AUTOMATIC VARIABLE VENTILATION CONTROL SYSTEMS BASED ON AIR QUALITY DETECTION

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DISCLAIMER

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Automatic variable ventilation control systems based on air quality detection

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SUMMARY

Mechanical ventilation systems usually provide a fixed quantity of "fresh" air to a building space based upon the maximum number of people expected to occupy that particular space. When the use of a building space is below its design maximum, the amount of outside air brought into that space can be reduced, thus generally also reducing energy consumption through lower heating and cooling loads. One method of determining the necessary ventilation rate for a particular space is to utilize an air quality detector (e.g., CO_2 or O_2) sensitive to building occupancy and activity load. The output of this detector can in turn be used to control ventilation rates.

Systèmes de contrôle de ventilation automatique et variables basés sur la détection de la qualité

Les systèmes de ventilation méchanique fournissent habituellement à un espace construit une quantité fixée d'air frais, basée sur le nombre maximum de personnes censée occuper cet espace particulier. Quand l'usage de cet espace n'atteint pas le maximum prévu, la quantité d'air exterieur introduit peut être réduite. De ce fait, la consommation d'énergie est generalement aussi réduite grace à une demande moindre en chauffage et refroidissement. Une des méthodes de détermination du taux de ventilation necessaire pour un espace particulier est l'utilisation d'un détecteur de qualité d'air (par example: CO_2 ou O_2) sensible a l'occupation du bâtiment et à son activité. Les résultats de ce détecteur peuvent à leur tour être utilisés pour contrôles les taux de ventilation.

Introduction

Institutional and commercial buildings together use approximately 15% of the energy consumed in the United States. More than half of this energy is used to heat and cool buildings. Since the heating or cooling of outside air as it is introduced to a building requires a significant amount of energy, considerable energy savings can generally be effected by minimizing the use of ventilation air. This paper discusses the energy savings that would result if the amount of outside air supplied to occupied spaces in institutional and commercial buildings was automatically controlled by an air quality sensor.

Ventilation Requirements and Indoor Air Quality Parameters

Ventilation of buildings with outside air is needed for:

- Establishment of a satisfactory balance between the metabolic gases (oxygen and carbon dioxide) in the occupied environment.
- Removal of moisture from internal sources.
- Dilution of human and non-human odors to a level below an unacceptable olfactory threshold.
- Removal of contaminants produced by human activity, construction materials, etc. within the ventilated space.

The American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) has developed a ventilation standard giving recommended and minimum ventilation rates for several types of building spaces. This standard (ASHRAE 62-73) (1) has been adopted by many states and local governments and is widely accepted in the United States. More recently, a new standard, ASHRAE 90-75R, Energy Conservation in New Building Design, has specified that the minimum ventilation rate given in ASHRAE 62-73 for each type of occupancy shall be used for the design of new buildings.

ASHRAE 62-73 specifies 5 cfm (cubic feet per minute)/8.5 cubic meters per hour (m^3/h) per person of outside air as the minimum allowable ventilation rate for most occupied spaces. It appears that this minimum ventilation rate is based largely on odors research performed by C.P. Yaglou et al (2) over 40 years ago and on the need to limit carbon dioxide (CO_2) concentrations to less than 5000 ppm (3).* At 8.5 m^3/h per person and at equilibrium, the concentration of oxygen (O_2) would decrease from 20.6% to 20%, still considerably above the level at which adverse physiological effects such as dizziness and headaches may occur (∼16.5%).

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*ASHRAE is now expected to recommend 2500 ppm as a maximum indoor concentration of CO_2 in the revised Standard 62 (4).

In addition to metabolic gases and odors, moisture and contaminant removal must be examined in setting outside air ventilation requirements. Recent research in residential buildings (5,6,7) has shown that air exchange rates less than one air change per hour may allow the concentrations of certain contaminants [e.g., formaldehyde (HCHO), nitrogen dioxide (NO_2), carbon monoxide (CO), and radon] to reach levels at which there is a health risk to the occupants. In institutional and commercial buildings, NO_2 buildup from gas stove emissions will not be a significant problem; however, CO from tobacco smoking and emanation of HCHO, other organics and radon from certain building materials could limit outside air reductions. Because there are fewer sources (e.g., less cooking and showering) of water vapor in non-residential buildings, condensation of water vapor should be less of a problem.

Air Quality Sensors

A number of parameters could be chosen as indicators of indoor air quality. The concentrations of such parameters might serve as a ventilation rate controlling factor. In an occupied room with no supply of outside air, the concentration of various odorants, CO_2, and water vapor will increase and that of O_2 will decrease with time. Therefore, in principle, any of these constituents of the indoor air could be used as a measure of required ventilation of a building space with no unusual contaminant emanation or activity loads. In spaces where there is smoking, the CO concentration may increase and could also be monitored and used to control the ventilation.

The air quality sensor chosen to measure any of these parameters must be able to satisfy the following requirements:

- Sufficient sensitivity to detect and measure changes in the range of concentrations required for ventilation rate control
- No significant interferences
- Continuous measurement capabilities
- Automatic operation
- Low maintenance
- Commercial availability
- Low cost

Since CO_2 provides a more stringent ventilation requirement than O_2, there could be situations where the O_2 requirement is satisfied while the CO_2 concentration rises to an undesirable level. For example, when equilibrium is reached in a classroom or office, with a ventilation rate of 4.7 m^3/h (3 cfm) per person, the CO_2 concentration will reach 5000 ppm but the O_2 concentration will drop to only 20.1%. No action is called for at this oxygen level, but it would probably be desirable to decrease the CO_2 concentration by letting in more outside air. Thus, CO_2 is a more sensitive indicator of occupancy than O_2.

Water vapor is always present indoors, and its concentration is a function of outdoor conditions as well as human occupancy and activity. In principle, it should be possible to look at the difference in water vapor content between supply and return air, thus sensing the addition from occupants. However, infiltration or non-human indoor generation of water vapor could cause incorrect results unless their effects on water vapor content can be determined. In addition, except at extremes in humidity, we cannot directly correlate water vapor content to ventilation requirements (via health or comfort effects), as we can with CO_2 or O_2. For these reasons, water vapor content is unsatisfactory as a parameter for ventilation control.

The concentration of CO does not vary appreciably with occupancy unless smokers are present; therefore, CO alone is not a satisfactory indoor air quality parameter. However, CO sensor output might be an override control option if ventilation is required for spaces where smokers are present. The measurement of odorant concentrations can only be done by non-continuous, non-automatic methods such as psychophysical or gas chromatographic techniques (8).

CO_2 seems to be the most satisfactory air quality parameter for ventilation control. CO_2 sensors, utilizing non-dispersive infra-red analysis, satisfy the criteria listed above except for low cost; however, development of low-cost CO_2 sensors is in progress. The possibility that CO_2 needs are met but odor and chemical contaminant (e.g., carbon monoxide) levels are too high must always be considered.

The authors are aware of two systems demonstrating ventilation control based on air quality sensing. One system uses a fuel cell as an oxygen sensor (9). The sensor drives a damper motor to admit outside air if the concentration of O_2 in the occupied space falls below 19.5%. Ventilation with outside air continues until the O_2 concentration rises to 20.5%, at which time outside air is excluded. At the present time, this oxygen based system is used mostly in theatres where large changes in occupancy (and, accordingly, O_2 levels) are commonplace. An important deficiency of any O_2 based ventilation control system is that a ventilation rate which maintains oxygen at a safe level may not limit CO_2 to a safe level.

A ventilation control system based on CO_2 detection has been installed in an office building in Osaka, Japan, by Nakahara et al (10). Their study showed that 5 m^3/h per person was the lowest fresh air ventilation rate found satisfactory for maintaining the CO_2 concentration below the Japanese indoor standard of 1000 ppm CO_2.

HVAC Systems

HVAC (heating, ventilation and air conditioning) systems can be grouped generically into two major groups: "multiple-zone" systems, or those in which a single fan serves a number of zones, such as double duct, multi-zone, induction and reheat; and "single-zone" systems, or those in which a fan serves a single zone, such as single-zone and through-the-wall systems. Each of these groups can be further divided into those systems which provide 100% outside air ("once-through" units), and those which recirculate some air. To minimize cooling requirements, many recirculating systems have an economizer scheme which, as a function of the weather, varies the amount of outside air. During cold or hot weather conditions, it provides a minimum of outside air to minimize heating or cooling loads on the system; in mild weather, maximum outside air is used. The economizer cycle, is illustrated in Figure 1. The minimum ventilation rate shown is based on maximum expected occupancy of the facility. Significant reductions of this rate are possible if the fixed minimum control is replaced with air quality sensor control. For recirculating systems, the sum of return air plus outside air is generally constant, and adequate for temperature control at design conditions; thus, the outside air control can always operate independently of the temperature control system.

Once-through systems are more complicated because there is no recirculated air, and the quantity of outside air must be sufficient for heating and cooling at design conditions, as well as for necessary ventilation. In these systems, ventilation can be reduced during mild weather when system loads are light. Although temperature differences are small during these conditions, the conditions prevail for a large number of hours in most climates, so total savings can still be significant. In addition, reduced air flow through the fan saves much fan energy.

To achieve the savings in the ventilation portion of the heating and cooling load that are possible through the use of air quality sensors, one must integrate the sensors into existing temperature and air flow controls of an HVAC system. An example of such a system is illustrated in

Figure 2. This system, a dual duct with economizer control, selects (in its original configuration) varying quantities of outside and return air according to weather conditions (see Figure 1). Each zone selects a mixture of hot and cold air from the ducts, under control of the zone thermostat, to satisfy its heating or cooling load. In the revised configuration, with a CO_2 monitor installed as shown, an additional control input is provided to the economizer control. A multiplex sampler draws air samples from each zone, in rotation. Each air sample is analyzed by the CO_2 monitor, which provides a signal representing the highest CO_2 concentration from any zone to the economizer control logic. When occupancy is below maximum, the air quality sensor would permit further reductions in outside air, below the minimum established by design criteria.

Potential Energy Savings

The potential energy savings of such a control system can be demonstrated for various building types. The savings are shown below for educational buildings, although such a control system should be useful in any building with variable occupancy. Educational buildings have been chosen for several reasons:

1. Their significant variation of occupancy with time (particularly in high schools and colleges)
2. The acceptance of longer payback periods by public institutions than by private enterprises
3. The focus of the U.S. National Energy Act to provide support for the retrofitting of schools and hospitals
4. Their relatively high energy use among institutional and commercial buildings.

Table 1 shows the yearly heating loads for seven selected cities representing four different geographic regions of the United States.

Table 1 Heating Load Per m^3/h of Outside Air for Selected Cities

City	Degree Days (Base 18.3^oC)	Region	Heating Load (Kwh/m^3h^{-1})
Albany, New York	3819	Northeast	9.97
Pittsburgh, Pennsylvania	3326	Northeast	8.97
Chicago, Illinois	3419	North Central	9.65
Minneapolis, Minnesota	4657	North Central	11.78
San Francisco, California	1675	West	4.12
Los Angeles, California	1145	West	2.00
Jacksonville, Florida	688	South	1.53

The heating load in kwh/m^3h^{-1} is computed by using equation (1)

$$\frac{kwh}{m^3h^{-1}} = .33 \times 10^{-3} \Sigma_i (21.1 - \bar{T}_i)t_i \qquad (1)$$

where t_i is the number of hours during the school year that the outside dry bulb temperature T_i is in the bin range $(\bar{T}_i - 1.4)$ to $(\bar{T}_i + 1.4)$ during the time period 9:00 a.m. to 5:00 p.m. $\bar{T}_i$ is the midpoint of the various 2.8-degree wide temperature bins (11).

As can be seen from Table 1, the greatest energy savings for schools will occur in the Northeast and North Central regions of the United States. Cooling loads have not been calculated here, but for buildings operating year-round, considerable savings (mainly in peak power, partly in energy) can also be expected during the summer in most regions of the United States.

In order to calculate the estimated energy savings for a particular school building, we need to know the magnitude of the reduction in outside air that is consistent with good indoor air quality. Data obtained by the Lawrence Berkeley Laboratory's (LBL) Ventilation Program staff and by other experimenters (10) suggests that a reduction of 17 m^3/h/person is reasonable for an average school. LBL has carried out field monitoring activities at an air conditioned high school building with 700 occupants and 40 classrooms located in Concord, California, and at a smaller elementary school in Columbus, Ohio. In the Concord school, the outside air ventilation rate ranged from an initial value of 22.6 m^3/h per occupant to 2.6 m^3/h per occupant in the classrooms during air quality monitoring. Figure 3 shows CO_2 concentration as a function of time in two high school classrooms and in the outside air for a typical school day when the classroom ventilation rate is 4.3 m^3/h per occupant. Measurements of gases such as CO, CO_2, SO_2, NO_2, O_3, of particulate matter and of microbial content indicated that CO_2 was the only parameter that changed appreciably in concentration when the ventilation rate was lowered by more than 17 m^3/h per person. While CO_2 levels increased, concentrations were still far below levels considered to be a health hazard. Results of a survey of subjective perception of indoor air quality (includes odor intensity and other comfort factors) showed no deterioration of student comfort caused by decreased ventilation rates. Similar results were obtained at the Columbus, Ohio, school.

To estimate energy savings in a typical school, we assume that the ventilation rate is reduced by 17 m^3/h/person throughout the school year. In practice, this reduction in ventilation rate will vary in magnitude with type of ventilation system, weather conditions, and schedules of occupancy. Further reductions might be possible due to the fact that

CO_2 levels in a school will be approximately equal to outside levels at the beginning of the day, allowing ventilation to be eliminated until CO_2 levels start to rise (unless outside air flow is required for temperature control). With hourly class changes, involving repeated opening of doors, enough natural infiltration may occur to hold CO_2 levels within acceptable limits for most or all of the school day without any additional outside air.

While much of the potential energy savings could be obtained solely by lowering outside air ventilation quantities to a constant lower amount, the advantages of using an air quality sensor to control ventilation rates are that even further energy savings are effected by reducing the average ventilation rate to less than 8.5 m^3/h/person and the maintenance of indoor air quality is assured (quantitative assurance for school and code officials). The use of an indoor air quality sensor will allow the building service engineer to reduce the quantity of outside ventilation air to a value for enough below the current minimum standard (8.5 m^3/h/person) so that the energy cost savings more than pay for the sensor installation in a few years. It is likely that, in the near future,, building codes will permit less than 8.5 m^3/h/person if adequate indoor air quality is assured.

For an occupancy of 50 students per 93 m^2 (1000 ft^2) and a ventilation rate reduction of 17 m^3/h/person, we obtain a ventilation reduction of 9.14 $m^3/h/m^2$. For a typical school building of 4650 m^2, we obtain a reduction of 42,500 m^3/h of outside air. For cities in the Northeast or North Central U.S. (these regions represent 55% of the total floor space in U.S. schools), the heating load reduction would vary from .273 to .358 million kwh per year. There would be additional savings for peak power and energy for cooling in some 25-30% of the schools in this region of the nation. For buildings heated with oil (at 1978 prices of ∿$0.01 per kwh) and with a heating system efficiency of 65%, the energy cost savings for the heating season would range from $4300 to $5600 per year. These cost savings when compared to preliminary cost estimates of automatic variable ventilation control systems, result in a payback period of 3-4 years.

In mid-1979, LBL and its subcontractors plan to install an automatic variable ventilation control system in some educational buildings in the North Central region of the U.S. and study both the measured energy savings and indoor air quality at different times of the year. The cost effectiveness of this device will be determined for different types of buildings and mechanical ventilation systems.

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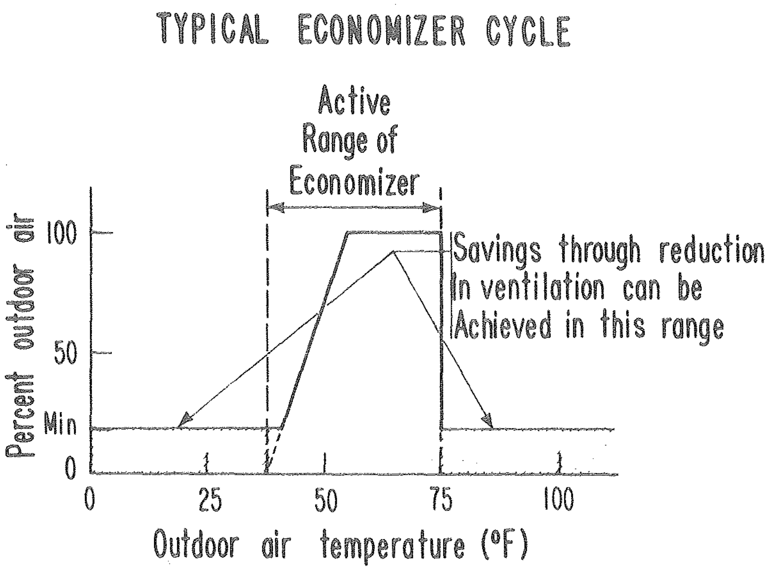

Fig. 1 Economizer controls use as much fresh air as necessary to reduce cooling cost during mild weather.

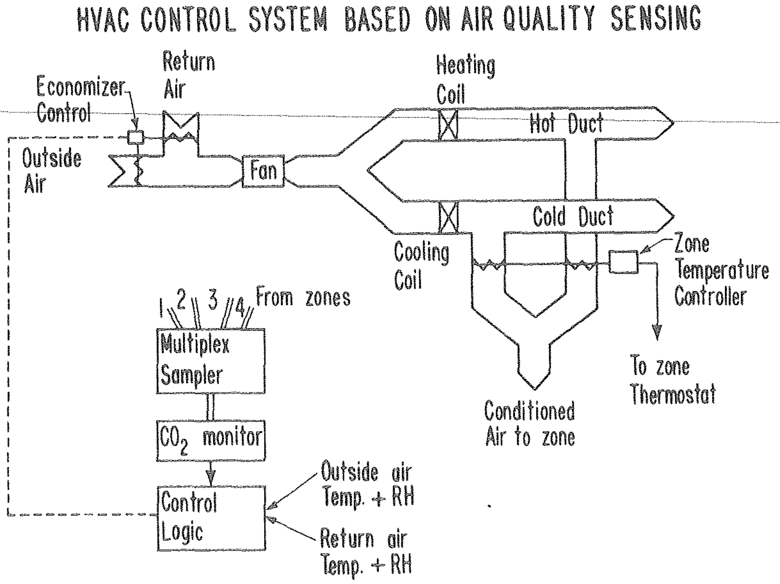

Fig. 2 Schematic of a double duct HVAC system with an air quality sensor control system

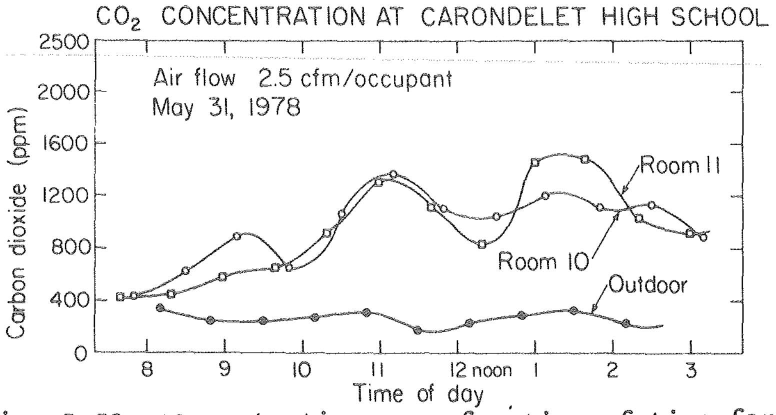

Fig. 3 CO_2 concentration as a function of time for a ventilation rate of 4.3 m^3 /h/ person.

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