Reduction of Errors in Ventilation Rate Determinations

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ABSTRACT

Reduction of energy usage in mechanically ventilated buildings, without violating minimum dilution and pressurization requirements, demands greater outdoor air control precision. Precision can be improved by avoidance of unwanted and unnecessary uncertainties from multiple design or operating assumptions. Indirect methods of outdoor air rate determination with multiple uncertainties propagate control errors. An undiscovered total uncertainty in control may prevent the satisfaction of minimum ventilation requirements, energy constraints and the concurrent requirements of ASHRAE Standards 62.1, 90.1 and 189.1. Direct methods of outdoor air intake rate and space population determination can minimize control uncertainties and improve air system repeatability for improved comfort and energy control. Design considerations and appropriate component selections provide the keys to a successful application of direct methods.

INTRODUCTION

The mandatory requirements for the dilution of recirculated air with outdoor air for acceptable IAQ are well documented. ASHRAE Standard 62.1-2007 (and pending 2010 version) addresses dilution airflow rates and is the current U.S. ventilation standard. This standard is also a prerequisite for compliance with Standards 90.1-2007 (Energy Standard for Buildings) and 189.1-2009 (Standard for the Design of High-Performance Green Buildings).

Standards compliance requires designs to “walk-the-walk.” This realization can make a big difference in design decisions. However, few acknowledge the operational impacts dictated by strict interpretation, mandatory language, minimum requirements and support from interdependent standards. ASHRAE Standard 62.1-2007 §8.1.2 clearly states: “The ventilation system shall be operated ... in accordance with the provisions of this standard. ” On the same issue, the *62.1 User’s Manual* states that any ventilation design function, capacity or “capability [shall] be maintained and used.” (ASHRAE 2007, 2008)

Ventilation codes typically require that mechanical systems “maintain” rates “not less than” the minimums prescribed (IMC 2006 §403.0). This is a ‘hard’ floor of -0% of reading. There is no negative tolerance allowed for compliance forcing many designers to include safety factors, hedge equipment selections or allow sloppy control sequences, negatively impacting operating costs and efficiency.

Current ASHRAE building energy initiatives together with increasingly more energy efficient designs have resulted in tighter buildings having minimal leakage and little natural dilution with outdoor air. Without a reliable method of control, neither of the concurrent requirements for indoor environmental quality and energy efficiency can be optimized.

Although the most direct solution would appear to be measurement at the air handling unit (AHU) intake, a number of alternative methods are used for intake rate determination or control in building designs and require manual validation by test and balance (TAB) contractors. However, the methods allowed in ASHRAE Standard 111 and all national TAB association guidelines (TABB, AABC and NEBB) provides alternatives to direct measurement at the intake.

This paper will review indirect techniques. Most of these depend on predetermined (fixed) damper positions and contrast their potential performance with direct measurement used for outdoor air control, revealing the more obvious sources of uncertainties.

COMMON METHODS OF OUTDOOR AIR DETERMINATION OR CONTROL

In many cases, outdoor airflow rates can be directly measured by the TAB contractor. Duct and system configurations that cannot be measured directly are estimated by calculation or by measuring related variables allowed in TAB guidelines. The result is typically reported by the TAB contractor as 'actual' flow without indicating how it was determined or the amount of uncertainty in the measurement.

Some common indirect methods for determining or controlling intake flow rates are listed below. Most require set-up and adjustment of the intake damper's 'minimum' position by TAB or controls contractors.

- Fixed Position Minimum Outdoor Air Intake Damper
- Mixed Air Plenum Pressure Control (using intake or recirculation damper positions)
- Temperature and CO_2 Mass Balance Methods
- Volumetric Tracking (Supply Air-Minus-Return Air Calculation, no AHU Relief)
- Demand Controlled Ventilation (with and without CO_2 inputs)

One alternative to these is the direct measurement of outdoor airflow rates with active control. All of these methods will be discussed in the following sections of this paper.

FIXED POSITION MINIMUM OUTDOOR AIR INTAKE DAMPER SYSTEMS

The majority of commercial HVAC systems utilize fixed position minimum outdoor air (MOA) intake dampers for control. Even when systems are set up properly, a fixed damper's blade position cannot result in efficiently sustained or consistent intake airflow rates.

Assuming that the intake flow rates can be measured accurately by the TAB contractor, a number of other factors influence fixed position damper systems. These factors affect both Constant Air Volume (CAV) and Variable Air Volume (VAV) designs. Without active control, outdoor airflow rates cannot be provided reliably over time (Solberg, Curtiss, Mumma). The total uncertainty of the field reference measurement adds to potential control errors during operation, but that discussion is outside the scope of this paper.

To understand intake systems, we must consider the factors which influence them. If the system is a VAV design, changes in mixed air (MA) plenum pressure result from changes in the supply airflow rate. Since this pressure change is across a fixed orifice (damper), the resulting intake airflow will also change. Since the intake flow rate is not directly related to mechanical load, the intake set point error will follow the supply fan linearly as it turns down during normal VAV operation.

A second factor that affects both CAV and VAV designs are the external winds acting on the intake system. The influence of wind pressures on intake systems that are set up and operated under differing conditions was modelled in a paper published twenty years ago. (Solberg)

A third factor is stack effect. Seasonal changes in outdoor air density impact all high-rise buildings, even those as low as 3-4 stories. Intake pressures change due to changes in outdoor air temperatures. Intake flow rates will change, if the intake system does not provide the means to accommodate changes in mixed air plenum pressure.

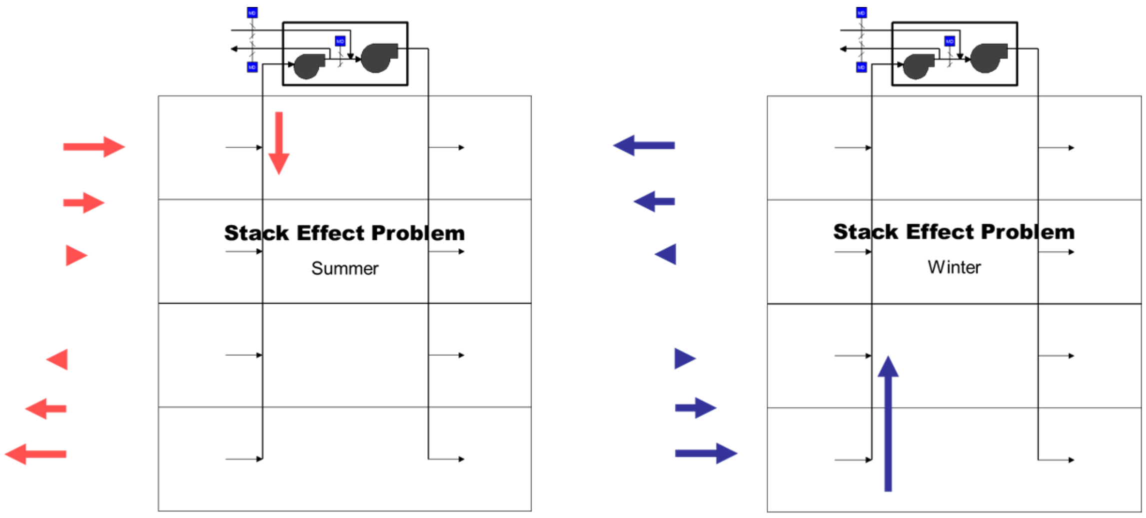

Figure 1a/1b – Temperature Induced 'Stack' Effect (summer/winter) (Dougan 2006)

The building would have serious intake flow variations that, in this case, would result in a shortage of outdoor air and possibly a negative building pressure condition. Should the setup and operating conditions be reversed, too much outdoor air would be brought into the system. If it becomes cold enough, the system would be in a serious freeze alarm situation.

If the wind and stack effects are cumulative, the control errors can become sufficiently severe to force air to exit through the intake system. These unintentional variations are not uncommon and are not restricted to VAV systems.

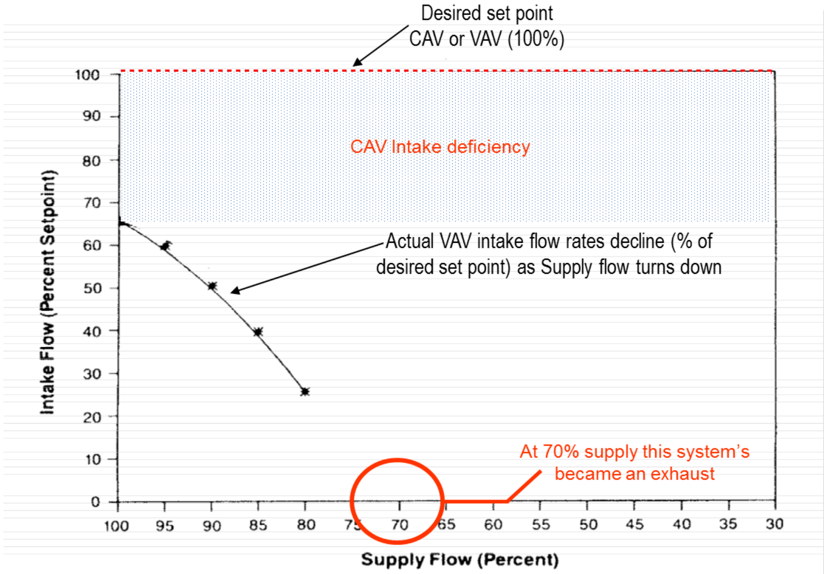

Figure 1c – Combined Wind & Stack Effect on Fixed Damper Systems

Analysis of an intake system with a set point velocity of 400 ft/min (2.03 m/s). Errors are amplified and in this case, the intake system was acting as an exhaust when the system was delivering less than 70% of the Supply fan's capacity. (Solberg, Dougan, Damiano 1990)

These examples illustrate control deficiencies, but just as easily could have illustrated the unnecessary conditioning of excessive outdoor air. Recognition of this potential led to the cautionary note on VAV systems in Standard 62.1 (§5.4). Periodic manual adjustments to CAV systems can not compensate for the seasonal, daily and even hourly changes in environmental conditions or changes to internal loads needed to assure adequate IAQ and long term efficiency for minimum energy usage.

MIXED AIR PLENUM PRESSURE CONTROL

By placing a pressure sensor in the mixed air plenum, some designs attempt to maintain a fixed MA plenum pressure through the modulation of the recirculation or outdoor air damper. This would allow the intake rate to remain constant.

Mixed air plenum pressure control can be done – as it has been shown in theory or with the right circumstances. (Graves, Elovitz, Krarti) However, in practice there are numerous factors that adversely affect the risk associated with this method of control. The first is damper controllability. Factors such as blade/jamb seal deterioration, blade linkage hysteresis, actuator hysteresis and wind pressure variations result in significant sources of control error. To maintain a constant pressure under dynamic conditions is very difficult. Most designs do not simultaneously measure intake rates directly and therefore have no continuous or long-term comparison available to adequately evaluate this alternative.

Applications research performed in 1998-99 included wind tunnel tests utilizing a full sized commercial intake louver and high quality airfoil damper in the set up. The tests were designed to determine if a minimum airflow rate could be maintained at various MA plenum pressure control levels. The test data illustrated a large range in airflow variation from linkage hysteresis (35% – 50%) when the pressure loss across the damper was maintained at a fixed value. (EBTRON TB 1999)

To validate these results, a full scale test utilizing a 10,000 CFM (4.7 L/s) air handler was fully instrumented to examine these same variables with automated test equipment. The reported variations in actual flow conditions were recorded during multiple test runs and displayed in figures 2a and 2b. The solid horizontal line indicates the airflow set point control objective, with relative flow variations indicated by the small ‘x’s. (Dougan 2008)

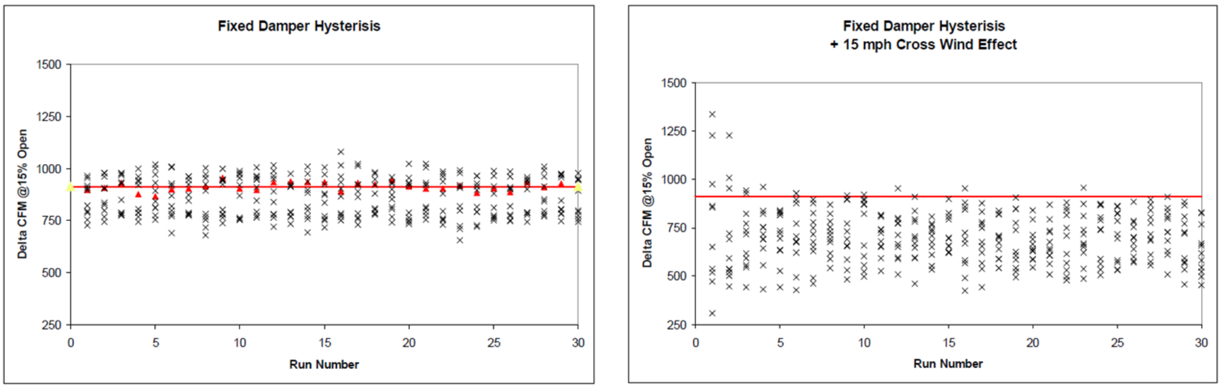

Figure 2a/2b – Full Scale Test Results Comparison, with and without Cross Wind

Real-Time, actual environmental conditions. Single flow set point. Full intake size damper.
Open/close, Return to set point, measure resultant flow. 30 runs and approx 10 samples per run. (Dougan 2008)

As with other methods of measurement, a single pressure sensor is highly unlikely to provide a reasonable average of pressure conditions, especially in a space where conditions are so dynamic. Averaging error alone can be offset to a limited degree by factoring the output based on field airflow measurements, but field references reflect conditions at one point in time and are only as good as the site conditions, the equipment used, the methodology and the practitioner's skill and experience. We can assume that field measurements and damper repeatability will be optimal, when we employ the method; but how probable is that assumption which is the key to the method? The test results referenced previously provide us with test data on only one source of uncertainty, but sufficient to demotivate additional testing at that time.

In addition to MA plenum pressure methods, any method of control that depends on predetermined damper positions to provide a specific airflow rate will suffer from these effects and significant control uncertainties.

TEMPERATURE AND (CO_2) MASS BALANCE METHODS

Other indirect methods have been used or considered for outdoor air control. Known by a number of names, including adiabatic mixing, proportional temperature or mass balance methods; it has been used by building controls and TAB contractors for many years.

By measuring the outside air, return air and averaged mixed air temperatures, the fraction of outside air in the mixed air can theoretically be determined. By multiplying the outdoor air percentage in the MA plenum by the supply airflow rate, the theoretical outdoor airflow rate can be calculated. The equation below illustrates the temperature balance equation (1) (Krarti, EBTRON 1999).

$$\%OA = [(T_{mix} - T_{ret})/(T_{oa} - T_{ret})] \times 100 \quad (1)$$

Where:
%OA = Proportion of Outdoor Air in Supply Air
T_{mix}= Average Mixed Air Temperature
T_{ret}= Average Return Air Temperature
T_{oa} = Average Outdoor Air Intake Temperature

Even if we assume that the temperature sensors have negligible errors, an error of the average temperature calculated will result due to insufficient sampling for the average (or averaging error). Figure 3 illustrates the uncertainty of a minimal 2 degree error in MA temperature determination. Accurate average temperatures are difficult to ascertain as a result of base sensor error, the large variability between flow patterns in the plenum and the temperatures of return air and the outdoor air.

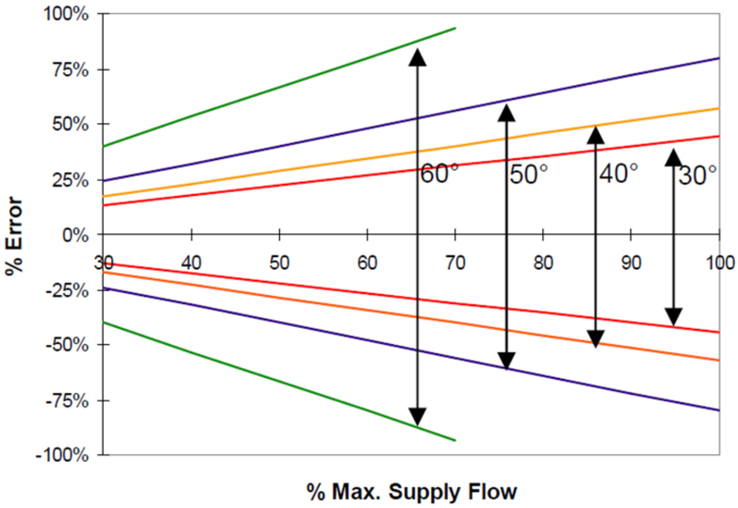

Figure 3 – Temperature Balance OA Control Errors

Mathematical model based on a 2 degree F error in mixed air temperature measurement only and no temperature or Supply airflow measurement error. Actual control errors could be much larger. (Dougan 2004)

ASHRAE research (RP-980) published in 1999 warned against using these methods for control due to the large uncertainties involved. By using a similar analysis, CO_2 mass balance techniques also have the potential for significant error especially as the outside air CO_2 level approaches the return air CO_2 level. Systems utilizing a single sensor to sample the outside air, return air and supply air CO_2 levels can improve the accuracy but still can result in significant intake flow rate uncertainties.

VOLUMETRIC DIFFERENTIAL BETWEEN SUPPLY AND RETURN AIRFLOW RATES (DELTA CFM)

Calculating outdoor airflow rates by using the volumetric difference between the supply and the return airflow rates (with no relief at the air handler) has been widely practiced as both a control strategy and TAB technique. Unfortunately, the differential airflow being calculated can be more than ten times smaller than the Supply and Return airflow averages or signals being measured. An unlikely maximum Supply/Return measurement error would be required (<±1% of reading) in most cases to equal an intake control accuracy of ±10% of reading.

As an example, consider the data in table 1. The measured airflow that would be reported by TAB or a DDC panel using this technique would indicate an outdoor airflow rate of 10,000 cfm (4.7 L/s), when the actual outdoor airflow rate would be 500 cfm (0.19 L/s). Regardless of the instrument used or its accuracy, the errors produced by this method are unacceptable for determination or control of outdoor air intake flow rates. (EBTRON 1999)

	MEASURED CFM	ACTUAL CFM
SUPPLY	100,000	95,000
RETURN	90,000	94,500
OA	10,000	500

Table 1 – Delta CFM Errors (no relief @ AHU)

This method has been practiced for decades to determine, set and validate intake flow rates. (EBTRON 1999)

DEMAND CONTROLLED VENTILATION: CO_2–BASED

Figure 4 illustrates typical pollution sources found in an office building used for a GSA study. (EBTRON 1999) Pollution sources are predominantly from the building and not from the occupants, who are the primary source of interior CO_2 but not the majority of the total contaminant load. (Linddament, et. al.) This revelation, in part, led to addendum 'n' for ASHRAE Standard 62-2001, which changed the structure of the 62.1 Ventilation Rate Procedure (VRP) and the rates in Table 6.

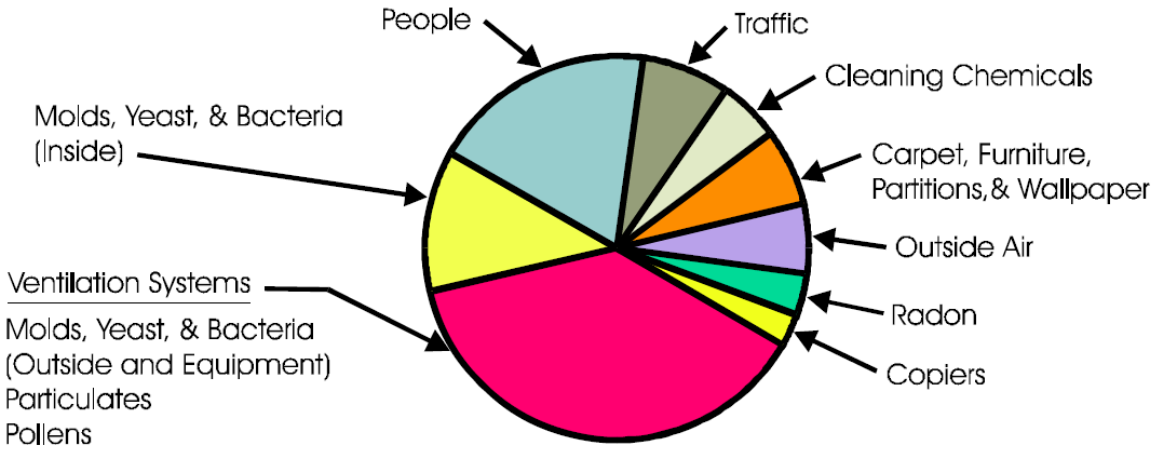

Figure 4 – Building Contaminant Emission Sources

Adjusting outdoor air ventilation rates to CO_2 levels alone cannot assure proper dilution rates for non-human sources of emissions; plus, has no relationship to pressurization requirements. (Linddament, EBTRON 1999)

According to the International Energy Agency, demand controlled ventilation should only be used if there is unpredictable occupant demand and all other sources of contaminants are known. (Mansson, et. al.) Furthermore, a base ventilation rate must be established to dilute the contaminants unrelated to changes in human occupancy and the CO_2 levels they influence. An example of the impact of these changes on the steady-state CO_2 differentials required to meet 62.1 minimum rates are shown in table 2.

Occupancy Change	Prior to 2004 (Office @ 20 CFM/pers)		Post 2004 (Office $V_{bz} = R_pP_z + R_aA_z$)		
# People	Total OA CFM	C_z-C_o Set point (Δ CO_2)	Total OA CFM	CFM/pers	C_z-C_o Set point (Δ CO_2)
7	140	548 ppm	95	13.5	811 ppm
5	100		85	17	644 ppm

Table 2 – Minimum Ventilation Requirements at Equivalent Steady-state Δ CO_2

As a result, there no longer is a single, fixed CO_2 control set point applicable to the ventilation rates prescribed by Standard 62.1 and associated codes, as population in the space changes. If single set point techniques were employed and designs included base ventilation rate control, the total rate provided would contain serious errors. CO_2–based DCV methods are generally designed to compensate for the worst-case condition expected, to avoid under ventilation and ensure code compliance. This practice increases the relative energy inefficiency of the method.

Many other factors affect CO_2–based DCV, such as: sensor precision, drift and the lag in control experienced by as much as 3 to 4 hours (Emmerich, Persily). Although control lag can be reduced with appropriate techniques, this makes its use in any type of short-meeting space less than optimal.

More recently, studies on CO_2 sensor accuracy and reliability confirmed many potential sources of error including sensitivities to changes in environmental conditions: temperature, barometric pressure and humidity. (NBCIP, Fisk)

Commercial CO_2 sensors' accuracy as used in HVAC is published to be generally around ±75 to 125 ppm. Standard 189.1 is seeking to require a CO_2 sensor minimum accuracy of ±50 ppm when CO_2-based DCV systems are used in high density spaces, presumably in recognition of the impact that CO_2 measurement error could have on ventilation set point control. (ASHRAE Std. 189.1-2009, §7.4.3.2b)

The relationship between the errors in measured or calculated CO_2 differentials and the errors they propagate in OA control are cumulative and often overlooked by engineers. A conservative minimum ±50 ppm CO_2 error can be anticipated for each of several variables required for a valid relationship to exist between CO_2 and intake rate/person, namely: sensor accuracy, OA CO_2 concentration variability, CO_2 generation rate variability, sensor density and placement (sampling error).

- Manufacturer's published sensor error alone translates to large OA control errors, e.g. each ±75 ppm uncertainty in CO_2 (±7.5% of reading @ 1000 ppm) can readily create -13% to +15% OA set point control error.

- A ±50 ppm error in OA CO_2 determination translates to an additional -7% to +11% OA (Vot) set point control uncertainty. (Dougan 2004)

- When the occupant average CO_2 generation rate is unknown or assumed in error, changes in activity from 'seated' (N=0.31) to 'light work' (N=0.50)can mean an 80% uncertainty in population determination. (Dougan 2009)

In a mathematical model constructed for a single classroom, the range of combined sources of OA control error in a CO_2-based system overwhelm the ability of one CO_2 set point to provide efficient control.

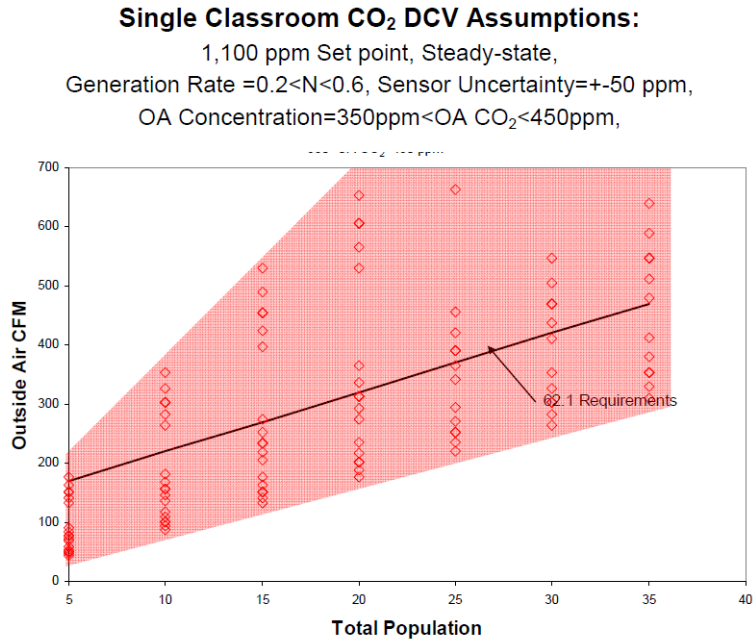

Figure 5 – CO_2 DCV Operational Uncertainty from Multiple Error Sources – Single Classroom Model

Model included errors from: sensor inaccuracy, OA concentration uncertainty, metabolic variation from that assumed as fixed. (Dougan 2006)

CO_2 methodology appears to persist in spite of the uncertainty in control, possibly because there is rarely a direct comparison to actual intake rates over time. CO_2-based ventilation control does not necessarily ensure compliance with the VRP in ASHRAE Standard 62.1 - only maintaining the prescribed minimum rates can do this. (ASHRAE 2007) CO_2 is not considered a 'contaminant of concern' or an indicator of overall IAQ by the standard and cannot be used by itself for compliance with the IAQ Procedure. Under strictly defined conditions, •CO_2 may at best indicate an airflow rate per person. (Emmerich, Persily) It is incapable of providing the required floor-area component of the ventilation rate without some significant design and operating assumptions.

Therefore, how can CO_2-based DCV reduce energy use? One can conclude that even with a high level of operating inaccuracy, •CO_2-based methods may contribute some savings, when compared to design maximum occupancy assumptions, by adjusting ventilation against large changes in space population, however imprecisely. The inherent tendency for •CO_2-based methods is to over ventilate, especially during periods of high space density, wasting energy. (Dougan 2004) The designer and owner must weigh the costs and performance issues against design alternatives.

DEMAND CONTROLLED VENTILATION: NON-CO_2 INPUTS

DCV is not defined by the use of CO_2. ASHRAE 62.1-2007 addendum 'g' defines DCV as "any means by which the breathing zone outdoor airflow (Vbz) can be varied to the occupied space or spaces based on the changing number of occupants and/or ventilation requirements of the occupied zone." That is consistent with the VRP in 62.1 which recognizes population (Pz) as a basic element needed for calculation Vbz= Rpx**Pz** + RaxAz. (6-1, ASRAE 2007) However, 62.1 addendum 'g' [§6.2.7(.1)] does not explicitly acknowledge 'space population' as the common denominator required for VRP compliance in all ventilation solutions, including dynamic reset. Reading the entire standard and not selective portions, leaves little room for interpretation or misunderstanding.

There are a number of non-CO_2 alternative inputs for DCV and techniques for intake rate control. They are valid methods of ventilation reset, and they possess the potential for greater precision, reliability, total savings and less maintenance than CO_2-based DCV systems.

- Reset the outdoor air set point when the critical zone is occupied based on design conditions, regardless of the actual population. If variance is not very often, unpredictable and situational, it may not be worth the risk of CO_2-only control. (Dougan 2004)

- Increase the critical zone supply flow (may require additional reheat) based on design conditions when occupied. (Mumma)

- Use Binary Occupancy sensors and/or time-of-day Schedules (on/off – design occupancy / minimum)

- Provide a dedicated outdoor air system (DOAS) for variable occupancy spaces based on design conditions when occupied.

- For multiple spaces, estimate the population in those spaces that are variable and reset the intake flow control set point using the measured or estimated variable space populations (plus the design occupancy of the fixed spaces). Multiply these totals by the minimum rate(s) required. (Dougan 2008)

- Reset the outdoor air set point based on estimated population, as dynamically calculated using differential CO_2 plus airflow rate inputs. When conceptually simplified, OA CFM/p = 10,951/(Cz-Co); Pz or persons = (OA CFM)/(OA CFM/person) for single zones (Ke, Mumma 2004, Dougan 2008)

- Directly count the population of the variable space, calculate the exact minimum requirements and adjust the space outdoor air and/or supply air to accommodate the requirement. (e.g. microprocessor-based thermal counters, video or any direct counting systems; security system entry/exit data, turnstiles, ticket sales, occupancy indicators like CRT or room lights 'on,' etc.)

DIRECT MEASUREMENT OF SPACE POPULATION (FOR VENTILATION RESET CONTROL)

Regardless of what device is used to measure space populations for ventilation reset control (DCV), a reliable fixed error rate is preferable and substantially more reliable than methods having multiple sources of error. (Dougan 2008)

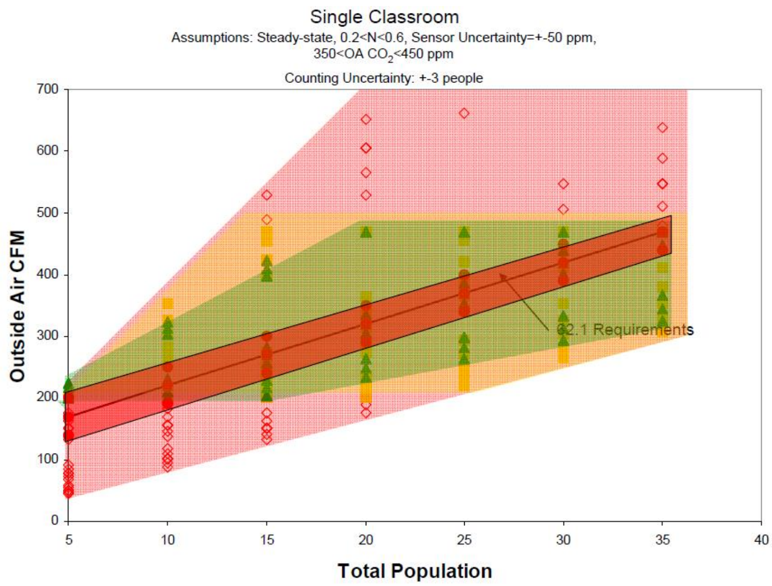

Figure 6 – Comparison of Dynamic Rest Methods
having Variable and Fixed Errors – Single Classroom Model (Dougan 2008)

In this comparative model, total error in ventilation control was compared to several methods with increasing measurement certainty. The same assumptions were used for all methods. •CO_2-based DCV provided the largest uncertainty in control for this classroom model (pink). Next, direct OA airflow measurement was added to cap the upper and lower CO_2 control limits (yellow), preventing under and over ventilation tendencies. Subsequently, direct Vot measurement provides the missing variable for population determination and was used to dynamically calculate space population, then reset the intake rate set point (green)(Mumma, Dougan 2008). The greatest confidence in control is achieved with a fixed error from the target set point (red) – 62.1 minimum requirements, varied by detected population. This last method combines direct population measurement with direct intake measurement.

DIRECT MEASUREMENT OF OUTDOOR AIRFLOW RATES

Another and likely the most efficient approach is to directly measure intake flow rates at the AHU and control to a fixed set point with a fixed margin of measurement error. There are several permanently mounted duct measurement technologies available to accomplish this. Each has its individual strengths and weaknesses. The oldest and easiest to recognize are those that determine velocity by measuring velocity pressure or differential pressure.

Velocity pressure (Pv) devices used in outdoor air applications must overcome a number of limitations to succeed: minimum velocity limits (usually about 600 fpm or 3.05 m/s to minimize measurement uncertainty), zero drift, regular maintenance, duct placement conditions, quality of the field reference used for calibration and environmental sources of measurement uncertainty (primarily temperature and air density adjustments.) (ASHRAE 2009 Fundamentals p.36.16, Dougan 2003) With properly selected higher quality transducers, measurement range, turndown and drift issues can be diminished. Appropriately sized ductwork can help provide the required minimum velocities at maximum system turn down. Avoiding unpredictable measurement errors due to close proximity to duct disturbances is more difficult for Pv devices in MOA applications and can produce large errors. (Dougan 2003, Damiano)

Today there are several commercial velocity meters promoted as capable or designed specifically for permanent installation and the measurement of outdoor airflow rates, some for use in limited ductwork. Because thermal sensor sensitivity naturally increases with decreasing airflow rates, they tend to be better suited to the measurement of low flow rates, even much lower than this velocity. Some thermal sensor designs do not require the lengths of ductwork needed for a ‘developed’ total and static pressure profile, a prerequisite for accurate Pv measurement. Samplings with independent velocity sensor nodes allow some thermal products to overcome the placement limitations of Pv technologies. (Damiano, Dougan 2003)

Outdoor airflow can be accurately measured at the intake with numerous commercially available products, the control performance of one is displayed in figure 7. Each has its own advantages and disadvantages, but this performance can be accomplished with several technologies, giving designers a number of options for control instrumentation and strategies.

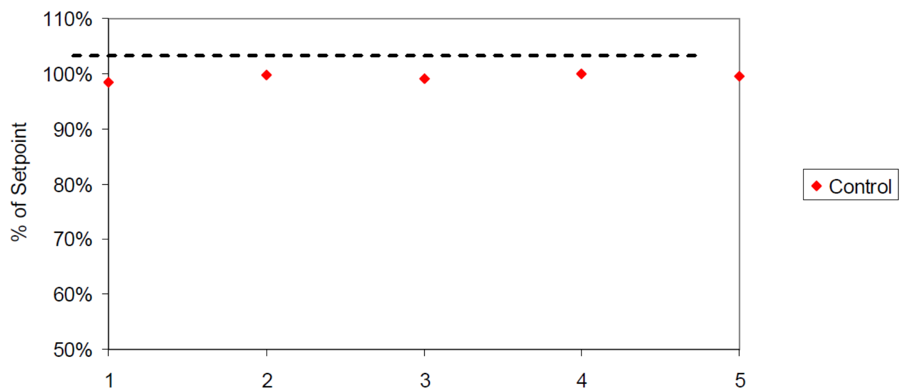

Figure 7 – Active Intake Control, Light and Variable Winds (Dougan 2008)
Real-Time environmental conditions. Single flow set point. Full size intake damper.
Open/close, Return to set point, measure resultant flow. 5 runs, 30 samples per run.

Regardless of the technology used, airflow measurement instruments should never be used or installed close to the MA plenum. Unpredictable flow patterns makes conditions impossible for accuracy or stability. Neither should they be placed downstream of modulating, partially open dampers or downstream of a fan with dampers that that modulates or closes farther downstream. Sound attenuators and humidifiers should also be avoided. Measurement devices should normally be used upstream of duct disturbances. Relative distances allowed will vary by the measurement technology used, the nature of the sensing elements and by the configuration of the specific model. 150 fpm (0.76 m/s) is generally considered the minimum velocity needed to avoid most wind effects and to provide sufficient damper authority for effective control.

Care should be taken not to rely on control from the outdoor air damper alone, since wind and stack effects can create a negative pressure on the intake system greater than the mixed air plenum pressure can overcome. Under the right conditions, the intake damper may reach full open yet the flow rate will not satisfy its set point. The recirculation damper or (Return/Relief Air) fan speed must also be modulated in sequence with the MOA damper. Ideally, sequences should be used that modulate flows with Return/Relief fan speed, with dampers maintained at full open. Upwards of 20-30% fan energy savings are possible with decoupled dampers and the correct control sequence, compared to mechanically linked damper arrangements. (Dougan 2003)

In applications where the AHU cannot accommodate the quantity of outdoor air required for a space, consideration can be given for the use of a makeup fan or air handler dedicated to preconditioning outdoor air (DOAS, ERV/HRV). This technique has increased in popularity. However, changes in stack, wind and MA plenum pressures warrant an airflow measuring station for proper control of intake airflow rates to spaces or equipment that these dedicated air units serve (Mumma) and is recommended by this author and in the *62.1 User's Manual* §5 for these applications.

CONCLUSIONS AND COMMENTS

Traditional indirect methods of outdoor air intake control are unsatisfactory and cannot provide positive, reliable and documented control. External environmental factors and internal load are variables that must be accommodated (e.g. worst-case design assumption or active direct control).

To satisfy energy goals and not risk under ventilation, active control is the more logical alternative.

Airflow is a significant control variable needed to help achieve increasing operational energy efficiencies. Direct measurement can improve ventilation system performance and may compensate in operation for conditions that differ from design assumptions. Data logs can indicate faults or component failures. Indirect methods may be less expensive, but are more imprecise and unable to provide positive and verifiable control performance. Airflow input for control is much more precise, more predictable and more efficient than any indirect method of airflow rate determination.

Additional research directly comparing the performance of several CO_2–DCV methods to direct measurement of Vot Outdoor Air Intake Flow, Vpz Zone Primary Airflow, and Pz Zone Population in real time and logged over a significant period of time, will allow us to evaluate the relationships between the CO_2 chamber study theories with a non-steady-state application using non-scientific commercial instruments. It may also produce quantitative data useful to justify the continued use of CO_2–only DCV or to improve applications of the method by identifying its strengths, weaknesses or limitations. Further calculations and analysis based on theory alone may have reached their maximum supportable conclusions, yet still leave us with many questions.

Direct measurement of outdoor airflow rates is a practical alternative with significant energy-saving and performance improvement implications. Newer measurement technologies are designed for low velocities and possess capabilities unlike those used a generation ago. However, care should be taken to insure that the technology selected is suitable for the design conditions (ASHRAE 2009), and that operational performance can be verified. Life-cycle cost (LCC) analysis should be used to evaluate alternative controls equipment or methods. Energy analysis of the savings potential may demand it. Nominal first cost advantages will not justify high maintenance costs or higher LCC.

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