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Study and Analysis of Demand Controlled Ventilation Using CO_2 Sensors for HVAC Systems Serving Multi Zone with Variable Occupancy

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***Abstract*— In this paper the demand controlled ventilation for systems serving multiple zones has been analyzed and the result for the effective DCV is discussed. The study is undertaken on HVAC systems for the construction of schools by Royal commission of Jubail, Kingdom of Saudi Arabia. The main theme of this paper is to identify the problems with CO2 sensors for systems serving multiple zones having variable occupancies. In conventional systems the CO2 sensors will be used to find the CO2 concentrations, and depending upon the concentrations the OA will be varied. This system may not meet the actual demand at each zone. This paper summarizes the analysis of demand controlled ventilation for HVAC systems serving schools and the results are discussed. Carbon Dioxide (CO2) based demand controlled ventilation (DCV) is an economical means of providing outdoor air to occupied spaces at the rates required by local building codes and ASHRAE Standard 62, "Ventilation for Acceptable Indoor Air Quality." CO2-based DCV offers designers and building owners an ability to monitor both occupancy and ventilation rates in a space to ensure there is adequate ventilation at all times.**

***Index Terms*—Ventilation, serving multiple zones, DCV, HVAC System, CO2 sensors**

I. Introduction

With a conventional DCV system, discrete CO_2 sensors are installed in the spaces to be controlled. These sensors generally report to a building-management system (BMS) or, in the absence of a BMS, directly control outside-air dampers or variable-air-volume boxes. The conventional system may not satisfy the variable occupancy conditions in the multiple zones which is served by a single system. Spaces with high design occupant densities offer an excellent opportunity for demand controlled ventilation (DCV) systems since these spaces are seldom occupied at their design occupancy. DCV systems modulate the amount of outdoor air supplied to a space as a function of the number of people present, providing significant energy savings when spaces are only partially occupied. The Standard requires DCV for all ventilation systems with design outside air capacities greater than 3000 CFM serving areas having an average design occupancy density exceeding 100 people per 1000 ft². DCV systems must maintain ventilation rates in accordance with ANSI/ASHRAE Standard 62.DCV offers a higher level of controlin that it monitors conditions in the space and constantlyadjusts the system to respond to real time occupancyvariations.

Demand-controlled ventilation (DCV) using carbon dioxide (CO_2) sensing is a combination of two technologies: CO_2 sensors that monitor the levels of CO_2 in the air inside a building, and an air-handling system that uses data from the sensors to regulate the amount of outside air admitted for ventilation. DCV operates on the premise that basing the amount of ventilation air on the fluctuating needs of building occupants, rather than on a pre-set, fixed formula, will save energy and at the same time help maintain indoor air quality (IAQ) at healthy levels. CO_2 sensors continually monitor the air in a conditioned space. Because people constantly exhale CO_2, the difference between the indoor CO_2 concentration and the level outside the building indicates the occupancy and or activity level in a space and thus its ventilation requirements.

II. CO_2 LEVELS IN INDOOR:

Indoors in commercial buildings people are theprincipal source of CO_2Plants, due to their low levelof metabolic activity contribute an insignificant amountof CO_2 to indoor spaces. Unvented combustionsources can also contribute to indoor CO_2concentrationsbut are generally not present in commercialbuildings. In fact highly elevated levels of CO_2 (e.g.,3000 to 5000 ppm) can indicate the presence ofpotentially dangerous combustion fumes. CO_2 is oneof the most plentiful byproducts of combustion andcan account for 8% to 15% by volume of the contentof a combustion exhaust.For ventilation control, it is people as a sourceof CO_2 that we are interested in. People exhalepredictable quantities of CO2 in proportion to theirdegree of physical activity.

III. DEMAND CONTROLLED VENTILLATION (DCV):

DCV as a ventilation control strategy was clarifiedin 1997 in interpretation IC 62-1999-33 (formerly IC 62-1989-27).The use of CO2 is applied using the VentilationRate Procedure of Standard 62, which establishesspecific CFM/person ventilation rates for mostapplications. By definition, ASHRAE Standard 62says that acceptable indoor air quality is achievedby providing ventilation air of the specified qualityand quantity (Table 1 in the Standard) to thespace. The standard states.CO2 is applied using the provisions of section6.1.3.4 of the standard that address variable andintermittent occupancy. The CO2 control strategycan be

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used to modulate ventilation below thedesign ventilation rate while still maintainingTable 1 ventilation rates (e.g., 15 CFM per person).Sensor location and selection of the controlalgorithm should be based on achieving the rates.

The control strategy should also bedeveloped considering inside/outside CO2 levels.The control strategy must provide adequate lagtime response as required in the Standard.If CO2 control is used, the design ventilation rate may not be reduced to consider peak occupanciesof less than 3 hours (often called diversity). In other words, the variable provision of 6.1.3.4 cannotbe applied to lower the estimated maximumoccupancy for the purpose of reducing the designventilation rate while using DCV.CO2 filtration or bioeffluents removal methodsother than dilution should not be implemented inthe space.A base ventilation rate should be provided during occupied periods to control for non-occupantrelated sources.Implementing CO2-based DCV isa matter of estimating the CO2generation rate of the occupants (*N*),measuring the concentration differencein the space versus outdoors (*Cs* – *Co*),and then using this difference todetermine the rate at which ventilationair (*Vo*), on a per-person basis, isdelivered to the space.In most locations, the outdoorconcentration (*Co*) of carbon dioxideseldom varies by more than 100 ppmfrom the nominal value.* Because ofthis and in lieu of installing an outdoorCO2 sensor, most designers use either one-time reading of the outdoor CO2concentration at the building site or a conservative value from historical readings.

IV. SYSTEMS SERVING MULTIPLE ZONES WITH VARIABLE OCCUPANCY:

In this school also a single system is serving more than 30 rooms with variable occupancy. In theseapplications, if a duct-mounted sensor is used, it will samplethe average of all the spaces and may not control levels basedon the actual conditions in the space. By considering an averageof all spaces, this approach cannot ensure that target per person rates established by local codes or Standard 62-1999would be met in all spaces (often termed .critical. spaces).

As aresult, the use of duct sensors in this application would likelynot meet the requirements of local codes and Standard 62-1999.An effective, but slightly more costly approach is to install awall-mount sensor in each of the occupied spaces. Each sensoroutput is then sent to a signal transducer that will read all thesensors and pass through one signal that represents the sensor with the highest reading to the air handler. As a result, ventilationrates will be controlled to ensure the most critical space is alwaysadequately ventilated. This approach also can be used with largespaces such a retail establishments or large floor plates on multiplestory buildings.

V. STANDARS FOR VENTILLATION:

Ventilation rates for schools and office spaces are defined by various codes andstandards. The most widely accepted standard is the American Society of Heating,Refrigeration, and Air Conditioning Engineers (ASHRAE) Standard 62. Some state andlocal codes have adopted the ASHRAE Standard 62 ventilation requirements.According to ASHRAE Standard 62, classrooms should be provided with 15 cubic feetper minute(CFM) outside air per person, and offices with 20 CFM outside air per person.Ventilation rates for other indoor spaces are also specified. Standard 62 is currently beingrevised, so these rates may change.Using CO_2 as an indicator of ventilation, ASHRAE has recommended indoor CO_2concentrations be maintained ator below1,000 ppm in schools and 800 ppm inoffices (see chart below). Clearly the outdoor CO_2 concentration directly impacts theindoor concentration. Therefore, it is critical to measure outdoor CO2 levels whenassessing indoor concentrations. ASHRAE recommends indoor CO2 levels not exceed theoutdoor concentration by more than about 600 ppm.

To properly use CO2 for DCV, the system should be designed as follows:

A. *D*etermine the design outdoor air rate based on the maximum (design) number of people expected to occupy the space. No diversity is allowed in the design population assumption. Some standards, such as Standard 62 (§ 6.1.3.4), allow a designer to reduce the design occupant count by some percentage because people are not expected to be present for a period long enough to reach steady state. A good example is a perfection area of an assembly space; it can have a very high peak occupancy, such as during the intermission of a performance, but the peak seldom lasts more than a half hour or so. Credit for such occupant diversity cannot be taken when DCV systems are used because the outdoor air rate tracks the occupant load; the space is not over ventilated before and after the occupant peak the way it would be if no outdoor air controls were specified.

B. CO_2 sensors must be located within the occupied zone of the space served.

Alternatively, the sensor may be located in the space return air grille provided the set point or sensor reading is adjusted to reflect any short circuiting that may occur in the air distribution system. Fortunately, most densely occupied spaces are always in a cooling mode (the temperature of the air being supplied to die space is less than the space temperature), which results in nearly perfect mixing even with less than ideal ceiling supply and return systems. In this case, die CO_2 sensor may be located almost anywhere in the room or in the return air duct from the room. If located in the return air duct, the sensor should be located as close to the room as possible so that return air duct leakage does not distort the concentration reading.

For systems serving more than one room, locating the sensor in the common return from all zones is not acceptable since it would indicate only average CO_2concentration, possibly allowing some spaces to be under ventilated while others were over ventilated. Doing so is analogous to controlling room temperature, in multiple rooms with a return air temperature sensor. For systems serving multiple rooms, CO_2 sensors must be installed either in all rooms, or possibly only in those rooms that are judged to be "critical." Critical rooms are those requiring the highest percentage of outdoor air. If CO_2 is not measured for all rooms, spaces for which CO_2 concentration is not measured should be assumed to be occupied at peak occupancy conditions at all times the system is operating.

C. Determine the CO_2 concentration set point using the following equation:

$$C_R = C_{OA} + \frac{8400\ m}{R_P}$$

Where C_R is the room CO2 concentration, C_{OA} is the outdoor air CO2 concentration, m is the metabolic rate (1 met = 58.2 W/m², see Table 1for typical values), and R_P is the rate of outdoor air per person. This equation assumes that the air change effectiveness of the air distribution system is near unity (a good assumption for systems in the cooling mode). An outdoor air CO2 sensor is not required if the outdoor air CO2 concentration in the equation is set to a conservatively low value (e.g., 350 ppm). As an example, a movie theater CO2 concentration at 15 CFM/p, 350 ppm outdoor air CO2 concentration, and a metabolic rate of 1.0 would be 910 ppm.

D. If separate CO2 sensors are used forroom and outdoor air concentrationmeasurement, they each should have an accuracy of ±50 ppmin the range 300ppm to 2000 ppm. If a single sensor is used to measure both points, or only anindoor sensor is used, the sensor should have an accuracy of ±100 ppm in therange 300 ppm to 2000 ppm.

E. The system must be designed to ensure that a minimum outdoor air intakeis maintained regardless Of CO2concentrate. Ton to account for contaminant sources from building materials, furnishings, etc. Unfortunately, Standard 62-1989 and most building codes do not provide any data on what this minimum rate should be. An addendum to Standard 62 to provide building related air flow requirements is being developed. Contact ASHRAE for current information on thestatus of this addendum.

F. Outdoor air rates must be controlled to maintain the measured space CO2 concentration at or below the setpoint determined above. Any type of control logic is acceptable that meets this criterion, including on/off and modulating control. The latter is preferred for system stability and to avoid rapidly changing space temperatures when outdoor air conditions are extreme.

VI. ANALYSIS OF DCV IN SCHOOLS:

For analysis of the Demand controlled ventilation (DCV), the HVAC systems for the schools constructed by **Royal Commission of Jubail**, **KSA**is utilized. The single floor building has 30 class rooms with 25 students each. It also has labs, multipurpose hall, and etc.The total built area of the school is about 743Om2.The HVAC system of the school consist of 7 AHUs, served by a chiller plant. The AHUs are serving near about 131 rooms and most of the rooms are class rooms and office rooms. The requirements of outdoor for the systems are summarized below. In this case one AHU is serving the following multiple zones, and most of the zones are having variable occupancy. For the breathing zone the ventilation should be provided based on ventilation rate procedure by ASHRAE 62.1-2007.Based on that the zones ventilation requirement is summarized below for a single AHU.

No ofpeople	As per ASHRAE 62.1-2007 lps/person	Area (m^2)	As per ASHRAE 62.1-2007 lps / m^2	Total OA as per ASHRAE	From heat load calculation cooling lps (V_{dz})	No. of stalls toilet	Exhaust lps/m^2 or lps/unit	Exhaust lps	Final OA lpsV_{oz}	Discharge outdoor air fraction(as per ASHRAE) $Z_d = V_{oz}/V_{dz}$	Zone ventilation efficiency(as per ASHRAE) $E_{vz} = 1 + X_s - Z_d$
26	5	88	0.6	182.8	409.0				182.8	0.45	0.88
		10	0.3	3.0	180				3.0	0.02	1.31
		38		0.0	61	8	25	200	0.0	0.00	1.32
8	2.5	38	0.3	31.4	185				31.4	0.17	1.16
26	5	74	0.6	174.4	386				174.4	0.45	0.87
26	5	74	0.6	174.4	386				174.4	0.45	0.87
26	5	74	0.6	174.4	358				174.4	0.49	0.84
26	5	74	0.6	174.4	358				174.4	0.49	0.84
26	5	74	0.6	174.4	346				174.4	0.50	0.82
		10	0.3	3.0	200				3.0	0.02	1.31
		32		0.0	36			26.4	0.0	0.00	1.32
		27	0.3	8.1	98				8.1	0.08	1.24
		112	0.3	33.6	296				33.6	0.11	1.21
		38		0.0	48	8	25	200	0.0	0.00	1.32
		10	0.3	3.0	153				3.0	0.02	1.31
164		773		0.0	3500.0			426	1137		

(a) OA calculation for multiple zone as per ASHRAE 62.1		
1)	Total supply V_{ps}=	**3500.0**
2)	OA as per calculation V_{OU}=	**1137**
3)	Average outdoor air fraction $X_s=V_{OU}/V_{PS}$	**0.32**
4)	Outdoor air intake $V_{ot}=V_{ou}/\min E_{vz}$	**1385**

Table 1: calculation of total air volume

(b) OA by considering exhaust & pressurization		
5)	5% of SA + Exhaust	**601**
Use the governing of the above value		**1385L/S**

The total OA requirement is 1385L/s, if we supply all the 1385L/s at all conditions, then the energy requirement will be high and the running cost also will be very high. The zones will not be occupied by the student at all time, depending upon the schedule the requirement will change. At that time for the particular zone we can supply reduced OA.The presence of occupancy will be sensed by CO2 sensors.CO2 based ventilation control is very good at modulating ventilation based on actual occupancy. In some cases, the thought is there may not be a great opportunity to save energy because classrooms at a particular school are always full. However in many cases classrooms may be subject to variable occupancy for the following reasons:

1. Lunch hours, recesses and staggered classroom hours may cause unoccupied periods.

2. Night school or other after hour activities may not result in the same densities that occur through theday in all classrooms.

3. Field trips, assemblies, teacher days and other events may cause a classroom to be unoccupied for one to three days per month that may not be accounted for in automated operational schedules.

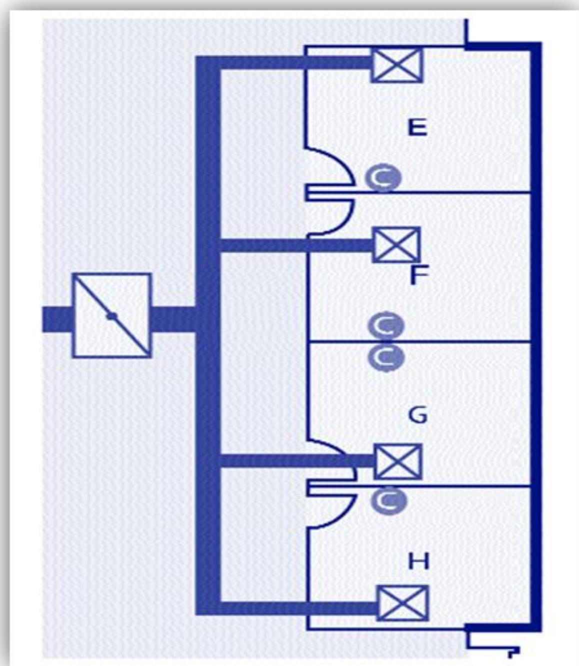
4. Classrooms may be near full but even a classroom that is 80% full can reduce ventilation costs withCO2 controlled ventilation.

All of these conditions can lead to enough variability where the use of CO2 sensors makes sense both byreducing over-ventilation and by modulating ventilation based on occupancy. Energy analysis programs areavailable that can estimate the impact of even minor variation in occupancy on energy savings.

The outdoor air requirement for the various zones is calculated based on the ASHRAE 62.1-2007, ventilation procedure. Because depending upon the class schedules the occupancy in the class rooms may change. If the system is serving the same outdoor air at all conditions, then some areas may under ventilated or over ventilated. In order to avoid this problem the CO2 sensors are used to vary the OA rate. The usage of CO2 sensors will be very effective in systems serving single zones, and depending upon the CO2 concentration the unit will supply the outdoor. In our case the systems are serving the class rooms along with variation in occupancy. If we use the CO2 sensors to identify occupancy, it may not give the actual occupancy, but it can be possible by using individual sensors in each zones. The individual sensor usage will make the total control system as a complicated one. If we follow the first one, that is using common CO2 sensor to find the occupancy then also we cannot able to identify the actual occupancy. Because when we place the CO2 sensor in the common return duct it will read the average concentrations, and again the proper ventilation will not be obtained.

VII. LOCATING CO_2SENSORS FOR DCV:

The key is toselect a location where the sensor can accuratelymeasure the CO2 concentration and is representativeof the area or zone served. The exact criteria will varybetween different buildings and system types. In eachcase, the designer must apply good engineering judgmentto assure that both the sensors and the completeventilation system performs effectively.In general, a CO2 sensor will be less susceptibleto stratification issues than temperature sensors dueto the tendency of gases to quickly equalize within aspace. A special consideration for CO2 sensor placementis to ensure it is not located in an area wherepeople might be directly breathing on the sensor. In



two methods we can locate the sensors,1. Wall mounted type,2. Duct mounted type.

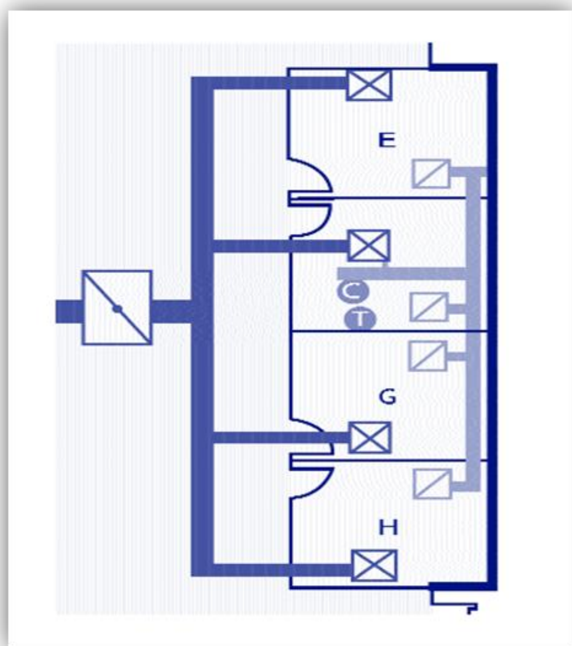


Fig1: Locating CO_2 sensor for DCV

Measurement of CO_2 in the space using wall mountedsensors is preferred for the same reason thattemperature sensors are mounted within the space.In multiple space applications, duct-mountedsensors may reflect an average of all spaces and willnot provide indication of ventilation requirements inindividual zones. The result is that ventilation to theindividual spaces (i.e., the "critical" space) may not bemaintained and compliance to ASHRAE 62 requirement will be compromised.Space-mounted sensors can also give a goodindication of the ventilation effectiveness in the spaceand will operate the system based on the characteristicsof the space. Duct-mounted sensors cannot indicateventilation effectiveness.The principal driver for use of duct-mounted sensorshas been to reduce costs by reducing the numberof sensors required for a job. In the past few years,CO_2 sensor pricing has dropped dramatically meaningthat the cost difference between using duct-mountedand multiple space-mounted sensors is a minimalportion of job cost. Some sensors now even combinetemperature and CO_2 measurement functionality tofurther reduce purchased and installed cost.

Duct-mountedCO_2 sensors are best suited tosingle zone systems that run continuously.Duct-mounted CO_2 sensors should be locatedto serve a single zone, or multiple spaces withina single zone that have similar activity levels. Locate the sensor as near as possible to thespace being served. When using duct-mounted sensors for ademand controlled ventilation system, the designer must consider ventilation effectivenessin the occupied space (just the same as is necessary when using the VentilationRate Procedure). Locate duct-mounted sensors where they areaccessible for inspection and maintenance.

VIII. SEQUENCE OF OPERATION:

a. The DCV strategy would be timed to operate during all occupied hours. The economizer would be programmed to override DCV control if outside air could be used for free cooling.
b. A morning pre-occupancy purge would be included in the sequence of operation of the air handler.
c. The maximum position of the air handler for delivery of ventilation under the DCV strategy would be would be 3500 L/S.
d. The base ventilation rate would be set to 600 L/S
e. The air handler would be set up to begin modulation of outside air when inside concentrationswere 100 ppm over outside concentrations (500 ppm). The damper position on the air handler would be proportionally modulated so that when levels reached the equilibrium anchor point the design ventilation rate of 1385 L/Swould be provided.

IX. CONTROL STRATAGY:

Set Point control would probably work very wellfor a single school classroom given the relatively highdensity of the space and small volume of air. Thisstrategy could become much more complicated whentrying to control ventilation for spaces simultaneouslyand may result in excessive damper movementand wear as the damper continually opens and closes.For this application proportional modulated controlwas chosen because the rooftop system selectedhas proportional modulation capability.

The outside air damper will be modulated between the minimum positiondescribed above and the maximum position described above necessary to provide theDVR to the space based on CO_2 concentrations. It is highly recommended that aproportional control approach be used to modulate the damper based on CO_2 readingsbetween a lower and upper control limit. This proportional modulation will ensure that 15CFM per person of outside air is provided at all times based on actual occupancy.

A. Upper Control Limit: The proportional control strategy should be designed to position the damper to provide the DVR when the CO_2 levels are equivalent tothe equilibrium concentration Of CO_2 corresponding to the target CFM per personventilation rate in the space. For 20 CFM/person the upper set point is 930 ppm,for 15 CFM per person the upper set point is 1100 ppm. (This assumes a typicaloutside concentration of 400 ppm)

B. Lower Control Limit: The proportional control strategy would position the damper in the minimum position until indoor levels exceed a certain CO_2 threshold above outside levels. Typically this threshold should be set at 150 to200 ppm CO_2 above outside levels of at 550 to 600 ppm.

C. *Multiple Sensors Controlling a Single AHU:* Control should be based on thehighest CO_2 concentration measured in all spaces served by the air handler.This can be accomplished within the programming capabilities of most buildingcontrol systems. Alternatively, transducers are available that can take in multipleinputs and pass through the highest value.

D. Benefits: DCV saves energy by avoiding the heating, cooling, and dehumidification of more ventilation air than is needed. CO_2 sensors are the most widely accepted technology currently available for implementing DCV. Additional benefits of CO_2-based DCV include

a. Improved IAQ—By increasing ventilation if CO_2 levels rise to an unacceptable level,

b. Improved humidity control—in humid climates, DCV can prevent unnecessary influxes of humid outdoor air that makes occupants uncomfortable and encourages mold and mildew growth.

X. Conclusion

CO_2 demand control ventilation is a real-time, occupancy basedventilation approach that can offer significant energysavings over traditional fixed ventilation approaches, particularlywhere occupancy is intermittent or variable from designconditions. Properly applied, it allows for the maintenance oftarget per-person ventilation rates at all times. Even in spaceswhere occupancy is static, CO_2 DCV can be used to ensure thatevery zone within a space is adequately ventilated for its actualoccupancy. Air intake dampers, often subject to adjustment or arbitrary adjustments over time can be controlled automaticallyavoiding accidental and costly over or under ventilation.Measurement and control technology using CO_2 sensors isquickly evolving to a stage of maturity where cost and reliabilitywill likely approach that of conventional temperature measurementand control in the near future. As a result, the use ofCO_2 as an indoor comfort, ventilation and air quality controlparameter has the potential to be as widely used as temperatureand humidity measurements are today. There also exists a goodopportunity to reduce energy consumption due to reduced.

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