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DEMAND CONTROLLED VENTILATION SYSTEMS

CO_2 controlled ventilation systems

Bachelor's thesis

Building Services Engineering

September 2011

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CONTENTS

1 INTRODUCTION

Currently most of people tend to spend most of their time in the interior of the building, e.g. at home, offices and hospitals, in schools and universities. That is why breathing fresh indoor air is vital for our health.

Ventilation is considered to be one of the most important factors for maintaining acceptable indoor air quality in any space. It is used to introduce outside air, control temperature and remove excessive moisture, odors, smoke, heat, dust, airborne bacteria, and carbon dioxide.

However, ventilation consumes energy in terms of electrical fan power as well as cooling and heating energy. Energy production also affects negatively on our environment and contributes to CO_2-emissions to the atmosphere.

Many types of ventilation systems encounter problems to control minimum supply air and thus to consume minimum amount of energy. But a ventilation system based on registration of increasing CO_2 concentration can facilitate in solving the given problem. Such a technology is called CO_2-based demand controlled ventilation (DCV).

The experience and field studies have shown that the level of carbon dioxide in any space can be a reliable indicator and quite a cheap instrument of the air quality and ventilation rate. That is why CO_2 is used as an indicator of air quality in demand controlled ventilation systems.

CO_2-based demand controlled ventilation system controls the amount of supply outdoor fresh air in a building depending on a number of people and their activity. People are the main source of CO_2 in a building. If a number of people in a room is doubled, the CO_2 level will accordingly double. If one or few people leave a room, the level of CO_2 will proportionally decrease. Thus DCV saves energy solely by not heating or cooling unnecessary amount of outdoor air. The benefits of such a ventilation system are maximal when a number of people continuously changes in a building, in the extreme climate conditions or when the electricity cost is quite high.

Taking into account the above mentioned, the objectives of the given Bachelor’s Thesis are as follows:

- to define benefits of demand controlled ventilation;
- to investigate the standards which describe the required limits of CO_2 concentration;
- to compare CO_2-based DCV and the conventional ventilation system;
- to explore different types of CO_2 sensors;
- to consider the application of DCV in different buildings and situations.

2 THEORETICAL BACKGROUND

This chapter provides clear understanding of the main concept of CO_2-based DCV. The chapter may provide a necessary background to understand how CO_2-based DCV operates and how it is applied under current codes and standards. The given chapter introduces the information about human breathing and the way it influences the air quality in the interior of the building. The chapter also explains the required ventilation rates and CO_2 differential.

2.1 CO_2 DCV concept

The concept of DCV has been known for over 20 years. The sensors of the first generation did not provide the required reliability, and the cost of the sensors was high.

In recent years, the advances in sensor technologies have made demand controlled ventilation both reliable and cost-effective. The ASHRAE Standard 62.1-2004 indicate that the demand controlled ventilation is acceptable when correctly designed and installed /1/.

CO_2-based demand controlled ventilation is a combination of two technologies:

1. CO_2-sensors monitor carbon dioxide level in the air in the interior of the building.
2. An air-handling system that employs data from the sensors to regulate the amount of supply air.

CO_2 sensors continually monitor air in a conditioned space. Since people exhale carbon dioxide, the difference between the CO_2 concentration in the interior of the building and the level in the exterior of the building indicates the occupancy and activity level in a space and, thus, its ventilation requirements. The sensors send carbon dioxide data to the ventilation controllers, which automatically increase ventilation when carbon dioxide concentrations exceed a certain level in a space.

Ventilation rates can be measured and controlled based on real occupancy. This contradicts the conventional method of ventilating at a fixed rate independent of occupancy. This results in much larger air flow rates coming into buildings than necessary. That quantity of air must be taken into account, because it increases energy consumption and costs. In humid climates, the excess ventilation also can result in uncomfortable humidity and mould growth, making the indoor air quality quite inappropriate. Furthermore, the lack of fresh air can make building occupants drowsy. To avoid the problems of excessive and insufficient fresh air, people can apply demand controlled ventilation.

CO_2-based DCV provides a possibility to monitor both occupancy and ventilation rates in a building all the time. Most ventilation systems are often regulated and adjusted only at the time they are installed. DCV provides a higher level of control when monitoring conditions in the space and constantly adjusts the system to the respond to the change of parameters.

2.2 CO_2 in the exterior of the building

Clean atmospheric air consists of different gases in the proportions given in Figure 1.

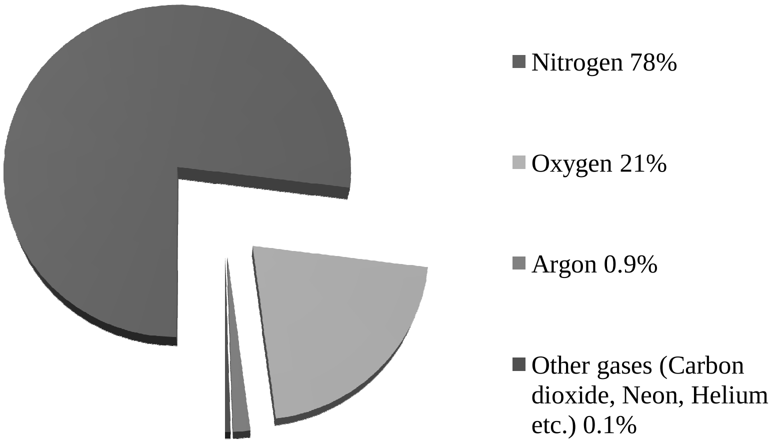

Figure 1. Chemical composition of clean and dry atmospheric air /2, p. 116/

The given figure illustrates the content of clean atmospheric air. However, due to human activities and natural processes, the real atmospheric air can contain the variable amount of water vapor (on average around 1%), dust, pollen, spores, sea spray and volcanic ash. Various industrial pollutants may also be present, such as chlorine (elementary or in compounds), fluorine compounds, elemental mercury, and sulfur compounds such as sulfur dioxide (SO_2). /2, p. 116/

The carbon dioxide concentration in the atmosphere may alter during a year due to any combustion device or process throughout the world, such as burning of fossil fuels. Yearly the concentration of carbon dioxide increases more and more. Scientists suppose the increase of CO_2 may cause the global warming.

For example, the history of atmospheric carbon dioxide concentrations, directly measured at Mauna Loa, Hawaii, is given in Figure 2. This curve shows the annual increase of CO_2 in the atmospheric air. The annual fluctuations of carbon dioxide exist due to CO_2 absorption of land plants in different seasons. The zigzag curve shows the average monthly concentrations, and the full curve shows the 12-months average change. /3, p. 49/

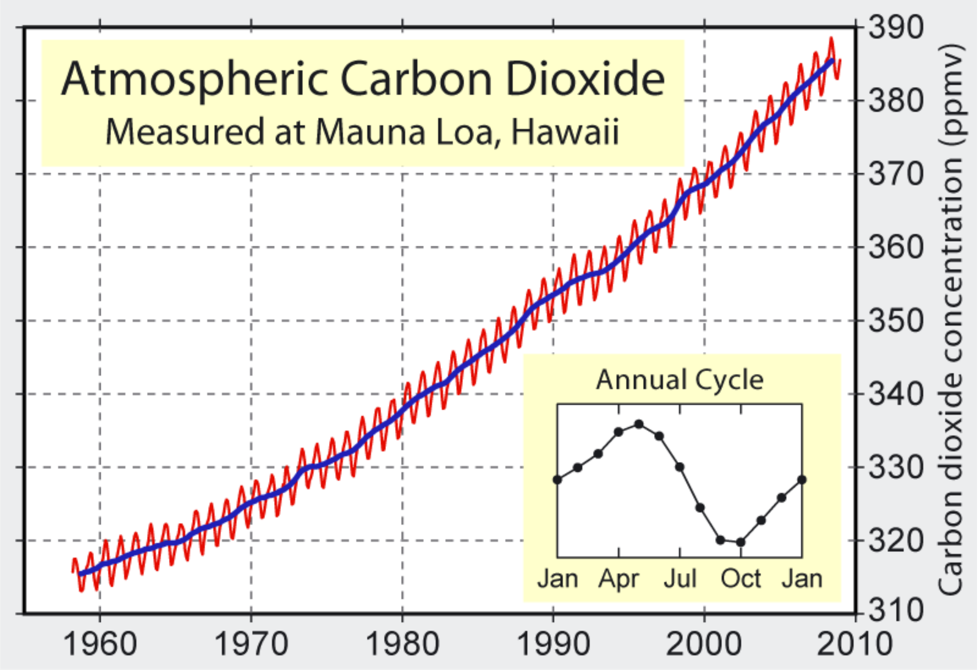

Figure 2. Change of carbon dioxide in the atmosphere observed at Mauna Loa, Hawaii, from 1958 to 2009 /3, p. 49/

As Hawaii is located in the central Pacific Ocean, these concentrations represent the lowest concentrations in the world. In urban areas outdoor CO_2 levels typically range from 360 to 450-500 ppm. But carbon dioxide levels can be even higher when in close proximity to a source of CO_2.

CO_2 has low molecular weight. Therefore carbon dioxide easily occupies the whole open space. It is possible to assume outside CO_2 levels are constant for large geographic regions. Consequently, CO_2 is a baseline reference for outside air for the purpose of measuring and controlling ventilation.

2.3 Carbon dioxide in the interior of the building

There are a number of sources of CO_2 production in the exterior of the building, such as burning of fossil fuels, producing cement and other products, forest combustion and so forth. But humans and their activity is the major source of carbon dioxide in the interior of the building. Plants contribute CO_2 insignificantly in the interior if the building, due to their low level of metabolic activity. Combustion sources can accordingly contribute to carbon dioxide in the interior of the building, but they are normally not present in residential buildings and public places.

The main process of CO_2 production by humans in the interior of the building is respiration. For adults CO_2 production varies from about 10 dm^3/h per person when sleeping to about 170 dm^3/h per person at high levels of physical activity. CO_2 production is different for children and adults. For instance, in kindergartens an activity level of 157 W/m^2, CO_2 production is 18 dm^3/h per person. In schools with children aged from 14 to 16, the CO_2 production is about 19 dm^3/h per person. It is equal to CO_2 production of adults during sedentary activity. /2, p. 144/ More information is provided in Table 1.

Table 1. The generation of carbon dioxide by humans at six activity levels /2, p. 144/

Activity	*Carbone dioxide (dm^3/h per person)*
Adults, sedentary (58-70 W/m^2)	19
Adults, low level of physical exercise (174 W/m^2)	50
Adults, medium level of physical exercise (348 W/m^2)	100
Adults, high level of physical exercise, athletes (580 W/m^2)	170
Children of kindergarten age, 3-6 years old (157 W/m^2)	18
Children of school age, 14-16 years old (58-70 W/m^2)	19

The rate of carbon dioxide production by human respiration is related to the metabolic rate by Formula 1 /4, p. 36/:

$$G = 4 \cdot 10^{-5} \cdot M \cdot A \qquad \text{Formula 1}$$

where: G - CO_2 production, dm^3/s; M - metabolic rate, W/m^2; A - body surface area, m^2

For example, for an adult person occupied with sedentary activities ($M = 70\ W/m^2$ and $A = 1.8\ m^2$), such as office work, the CO_2 production by respiration is about 0.00504 dm^3/s (18.1 dm^3/h) per person.

As people exhale a predictable quantity of carbon dioxide depending on their physical activity, it can be used as a good indicator of CO_2 for ventilation control. It is important to lay emphasis that CO_2 concentration in the interior of the building does not provide enough information of the actual number of people, but it can be used in combination with CO_2 concentration in the exterior of the building.

The required amount of CO_2 concentration in the interior of the building according to Finnish Classification of Indoor Climate is represented in Table 2. Indoor climate is divided into 3 categories in that table, i.e. individual indoor climate (S1), good indoor climate (S2) and satisfactory indoor climate (S3) /5, p. 647/.

Table 2. Target values for indoor air quality /5, p. 647/

Unit	*Indoor climate category* *Maximum values*			*Note*
	*S1**	*S2***	*S3****	
Carbone dioxide CO_2 ppm	700	900	1200	(II)
II The concentration of carbon dioxide includes carbon dioxide from outdoor (350 ppm) and human sources. The CO_2 concentration can be measured, for example, with an infrared analyzer.				

*S1: Individual Indoor Climate
The indoor air quality of the space is very good and the thermal conditions are comfortable both in summer and winter. The user of the space may individually control the thermal conditions and improve the indoor air quality by increasing the ventilation when necessary. The thermal conditions and indoor air quality satisfy, as a general rule, the special requirements of the users (e.g. elderly people, people with allergies or respiratory illnesses, and others).
**S2: Good Indoor Climate
The indoor air quality of the space is good and no draughts occur. The temperature rises above comfortable levels during the hottest days of the summer.
***S3: Satisfactory Indoor Climate
The indoor air quality and the thermal conditions of the space fulfill the requirements set by the building codes. The indoor air may occasionally feel stuffy and draughts may occur. The temperature usually exceeds comfort levels on hot summer days.

2.4 CO_2 differential and ventilation rates

If the ventilation rate in an occupied space decreases, the carbon dioxide concentration will begin to increase and vice versa. Once people enter a room, CO_2 concentration will begin to increase. This level will continue to increase until the amount of CO_2 produced by the space occupants and the dilution air delivered to the space are in balance. Such a state is called the equilibrium point.

The relation between CO_2 level and outside air ventilation rates can be described using a simple two chamber model. This is illustrated in Figure 3.

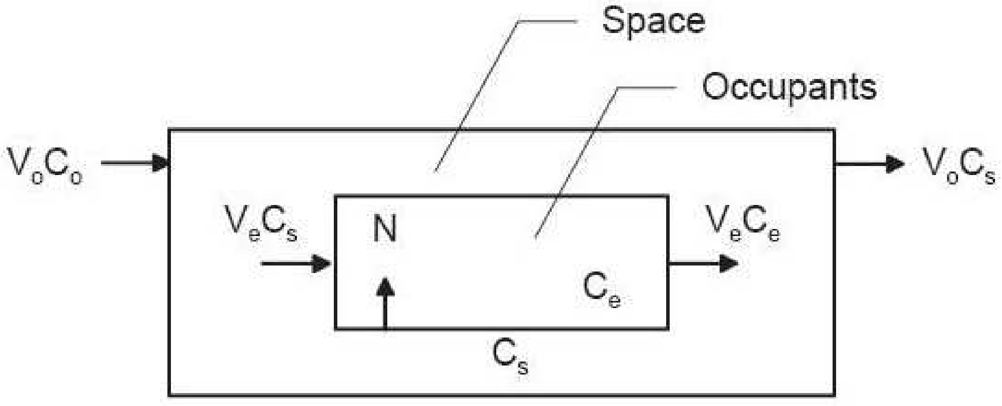

Figure 3. Two chamber model /1, p. 35/

Formula 2 /1, p. 35/ shows the mass-balance equation to predict the difference between indoor and outdoor CO_2-concentrations at steady-state conditions, given a constant ventilation rate per person and a constant CO_2-generation rate:

$$V_o = \frac{N}{C_s - C_o} \qquad \text{Formula 2}$$

where: Vo – outdoor airflow rate, dm^3/s*person; N - CO_2 generation rate, dm^3/s*person; Cs - indoor CO_2 concentration, ppm; Co - outdoor CO_2 concentration, ppm.

The equation can also be restated so that the equilibrium level (Ceq) for a particular ventilation rate can be calculated using Formula 3:

$$C_{eq} = C_s = C_o + \frac{N}{V_o} \qquad \text{Formula 3}$$

The correlation between indoor / outdoor CO_2 differential and ventilation rate do not depend on volume of a room. However, the volume of a room will affect the time it takes for CO_2 to build up to an equilibrium level. This equation can be only applied when equilibrium conditions exist. To make an accurate determination of dm^3/s*person rates one should take CO_2 measurements when the occupancy has stabilized. Measuring CO_2 concentrations that are still in transition to an equilibrium level can result in overestimation of the ventilation rate. Applied properly spot measurements can be extremely useful in helping to qualify if a space is overventilated. /1, p. 35/

The ANSI/ASHRASE Standard 62.1-2004 states that comfort (odor) criteria with respect to human bioeffluents are likely to be satisfied if the ventilation results in indoor CO_2 concentrations are less than 700 ppm above the outdoor air concentration /1/.

Appendix D of Standard 62.1-2004 provides an example that shows how this 700 ppm level is derived from the 7.5 dm^3/s per person minimum ventilation rate established in the standard /1/. The calculation below assumes an activity level of 70 W/m^2 (which is equal to 1.2 MET) which would be considered equivalent to the office activity type. Average CO_2 production at this activity level (as provided in Figure C.2 taken from Appendix D of Standard 62.1-2004) is 0.00517 dm^3/s. Outside CO_2 concentrations are assumed to be 400 ppm. If this turns out to be the case then the CO_2 level for a 700 ppm differential will be 1100 ppm. It can be calculated applying Formula 3.

$$C_{eq} = C_s = 400 + \frac{0.00517}{7.5} = 1100 \text{ ppm}$$

These two tables show the differences between air flow rates for office buildings in different standards and countries (USA and Finland). They are vary significantly. For instance, in USA the minimum ventilation rate for offices is 2.5 dm^3/s per person, while in Finland is 8 dm^3/s per person.

Table 3. Minimum ventilation rates in breathing zone in office buildings in Finland /1, p. 13/

Occupancy Category	*People Outdoor Air Rate R_p*	*Area Outdoor Air Rate R_a*	*Default Values*		*Air Class*
			Occupant Density	*Combined Outdoor Air Rate*	
	dm^3/s person*	*dm^3/s*m^2*	*#/100 m^2*	*dm^3/s* person*	
Office space	2.5	0.3	5	8.5	1
Reception areas	2.5	0.3	30	3.5	1
Telephone/ data entry	2.5	0.3	60	3.0	1
Main entry lobbies	2.5	0.3	10	5.5	1

Table 4. Minimum ventilation rates in office buildings in USA #1 /6, p. 33/

Space type	*Outdoor air flow (dm^3/s) per person*	*Outdoor air flow (dm^3/s)/ m^2*	*Extract air flow (dm^3/s)/ m^2*	*Sound level $L_{A,eq.T}$/ $L_{A,max}$ dB*	*Air velocity (winter/ summer) m/s*	*Note*
Office and similar rooms	8	1.5		33/38*	0.20/0.30	*C1 guidel
Conference room		4		33/38	0.20/0.30	#3
Customer area		2		38/43	0.30/0.40	#2
Corridor area		0.5		38/43	0.30	#2
Canteen, break area		5		38/43	0.25	
Archive, storage room			0.35			
Smoking room:						
-during building occupancy		10	20	38/43	0.30	#4
-outside building occupancy			10			#4
Copying room		1	4			

#1 For hygiene rooms' extract air flows, see Table 11 Hygiene rooms (D2).

#2 Guideline values for air velocity at fixed work stations are the same as for offices.

#3 If a building has three or more conference rooms, it shall be possible to control their ventilation according to the actual demand.

#4 The pressure in smoking rooms shall always be lower than in the surrounding rooms.

3 BENEFITS OF CO$_2$-BASED DCV

Compared to conventional ventilation, DCV provides considerable advantages.
The three major benefits of demand controlled ventilation should be mentioned in connection herewith:

First of all, demand controlled ventilation saves energy by avoiding the heating, cooling, and dehumidification of more ventilation air than it is needed. According to the observations, the savings range from 5 to 80 percent in contrast to the conventional ventilation system. The payback can vary from several months to two years and can often be significant enough to facilitate to pay for other building systems. /7/

The payback from CO_2-based DCV will be greatest in higher density spaces, where occupancy constantly changes (e.g. schools, theaters, retail establishments, meeting and conference areas). In spaces with more static occupancies (e.g. offices) DCV can provide control and verification that adequate ventilation provided to all spaces. For example, a building operator may arbitrarily and accidentally establish a fixed air intake damper position that results in over- or underventilation of all or some parts of space. A CO_2 control strategy can ensure the position of the intake air dampers is appropriate for the ventilation needs and occupancy of the space at all times.

Secondly, active control of ventilation system can provide the opportunity to control indoor air quality. Demand controlled ventilation creates improved IAQ by increasing ventilation if CO_2 level rise to an unacceptable level.

And the last advantage is simplicity and reliability of DCV.

4 CO_2 MEASUREMENT TECHNOLOGY

Although relation between CO_2 and controlled ventilation has been known to the general public from 1916, CO_2 as a reliable and economic method of control ventilation began to be used not long ago. The first CO_2 sensor used for controlling ventilation in HVAC application appeared on the market only in 1990 /8, p.20/.

CO_2 measurements in HVAC applications are based exclusively on the Infrared (IR) absorption principle. This is because different gases absorb infrared energy at specific and unique wavelengths in the infrared spectrum.

There are two types of sensors to measure CO_2 concentration with help of the IR absorption method:

1. Non-Dispersive Infrared (NDIR) absorption sensor
2. Photo-acoustic sensor

These technologies can be cost-efficient, but have different operational characteristics.

4.1 Non-Dispersive Infrared (NDIR) CO_2 sensor

Sensors based on non-dispersive infrared detection search the net increase or decrease of light that occurs at the wavelength where CO_2 absorption takes place. The light intensity change depends on the concentration of carbon dioxide.

Figure 4 shows an example of a typical NDIR sensor where air is penetrating into a sample chamber that contains a light source on the one end and a light detector on the other.

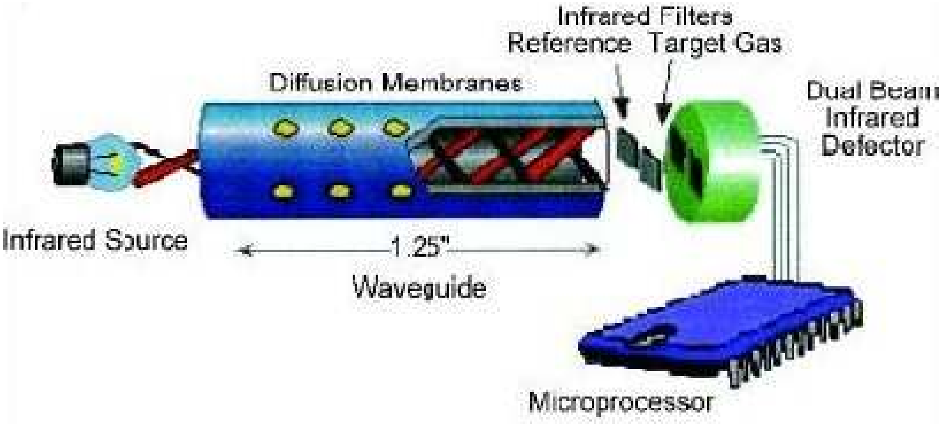

Figure 4. Basic parts of non-dispersive infrared detection (NDIR) CO_2 sensor /8, p.19/

A selective optical filter is fixed over the light detector to allow light at the specific wavelength where CO_2 absorbs light. This figure also illustrates the second detector and filter, although it is not always applied. The second optical filter is adjusted at the wavelength where there is no gas absorption. This second detector and filter are used as a reference to correct changes in the sensor optics that may be the result of sensor deviation over a time period. One of the important parts in the design of this sensor type is to minimize or remove sensor deviations that may occur because of accumulation of particles in the sensor and aging of a light source. One method of minimizing accumulation of particles is to use a gas penetrable membrane that facilitates penetration of gas molecules but locks larger particles that may change the sensor optics.

The second factor of deviation is aging of a light source. It can be minimized by selection of sources with stable characteristics. The method based on dual beam detector application, shown in Figure 4, is one of the methods to compensate both aging and particle accumulation.

Compared with photo-acoustic sensors, NDIR sensors have the following advantages:

Firstly, NDIR sensors are less sensitive to pressure changes. Secondly, these sensors are less sensitive to vibrations and acoustic interferences. And the last advantage is that such sensors have a compact design.

But photo-acoustic sensors also have benefit, such as nonsensitivity to dirt and dust.

4.2 Photo-acoustic CO_2 sensor

Another sensor type to measure CO_2 using IR is called photo-acoustic sensors. This type of sensor is designed with a chamber which is open to the atmosphere. Such a sensor exposes air in the chamber to flashes of infrared light specific to the gas absorption wavelength for CO_2. This flashing light produces vibrations of CO_2 molecules as they absorb infrared energy. A small microphone in the chamber monitors this vibration and then microprocessors in the sensor calculate CO_2 concentration.

Figure 5 shows a schematic of a photo-acoustic sensor. This type of sensor is not so sensitive to dirt or dust. But it can also have sensor deviations due to aging of a light source. Photo-acoustic sensor can also be affected by vibration and atmospheric pressure changes. More accurate sensors often use a pressure sensor to correct the range of pressures.

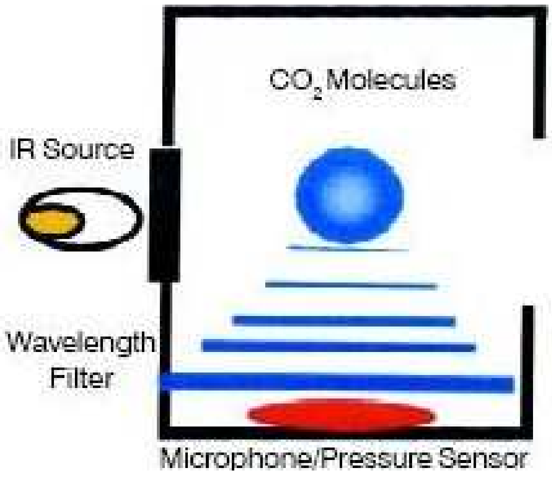

Figure 5. Basic parts of photo-acoustic CO_2 sensor /8, p.20/

5 APPLICATION OF DCV

DCV has a number of applications in various types of buildings. Firstly, DCV is applied in buildings where the number of people changes continuously during the whole day (24-hour period). It is also applied in places where occupancy is unpredictable and attains a high level. In buildings with a more stable occupancy level, DCV provides enough amount of fresh supply air per person all the time. But this will turn out to be uneconomical. Demand controlled ventilation reduces energy costs in the areas with a high utility level.

Secondly, DCV is used in spaces where heating and cooling for most parts of the year are required. Thirdly, demand controlled ventilation is utilized in the areas with high utility rates, high energy demand and energy costs.

Thirdly, DCV is used in buildings with low average occupancy in comparison with design occupancy. DCV is also applied in such types of buildings as office centers, governmental facilities, banks, shops and shopping malls, cinemas, auditoriums, lecture halls, schools, outpatient areas in hospital, hotel atriums or lobbies, restaurants, bars, nightclubs and so forth. Demand controlled ventilation is used in the areas with warm and humid climates or extreme climate conditions, and buildings which have equipment for automated adjusting of air supply (for example, variable speed fans or variable damper arrangement).

DCV is applied in spaces where CO_2 from human respiration and human activity is the main source of pollution. But CO_2-sensors used for DCV are not applied to monitor CO_2 for medical or industrial purposes, because they demand more exact air quality control.

And the last point to consider is that DCV may be applied in buildings where there is poor indoor air quality related with under- or over-ventilation or excessive humidity.

CO_2-based DCV can operate in combination with a heat recovery or other systems that supply outdoor air in buildings for heating or cooling. However, energy savings may be less where heat exchangers are used depending on climate, occupancy and a building type.

Several manufacturers produce CO_2-sensors that can be used in demand controlled ventilation. Most manufacturers of thermostats and air handling units integrate CO_2-sensors into their products. And major manufacturers of HVAC systems offer to install CO_2 sensors at the factories as an option.

6 DESIGN CONSIDERATIONS FOR DCV

CO_2-sensing is a rather uncomplicated technology, and installation of CO_2 sensors is a trouble-free procedure. Sensor voltage, power and control of output requirements are similar to those ones commonly used in thermostats.

There are two types of sensors: wired and wireless. Data from wireless sensors is delivered with the use of signal communications. Wireless sensors have self-contained power supply. Such sensors are used on-board power controlling to alert a building operator when battery charge is low and needs be changed.

All suppliers of HVAC systems frequently offer systems for located demand controlled ventilation and reading data from sensors. Therefore, putting into operation of CO_2-based DCV is not a complicated process. However, upgrading previous systems with pneumatic controls for operation with DCV may be more challenging.

Sensors are typically mounted on walls similar to thermostats. Some manufacturers offer standard sets, which include a thermostat and sensor. The standard sets which can monitor temperature, CO_2 and humidity are also available. They are used in systems that include a drier to control humidity in ventilation air.

Data from CO_2-sensors delivered to HVAC control system in a building or to an actuator that controls the amount of ventilation air. For reconstruction of HVAC system it may become necessary to repair or upgrade dampers. Good operating of dampers that can be automatically controlled is of great importance. Pneumatic controls will need to be replaced with electronic control or Direct Digital Control (DDC). Actuators which do not have input points for the sensors will need to include these points.

But it is not simple to upgrade and calculate HVAC systems for more complex systems, such as variable-air-volume systems, as it may seem. One needs a more complex algorithm.

CO_2-sensors can be mounted in the interior of the building or by integration into an air-handling system. The data from sensors to regulate the amount of supply outdoor ventilation air are applied in them. The illustration of this is provided in Figure 6.

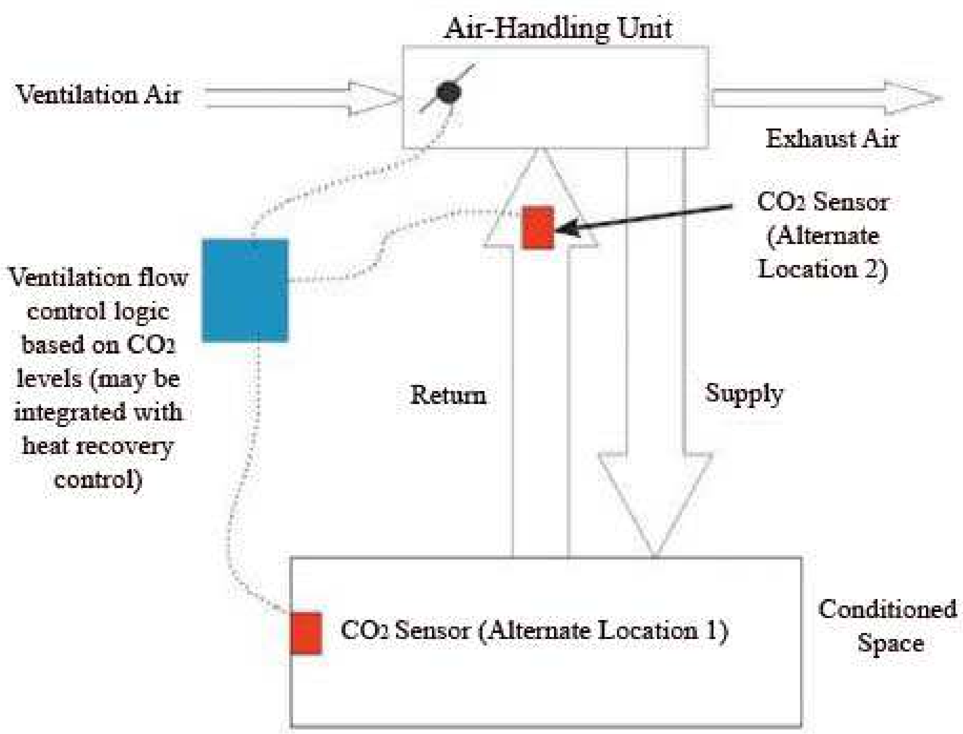

Figure 6. Generalized DCV integration into HVAC system /9, p.118/

When CO_2-sensors are installed it is imperative to pay attention to the following technological things, such as measurement accuracy, temperature resistance, waterproof and protection of dust, solar resistance, frequency of settings, resistance to mechanical vibrations, resistance to electrical interferences, placement of sensors and number of sensors.

7 ENERGY EFFICIENCY

One of the methods to save energy in a building is using CO_2-based demand controlled ventilation. Maximum saving energy with using DCV is provided in a building, where the number of people continuously changed. But DCV can provide people with needed amount of air, and not more. If a building is only 50% occupied, then only 50% of air for ventilation is required. Demand controlled ventilation saves energy by avoiding heating, cooling, and dehumidification of more ventilation air than it is needed.

7.1 Energy saving potential

If demand controlled ventilation lowers excessive supply outdoor air in a building during heating and cooling seasons, then annual energy expenses for heating and cooling the outdoor air reduce correspondently. In addition, lower outdoor air requirements decrease the fan energy expenses to supply or extract air from a building. Actual occupancy levels in buildings are generally significantly lower than the design occupancy levels. The experience indicates that actual occupancy levels may be 25-30% and 60-75% lower in some buildings than the design levels /10, p.91/. The first and last, saving energy potential using demand controlled ventilation may vary depending on climate, type of a building, type of HVAC system and occupancy in the space in which DCV is implemented and other operating conditions. The capability of authorized staff to maintain and operate equipment properly may also positively affect savings.

Available data suggest that demand controlled ventilation reduces ventilation, heating and cooling loads by 10% to 30% /10, p. 91/. Buildings with large fluctuation of occupancy, such as office buildings, shopping malls, cinemas, auditoriums, schools, nightclubs etc., realize the largest saving energy.

Demand controlled ventilation reduces electricity requirements when actual occupancy level is below than design occupancy level during the demand periods. Lower amount of supply of outdoor air reduces cooling and ventilation loads and thus, air-conditioning power reduces. Generally speaking, energy saving potential varies from building to building. It depends on its occupancy.

Figure 7 shows an example of graphical representation of energy saving potential.

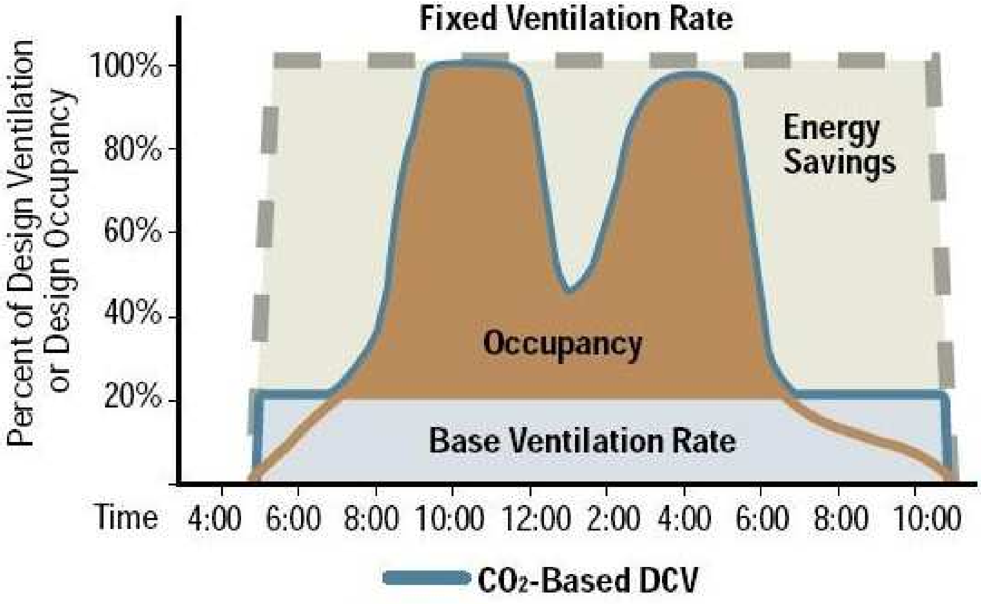

Figure 7. A graphic representation of energy saving potential /11, p.1214/

The figure shows the importance of providing a base ventilation rate for non-human contaminants. The example showed in Figure 7 assumes 20% of the design capacity would be provided all the time.

7.2 Market factors

Costs of CO_2-sensors with installation on the average vary from EUR 300 to EUR 400, with one sensor installed per zone (185-280 m^2) /10/. This also depends on a manufacturer, quality and technical characteristics of sensors and an installation company. Potential of saving energy with CO_2-based DCV has been estimated in some sources as from EUR 0.39 to more than EUR 7.75 per m^2, depending on types of buildings /10/.

The quick pay-off period of CO_2 sensors can be expected in spaces, in which occupancy is variable and unpredictable (auditoriums, some school buildings, shops etc.), as well as in the areas with high heating and/or cooling demand and high utility rates. On the average demand controlled ventilation has a payback period of two to three years that can be cost-attractive for many customers /10/.

But many buildings do not use DCV that is due to some disadvantages, namely that CO_2-sensors of DCV system do not respond to other indoor pollutants and expensiveness of operational personnel. DCV is a new concept for standards and local building codes, which one should not hurry to apply. Contractors and designers have questions and doubts about liability of systems, if they can meet indoor air quality standards. Because of that it may be due to incorrect installation of CO_2-sensors and presence of large amount of non-human pollutants exceeding the acceptable level. On the other hand, DCV requires installation and operational personnel, which are more expensive and difficult to find. But the energy saving can compensate these disadvantages.

8 DESIGN EXAMPLE OF DCV

This chapter considers an example of applying of CO_2-based demand controlled ventilation system in a single zone with a large open area (retail-clothing store) and central indoor sensor location. The given chapter introduces the calculation of the required ventilation rates in a retail-clothing store. The chapter describes determination and selection of a suitable control strategy for the given example and considers the selection of a sensor type and its location.

8.1 Concept of architecture and ventilation system

The described example shows the application of a large single zone space used for a retail-clothing store. The store contains a 400 m^2 retail floor, 40 m^2 storage area and 12 dressing rooms covering 60 m^2. Each area is separated but left open to 5 m high ceilings. The volume of the space is 30 persons/100 m^2, and the total occupancy is 160 people.

The calculations of this example can be used for other similar applications, where one or more air handlers provide a large single zone, such as theaters, large ballrooms or conference areas, multi-purpose gymnasiums, cafeterias or other retail applications.

The architectural drawing of the retail-clothing store is shown in Figure 8.

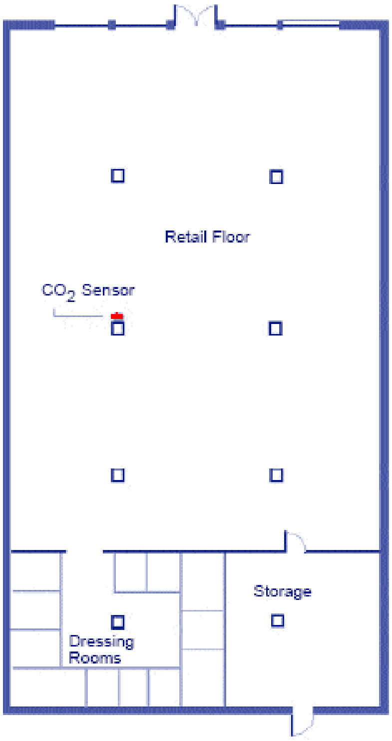

Figure 8. Single zone retail space - retail clothing store /12, p.29/

Similar to many other retail spaces, the given store has continuously changeable occupancy, which can change at various times during the whole day. Many types of retail spaces have front doors open to increase customer traffic. Fresh air entering through the front doors can be measured by a CO_2 sensor and exclude a part of mechanical ventilating that would have to be included if the doors were closed.

Retail-clothing space has a single-zone HVAC system. A ventilation system operates as follows: outdoor air is pumped by fan 1 through heating or cooling coils. Heated or cooled air flows into the occupation zone. Room air with some CO_2 level is pumped from occupation zone by fan 2. A part of exhaust air recirculates in a by-pass duct. There are two regulated dampers in the system, the first one in the supply outdoor air duct and the second one in the recirculated by-pass duct. The data from CO_2 sensor are delivered to a controller which regulates dampers.

The schematic of a ventilation system in the retail store is represented in Figure 9.

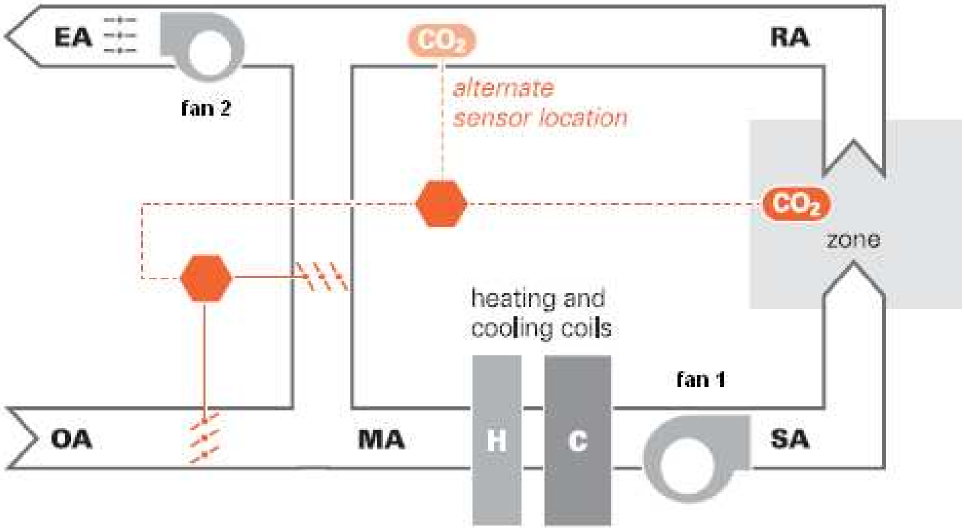

Figure 9. Ventilation system of the retail clothing store schematic /13, p.2/

Because the recirculated air returns from only one zone, it may be possible to place a CO_2 sensor in the return-air (RA) duct as an alternative sensor location. But if any supply air bypassed the breathing zone, the sensor in the RA duct may register a less-than-actual indoor CO_2 concentration. In the given example a CO_2 sensor is installed on the wall in the breathing zone. For expedience the outdoor CO_2 concentration is generally assumed to be constant, so the indoor concentration (rather than the difference between the indoor and the outdoor concentrations) is measured and used to modulate the position of the outdoor air damper and, thereby, provide the space with the proper amount of ventilation air on a per-person basis.

8.2 Control strategy selection

There are two possible control strategies to CO_2-based DCV – the set-point control and the proportional control, which is described in ASHRAE Standard 62.1-2004 /1/.

The set-point control strategy has limited application, since it will not increase outdoor air intake within acceptable lag times in many cases. Spaces with higher occupant densities, which reach full or nearly full occupancy rapidly once occupancy commences, can be suitable candidates for this strategy. But the given example represents the clothing retail store with continuously changeable occupancy and large space volume. Accordingly, set point control would not be a recommended approach for the described example.

The used ASHRAE Standard, a paraphrase of a proportional control method is as follows:

1. To determine the required intake flow of outdoor air for the design zone population

The required rate is based on the number of occupants in the zone and the zone floor area. Therefore, ventilation rates for people-related sources and building-related sources have to be taken into account. The reason the standards and some codes state is that the ventilation rate has to provide space with fresh air which is contaminated by both people and materials when a fixed ventilation rate is provided. With DCV the ventilation rate will be provided continuously for materials, and a part will be changeable for people.

The required intake flow of outdoor air is calculated applying Formula 4.

$$\mathrm{V_{ot-design}} = \frac{(\mathrm{R_P} \times \mathrm{P_Z}) + (\mathrm{R_a} \times \mathrm{A_Z})}{\mathrm{Ez}} \qquad \text{Formula 4}$$

where: Vot-design – required intake flow of outdoor air, dm^3/s; Rp – required outdoor airflow rate per person, dm^3/s *person; Pz – zone population, person; Ra – required outdoor airflow rate per unit area, dm^3/s *m^2; Az – zone flow area, m^2; Ez – zone air distribution effectiveness.

Except for 40 m^2 of the storage area, 460 m^2 is used for public needs. Then the inside space is taken as the retail space. The data for the retail space are taken in Table 6.1 and Table 6.2 from ASHRAE Standard 62.1-2004 /1/.

$$\mathrm{V_{ot-design}} = \frac{(3.8 \times 30) + (0.3 \times 460)}{1.0} = 252\ \mathrm{dm^3/s}$$

2. To determine the required intake flow of outdoor air when the zone is unoccupied, that is, Pz = 0 person

$$\mathrm{V_{ot-min}} = \frac{(3.8 \times 0) + (0.3 \times 460)}{1.0} = 138\ \mathrm{dm^3/s}$$

3. To determine the target indoor CO_2 concentration at design outdoor-air intake flow

After frequent measuring during a week at lunchtime the target indoor CO_2 concentration at minimum outdoor-air intake flow (Co), which is equal to the outdoor CO_2 concentration, appears to range from 400 to 420 ppm. As the levels appear to be consistent, the designer has assumed that the outside level will be 400 ppm.

The target indoor CO_2 concentration is calculated with Formula 5.

$$\mathrm{C_{s-design}} = \mathrm{C_o} + \frac{\mathrm{N}}{(\mathrm{V_{ot-design}}/\mathrm{P_{z-design}})} \qquad \text{Formula 5}$$

where: Cs-design – target indoor CO_2 concentration at design outdoor-air intake flow, ppm; Co – target indoor CO_2 concentration at minimum outdoor-air intake flow, ppm; N – CO_2 generation rate, dm^3/s*person; Vot-design – required intake flow of outdoor air, dm^3/s; Pz-design – target zone population, person.

$$\mathrm{C_{s-design}} = 400 + \frac{0.00517}{(252/30)} = 1015\ \mathrm{ppm}$$

When the indoor CO_2 concentration equals to Cs-design (1015 ppm), the required intake flow of outdoor air has to be equal to Vot-design (252 dm^3/s). When the concentration of CO_2 indoors equals to Cs-min (400 ppm), the required intake flow of outdoor air has to be equal to Vot-min (138 dm^3/s). When the CO_2 concentration in the interior of the building is between its minimum (Cs-min) and designed (Cs-design) values, a controller has to adjust outdoor-air intake flow Vot proportionally between Vot-min and Vot-design using Formula 6:

$$V_{ot} = \frac{C_{s-actual} - C_{s-min}}{C_{s-design} - C_{s-min}} \times \left(V_{ot-design} - V_{ot-min}\right) + V_{ot-min} \qquad \text{Formula 6}$$

As Figure 10 shows, the proportional control approach yields an outdoor-air intake flow (Vot) that equals or exceeds the requirement of the ASHRAE 62.1-2004 standard. It requires a modulating outdoor-air damper, and a controller with two CO_2 limits (Cs-design, Cs-min) and two OA-damper limits that correspond to intake airflows (Vot-design, Vot-min).

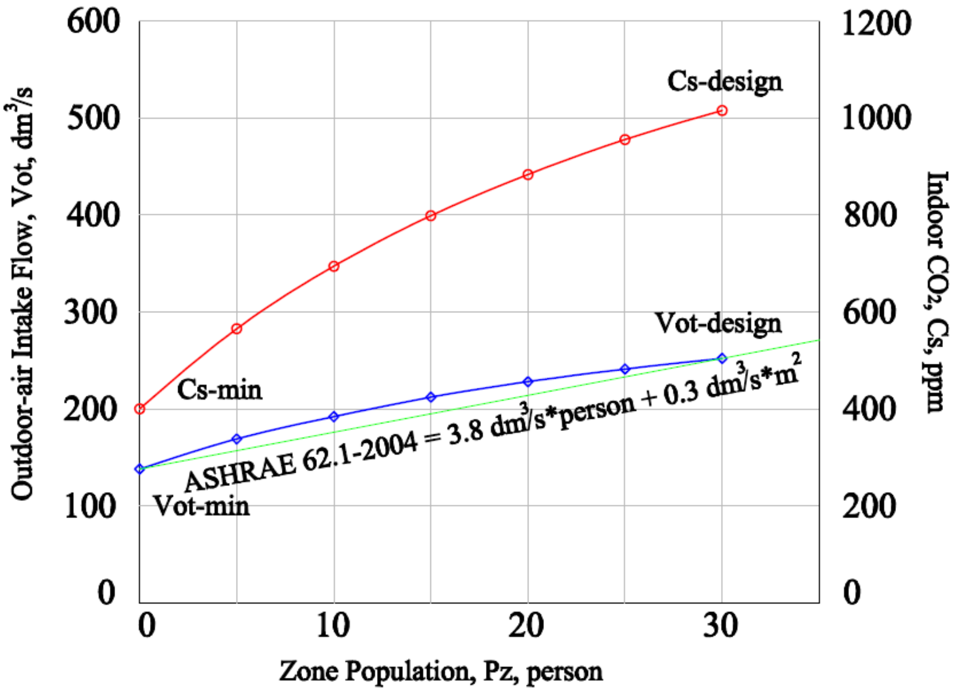

Figure 10. Proportional control strategy

Outdoor-air intake flow (Vot) and CO_2 are proportional (or linear) to each other, but neither is linear with respect to zone population. The controller adjusts intake airflow (Vot) in proportion to the percentage of the CO_2 signal range. But when the controller changes outdoor airflow, the indoor CO_2 concentration changes, too. So, the controller has to adjust Vot in small increments until the indoor CO_2 reaches a stable value. When plotted in relation to zone population, the results of these control actions are curves for both Vot and indoor CO_2.

8.3 Sensor selection

As a proportional control is selected, one CO_2 sensor is recommended for using in the given example. A sensor has to be capable to handle about 500 m^2. A sensor has to be provided with a self-calibration feature. For more correct operation of this feature a sensor will utilize a pre-occupancy purge of the system that will automatically occur every morning to provide inside CO_2 levels are similar to outside levels. This will also ensure that any contaminants appearing over closing hours are exhaust of the space before occupancy begins.

The sensor will be mounted open on a centrally located support post and about 1,8 m above the floor but is placed in such a way that occupants cannot directly breathe on the sensor. The proportional signal from the CO_2 sensor is provided directly to an air handling unit. The CO_2 sensor will be located as shown in Figure 8.

To conclude it has to be said that DCV will operate during all occupied hours. The economizer will be programmed to override DCV control if outside air is used for free cooling. Every morning pre-occupancy purge can be used in the sequence of operations of the air handler. The air handler can be set up to begin modulation of outside air when inside concentrations are 100 ppm over outside concentrations (500 ppm). The damper position on the air handler will be proportionally modulated so that when levels reached the equilibrium point the design ventilation rate of 252 dm^3/s are provided. The maximum position of the air handler outdoor air damper for ventilation delivery under the DCV strategy will be 252 dm^3/s (based on 3.8 l/s*person and volume of the space of 30 people/100 m^2).

9 DISCUSSION AND CONCLUSIONS

DCV system controls the amount of outdoor fresh air supply, depending on the number of people in a building and their activity. DCV makes it possible to maintain the needed ventilation and improve indoor air quality while saving energy. Such systems benefit both building operators and building occupants.

CO_2-based DCV, when applied in spaces subject to variable or intermittent occupancy or in spaces where actual occupancies are greatly below design occupancy, reduces unnecessary overventilation while ensuring that target per person ventilation rates are met. Such ventilation systems use CO_2 as a control input to modulate ventilation below the maximum total outdoor air intake rate while still maintaining the required ventilation rate per person. Using CO_2 data logged over time in an occupied space, it is possible to estimate the ventilation rate of a continuously ventilated space, even if equilibrium levels have not been reached, provided that occupancy age, activity level, and varying densities within the space over time are known. In such a way, demand controlled ventilation saves energy by preventing heating, cooling, and dehumidification of more ventilation air than it is needed. DCV reduces electricity requirements when an actual occupancy level is below than the design occupancy level during the demanded periods. The lower amount of supplied outdoor air reduces cooling and ventilation loads and, therefore, air-conditioning power reduces. Maximum saving energy using DCV is provided in buildings, where the number of people continuously changed, is unpredictable and attains a high level, for example, office buildings, shopping malls, cinemas, auditoriums, schools, nightclubs etc.

In buildings with a more stable occupancy level, DCV provides enough amount of fresh air supply per person all the time. But it could be uneconomical, because DCV reduces energy costs less in the areas with a high utility level.

Saving energy potential can change as well, depending on climate, the type of a building, the type of a HVAC system with which DCV is implemented and other operating conditions. The achievement of improvements in the design characteristics of DCV is feasible with minimal additional equipment and modifications of the system. This may be also mentioned as one of many advantages of DCV.

Controlling indoor air quality is carried out by active control of the ventilation system. Demand controlled ventilation creates improved indoor air quality by increasing ventilation, when CO_2 level rises to an unacceptable level.

One of the most important aspects of designing DCV is correct control strategy selection. In such a manner the set-point control strategy can be designed for spaces with high occupant densities, which reach full or nearly full occupancy rapidly once occupancy commences. While the proportional control strategy is applicable to a wide range of occupant densities and patterns. A proportional control approach starts to open a damper or increase the introduction of outdoor air when indoor CO_2 levels are a certain amount above outdoor levels. This lower control set point in the control range is 100 to 200 ppm above outdoor levels. As CO_2 levels in the occupied zone rise, the damper opens wider. Two important criteria for any CO_2 control strategy are that the target per-person ventilation rate is met at all times and that during periods of changing occupancy the lag times as prescribed in ASHRAE standard 62.1-2004 are met. It is possible to determine the number of sensors and to select types of sensors, when a control strategy is chosen correctly.

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