COMPUTER SIMULATION OF THE IMPACT OF CO_2-BASED VENTILATION CONTROL

Radu Zmeureanu and Fariborz Haghighat
Centre for Building Studies
Concordia University, Montréal
CANADA H3G 1M8

ABSTRACT

This paper presents; the evaluation, of the impact of a CO2-based DCV system, which was performed by computer simulation. A subroutine was developed, and then integrated, using the Functional Values feature, within a model of a large existing office building, which was developed using the **MICRO-DOE2** software, version E. Since the CO2-based DCV system has to be integrated with a conventional control system, which maintains the desired mixing air temperature, the impact on the indoor air quality and the energy performance of the building depends on the type of conventional control. The reduction of annual energy cost is evaluated to be between 3 and 7.6%, and the annual energy consumption between 1.1 and 4.9%.

INTRODUCTION

ASHRAE Standard 62-89 recommends two methods for maintaining acceptable indoor air quality (IAQ): ventilation rate procedure and indoor air quality procedure (ASHRAE 1989). The ventilation rate procedure assumes that the acceptable indoor air quality is achieved when the building is ventilated at the prescribed ventilation rate, that is based on the type of activity and the occupation density (e.g., for an office building with 14 m^2 of floor area per person, the minimum outdoor ventilation rate per person is equal to 10 L/s, to limit the concentration of carbon dioxide CO_2 in the indoor air at 1000 ppm). The main assumption is the absence of abnormal sources of contaminant emissions. Earlier work by Yaglou (1930, 1937) indicated that CO_2 concentration and indoor air quality in occupied buildings are related. If there are other sources of contaminants present, generated by occupants or their activities, the extraction at the source is the best solution. The ventilation rate procedure is used for the design and operation of the heating, ventilating and air conditioning (HVAC) systems, and by software developers in modelling the thermal performance of buildings. The inherent drawback of this procedure, that is the deterioration of the air quality in occupied spaces, is noticed when the occupation density is greater than the design condition. While some spaces are inadequately ventilated and experience air quality problems, other spaces with a seldom use, such as meeting rooms, are overventilated resulting in needless energy use. Moreover, the recommended ventilation rate was developed assuming a constant concentration of CO_2 of 500 ppm in the outdoor air. In reality, the concentration of CO_2 varies from location to location, and also fluctuates during the day; for instance, for a particular location it can vary between 350 to 450 ppm. In the indoor air quality procedure, the ventilation rate is controlled to maintain the contaminant concentration level within the recommended limits. This procedure seems to offer means of improving the quality of indoor air in the high demand zone by increasing the ventilation rate when is needed, and saving energy by reducing the ventilation rate when is not needed.

Earlier work showed that the concentration of CO_2 can be a very good indicator of indoor air quality in an occupied space where the persons are the main source of pollution (Haghighat 1992 and IEA 1990). Other work has identified a theoretical relationship between CO_2 concentration and ventilation air supply rate in buildings where CO_2 concentration is primarily in proportion to the number of occupants. Therefore, the CO_2-based Demand Controlled Ventilation (DCV) is an intelligent approach to regulate the ventilation rates in buildings. Research has been done with CO_2-based DCV, in the form of case studies (Haghighat 1992, Reardon 1992 and Bearg 1995) and computer simulation (Haghighat 1993 and Emmerich 1995). When occupants are not the main source of pollution, the use of mixed-gas sensors is suggested. More sophisticated and state-of-the-art control equipment and sensors are now available. A variety of sensors have been developed for this application. These sensors can be activated by an indicator or by a pollutant. The simplest indicator sensor is the presence sensor, which is activated by the presence of persons, and is not influenced by the activity level. Therefore, the indicator sensor is insensitive to the generation intensity of CO_2. Pollutant indicator sensors are: humidity sensors, carbon dioxide sensors, mixed gas sensors (IAQ sensors). Mixed gas sensors are sensitive to more than one contaminant. They detect human presence by measuring human odours. Bischof (1993) suggested that it is impossible to determine the air quality level by using sensors of the present generation. A variety of studies reported the potential of DCV systems for providing acceptable indoor air quality, as well as energy savings in a wide area of application. Fehlman et al. (1990) reported that the CO_2-based ventilation system consumes 80% less energy during summer and 30% less during winter than the conventional one. Meier (1993) conducted a field study to compare the associated energy savings of three systems: (i) mixed-gas based, (ii) CO_2-based and (iii) conven-tional. He reported that considerable savings can be achieved by using the DCV system for operating the mechanical systems, which does not significantly affect the occupants' thermal comfort and perceived IAQ.

COMPUTER SIMULATION

The DOE2.1E program is well-known for its capabilities to evaluate the energy performance of large buildings with complex HVAC systems and schedules of operation. However, the program does not allow for a direct evaluation of the impact of DCV systems. The user can modify some calculations performed within the LOADS and SYSTEMS blocks, without recompiling the program, by using the Functional Values feature (DOE-2 1993). In this study, this approach was used to modify the subroutine ECONO in the SYSTEMS block and to perform the following operations: (i) the evaluation of the concentration of CO_2 in the main return air duct, (ii) the comparison between the estimated concentration of CO_2 and the maximum acceptable value; if this value is exceeded then the ventilation rate is increased, and (iii) the control of the outside air flow rate.

Concentration of CO_2 in the return air is evaluated using the "one-compartment" model, by neglecting the natural pollutant decay, and assuming that the filter efficiency for retaining the carbon dioxide is equal to zero (Wadden 1983):

$$c_t=\frac{k\cdot(m_o+m_i)\cdot c_o+NOP\cdot S}{k\cdot(m_o+m_i)}\cdot[1-\exp[-\frac{k}{V}\cdot(m_o+m_i)\cdot t]]+$$

$$c_1\cdot\exp[-\frac{k}{V}\cdot(m_o+m_i)\cdot t]$$

where:

m_i = total air infiltration rate for all zones served by the HVAC system,
m_o = outdoor ventilation rate,
$m_o = PO\cdot SUPPLY$
PO = ratio of outside air flow rate to total supply air flow rate,
SUPPLY = total supply air flow rate for all zones served by the HVAC system,
c_o = concentration of CO_2 in the outdoor air,
c_1 = initial concentration of CO_2,
NOP = total number of people in all zones served by the HVAC system,
S = intensity of generation of pollutant per person,
k = average coefficient of inefficient mixing for all zones,
V = volume of all zones served by the HVAC system,
t = time.

Initially, PO is equal to the minimum value, which is assigned to the system during the operating hours. If the estimated concentration of CO_2 in the main return duct exceeds the maximum acceptable value, then the ventilation rate is increased (PO is increased by 0.0001), and the concentration of CO_2 is estimated again. This iterative process continues until the concentration of CO_2 in the main return duct is lower than or equal to the maximum acceptable value. The modifications to the ECONO subroutine enable the user to evaluate the impact of a CO_2-based DCV system, when it is integrated with one of the following conventional strategies for controlling the outdoor air flow rate: (i) fixed amount of outdoor air, or (ii) variable amount, which is controlled by a dry-bulb temperature economizer system. There are three types of operating conditions when the temperature economizer is used: (i) when the outdoor temperature is lower than the setpoint temperature of supply air after the cooling coil (cold deck temperature), the economizer system increases the amount of outside air to obtain a mixed air temperature equal to the desired supply air temperature; the amount of outdoor air can vary between a minimum and a maximum (100% of the total supply air when the outdoor air temperature is equal to the supply air temperature); (ii) when the outdoor temperature is between the setpoint temperature of supply air and a reference temperature, called "switchover temperature", the economizer system allows a larger amount of outdoor air (equal to 100% of the total supply air flow rate) to be brought into the building; the "switchover temperature" is used to avoid the operation with 100% of outside air during the hot and humid weather; (iii) when the outdoor air temperature is higher than the "switchover temperature", the economizer system reduces the amount of outdoor air to a minimum. The first two operating conditions are used to reduce the energy consumption for cooling, by taking advantage of the "free cooling." In the same time, these two operating strategies help to increase the indoor air quality, by supplying more outdoor air than the minimum required. Therefore, the CO_2-based DCV has practically no impact during the second type of operating conditions, and has a limited impact during the first one.

The first group of parameters required by the calculations is obtained directly from the DOE program. The air infiltration rate is calculated in the LOADS block, based on the user-defined average air changes per hour and the volume for each zone, corrected with the wind speed from the weather data file. The total air infiltration rate for all zones served by the HVAC system is available in the SYSTEMS block under the name CINF, and therefore can be read by the new subroutine. Other parameters are: month, day and hour of simulation (IMO, IDAY, IHR), minimum proportion of outdoor air (POMXXX), total supply air flow rate (CFM), outdoor dry-bulb temperature (DBT), air temperature in the main return duct (TR), and "switchover temperature" of the economizer system (ECONO-LIMIT-T). The second group of parameters required by the new subroutine must be defined by the user: total floor area and volume of all zones deserved by the HVAC system, average occupation density (floor area per person) during the normal hours of operation, ratio between the number of people during the lunch break and the number of people for normal occupancy, start and stop time for fans and occupancy, setpoint temperature of supply air after the cooling coil, source intensity, mixing efficiency, concentration of CO_2 in the outdoor air, and maximum acceptable concentration in the indoor air.

In this study, a model of a large existing office building in Montreal, which was previously developed with the MICRO-DOE2 program, version E, a PC-version of DOE2.1E program (MICRO-DOE2 1994) was used. The base case was developed by considering the following assumptions:

average occupancy density is equal to 14 m^2/person from 9:00 to 18:00; during the lunch break (12:00 to 13:00) the number of people is reduced by 50%;

central Variable Air Volume system operates from 7:00 to 23:00, with a maximum supply air flow rate of 4.65 $L/s{\cdot}m^2$; the setpoint temperature of supply air is equal to 13.9°C;

"switchover temperature" of the economizer system is set equal to 22°C;

indoor air temperature is maintained at 23-24°C in the summer and 20-21°C in the winter;

outside the operating hours of the HVAC systems, the infiltration rate is about 0.2 ach, while during its operation, the infiltration rate is reduced by 50%;

rate of emission of CO_2 is equal to 0.30 L/min·person;

mixing coefficient is equal to 0.7;

CO_2 concentration in the outdoor air is 380.0 ppm and the maximum acceptable concentration of CO_2 in the return air is 800 ppm;

when the CO_2-based DCV system is used, the outside air dampers do not close completely the air intake, and the minimum proportion of outdoor air is equal to 5% of the total supply air flow rate;

when the CO_2-based DCV system is not used, the minimum amount of outdoor air is equal to the recommended ventilation rate (10 L/s·person) multiplied by the maximum number of people in all zones; this value corresponds to 16% of the total supply air flow rate.

The impact of a CO_2-based DCV is evaluated for a system using a dry-bulb temperature economizer and for another using a fixed amount of outdoor air. Figures 1 and 2 show the hourly variation of CO_2 concentration in the return air duct and the corresponding outdoor ventilation rate for a warm day in June (day I), when the outdoor temperature varies between 22°C and 28°C. Since the outdoor temperature is greater than the "switchover temperature," the conventional dry-bulb economizer uses the minimum outdoor ventilation rate, which is equal to 10 L/s·person and is kept constant during the operation of fans. In this case, the concentration of CO_2 follows the occupation density. When the CO_2-based DCV is used with the conventional dry-bulb economizer, the outdoor ventilation rate varies in terms of occupation density, and is controlled to maintain the concentration of CO_2

in the return duct lower than or equal to 800 ppm. During the lunch time, the outdoor ventilation rate required to eliminate the carbon dioxide from the space is about 3.0 L/s·person or 33% of the recommended design value. Figures 3 and 4 show the impact of weather conditions, using a warm day (day I) vs a cool day (day II), on the operation of a CO_2-based DCV integrated within an economizer. During the day II, when the outdoor air temperature varies between 12.7 and 13.9°C, the economizer system uses a larger proportion of outdoor air (between 26.4 to 29.3 L/s·person). Consequently, the maximum concentration of CO_2 in the return air duct is about 500 ppm.

The annual energy performance of the base building, without a CO_2-based DCV system, can be summarized as follows: 17.0 $\$/m^2$ and 265 kWh/m^2 (when the conventional economizer system is used), or 17.4 $\$/m^2$ and 275.5 kWh/m^2 (when a fixed amount of outdoor air is used). The impact of CO_2-based DCV system with respect to the base building is presented in Table 1:

- when the DCV system is integrated within a conventional temperature economizer, the annual energy use for cooling is reduced by about 4.3%, while the total energy consumption by 1.1 to 1.3%; in addition to the reduction of energy consumption, the peak electric demand is reduced by about 10%; the annual energy cost is reduced by about 3.4%;

- when the DCV system is integrated within a conventional system with a fixed amount of outdoor air, the annual energy use for cooling is increased by 3.4% (when the HVAC system is used only between 7:00 and 23:00) and by 26.4% (when the HVAC system operates 24 hours per day), since the potential "free cooling" is not entirely used; the total annual energy consumption is increased by 2.3 %, when the HVAC system operates 24 hours per day, and is decreased by 4.9%, when the system operates betwen 7:00 and 23:00; the annual savings are mainly due to the reduction by about 18% of the energy used for heating; the peak electric demand is reduced by about 9%; hence the annual energy cost is reduced by 3 to 7.6%.

The benefit of using a CO_2-based DCV system is more evident when the number of people in the building diminishes. For instance, when the proposed DCV system is used along with a conventional system that maintains a fixed amount of outdoor air, and the number of people is reduced to about 10% of the design value, the annual energy use for cooling is reduced by 100%, the total annual energy consumption by 5.7%, and the annual energy cost by 2.7%.

CONCLUSIONS

This paper presented the development of a subroutine for evaluating the impact of a CO_2-based DCV system, and its integration within a model of a large existing office building, which was developed using the MICRO-DOE2 software, version E. Since the CO_2-based DCV has to be integrated with a conventional control system, which controls the mixing air temperature, the impact on the indoor air quality and the energy performance of the building depends on the type of conventional control. In addition, the results presented in this paper cannot be extrapolated without a further analysis to other buildings or climatic conditions.

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Table 1
Impact of the CO_2-based ventilation control on the energy consumption and cost

Reference System	Operating Hours	Annual Energy Cost	Annual Energy Consumption	Annual Energy Use for Cooling	Seasonal Load on Cooling Coils (May to September)
Dry-bulb temperature economizer	1:00 - 24:00	-3.5%	-1.3%	-4.4%	-4%
	7:00 - 23:00	-3.4%	-1.1%	-4.3%	-4%
Fixed amount of outdoor air	1:00 - 24:00	-3%	+2.3%	+26.4%	+2.8%
	7:00 - 23:00	-7.6%	-4.9%	+3.4%	+2.8%

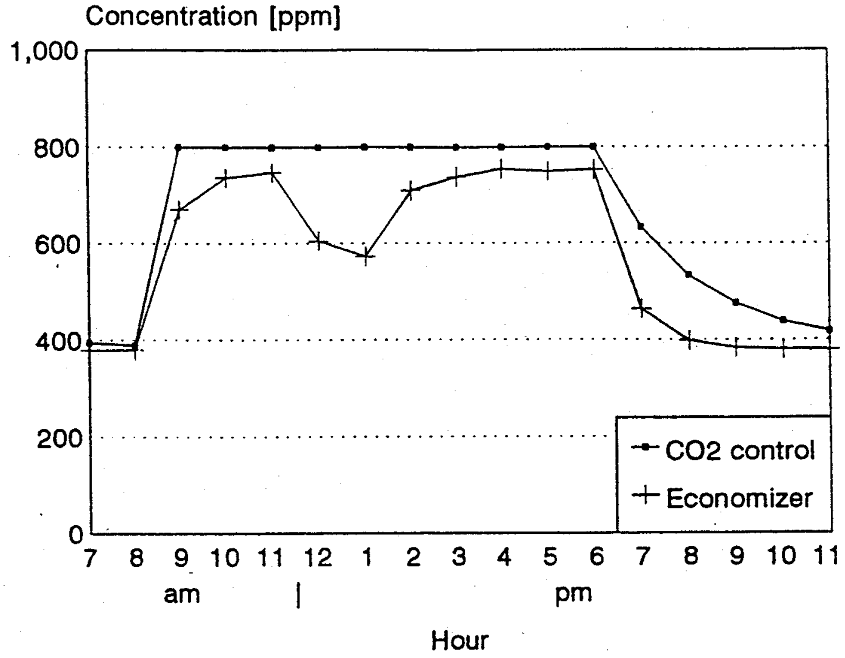

Figure 1. Hourly variation of the CO_2 concentration in the return air duct, for a warm day in June (day I). CO_2-based Demand Controlled Ventilation system vs conventional economizer system.

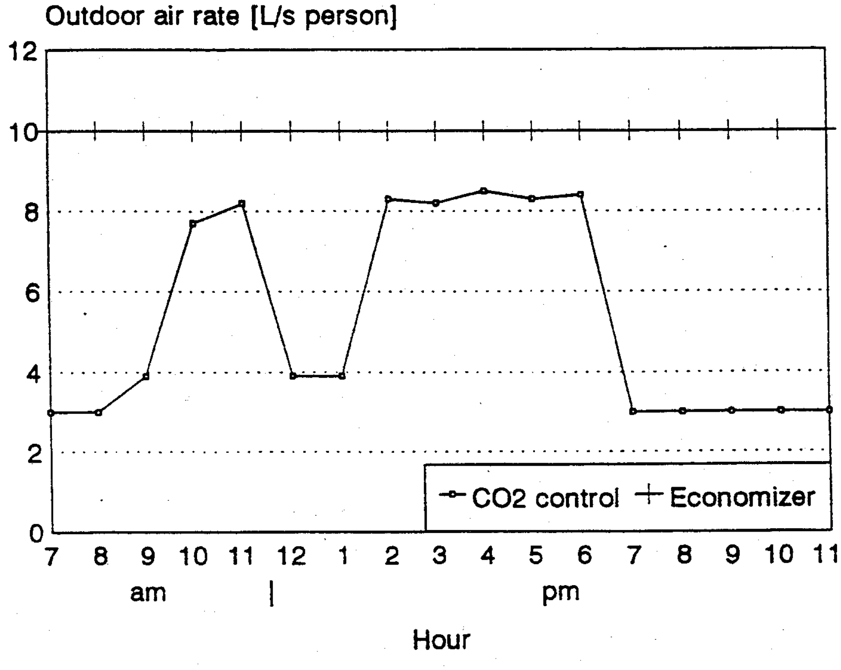

Figure 2. Hourly variation of the outdoor ventilation rate for a warm day in June (day I). CO_2-based Demand Controlled Ventilation system vs conventional economizer system.

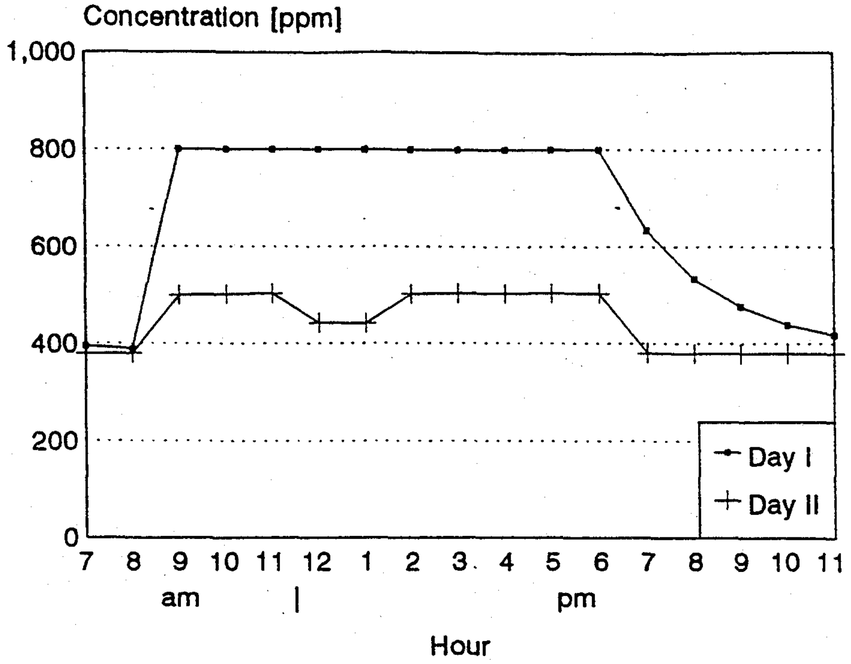

Figure 3. Hourly variation of the CO_2 concentration in the return air duct, when a Demand Controlled Ventilation is integrated within an economizer system. A warm day (day I) vs a cool day (day (II).

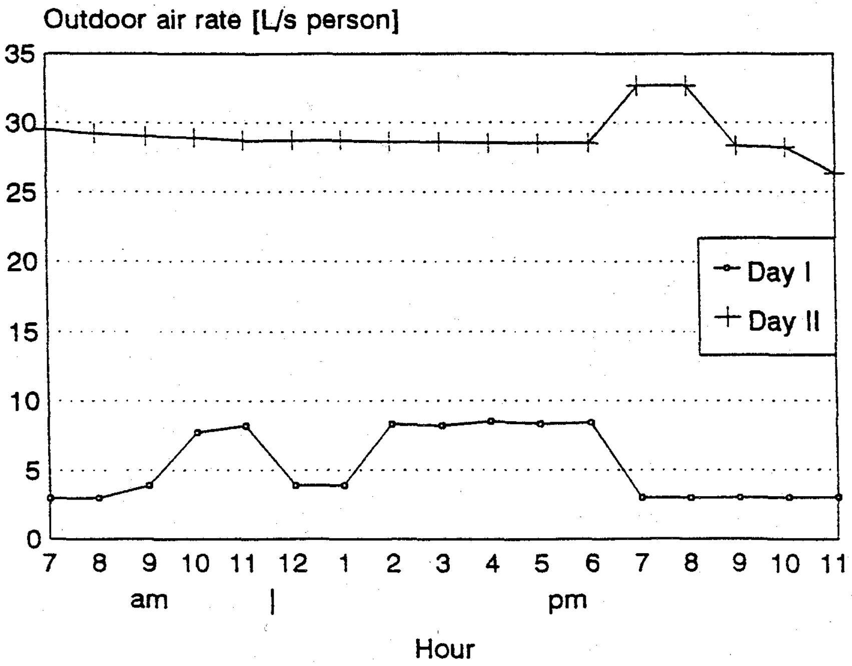

Figure 4. Hourly variation of the outdoor ventilation rate, when a Demand Controlled Ventilation is integrated within an economizer system. A warm day (day I) vs a cool day (day (II).