

# AIR CONDITIONING AND REFRIGERATION Journal

The magazine of the Indian Society of Heating, Refrigerating and Air Conditioning Engineers

Issue : October-December 1999

## Indoor Air Quantity Control Of VAV Air Handling Units - Part 4.



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Previous articles addressed the design issues with a VAV system, the control of the VAV AHU and control of the VAV box. This article the last in the series, addresses an issue of increasing concern in India - Indoor Air Quality Control.

Variable air volume systems have become the air conditioning system of choice for office environments throughout Southeast Asia because they are energy efficient and allow zone control of temperature. To date, little attention has been paid to the issue of indoor air quality control with VAV AHUs. The issue of indoor air quality is gaining increasing attention in Southeast Asia and Singapore has already issued indoor air quality guidelines.

ASHRAE has done considerable research into indoor air quality and published a standard (ASHRAE Standard 62 - 1989, Ventilation for Acceptable Indoor Air Quality). One of the key; parameters contained in the ASHRAE standard is the amount of fresh air

required per person for various types of building environments. For an office environment, the minimum amount of fresh air is specified to be 20 CFM per person.

Designs of air conditioning systems in Southeast Asia generally follow ASHRAE standards. In Southeast Asia, it is not common to modulate the outdoor air dampers. If a designer wishes to meet the ASHRAE Standard 62 with a VAV AHU using fixed fresh air dampers, it will be necessary to size the fresh air inlet to allow the required CFM of fresh air per person at minimum fan speed. When the fan is running above the minimum speed the amount of fresh air being introduced will be more than the specified requirement. Cooling this additional fresh air wastes energy.

This article shows a cost-effective way to measure the amount of fresh air being introduced and a way to modulate fresh air dampers to ensure that the required amount of fresh air is being introduced, even at part loads on the VAV AHU. In other words, the approach described in this paper will ensure compliance with the ASHRAE Standard 62 ventilation rates while using the minimum possible energy.

The key to this approach is the calculation of the percentage of fresh air in the supply air stream (%FA). The %FA can then be multiplied by the measured airflow through a VAV box to calculate the amount of fresh air being delivered to a zone. The amount of fresh air being delivered by the AHU can be calculated by totaling the airflow from all of the VAV boxes and then multiplying this total by %FA. In North America, an air flow monitoring station is often installed in the supply air to read the total airflow for the AHU directly, but this is not done in Southeast Asia.

## Calculating the percentage of Fresh Air in Supply Air.

The supply air is a mixture of fresh air and return air. If we assume that all of the airstreams have a measurable property, X, then the percentage of fresh air in the supply air is as follows:

$$\%FA = \frac{X_{RA} - X_{SA}}{X_{RA} - X_{FA}}$$

Where:

$X_{RA}$  = Measured value for return airstream

$X_{SA}$  = Measured value for supply airstream

$X_{FA}$  = Measured value for fresh airstream

## Using Temperature

The most obvious and least costly airstream measurement is temperature. Using temperatures to calculate the percentages of fresh air is called the "energy balance method". In this case a mixed air sensor would have to be used rather than a supply air sensor. Unfortunately, the energy balance method does not give accurate results for the following reasons:

- Stratification of airstreams makes it difficult to get an accurate temperature reading. This is particularly true for the mixed air where an averaging sensor must be used. This means that the measurement error for each value can be significant
- Placement of the mixed air sensor (not provided with AHUs in Southeast Asia) is critical. The sensor must be mounted such that the reading is not affected by the radiant cooling from the coil. Radiant cooling from the cooling coil introduces error into the mixed air temperature sensor reading.
- In a tropical climate such as Southeast Asia, the temperature difference between the return airstream and the mixed airstream is quite small. Similarly the temperature difference between the return airstream and the fresh return airstream is also quite small.

To illustrate the problem considers nominal values for the various temperatures with reasonable measurement errors:

$$X_{RA} = \text{Return air temperature} = 28^{\circ}\text{C} \pm 0.2^{\circ}\text{C}$$

$$X_{SA} = \text{Mixed air temperature} = 28^{\circ}\text{C} \pm 1^{\circ}\text{C}$$

$$X_{FA} = \text{Fresh air temperature} = 32^{\circ}\text{C} \pm 0.2^{\circ}\text{C}$$

Using the nominal values, we calculate %FA as follows using Equation 1:

$$\%FA = \frac{X_{RA} - X_{SA}}{X_{RA} - X_{FA}} = \frac{28 - 28.8}{28 - 32} = 20\%$$

Consider the numerator of the equation ( $X_{RA} - X_{SA}$ ). It has a nominal value of  $0.8^{\circ}\text{C}$ , but the error in this value<sup>1</sup>,  $\pm 1.02^{\circ}\text{C}$ , is even greater than the nominal value. With the error in the numerator greater than the nominal value, it is obvious that temperature readings cannot provide an accurate result for the calculated percentage of fresh air in the supply air.

### Using Carbon Dioxide (CO<sub>2</sub>)

Using CO<sub>2</sub> to calculate the percentages of fresh air has a number of advantages:

- Because CO<sub>2</sub> is a gas and mixes completely with the airstream, the location of sensors is not critical and there is no issue of stratification
- The CO<sub>2</sub> sensor in the supply air does not have to be mounted in the limited space before the cooling coil; the CO<sub>2</sub> sensor can be mounted in the supply air duct after the coil and fan. The coil and fan do not affect the CO<sub>2</sub> reading.

Using CO<sub>2</sub> to measure the percentages of fresh air is called the "mass balance method". CO<sub>2</sub> is a naturally occurring gas and is generated by people in the space as they breathe. Fresh air has a CO<sub>2</sub> concentration of 350 ppm to 420 ppm. A typical indoor office environment will have a CO<sub>2</sub> concentration of 500 ppm to 800 ppm, and an office with poor ventilation may have a CO<sub>2</sub> concentration of up to 1200 ppm.

On first inspection, it appears as though the mass balance method will also not be able to provide accurate results. This is because even good quality commercial grade CO<sub>2</sub> sensors have an accuracy of  $\pm 100$  ppm. Substituting nominal CO<sub>2</sub> values into equation 1 shows:

$$\%FA = \frac{X_{RA} - X_{SA}}{X_{RA} - X_{FA}} = \frac{700 - 640}{700 - 400} = 20\%$$

Where:

$X_{RA}$  = Return air CO<sub>2</sub> concentration = 700 ppm  $\pm$  100 ppm

$X_{SA}$  = Supply air CO<sub>2</sub> concentration = 640 ppm  $\pm$  100 ppm

$X_{FA}$  = Fresh air CO<sub>2</sub> concentration = 400 ppm  $\pm$  100 ppm.

As with the energy balance method the mass balance method has an error in the numerator ( $\pm 141$  ppm) that is greater than the nominal value (60 ppm)

<sup>1</sup> The error is calculated as  $[(1)^2 + (0.2)^2]^{1/2}$

## CO<sub>2</sub> Sensing Technology

With the energy balance method, much of the measurement error comes from the location of the sensors. With the mass balance method, the sensor location is not critical as the error comes from the CO<sub>2</sub> sensing technology.

Two common CO<sub>2</sub> sensing technologies are "non-dispersive infrared" and "photoacoustic". Non-dispersive infrared technology is preferred over photoacoustic for two reasons:

- Photoacoustic sensors have increased error at low humidities (i.e. less than 25% RH). This is not an issue for Southeast Asia

- Photoacoustic sensors generate a relatively "noisy" output signal

Both non-dispersive infrared and photoacoustic CO<sub>2</sub> sensor technologies are subject to drift ( $\pm 100$  ppm / year) and inaccuracy ( $\pm 100$  ppm). Both types of sensing technologies require annual calibration to maintain accuracy.

Field experience has shown that the signal from a CO<sub>2</sub> sensor should be smoothed using a first order differential filter algorithm before being used as part of control algorithms. Filtering uses the following formula to eliminate spikes:

$$\text{Value}_{\text{Filtered}} = \text{Value}_{\text{Previous}} + \frac{\text{Value}_{\text{Current}} - \text{Value}_{\text{Previous}}}{10} \quad (\text{Equation 2})$$

### Using Multipoint CO<sub>2</sub> Sensing

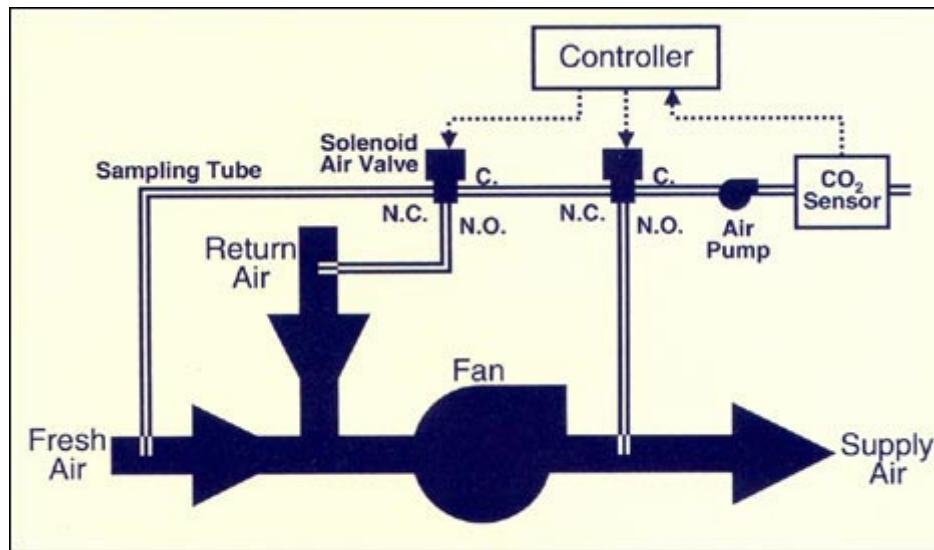


Figure 1 - Multipoint Co<sub>2</sub> Sensing

**Figure 1** shows how a single sensor can be used to collect air samples from multiple locations. The two solenoid air valves are controlled to select which of the airstreams (fresh air, return air or supply air) is drawn across a single CO<sub>2</sub> sensor. **Figure 2** shows how the controller activates the solenoid air valves and when the CO<sub>2</sub> reading is sampled. Test results have shown a sampling time of five seconds on a one-minute interval to be effective. The limitations of CO<sub>2</sub> sensing technology in calculating the percentage of fresh air can be overcome using a multipoint approach. The calculation of the percentage of fresh air depends on the difference between CO<sub>2</sub> readings rather than the raw CO<sub>2</sub> reading itself. By using a single sensor to measure all CO<sub>2</sub> readings, the inherent inaccuracy of the sensor is "cancelled" when the difference reading is taken. As mentioned above, the error in the numerator of Equation 1 when using two independent CO<sub>2</sub> level is about 141 ppm. This is an unacceptable degree of error when the nominal value is 60 ppm. Experiments have shown that the multipoint sensing approach has an error in the numerator of Equation 1 of less than  $\pm 5$  ppm, which is quite acceptable if the nominal value is 60 ppm.

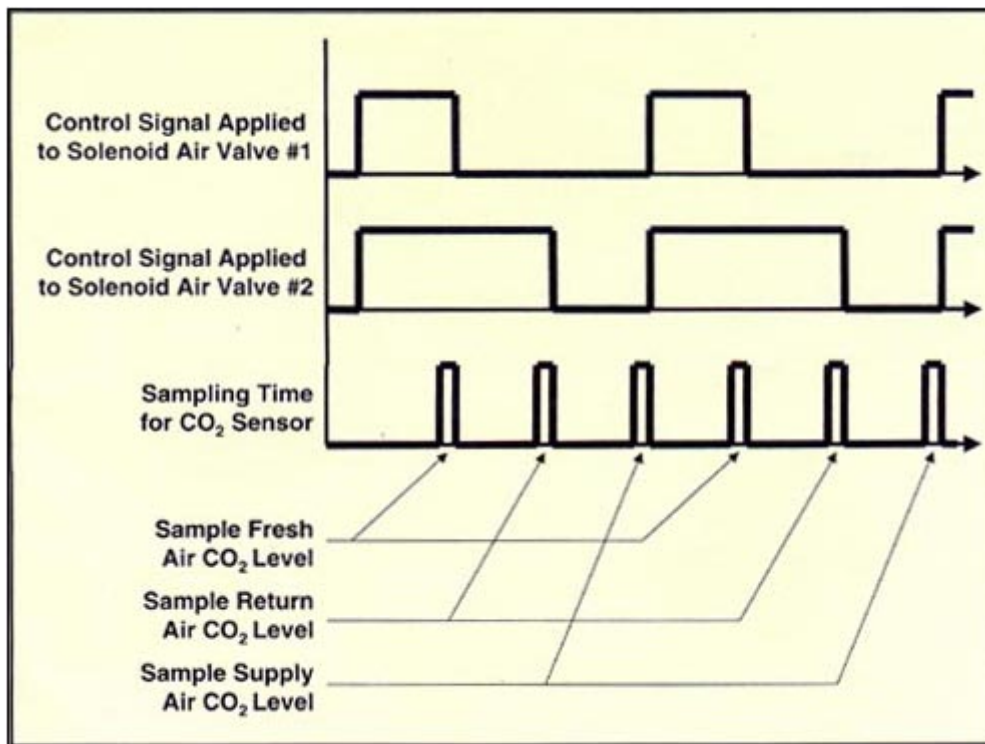


Figure 2 - Control Logic for CO Multipoint Sampling

It is important to note that the reading of any one CO<sub>2</sub> value (Fresh Air CO<sub>2</sub>, Return Air CO<sub>2</sub> or Supply Air CO<sub>2</sub>) will still have an error of  $\pm 100$  ppm when using the multipoint approach. The advantage of the multipoint approach is that the error in differences in CO<sub>2</sub> levels between airstreams become small. For example, if the CO<sub>2</sub> sensor is reading high by 50 ppm because of the limitations of the sensing technology, the error between two readings taken with the same sensor is not affected.

The error of  $\pm 5$  ppm is quite acceptable when the nominal value is 60 ppm, but becomes excessive when nominal value for the numerator of Equation 1 drops below 30 ppm. The numerator of Equation 1 will reduce when the CO<sub>2</sub> level in the Return Air is only a little bit higher than the CO<sub>2</sub> level in the Supply Air. This would only occur during very low occupancy in the space. Indoor air quality is typically not a problem under these conditions and can best be assured by establishing a minimum fresh air damper position.

We have not discussed the denominator of Equation 1 because the error in the denominator will be the same as in the numerator but the nominal value will always be higher than the numerator.

## CO<sub>2</sub> and Indoor Air Quality

So far, this article has described the use of CO<sub>2</sub> as part of mass balance approach to calculate the percentages of fresh air in the supply air stream (%FA). When using the mass

balance approach, CO<sub>2</sub> is used as a "tracer gas" and it is the differences in CO<sub>2</sub> level between airstreams that is important rather than the absolute value of the CO<sub>2</sub> level.

In ASHRAE Standard 62 - 1989, the absolute value of CO<sub>2</sub> level is an important parameter for demand controlled ventilation and for ventilation alarms. An important benefit of the multipoint CO<sub>2</sub> sensing approach is that the same sensor can be used for ventilation measurement and control (using mass balance approach), demand controlled ventilation (using Return Air CO<sub>2</sub> value) and ventilation alarms (using Return Air CO<sub>2</sub> value).

Outdoor air CO<sub>2</sub> levels range upwards from 350 ppm and are produced by natural processes such as combustion CO<sub>2</sub> in the indoor air is generated by human respiration. Other sources of CO<sub>2</sub> such as cigarette smoke are typically negligible in an office environment. The CO<sub>2</sub> generation rate is a function of diet and levels of activity. A typical person generates 0.0106 CFM of CO<sub>2</sub>. People emit a large variety of bioeffluents from sweat, respiration, etc. These bioeffluents are a major factor influencing Indoor Air Quality, but their concentration cannot be cost effectively measured. The indoor air CO<sub>2</sub> concentration is the best indicator of occupancy and the corresponding bioeffluent level. Many experiments have been performed to establish the relationship between bodily emissions, CO<sub>2</sub> level and occupant comfort and these experiments show that a 20% dissatisfaction criteria corresponds to a CO<sub>2</sub> level of 1000 ppm. In other words, when the CO<sub>2</sub> level is above 1000 ppm, 20% of the people will find the air quality unacceptable; this is not because of the CO<sub>2</sub> (CO<sub>2</sub> levels below 5000 ppm are do not affect people), but rather because of the level of bioeffluents and other pollutants.

The following equation can be used to determine the amount of fresh air per person to maintain the CO<sub>2</sub> level below 1000 ppm when the outdoor air CO<sub>2</sub> level is 350 ppm:

$$V_o = \frac{N}{C_{SP} - C_{FA}} \quad \text{Equation 3}$$

$$= \frac{0.0106}{0.001 - 0.00035} = 16.3 \text{ CFM}$$

Where:

V<sub>o</sub> = Fresh air flow rate per person

N = CO<sub>2</sub> generation rate per person = 0.0106 CFM

C<sub>SP</sub> = Space CO<sub>2</sub> concentration = 1000 ppm

C<sub>FA</sub> = Fresh air CO<sub>2</sub> concentration = 350 ppm

In this example, the CO<sub>2</sub> concentration in occupied space will not exceed 1000 ppm as long as 16.3 CFM per person of outdoor air (with CO<sub>2</sub> concentration of 350 ppm) is continuously being added to the space to dilute the CO<sub>2</sub> generated by people's respiration.

More importantly, the outdoor air dilutes the other air pollutants so that an acceptable indoor air quality is maintained. This calculation illustrates the approach taken by the ASHRAE Standard 62 - 1989 in determining the outdoor air flow requirements for ventilation. The ASHRAE Standard requires fresh air flow rates of 20 CFM (i.e. higher than 16.3 CFM) for the following reasons:

- If the fresh air CO<sub>2</sub> level is higher than 350 ppm, more fresh air is required (if a fresh air CO<sub>2</sub> concentration of 420 ppm is put into Equation 3, the CFM increases to 18.3)
- The return air CO<sub>2</sub> represents an average level and individual zones may be higher
- There may be other air pollutants in the space in addition to those generated by people
- 1000 ppm is the high limit and CO<sub>2</sub> concentrations should be kept below this value.

### Fresh Air Damper Control Strategy

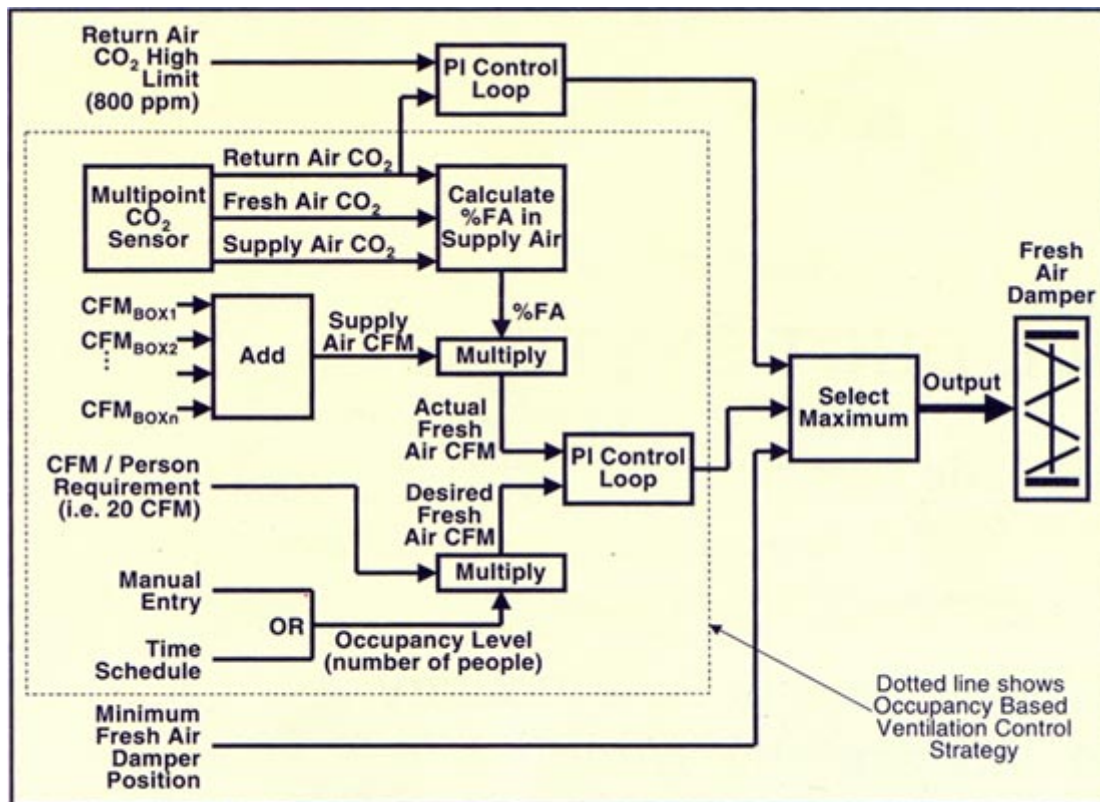


Figure 3 – Control Strategy for Fresh Air Damper Control

As shown in **Figure 3**, the output signal to the fresh air damper is the maximum of three values:

### Fresh Air Damper Control Strategy

- A control signal to achieve a return air CO<sub>2</sub> level of 800 ppm. This is called a demand strategy (DCVCS).

- A control signal to achieve the required fresh air CFM based on occupancy level. This is called occupancy based ventilation control strategy (OBVCS).
- A minimum damper position.

Because there is some interdependence between the three inputs, the "Select Maximum" function should add a time delay before switching. In other words, an input must be the maximum of the three for a duration of time before the input takes control of the Fresh Air Damper.

In addition to the control strategy shown in **Figure 3**, alarm limits should be placed on the Return Air CO<sub>2</sub> level. A Return Air CO<sub>2</sub> level in excess of 1000 ppm may indicate failure with the fresh air damper actuator or out-of-control conditions. A Return Air CO<sub>2</sub> level of less than 300 ppm indicates a faulty CO<sub>2</sub> sensor.

### **Demand Controlled Ventilation Control Strategy (DCVCS)**

The ASHRAE Standard requires an occupancy based ventilation control strategy (OBVCS). However, a demand controlled ventilation control strategy (DCVCS) can be used to supplement the OBVCS to save energy.

A typical office has fixed hours with minimal occupancy outside of those hours. The air conditioning system is operated for an extended period before and after typical occupancy to accommodate workers who come in early or leave late. For example, an office may be in operation from 09.00-17.00 while the air conditioning system operates from 08.00 - 18.30. Introducing extra fresh air ventilation between 08.00 - 09.00 and 17.00 - 18.30 will waste energy. During this period, the DCVCS can be used to provides the minimal level of fresh air ventilation based on the actual requirements at that time. If DCVCS is not used, the OBVCS must assume an occupancy level. Since this assumption must be based on worst-case conditions, energy will be wasted.

The DCVCS can provide additional energy savings during the day. If the DCVCS is not used, the OBVCS must assume a worst case occupancy level. If the DCVCS is used, the OBVCS can assume a typical occupancy level and rely on the DCVCS to provide and rely on the DCVCS to provide extra ventilation during periods of extraordinary occupancy.

Implementing the DCVCS does not require any additional hardware if an OBVCS is implemented. The actual return air CO<sub>2</sub> level can be read from the multipoint CO<sub>2</sub> sensor. If a DCVCS is used, the maintenance and calibration of the multipoint CO<sub>2</sub> sensor becomes an important issue. The DCVCS also requires the fixing of a high level setpoint for CO<sub>2</sub> level. Because the Return Air CO<sub>2</sub> represents an average of zone conditions, it is recommended that a setpoint of 800 ppm be used to ensure that the CO<sub>2</sub> level in any one

zone does not exceed 1000 ppm. If there are critical zones for which an additional CO<sub>2</sub> sensor is cost-justified, a room mounted sensor can be used and the DCVCS can be controlled based on the maximum of Return Air CO<sub>2</sub> and the room mounted CO<sub>2</sub> level.

### Occupancy Based Ventilation Control Strategy (OBVCS)

The ASHRAE Standard 62 - 1989 requires an occupancy based ventilation control strategy (OBVCS) as a "Ventilation Measurement and Control" procedure. The dotted lines in **Figure 1** shows the extent of the OBVCS. The OBVCS compares a desired Fresh Air CFM (setpoint) with the actual Fresh Air CFM (controlled variable) and calculates an adjustment to the fresh air damper. The Desired Fresh Air CFM is calculated by multiplying the CFM / person Requirement by the occupancy level. The CFM / person Requirement is typically a constant such as 20, based on the usage of the space (20 is the value prescribed by ASHRAE for office areas). The occupancy level can be manually entered or automatically changed based on a time schedule.

The Actual Fresh Air CFM is calculated by multiplying the %FA by the Supply Air CFM. The %FA is calculated using inputs from the Multipoint CO<sub>2</sub> sensor using **Equation 1**. The Supply Air CFM can be calculated by summing the individual CFM readings from each of the VAV boxes. In North America, an air flow monitoring station is often installed to read the Supply Air CFM for the AHU directly, but this is not done in Southeast Asia.

### Occupancy Based Ventilation Control Strategy on a Zone Basis

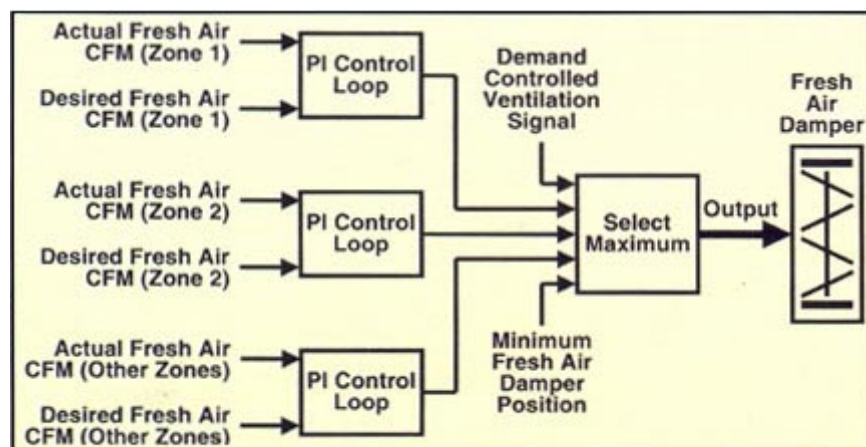


Figure 4 - Occupancy Based Ventilation Strategy on a Zone Basis

**Figure 4** shows how an OBVCS can be applied for specific zones. The "Select Maximum" function that decides the command to be sent to the Fresh Air Damper has more inputs. The Actual Fresh Air CFM for a specific zone is calculated by multiplying the actual CFM for the VAV box times %FA. The Desired Fresh Air CFM for a specific zone calculated by multiplying the CFM / Person Requirement (i.e. 20) times the occupancy level. As with the

more general OBVCS, the occupancy level may be fixed by a manual entry or a time schedule. An OBVCS on a zone basis ensures that critical zones have sufficient ventilation but adds to the number of variables (occupancy level for each zone) that must be managed

*Much of the material on this paper was extracted from a Project Report prepared by George J. Janu of Johnson Controls, Milwaukee Wisconsin Johnson Controls has patented the multipoint CO<sub>2</sub> mass balance method of calculating the percentage of fresh air in the supply air stream.*