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CO_2 concentration and occupancy density in the critical zones served by the VAV system

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Abstract. This article presents the results obtained from monitoring a VAV system with highly diversified zone occupancy density are presented in the article. The investigated VAV system meets the load for 72 zones (68 perimeters and 4 interiors) consisting of classrooms, offices, conference rooms, etc. with highly diversified occupancy densities from 1.875 to 2.5 m^2/person for the classrooms and from 10 to 15 m^2/person for the offices. The monitoring shows that the CO_2 concentration can exceed the set point in the critical rooms. Simulation results are also presented in the article to show that it is often impossible to adjust the operation of such VAV systems because the adjusted System Outdoor Air Fractions, % OA, can reach 100% even where the zone CO_2 concentration is not respected. The presented monitoring and simulation results were obtained in the winter, with the VAV system operating at partial load and with the minimum outdoor air flowrate required by the economizer system. As shown in the article, to respect the zone set point CO_2 concentration in such period, the VAV system must operate mostly at a %OA equal to 100% instead of its minimum value. To circumvent this, the supply zone air flow rate may have to be designed taking into account the CO_2 concentration resulting from the critical zones occupancy density.

1 Introduction

A VAV (variable air volume) system, recognized for its energy efficiency, is a system which controls the fan air flow rate according to the thermal comfort of occupants. The supply air temperature is held relatively constant, but could be moderately reset depending on the season. It must always be low enough to meet the cooling load in the most demanding zone. VAV terminal units measure supply airflow rate and control that flow in response to room temperature. The static pressure regulator controls motor-fan speed to maintain the inlet pressure in the VAV boxes. The minimum throttling ratio in the zones is 20%, while the system ratio is 50%. The supply zone air flow rate required is maintained by a specific control loop and depends on the zone temperature. In the perimeter zones, the supply zone air flow rate is at its minimum before the electric baseboard starts to heat. The main disadvantage of a VAV system is that when it is operating at partial load, the outdoor air flow rate supplied to the zones served by the system could be too low, and could result in poor air quality [2, 3]. This paper presents a study of CO_2 concentration in the zones of

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the existing VAV system, operated with an air-side economizer cycle to control the outdoor air flow rate.

2 VAV system description and monitoring

The investigated VAV system meets the load for 72 zones (68 perimeters zones with electric baseboards and 4 interiors zones), consisting of classrooms, offices, conference rooms, etc. The design system air flowrate $V_{ps,design}$ is 17.314 m^3/s and the minimum system outdoor air fraction is 15% of this $V_{ps,design}$ flowrate. The system outdoor air flowrate V_{oa} is controlled by economizer cycle, but the measurement of CO_2 concentration sensor is also used to control the V_{oa} flowrate if the 1000 ppm is exceeded. The system supply air temperature set point changes linearly within the 14 to 18°C range as a function of the outdoor temperature. It is corrected by adding a value of between -2 and +2°C when the fan airflow rate varies from 90 to 50%. The zone occupancy density is hifhly diversified, and varies from 1.875 to 2.5 m^2/person for the classrooms and from about 10 to 15 m^2/person for the offices. The system operates by applying RACO2-DAV (Return Air CO_2 Control – Demand Controlled Ventilation) [3, 6] with only one CO_2 concentration sensor to maintain the return CO_2 concentration set point.

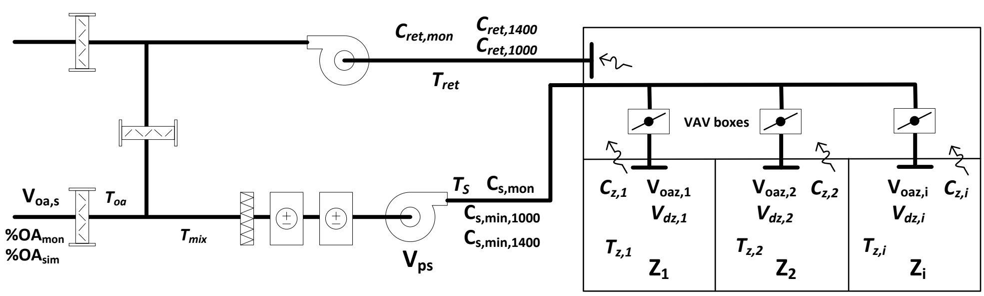

Fig. 1. Diagram of the VAV system with variables used.

Since, in the VAV systems, the system outdoor air fraction %OA is the same for all zones served, and since the CO_2 is only generated by occupants of these zones, the CO_2 concentration could respect the set point in the return duct by exceeding it in the critical zones with high occupancy density. To demonstrate the problems encountered in this system, we monitored of this CVCA system with the following considerations and steps:

- The winter is chosen for this monitoring because the VAV system operates during this period at the minimum $V_{oa,s}$ flowrate required by the economizer system;
- The classrooms Z_1 to Z_7 are identified as the critical zones in terms of occupancy density, and are presented in Table 1;
- The following data are measured by the VAV control system :
  - The zone supply airflow rate $V_{dz,i}$
  - Supply air T_s, return air T_{ret}, outdoor air T_{oa}, mixing air T_{mix} and zone air T_{zi} temperatures;
  - Applying the fan laws, fan speed in rpm used to determine the fan supply air flowrate V_{ps};
  - CO_2 concentration of return air $C_{ret,mon}$, where $_{mon}$ means monitoring.
- Missing data, such as the CO_2 concentration in the critical zone $C_{z,I}$, are measured by temporarily installing new CO_2 sensors.

The system outdoor air fraction $\%OA_{mon}$ ($V_{oa,s}/V_{ps}$) is calculated by applying the mass

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conservation and the energy balance using T_{mix}, T_{ret}, T_{oa} and V_{ps} data. It should be noted that the minimum %OA value of the investigated VAV system was 15%, but sometimes T_{ret} and T_{mix} were close or very close, and gave $\%OA_{mon}$ values lower than 15%. In those cases the minimum 15% was used in the monitoring data.

The zone outdoor airflow rate $V_{oaz,i}$ is calculated as $V_{oaz,i}=\%OA_{mon}*V_{dz,i}$ and is used to determine the $V_{oaz,i,pers}=V_{oaz,i}/P_{z,i}$ when $P_{z,i}$ is the zone population. The critical zones characteristics are as follows:

Table 1. Critical zone characteristics.

Zone	$P_{z,i}$	Area m²	m²/pers design	$V_{dz,design}$ l/s	$V_{dz,design}$ l/s/pers	$V_{dz,min}$ l/s
Z_1	30	62,1	2.07	272	9.1	81.7
Z_2	30	56,3	1.875	272	9.1	81.7
Z_3	45	86,3	1.912	500	11.1	113
Z_4	55	101,6	1.838	750	13.2	194.6
Z_5	48	92,7	1.931	600	12.5	180
Z_6	48	101,6	2.123	600	12.5	180
Z_7	50	106,5	2.132	600	12.0	180

The data acquisition was realized during the following periods: 2015: February 12, 13, and 25, and March 10 and 11; 2016: January 28, 29 and 30, February 1, 2 and 3, and March 9 and 10. Each day of monitoring covers three courses periods: 8:30 AM to 12:00 PM, 1:30 PM to 5:00 PM and 6:00 PM to 9:30 PM.

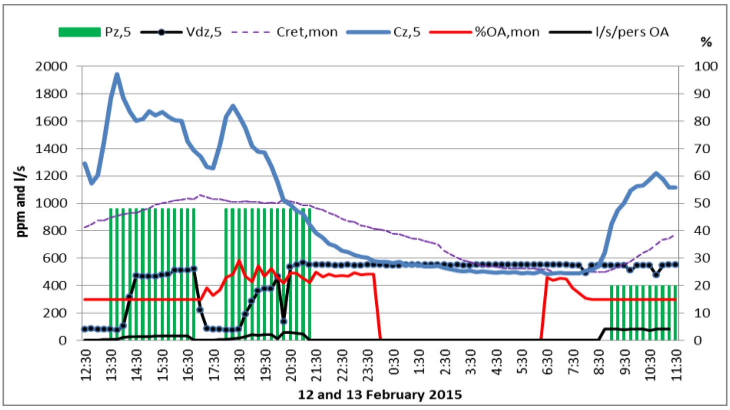

Fig. 2. Monitoring results for zone Z_5 recorded on 12 and 13 February 2015.

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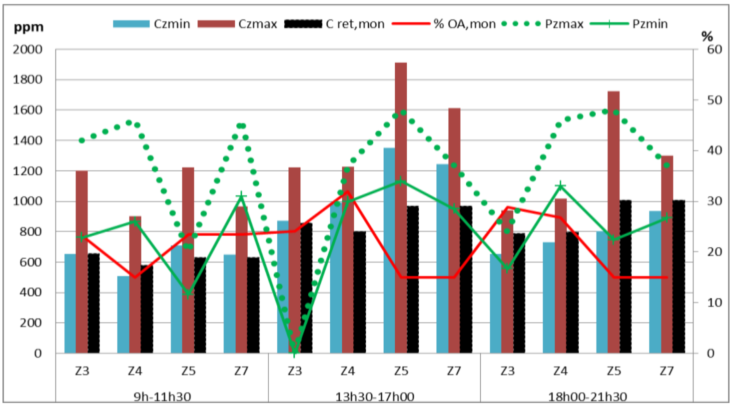

Fig. 3. Summary of recorded data for zones Z_3, Z_4, Z_5 and Z_7.

Figure 2 shows the results obtained in zone Z_5 from noon on February 12 to noon on February 13, 2015, the day when the worst results for $C_{z,i}$ are recorded. Figure 3 shows the min and max values of CO_2 concentration $C_{z,i}$ only the zones Z_3, Z_4, Z_5 and Z_7, obtained in 2015. The mean values of population, $\%OA_{mon}$, and of return air CO_2 concentration, $C_{ret,mon}$, are also presented in this figure. The following observations may be drawn from an analysis of the results in Figure 2:

- The CO_2 concentration $C_{z,5}$ is very high and widely exceeds the 1000 ppm limit. It varies with the population and with the $V_{oaz,i}$ using $\%OA_{mon}$ and $V_{dz,i}$ presented in the Figure 2. Finally, it depends on the $V_{oaz,i,pers}$ (l/s*person);
- The maximum CO_2 concentration value $C_{ret,mon}$ is 1033 ppm, but the $C_{ret,mon}$ mostly respects the 1000 ppm;
- The population $P_{z,i}$ is determined as the number of students registered in the courses;
- As mentioned above, when the $\%OA_{mon}$ presented in the figure is equal to 15%, it means that it could be lower according to the energy balance used in the calculation of $\%OA_{mon}$;
- The results show that V_{dz} is really a function of the zone temperature because it is not at its maximum (600 l/s) even if the CO_2 concentration exceeds the 1000 ppm limit.
- The fan is in operation during the night because of low outdoor air temperatures.

Concerning Figure 3, it can be noted that:

- The maximum values of the zone CO_2 concentration $C_{z,i}$ often exceed 1000 ppm;
- Zone Z_4 is the largest and most ventilated zone, and the $C_{z,i}$ of this zone exceeds the limit only slightly;
- The best factor explaining the CO_2 concentration overrun may be the l/s/person ratio, but it is calculated by taking into account the zone $V_{oaz,i}$ and the $P_{z,i}$. As already mentioned, $\%OA_{mon}$ (used to determine $V_{oaz,i}$) is calculated using the energy balance, and is sometimes corrected to 15%. The $P_{z,i}$ is based on the number registered students in the courses and it could be different from the real $P_{z,i}$. The l/s/person ratio can therefore sometimes be inaccurate.
- The CO_2 concentration of zone Z_3 is not normal during the PM period when the population is zero. This zone could very well have been occupied even if according to the course schedule, it should not have been.

The question now is how the operation of this VAV system should be adjusted in order to avoid exceeding the concentration in critical zones.

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3 Simulation of investigated system

3.1 $C_{z,i}$ model and calculation

The CO_2 zone concentration $C_{z,i}$ is determined through the model proposed by [1]:

$$C_{z,i} = \frac{1}{\frac{V}{\Delta\tau}+V_{dz,i}} \cdot \left[\frac{V}{\Delta\tau} \cdot C_{z,i-1} + V_{dz,i} \cdot C_{s,mon} + 4900 \cdot P_{z,i}\right] \tag{1}$$

where the zone air supply air flowrate $V_{dz,i,}$ and the zone population $P_{z,i}$ are recorded by monitoring, V is the zone volume, Δτ is the calculation step, and 0.0049 is the CO_2 generated by a person in l/s (4900 ppm). The CO_2 concentration of supply air $C_{s,mon}$ is calculated by equation 2 with $V_{oa,s}$ according to $\%OA_{mon}$ and $C_{ret,mon}$ from monitoring, and the CO_2 concentration of outdoor air $C_{oa,s}$ is equal to 450 ppm.

$$C_{s,mon} = (1 - \%OA_{mon}) \cdot C_{ret,mon} + \%OA_{mon} \cdot C_{oa,s} \tag{2}$$

Figure 4 shows the comparison between the calculated and measured $C_{z,i}$ for zone Z_5 on February 12, 2015.

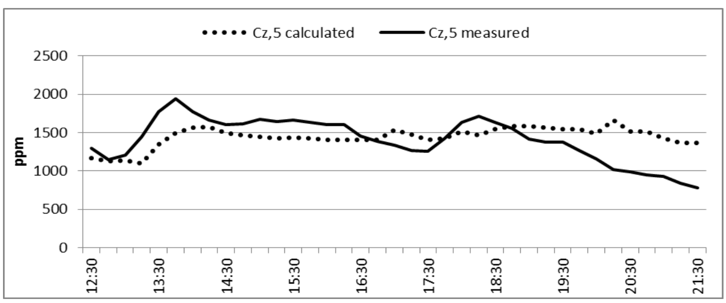

Fig. 4. Comparison between the calculated and measured CO_2 concentration in zone Z_5.

3.2 VAV-F system and application of $SACO_2$-DCV control system

The VAV-F system was created to simulate the corrected operation by applying the new SACO2-DCV (Supply Air CO_2 Control–Demand Controlled Ventilation) [4, 5] control strategy in order to respect the zone CO_2 concentration set point. This system includes only the critical zones presented in Table 1.

Since the CO_2 concentration is widely exceeded in the monitoring, the first question is: was the investigated VAV system well designed to respect the 1000 ppm set point? To answer this question, the $C_{z,i,design}$ was calculated for each critical zone, i.e., for all zones of the VAV-F system operating in design conditions. The model applied was that of the ASHRAE 62.01 Standard (Ventilation Rate Procedure). The following assumptions were used: (*i*) Zone Air Distribution Effectiveness (Ez) and Occupation Diversity (D) are equal to 1.0, and (*ii*) the zone air supply air flow rate $V_{dz,i}$, and zone population $P_{z,i}$ are the design values. This model determines factors such as the Zone Ventilation Efficiency, the System Ventilation Efficiency, the Supply Outdoor Air Fraction for each zone and finally the System Outdoor Air Fraction (Y) required in the air supply by system V_{ps}. If the CO_2 outdoor air concentration $C_{oa,s}$ is considered to be 450 ppm, the $C_{z,i,design}$ could be determined by the following equation:

$$C_{z,i,design} = C_{oa,s} + \frac{4900 \cdot P_{z,i,design}}{V_{dz,i,design} \cdot Y} \quad (3)$$

Table 2. Data used to determine the CO_2 concentration in the design condition.

Zone	$V_{dz,design}$ l/s	$P_{z,max}$	Area m²	R_a l/s/per s	Ra l/s/m²	Y	V_{oz} l/s	Z_p	$C_{z,i,design}$ ppm
Z_1	272	30	62.1	5	0.6	0.61	187.2	0.69	1400
Z_2	272	30	56.3	5	0.6	0.61	183.8	0.68	1400
Z_3	500	45	86.3	5	0.6	0.61	276.8	0.55	1180
Z_4	750	55	101.6	5	0.6	0.61	336.0	0.45	1100
Z_5	600	48	92.7	5	0.6	0.61	295.6	0.49	1100
Z_6	600	48	101.9	5	0.6	0.61	301.1	0.50	1100
Z_7	600	50	106.5	5	0.6	0.61	313.9	0.52	1150

The results in Table 2 effectively show that the CO_2 concentration $C_{z,i,design}$ in the zones is not respected, particularly in zones Z_1, Z_2 and Z_3. It therefore follows that these design parameters are not well selected for the investigated system.

3.3 Simulation results

The monitoring results show that the $C_{z,i}$ is widely exceeded in the critical zones. The principal question is then whether it is possible to adjust the CO_2 concentration of supply air Cs to meet the $C_{ret,mon}$ 1000 ppm set point? To answer this question, the following methodology for each monitoring instant is applied:

- Calculation of $C_{S,mon}$ for the operation during monitoring by equation 2 with V_{ps}, $C_{ret,mon}$, and $\%OA_{mon}$ from monitoring;
- Calculation of $C_{z,i,sim}$ of each zone by equation 1 using $C_{s,mon}$ determined before and $V_{dz,i}$ and $P_{z,i}$ from monitoring. This is presented in the Figure 5;
- Determination of the set point of $C_{z,i}$ for the zones. This could be the maximal value of $C_{z,i,sim}$ obtained in the preceding step but, as indicated in Figure 6, it mostly exceeds 1000 ppm, and the $C_{z,i}$ set point is taken as 1000 ppm and as 1400 ppm, which is the maximal value of $C_{z,i,design}$ in Table 2;
- Calculation of $C_{s,min,1000}$ and $C_{s,min,1400}$ i.e., the minimum values required to meet the $C_{z,i}$ set points for the zones (1000 and 1400 ppm) determined in the previous step;
- Calculation of the new adjusted System Outdoor Air Fractions $\%OA_{sim}$ in each instant (t) by equation 2 using $C_{s,min,1000}$ or $C_{s,min,1400}$ and $C_{ret,1000}$ and $C_{ret,1400}$ equal to 1000 and 1400 ppm, respectively. The $C_{ret,mon}$ from monitoring is also used for this calculation, and three curves of $\%OA_{sim}$ ($\%OA_{sim,1000}$, $\%OA_{sim,1400}$, $\%OA_{sim,mon}$) are presented in Figure 6.

$$C_{S,min}(t) = C_{z,i,setpoint}(t) - \frac{4900 \cdot P_{z,i}(t)}{V_{dz,i}(t)} \quad (4)$$

The results obtained by applying this methodology are presented in the Figures 5 and 6 for zone Z_5 and the VAV-F system respectively. The following remarks may be made:

- $C_{z,5}$ exceeds 1000 or 1400 ppm even if $\%OA_{sim}$ is 100%, but we see that $\%OA_{sim}$ is also 100% even if the $C_{z,5}$ is lower than 1000 or 1400 ppm. This happens for two reasons:

- ○ The $C_{oa,s}$ is considered and limited to 450 ppm;
- ○ The $\%OA_{sim}$ equal to 100% is required by other zones that Z_5 presented in Figure 5;

- Taking into account the $C_{ret,mon}$, as shown in Figure 6, the $\%OA_{sim}$ equals to 100% is also required by $C_{s,sim}$ determined using $C_{ret,mon}$.

The question now is why the application of SACO2-DCV is not sufficient to respect the CO_2 concentration $C_{dz,i}$ in the critical zones. One reasons for this is that the $V_{dz,i}$, which is controlled by the control loop, depends only on the zone temperature $T_{z,i}$ and, on the other hand, the design (maximum) supply zone air flowrate $V_{dz,i,design}$ is determined only as a function of the zone load. To meet the $C_{z,i}$ set point with the existing cooling charge in the critical zones when the %OA is already at 100%, the $V_{dz,i}$ should be increased. To that end the T_s (the system supply air temperature) must also be increased, but, depending on the cooling or heating demand, this can lead to overheating or overcooling of other zones. In the case of VAV systems with diversified zone occupancy density, the design and the operation control of these systems must be optimized.

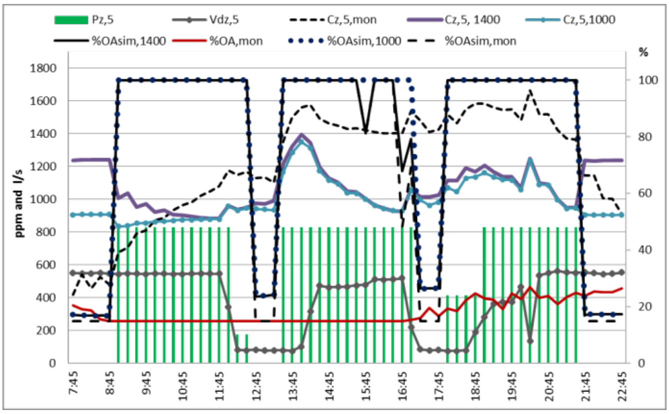

Fig. 5. Zone Z5 simulation and monitoring results recorded on February 12, 2015.

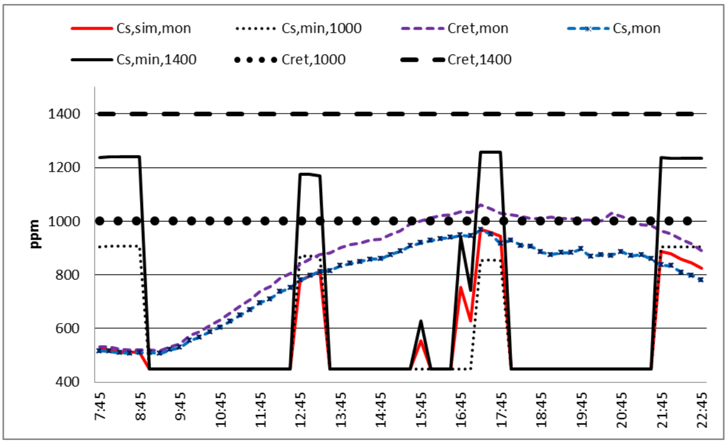

Fig. 6. System supply CO_2 (C_s) simulation and monitoring results recorded on February 12, 2015.

3 Conclusion

When the VAV systems are operating at partial load, the outdoor air flow rate supplied to the zones could be too low and result in poor air quality.

The results obtained when monitoring a VAV system with a highly diversified zone occupancy density show that the CO_2 concentration can exceed the set point in critical rooms. One reasons for this is that the $V_{dz,i}$, which is controlled by the control loop, depends only on the zone temperature $T_{z,i}$ and, on the other hand, the design (maximum) supply zone air flowrate $V_{dz,design}$ is determined only as a function of the zone load.

It is sometimes impossible to adjust the operation of such a VAV system because the adjusted System Outdoor Air Fractions % OA could reach 100% even if the zone CO_2 is not respected, as can be seen in this article.

The monitoring and simulation results presented were obtained in the winter during the operation of the VAV system at partial load, and with the minimum %OA outdoor air flowrate required by the economizer system. As shown in the article to respect the zone set point CO_2 concentration in such a period, this VAV system must operate mostly at an %OA equal to 100% instead of minimum. It would seem that to avoid such operations when the VAV system must meet the loads of zones with diversified occupancy densities, the design supply zone air flow rate should be determined while taking into account the CO_2 concentration resulting from the critical zones occupancy density.

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