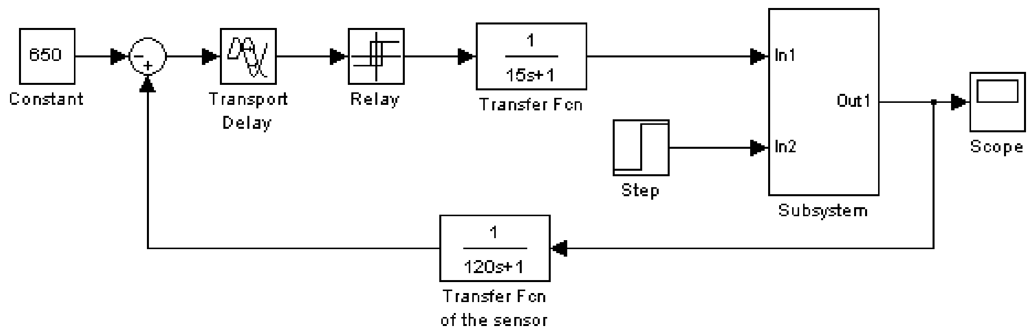

Figure 2 An ON–OFF controlled DCV system with a reference value equal to 650 ppm. Maximal and minimal control signals (outdoor air flow rate) can be 0.9 and 0.225 m^3/s, respectively. The time constants for the sensor and the actuator are 120 and 15 s, respectively, and the delay time for control signal transference is 15 s.

The ON-OFF controller used here is shown in Figure 3.

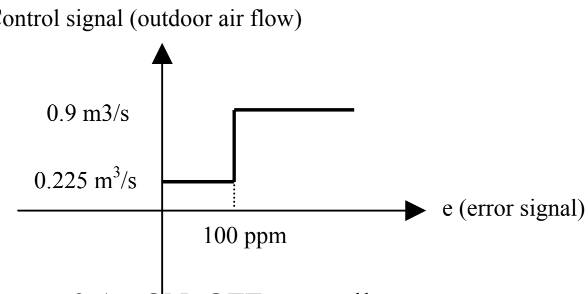

Figure 3 An ON–OFF controller.

Table 1 shows the total outdoor air flow (integrated value) during 45 min for different number of people and for both variable air flow (VAV) and constant air flow (CAV). For all VAV cases, the CO_2 concentration of indoor air does not exceed 900 ppm. For CAV, the forced ventilation rate is constant at 0.9 m^3/s.

Table 1 Total outdoor air flow is shown for both VAV and CAV during 45 min and for different occupancies when the reference value is 750 ppm

Number of people	Total outdoor air flow (m^3)	
	VAV	CAV
38	817.4	2430
55	1263	2430
88	1967	2430

For all VAV cases, the CO_2 concentration of indoor air does not exceed 900 ppm.

A comparison of table shows that the maximum and minimum difference in total outdoor air flow between VAV and CAV is 1612.6 and 371 m^3, respectively.

Demand-controlled Ventilation Using an ON–OFF Controller with Dead Zone

A drawback with an ON–OFF controller without dead zone is that the actuator is worn earlier than an ON-OFF controller with dead zone. The structure of an ON–OFF controller with dead zone is shown in Figure 4.

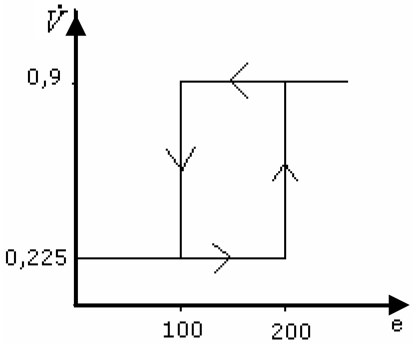

Figure 4 An ON–OFF controller with dead zone. The horizontal axes is the error signal (ppm) and the vertical axes is the outdoor airflow rate (m^3/s).

With same conditions as before, Table 2, which is similar to Table 1, is shown here.

Table 2 Total outdoor air flow is shown for both VAV and CAV during 45 min and for different occupancies when the reference value is 750 ppm

Number of people	Total outdoor air flow (m^3)	
	VAV	CAV
38	807.4	2430
55	1095	2430
88	1848	2430

A comparison of the tables shows that the maximum and minimum difference in total outdoor air flow between VAV and CAV is 1622.6 and 484 m^3, respectively. Here again, the carbon dioxide concentration of indoor air is below 1000 ppm for all cases.

Demand-controlled Ventilation Using a P-controller

Instead of an ON–OFF controller, a P-controller is used here. Other conditions are the same as before. The P-controller used here is shown in Figure 5.

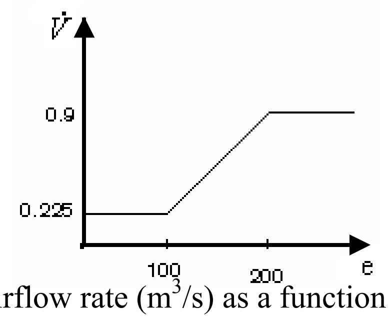

Figure 5 Outdoor airflow rate (m^3/s) as a function of error signal (ppm).

The results of simulations are presented in Table 3.

Table 3 Total outdoor air flow is shown for both VAV and CAV during 45 min and for different occupancies when the reference value is 750 ppm

Number of people	Total outdoor air flow (m^3)	
	VAV	CAV
38	766	2430
55	1116	2430
88	1779	2430

A comparison of the tables shows that the maximum and minimum difference in total outdoor air flow between VAV and CAV is 1664 and 439 m^3 respectively. Here again, the carbon dioxide concentration of indoor air is below 1000 ppm for all cases.

CONCLUSIONS

Different control strategies have been investigated and compared to the traditional base/forced ventilation systems. Comparisons show that demand-controlled ventilation using feedback system requires less integrated outdoor air flow in order to maintain an accepted air quality (no matter which controller is used) than base/forced ventilation. In our simulations the highest difference between CAV-system with a constant outdoor airflow rate on 0.9 m^3/s and demand-controlled ventilation with variable outdoor airflow rate is 1664 m^3 during 45 min. To show and demonstrate the potential of energy savings by going from a traditional system to the demand-controlled ventilation system, the underneath example is given:

In order to maintain an acceptable thermal comfort in a building, the supply air is handled (is warmed, cooled, and humidified, etc). To warm or cool 1664 m^3 outdoor air 10°C during winter and summer, respectively, 5.5 kWh energy is used according to following calculation:

$\rho_{air} \cdot C_{pair} \cdot 1664 \cdot 10°C = 1.2 \cdot 1000 \cdot 1664 \cdot 10 = 20$ MJ corresponding 5.5 kWh

ρ_{luft} = Density of air

C_{pluft} = Specific heat capacity of the air

The purpose of showing this simple example is just to illustrate the possibilities of saving energy by using demand-controlled ventilation. According to example 5.5 kWh can be saved only during 45 min. This is of course a very rough calculation, the saving of fan power is not included in this calculation likewise the energy which may be recovered by heat exchanger.

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