

Analytical Prediction of Carbon Dioxide Concentrations in Variable Air Volume Systems

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SUMMARY

A typical commercial/institutional building is modeled using a computer program developed by ASHRAE as research project number RP-590. The RP-590 program output was used as input in a separate program written to calculate the CO₂ concentration levels in the various zones of this typical building on an hourly basis for a one year cycle. This data allow one to see how VAV A/C systems affect the CO₂ levels in each zone as the VAV boxes modulate in response to the thermal load. The CO₂ concentration has been suggested to be a good indicator of indoor air quality (IAQ) in typical commercial and institutional settings. IAQ is a hot legal liability issue in the building industry.

The results show that a VAV A/C system, that is adequate in all other respects, can adversely affect the indoor air quality of the building. Factors responsible for this are discussed and recommendations and limitations are given for the utilization of this work.

INTRODUCTION

After the oil embargo, energy conservation became a key issue as companies faced rising operating costs due to the increasing energy cost. One quick way to slow down this rise in operating cost was to reduce the amount of outside air delivered to the occupied zones. Also, architects and designers began to apply Variable Air Volume (VAV) systems more and more in place of traditional constant volume systems. This allowed the total system airflow to be modulated relative to the thermal load demands thereby saving fan energy, duct sizing, etc. Buildings began to be designed and constructed more tightly reducing the amount of infiltration of outside air. These things together contributed to the increase in cases of sick buildings and building related illnesses. These problems had not previously manifested themselves, due to the generous use of outside air and relative "looseness" of building construction. There has been much information published concerning the types and sources of contaminants commonly found in buildings with poor indoor air quality. The ASHRAE current standard for ventilation is ASHRAE Standard 62.1-2004 [1]. This standard specifies the required ventilation rate for many types of buildings from 8 L/(s-person) to 25 L/(s-person). It retained many features from earlier standards including allowing two different procedures for ventilation design. The first procedure, "The Ventilation Rate Procedure" specifies minimum amounts of quality outside air for particular occupant densities. The second procedure, "The Indoor Air Quality Procedure", allows innovative solutions by other means, such as special filtration, to obtain acceptable indoor air quality. Carbon dioxide levels are recommended for use as an indicator to determine the quality of the air and a limit of 1000 ppm is established.

Objective

The objective of this research is to determine the effect that a Variable Air Volume (VAV) air-conditioning system has on the indoor air quality of the building or zones which it serves. Specifically, this analysis is concerned with the variation with time of the CO₂ concentration levels as the VAV system modulates relative to the thermal load.

Scope

The objective is accomplished by modeling a prototypical building that was developed for use in ASHRAE research project RP-590. The occupant density is 30 persons/100 m² which is typical of the several commercial/institutional examples found in ASHRAE Standard 62.1-2004. This model is analyzed for two ventilation design criteria: (1) 3L/(s-person)/person outside air, and (2) 10L/(s-person) outside air. Design criterion (1) was used in the 1970's and 1980's when energy conservation was a priority and indoor air quality (IAQ) issues had not yet surfaced. Criterion (2) comes from the most recent standards issued by ASHRAE concerning acceptable indoor air quality.

ASHRAE Research Project 590, *Control of Outside Air and Building Pressurization in VAV Systems*, developed a personal computer program, in Turbo CTM, that models seven basic types of VAV control systems in a prototypical four zone building. The results available from this program include pressures throughout the system/building, zone airflow rates, cooling/heating energy requirements, and certain warnings when pressures or air flow rates are outside prescribed limits. In this paper an algorithm is developed to calculate carbon dioxide levels in each zone based on (1) the amount of outside air delivered to each zone on an hourly basis as calculated by the modified RP-590 program, and (2) the amount of CO₂ generated in each zone during the same time periods.

Description of the Building

The building parameters used in this paper are such that they provide a convenient reference point for comparison with the facilities listed in ASHRAE Standard 62.1-2004, *Outdoor Air Requirements for Ventilation*. The building (see Figure 1) is single story, of medium mass, has an occupancy of 30 persons/100 m², and the occupants are the only source of carbon dioxide. This prototypical building, as developed in RP-590, is occupied 24 hrs/day. Each zone has identical thermal loads except for the external loads due to orientation. The interior zone is not connected to this system.

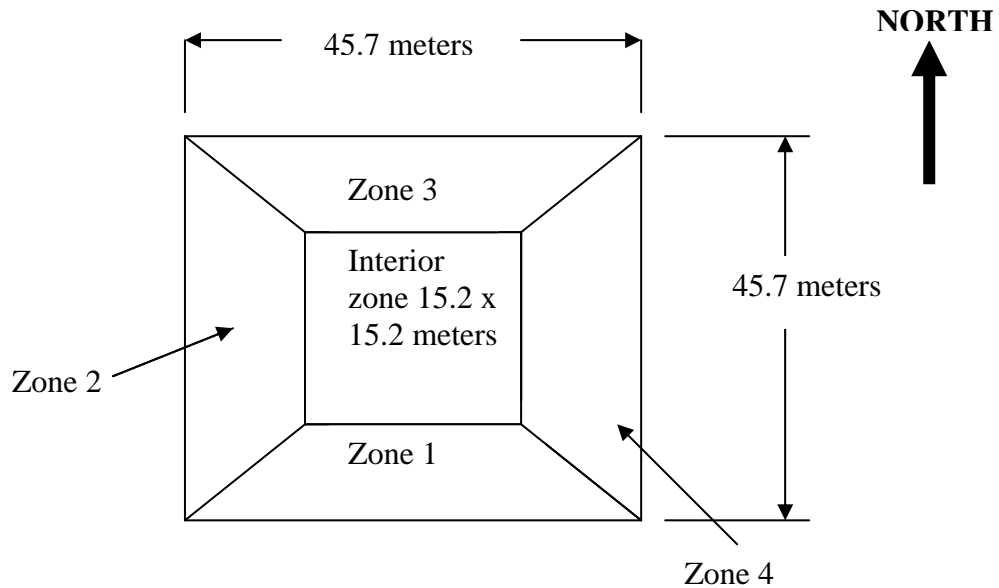


Figure 1. Floor Plan of the Building Used in the Analysis

Description of the VAV System

Of the seven types of VAV systems modeled in RP-590, system 2 is the system utilized in this research (see Figure 2). It has a return fan whose capacity is controlled by a signal from the return duct pressure. The supply fan capacity is controlled by a signal from the supply duct pressure.

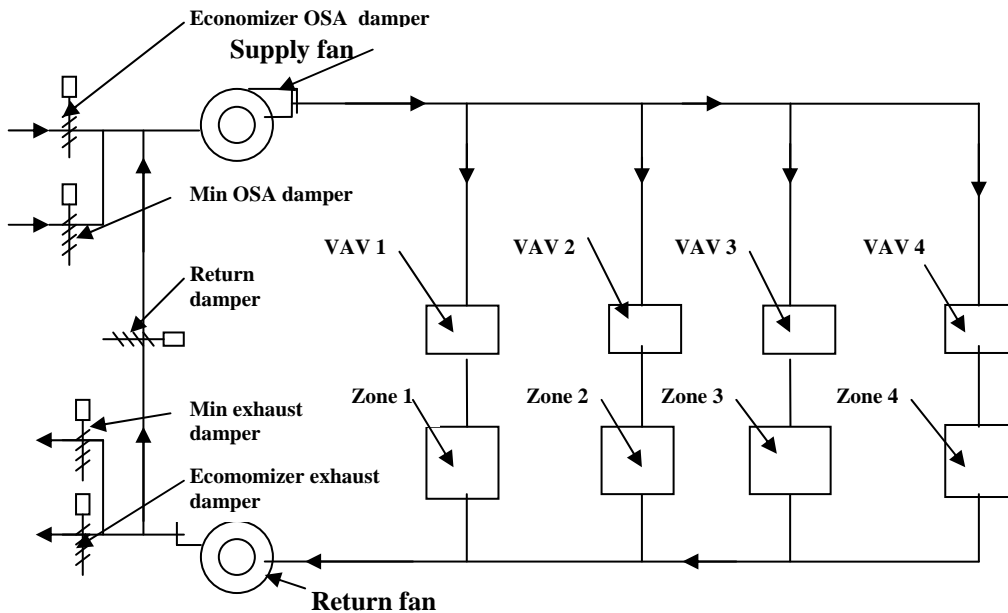


Figure 2. Schematic of VAV system Analyzed in this Work

Under the 3 L/(s-person) design criteria, the total amount of outside air is 1500 L/s (+0, -500). Under the 10 L/(s-person) design criteria, the total amount of outside air is 6,000 L/s. The desired zone pressure is 0.004 cm of H₂O (± 0.004) in all cases. Economizer operation is controlled by the mixed air temperature, which has a setpoint of 23 C. The total

air flow to a zone is modulated between a specified minimum turn-down ratio and wide open flow. Below that point reheat is added via baseboard heaters in order to regulate the zone temperature. VAV boxes are usually set to deliver some minimum amount of flow regardless of the room temperature. Turndown ratio is defined as the minimum percentage of wide open flow to which the VAV box will modulate. If the room is still too cool then a source of heat is activated to maintain the setpoint temperature.

For the 10 L/(s-person) design, the sizes of the minimum OSA damper (as compared to the ASHRAE RP-590 report) and the corresponding exhaust dampers were increased so that they would maintain their same respective pressure drops at the new airflow. The sizes of the other dampers were not changed.

A summary of the assumptions used follow:

1. Thorough mixing of outside air with return air takes place
2. dilution air mixes perfectly and instantaneously with the zone space air
3. Perfect control is assumed so there is no effect due to instrumentation lead/lag
4. The system attempts to maintain a slight positive pressure in each zone;
5. CO₂ generation and dilution in a zone remains constant (i.e., in a steady state)

Description of CO₂ Algorithm

The CO₂ concentration in each zone can be modeled, as it varies with time throughout the day, by considering the conservation of mass equation for a control volume. The resulting 1st order linear differential equation can then be solved. The general form of the conservation of mass equation can be simplified based on the assumptions stated above to :

$$\frac{\partial}{\partial t} \rho V = \rho_i V_i A_i - \rho_o \vec{V}_o A_o + \vec{M}G - \rho_A V_A A_A - \rho_R V_R A_R \quad (1)$$

The following symbols apply to the equation.:

A = area, ft ²	V = conditioned space volume, ft ³
C = CO ₂ concentration, lbmol/ft ³	\vec{V} = velocity, ft/min
E = filter CO ₂ removal efficiency, decimal	P = density, lb/ft ³
G = CO ₂ generation rate, lbmol/min	<i>Subscript i</i> = entering conditions
M = molecular weight, lbm/lbmol	<i>Subscript o</i> = exiting conditions
Q = volumetric flowrate, ft ³ /min	<i>Subscript A</i> = absorbed air conditions
T = time, min	<i>Subscript R</i> = return air conditions

This equation can be solved subject to the initial condition that at $t = 0$, $C(0) = C_o$. If it is assumed that the amount of CO₂ absorbed or filtered is negligible, the resulting solution to Equation (1) is

$$C(t) = C_i + (C_o - C_i) \exp\{-Qt/V\} + (G/Q)(1 - \exp\{-Qt/V\}).(2)$$

Note in Equation (2) under the assumptions of this work that $C_o = C_i$.

This solution to equation (2) was incorporated into a separate program written in Turbo CTM. The airflow output file from RP-590 is read into this program where it is used to calculate the CO₂ levels in each zone. A listing of the program code is given in Reference [4]. The program prompts the user for the following inputs:

1. Output filename from RP-590 that is to be used as the input for this program.
2. The filename for the output generated by this program.
3. CO₂ concentration of the outside air, ppm.
4. Conditioned volume in cubic meters of each zone.
5. Initial CO₂ concentration of each zone, ppm
6. Number of sources in each zone that generate CO₂. (Each source for a particular zone must generate the same amount of CO₂).
7. Generation rate of CO₂ in L/s of each source.

The following values were used as input to calculate the CO₂ levels in each zone:

- 400 ppm CO₂ in outside air
- 4,669 m³ of space in each zone (from RP-590)
- 400 ppm CO₂ initial concentration in each zone
- 150 people/zone (from RP-590) = only CO₂ sources
- 0.0053 L/s CO₂ generated per person [2]

The computer program used in this work was written specifically for system 2 from RP-590; however, it can also be used to model system 1. To model the other systems, minor modifications would have to be made to properly scan the input files.

RESULTS

The output of the computer model produces some very interesting results. Tables 1 is a summary of the raw data for the case of 3 L/(s-person) outside air criteria for zone 3 (CASE A). Table 2 is a summary of the raw data for the case of 10 L/(s-person) outside air criteria for zone 3 (CASE B). (Tables for all zones for both outside air requirement cases are included in reference[4]. The top twelve rows of data in each table show, for a particular turndown ratio (TD=fraction of maximum air flow), the number of hours for a typical day of the corresponding month that the 1000 ppm limit was equaled or exceeded. The bottom five rows show (1) the percentage of the yearly hours that the zone exceeds or equals the CO₂ limit, (2) the average value of the CO₂ concentration, (3) the standard deviation, (4) the maximum value, and (5) the minimum value. The American Conference of Governmental Industrial Hygienist has adopted a Threshold Limit Value – Time Weighted Average (TWA) of 5000 ppm for CO₂ [3]. Due to space considerations raw data can not be included in this paper but is included in reference [4]. The *maximum* data values listed in Tables 1 and 2 give evidence that this TWA may be exceeded. By referring to the raw data it can be seen that the TWA is indeed exceeded. For example for Zone 3 the TWA is exceeded for 32 consecutive hours for CASE A.

By referring to the *maximum* data values in Table 2 (for CASE B) it can be seen that the largest values are much less than the TWA.

On average for CASE A, the 1000 ppm limit is exceeded for all turndown ratios in all four zones. Even under constant volume operation, this design fails to maintain the CO₂ concentration below the 1000 ppm limit approximately 30% of the time. Surprisingly for CASE B, the percentage of time that this system equals or exceeds the limit is very close to the results for CASE A. However, the amount that the CO₂ concentration exceeds 1000 ppm for CASE B is much less than that for CASE A. These details can be seen in reference [4].

Although space does not allow the details for all zones to be presented, the complete results shown in reference [4] show that during mild months when Zones 1, 2, and 4 are well ventilated, Zone 3 (North) is not. This occurs because of the low thermal load in Zone 3, which requires that the VAV box modulate down.

Table 1. Zone 3-Number of hours (in bold) that CO₂ is above 1000ppm @ 3 L/(s-person)

Month	Days/Mon	TD=0.4	TD=0.5	TD=0.6	TD=0.7	TD=0.8	TD=0.9	TD=1
Jan	31	24	24	24	20	17	12	0
Feb	28	24	24	21	18	15	10	0
Mar	31	19	19	17	15	12	5	0
Apr	30	13	13	9	5	0	0	0
May	31	12	12	12	12	11	11	11
Jun	30	16	16	16	16	15	15	15
Jul	31	22	22	22	21	21	21	21
Aug	31	24	24	24	24	24	24	24
Sep	30	12	12	12	12	10	10	10
Oct	31	17	17	6	6	5	5	5
Nov	30	18	18	15	11	6	0	0
Dec	31	24	24	24	24	19	16	11
Yearly % time out								
Of compliance		78	78	70	64	54	45	34
Average CO ₂ ,ppm		2388	2356	2312	2272	2176	2052	1922
Std Dev CO ₂ ,ppm		1855	1889	1956	2034	1985	1863	1721
Maximum CO ₂ ,ppm		6821	6840	6982	7199	6498	5653	5253
Minimum CO ₂ ,ppm		828	824	828	821	821	787	749

Table 2. Zone 3-Number of Hours (in bold) that CO₂ is above 1000ppm @ 10 L/(s-person)

Month	Days/Mon	TD=0.4	TD=0.5	TD=0.6	TD=0.7	TD=0.8	TD=0.9	TD=1.0
Jan	31	24	24	24	20	16	13	3
Feb	28	24	24	21	18	15	10	0
Mar	31	20	19	17	15	11	5	0
Apr	30	13	13	9	4	0	0	0
May	31	12	11	10	11	11	11	11
Jun	30	16	16	16	15	15	15	15
Jul	31	21	22	21	21	21	21	21
Aug	31	24	24	24	24	24	24	24
Sep	30	12	12	11	10	10	10	10
Oct	31	16	17	6	5	5	5	5
Nov	30	18	18	15	11	6	0	0
Dec	31	24	24	24	24	19	15	10
Yearly % time out								
Of compliance		78	78	69	62	53	45	35
Average CO ₂ ,ppm		1759	1713	1653	1592	1514	1424	1334
Std Dev CO ₂ ,ppm		840	847	879	910	893	836	769
Maximum CO ₂ ,ppm		3570	3593	3600	3507	3197	2870	2586
Minimum CO ₂ ,ppm		834	823	828	822	823	789	753

DISCUSSION

The HVAC system analyzed was designed for the older ASHRAE recommendation of 3 L/(s-person) of outside air and consequently will not adequately keep the zone CO₂ levels below the current ASHRAE recommendation of 1000 ppm. However, even with the minimum outside air and corresponding minimum exhaust air dampers increased in size (maintaining the same pressure drops) for 10 L/(s-person) required by ASHRAE 62.1-2004, this system allows a significant number of excursions above the 1000 ppm limit. Simply increasing the size of the outside air dampers will not cure the problem. The thermal load can still dictate how much outside air is delivered to a zone. Even if the internal thermal loads are identical, the loads due to the external exposures can cause significant differences. The prudent engineer will utilize ASHRAE Standard 62.1-2004 that describes a method to calculate the required amount of outside air for multiple zone systems. This manifests itself as an increase in the total amount of outside air for the system over and above what would be calculated by simply multiplying the total number of people by the required ventilation per person as tabulated in the standard. This still leaves open the issue of how to maintain the minimum amount of outside air at the minimum turndown ratio for the zone VAV box. One strategy could be to install a CO₂ sensor in the critical zone that would override the thermostat and drive the VAV box open to deliver more air to the zone during low load situations. If the CO₂ sensor were still not satisfied, it could override the speed modulating controller for the supply fan and speed up the fan to call for more air. The supply duct pressurization would then have to be kept within allowable limits. This could be accomplished by proper placement of relief dampers or through utilizing a hi-limit pressure controller to open the other VAV boxes in some order to relieve the pressure. The thermostat would continue its normal operation and call for reheat to maintain the space temperature.

For both design cases, in each of Zones 1, 2, & 4 a turndown ratio of 0.7 performs about as well as a turndown ratio of 1.0. Zone 3 shows a significant percentage improvement with increasing turndown ratio. This would seem to indicate the need for other system design modifications. For the design analyzed in this paper, the return ductwork offers less resistance than the exhaust ductwork. Less resistance in this branch would allow more return air to re-circulate and keep the corresponding portion of outside air from being brought into the system. In this case the return air damper should be decreased in size, thereby, increasing the pressure drop and restricting the return air flow. Increasing the resistance in this branch would allow more outside air to enter the system.

Even with a turndown ration of 1.0, each zone in both design cases allows the CO₂ concentration to exceed the limit. This indicates that the outside air dampers and exhaust dampers are undersized.

The system modeled in ASHRAE Research Project RP-590 was not designed with a load diversity factor. Load diversity is a factor that takes advantage of the fact that the different zones reach their peak thermal load at different times of the day. When utilizing the load diversity factor, smaller equipment can be purchased resulting in lower initial cost. However, the engineer must be very careful to compare the ventilation load required by the CO₂ generators with the thermal load and select equipment capable of satisfying both loads at all conditions.

This model, though quite simple, provides valuable insight to those interested in analyzing the variations in CO₂ levels in many types of buildings. The steady state assumption will not be valid in all types of buildings and occupancies, but should be adequate in settings where the occupancy remains fairly constant throughout the day.

REFERENCES

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