A REVIEW OF HOW DIFFERENT ENERGY ANALYSIS TOOLS ADDRESS VENTILATION IN COMPLEX VAV HVAC SYSTEMS

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ABSTRACT

Variable Air Volume (VAV) Heating Ventilation and Air Conditioning (HVAC) systems are common design solutions for large buildings with complex zone arrangements.

In designing and analyzing these systems, it was found that where the building has large high occupancy center zones combined with a range of perimeter conditions, it is very easy to build an energy model that meets the ventilation code but that might not be supplying enough outside air to maintain CO_2 levels below a reasonable setpoint.

This paper explores whether this is leading us to underestimate the energy of these systems and offers a review of analysis methods that may enable more accurate asssessment of performance.

INTRODUCTION

During design on a project, studying the use of a Variable Air Volume (VAV) system in a courthouse, we sought to review the actual ventilation rates being achieved within the courtroom space in the thermal model.

The cause for the review was concern that, with a minimum turndown ratio equal to the ventilation rate requirements of the courtroom, and with design supply temperatures of 55F, anytime the central air handling unit was operating outside of economizer conditions and supplying 55F air, the courtroom would not be achieving actual outdoor air (OA) requirements within the zone.

The courtroom was initially being designed using the Californian Title 24 standard requirements for Ventilation, so the ASHRAE 62.1 requirements for ventilation were also implemented and studied separately.

Even with significantly increased minimum OA volumes at the Air Handling Unit (AHU), the

courtrooms still faced the same issue – if cooling air was not 100% OA and the air was supplied at 55F with a turndown at ventilation rates, then the OA entering the courtroom was not meeting the intent of the code.

This led to the following fundamental questions:

- If we designed the courtrooms to have CO_2 sensors and demand control ventilation, were we potentially under-estimating the energy use of the courtroom.

- If we were underestimating the energy use with the modeling method proposed, was there an analysis method that would allow us to correctly model the impact of CO_2 sensors;

- Would the analysis method allow us to vary both the turndown ratio and the OA rate at the AHU?

- How well would real-life operation of a buidling with CO_2 sensors mimic what we had modeled?

This paper investigates these questions with the following process:

- Review of the results from the Courthouse case study;

- Review of how commonly used analysis software deals with ventilation supply to zones;

- Review of what research is currently indicating about ventilation rates and CO_2 sensors in large buildings with VAV systems;

- Conclusions.

CASE STUDY - COURTHOUSE

To set the scene, results are presented from an analysis exercise conducted for a substantial courthouse buidling.

Project Description

The project consists of a large floor plate with multiple program spaces including perimeter offices, perimeter

corridor space, center zone office, circulation and courtrooms.

A zoning diagram of the typical spaces served by a single AHU is shown below. It can be seen that the AHU serves not only courtrooms but west and east-facing offices and public circulation at the perimeter as well.

The project included a requirement to obtain energy savings at least 15% better than code. The base case design solution was to provide efficient lighting and a low-flow overhead VAV HVAC system, with supply air temperatures of 55F and minimum turn downs in most zones of 20%. Full outside air economizer was also included.

The courtrooms were assumed to be fully occupied all day per the brief from the client. Internal loads from equipment and lighting were varied by about 50% from morning to afternoon to allow for some fluctuation in heat gain for the internal zones.

Under Title 24, the only requirement for outside air is to ensure that the sum of the minimum ventilation rates for each zone is applied to the air handling unit serving those zones. This approach makes it easy to model and design outside air considerations for VAV systems.

Typically Title 24 ventilation rates are comparable to ASHRAE 62.1 2004. In the case of courtrooms, the Title 24 requirements are much higher. Even with a highly occupant loaded "critical zones" method is applied using ASHRAE 62.1, the outdoor air rates required are not as high as Title 24.

In both instances, the standard generally focusses on the minimum OA contribution at the AHU. The zone is assumed to get enough ventilation if the AHU delivers what is requried to all zones served. This means that the turndown rate (minimum flow per zone) at full occupancy can be as low as the ventilation rate to that zone.

The key consideration is how much OA would actually

Description	Zone OA requirement at AHU	Minimum Zone Turndown Rate	AHU OA Rate	Courtroom Outside Air Rate (cfm/person)	Courtroom Minimum Turndown Rate (cfm/sqft)	AHU Net Min OA Requirement (cfm)
ASHRAE 90.1 Baseline	ASHRAE 62.1 "basic" method +30%	Max of OA requirement or 0.4 CFM/ft²	Sum of zone ventilation rates (incl. 30% additional)	8.06	0.40	2,294
Title 24 Original Design	Max of 0.15 CFM/ft² or 15 CFM/person	Max of 0.15 CFM/ft² or zone ventilation rate	Sum of zone ventilation rates	15.00	0.71	2,798
ASHRAE 62.1 Critical Zone Method	ASHRAE 62.1 "basic" method +30%	Max of 0.15 CMF/ft² or zone ventilation rate	Sum of zone vent rates divided by Ev value of 0.82	8.06	0.39	3,826
Title 24 with 100% OA and heat Recovery	Max of 0.15 CFM/ft² or 15 CFM/person	Max of 0.15 CMF/ft² or zone ventilation rate	100% OA with Heat Recovery	15.00	0.71	100% OA

Figure 1: Summary of Ventilation Requirements tested for Courtroom Example

The table above describes the options that were considered.

Ventilation Rate Background

The courthouse is located in the San Francisco Bay Area. In California, where Title 24 also provides the ventilation requirements, courtrooms end up having much higher ventilation requirements that the ASHRAE 62.1 guidelines.

need to be supplied to the zone to prevent a CO_2 sensor from calling for more ventilation. It is arguable that 8cfm of supply air per person in a center zone space fully occupied all day would result in CO_2 levels above a control point of say 800ppm. It is possible even that 15cfm of supply air per person could even touch 800ppm of CO_2 from time to time. This question was important, because it suggests that with CO_2 sensors overriding minimum code requirements, significantly more energy might be used.
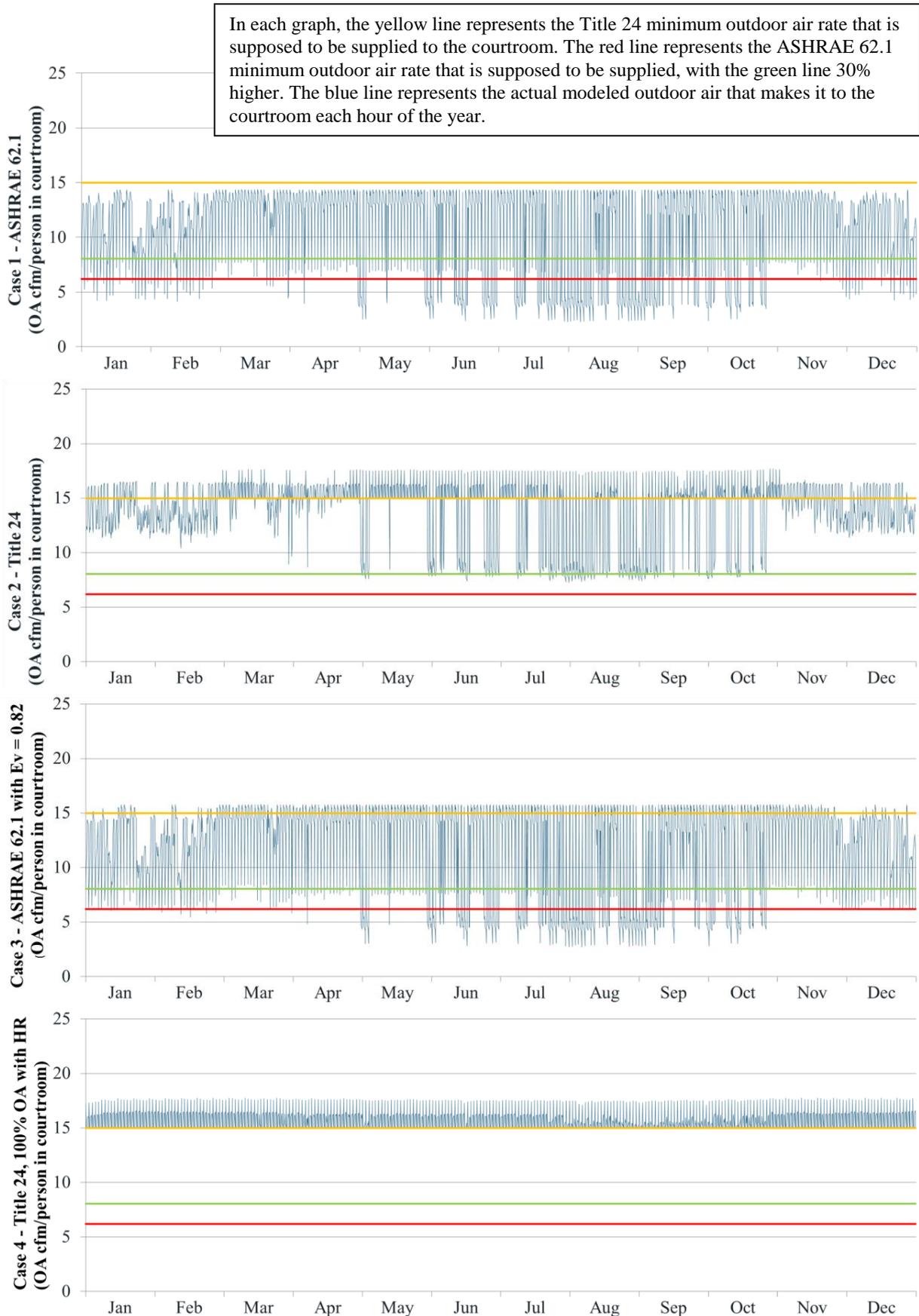
In each graph, the yellow line represents the Title 24 minimum outdoor air rate that is supposed to be supplied to the courtroom. The red line represents the ASHRAE 62.1 minimum outdoor air rate that is supposed to be supplied, with the green line 30% higher. The blue line represents the actual modeled outdoor air that makes it to the courtroom each hour of the year.

Figure 2: Modeled outdoor air rates received in a courtroom for different VAV Outdoor Air rate configurations studied (Courtroom being part of a larger building with a single VAV system)

Ventilation Distribution

All spaces were occupied per the expectations for the building, with most spaces fully occupied between 9am and 4pm. The hypothesis was that the courtrooms would be frequently underventilated, even with a full fresh air economizer on the AHU. This is because at times with both minimum OA at the AHU and peak solar loads at a façade, a dispropotionate amount of outside air would be distributed to the perimeter.

The charts on the previous page show the actual outside air volumes provided to these courtrooms over the course of the year for each option. The modeled amount of actual outside air that makes it to the zone is represented by the blue line. This is calculated from the % of outside air entering the AHU and the flow rate entering the space.

The solid orange line shows the Title 24, red line shows ASHRAE 62.1 and green line shows ASHRAE 62.1 plus 30% zone-minimum outside air requirement. Re-circulated "unused" OA has not been factored in.

These results show that outside air supplied to the courtroom is frequently below the zone requirement for outside air.

Energy impacts

The following graph shows how the changes in outside air rates affect the efficiency of the system. Note the Case 1 ASHRAE 90.1 (2007) baseline and so has characteristics inconsistent with the other models (such as a higher turndown rate).
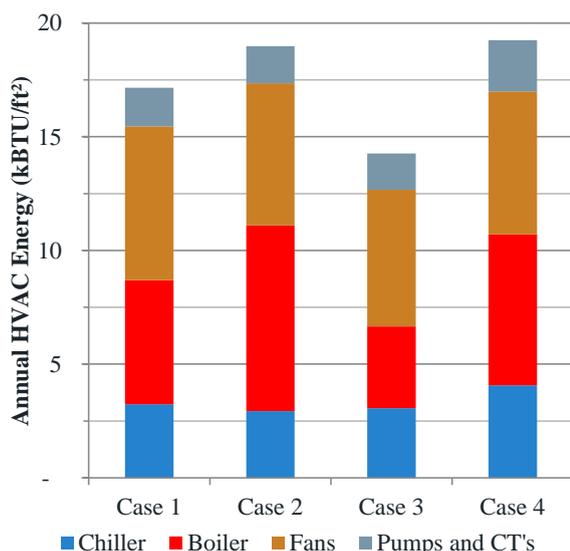
The key finding is that the increased minimum courtroom turndowns required by the increased minimum air to the room affects energy consumption much more significantly than increasing the OA rate at the AHU. The difference between the ASHRAE 62.1 + 30% option (case 3) and Title 24 (case 2) is upwards of 20% in energy consumption. Many analysts outside of California would probably model the system similarly to Case 3, but the ventilation results show that if those zones had CO_2 sensors and were trying to achieve reasonable CO_2 setpoints by increasing turndown, the actual energy would have been underestimated.

Interestingly, the energy difference between a return air option that achieves reasonable OA delivery in the zone and a 100% outside air option with heat recovery is low.

Analysis Obstacles

The analysis shown above was carried out in EDSL TAS v8.5 and provides a good example of the analysis challenges in addressing this issue.

In practice, and as required by ASHRAE 62.1 the courtrooms would almost certainly have CO_2 sensors. Depending on the sophistication of the BMS and VAV box DDC capabilites, these might provide anything from Demand Control Ventilation (DCV) turning the zone minimum flow down further to a fully optimized control system continuously monitoring the CO_2 in each zone and optimally adjusting both the AHU OA rate and zone flow rates to provide adequate ventilation to each space.

Some of the key analysis issues raised in this case study are as follows:

- Simple DCV mimicking the use of CO_2 sensors is only partially possible with this analysis software. Schedules reflecting different diversity in the spaces can be used to adjust turndowns at the zone and AHU. However actual CO_2 tracking following the position of the OA damper at the AHU is not possible.

- Input of sophisticated diversification of loads between zones is very cumbersome and requires hard coded changes to air flow and turndowns based on hand calculations;

- Optimization of turndowns and outside air rates at the AHU for energy performance is not possible.

- Calculation of the the AHU ventilation fraction and therefore the quantity of outside air entering each zone is only possible through post-processing hand calculations.

Based on these limitations, we determined it is very difficult to model demand control ventilation, or the controls that would actually be in effect to manage ventilation rates very effectively. Most commonly we

would be underestimating energy consumption by underestimating the ventilation needed in each space.

SOFTWARE METHODS COMPARED

Because the older version (8.5) of TAS was not suitable for properly controlling this type of VAV system, we reviewed the suitability of other energy analysis software commonly used in the design industry. This included the following analysis tools:

- eQuest (DOE 2.2)

- EnergyPro

- IES ApSYS (Apache Systems – basic HVAC)

- IES ApacheHVAC (more detailed HVAC version)

For each software tool, we have reviewed whether the tool can calculate and control:

- ASHRAE 62.1 ventilation rates easily
- simple demand control ventilation that varies the minimum zone turndown based on occupancy
- demand control ventilation that ramps down the minimum zone turndown based on a CO_2 sensor in the zone
- actual outside air rates going to a specific zone at any period of time and control to that requirement
- hourly energy optimization through increasing outside air rate at the AHU or increasing supply air rate to the zone and selecting the most efficient.

Ventilation in eQuest

The methods for demand control ventilation in eQuest are well documented Taylor et al (2005) describe 3 control sequences possible:

- Fixed minimum (peak occupancy drives a fixed minimum at the AHU)

- Demand Control Ventilation using Sum of Zones (Title 24 (2005) method)

- Demand Control Ventilation using Critical Zone (ASHRAE 62.1 (2004) method)

The important thing to understand with eQuest, is that although minimum zone ventilation rates are set for each zone, all this is doing is informing the amount of outside air that needs to be let in at the central air handling unit. In other words, there are controls that give the impression that a zone is going to get enough outside air, but as shown in the outputs from the original TAS analysis, this outside air rate is not guaranteed in the first instance, especially if the "sum of zones" method is used.

In addition, the demand control ventilation does not cause the turndown ratio in the zone to go above the

volume of minimum outside air for that zone. So whenever supply temperatures are low and the system is not operating on 100% outside air at the AHU, the rooms are under-ventilated in spite of the DCV settings.

None of the eQuest controls calculate CO_2 in a room and then control the minimum flow ratio to ensure enough outside air for each single zone, nor do they instantaneously calculate whether the actual amount of outside air being delivered to each zone is sufficient.

If CO_2 sensors were being used effectively in the highly occupied center zone in a real life scenario, they could be set to increase the flow rate to the zone to maintain acceptable CO_2 levels. eQuest does not capture this and it is quite likely it is underestimating energy consumption in instances like the case study above.

Ventilation in EnergyPro

Energy Pro v5 incorporates a Demand Control Ventilation box that can be checked for high occupancy spaces which have been designed to include a CO_2 sensor. (EnergySoft 2011)

This option provides a similar demand control ventilation option to the "sum of zones" method in eQuest. It has the same limitations as eQuest in terms of only varying the outside air rate at the AHU and not considering it in parallel with zone turn-down.

This means it is also likely that for certain VAV configurations, EnergyPro underestimates the amount of energy needed to achieve satisfactory ventilation conditions in some zones.

Ventilation in IESVE ApSYS

We consulted Timothy Moore at IES to understand how the software addresses ventilation control in both IESVE ApSYS and ApacheHVAC.

ApSYS is the simplest and most commonly used HVAC simulation tool in IES. It is more similar to eQuest in the way it is presented than the more sophisticated ApacheHVAC tool or other component-based simulation software.

Outside air rates have slightly more flexibility in IES ApSYS than in eQUEST or EnergyPro but the key limitation still exists. The following describes a typical process:

- Set a minimum outside air rate for each room or zone. This can be any number chosen by the modeler. There are no ASHRAE 62.1 calculatiosn embedded in this tool, so it is necessary to do this calculation either by had or using ApacheHVAC.

- Apply schedules and embedded formula-profiles to modulate the min OA value for each zone. The schedule and simple modulating value (0 to 1.0) used for each period within the schedule provide a modulating profile for the min OA value. Any time period within the schedule profile can use a formula rather than just a simple 0 to 1.0 modulating value.

Although a formula can be used to modulate the minimum OA value for each zone, this is still only the reference point that informs how much OA is needed at the AHU, and not a control point verifying the OA actually being distributed to the zone.

To this end, ApSYS is still prone to the same limitations as eQuest in the sense that the actual amount of outside air being delivered to the zone is not tracked, so zones such as the courtroom in the case study can still end up underventilated in the analysis model (with energy possibly underestimated again).

Ventilation in IESVE ApacheHVAC

ApacheHVAC is a sophisticated tool within IES that allows for a from scratch component builder of air-side HVAC systems. In this sense, it is more like TRNSYS or EnergyPlus than eQuest and for these reasons it is less commonly used in industry, particularly when it comes to code compliance and LEED submissions.

ApacheHVAC overcomes many of the issues that are described in this paper, through more thorough and flexible controls.

Although the method for calculating outside air rates required at the AHU are relatively similar, there are some key additional controls that can be used in IES ApacheHVAC to more realistically manage outside air delivery on a zone by zone basis. These include:

- Sensors that track actual volume of outside air being delivered to any given zone (based on the proprtion of outside air in the supply air and the proportion of air being delivered to the zone);

- Sensors that monitor CO_2 levels in any given zone, with sensors accounting for all zone level ventilation and infiltration effects.

These sensors are critical because they can then be used to modulate either the outside air rate at the central air handling unit or the turn-down ratio in the zone being served (or both in a sequence).

This mimics much more closely the operation of CO_2 sensors in such a building, where CO_2 sensors usually call for increased outside air at the air handling unit if CO_2 levels in a space are low. It increases complexity of the energy model, but enables the model to ensure all zones have adequate amounts of outside air delivered in the model, and therefore has the potential to provide a more realistic estimation of the building's energy use.

Other Software

EnergyPlus 7 includes a CO_2 sensor that can be controlled in a similar way to IESVE ApacheHVAC. TRNSYS can be programmed to output actual ventilation being delivered to zones or CO_2 in zones with that output used to control either the OA rate at the AHU or the zone turndown rate or both.

Conclusion

The most common software used for energy analysis of low-flow VAV systems in large multi-zone spaces do not have ventilation controls that can be used to prevent under-ventilation of spaces or used to mimic the way CO_2 sensors are usually designed to operate in reality.

The hypothesis of this paper is that this may cause energy analysis of VAV systems with these types of ventilation scenarios to be incorrect and underestimate the real life energy of those designs. This could be one cause of the energy from modern buildings with VAV HVAC systems not being consistent with design preductions.

REAL LIFE VENTILATION OF BUILDINGS WITH VAV HVAC SYSTEMS

As described and shown above, it can be easy to incorrectly model the ventilation distributed in complicated buildings with VAV AHUs serving a large number of diverse zones.

The varied real-life control options for these types of systems and the tendancy to value engineer down controls late in the design phase make it even harder to represent what is actual operation with an energy model.

Many good quality control systems now have the ability to monitor in real time the amount of CO_2 or the amount of actual OA going to each zone. Some even have optimization code that allows the most efficient combination of outside air rates at the AHU and turn-down rates in the zone to be selected to hit the appropriate ventilation rates. Technically it should be possible to use CO_2 or OA rate control points such as is possible in IESVE Apache HVAC or EnergyPlus and simulate reasonably well a building with an optimized control strategy.

However many buildings do not implement these sorts of controls systems in practice. The issue of what happens in real life is very contentious. Two key issues

that are not widely agreed on that affect our hypothesis include the following:

- That buildings are either over-ventilated (Apte, M. 2006) or not sufficiently ventilated, leading to Sick Building Syndrome (Seppanen et al, 1999, Wargoki and Wyon, 2007 in Fisk 2010)

- That CO_2 sensors are somewhat unreliable (Fisk et al 2010) or very reliable (DOE, 2004)

These two phenomena are described in additional detail below.

Whether buildings are over or under-ventilated

There is a growing consensus that ventilation rates currently required by code are not as high as they could be for optimum indoor environmental quality.

Many green building rating tools, including LEED and GreenStar offer credits for increasing the minimum outside air rates above the code requirements. With LEED, the credit was added for LEED 2009, with the reasons explained quite well in this summary by Taylor (ASHRAE Journal 2005).

At the same time, there are other studies indicating that buildings controls are frequently not commissioned properly and that this causes buildings to be over-ventilated and for demand control ventilation not to work properly. In these studies, the concern is that incorrect control of outdoor air is causing energy to be increased.

These parallel but somewhat contradictory points of view potentially suggest that the problem lies with the way systems are designed and controlled, and that in many cases, large buildings, especially those with overhead recirculating VAV systems, contain some zones that are over-ventilated and some zones that are under-ventilated.

If buildings are controlled the same way that they are modeled in tools such as the courthouse example shown at the beginning of this paper, it is very likely that they are simultaneously over ventilated and underventilated because ventilation is not controlled at the zone level.

This would mean some zones are suffering from poor indoor air quality through elevated CO_2 and indoor air pollutant levels while other zones are using more energy than necessary through over-ventilation, supporting both theories regarding poor ventilation distribution in buildings.

Whether Carbon Dioxide Monitoring is reliable or not

Some retro-commissioning studies indicate that CO_2 sensors 5-10 years ago are very frequently not working properly. Earlier models of CO_2 sensors were unreliable, requiring frequent recalibration. Many current models are still found to become declibrated outside acceptable ranges during the recommended 5 year recalibration period (Fisk 2010).

Another criticism of CO_2 sensors is that they are also often located in the wrong location within the zone (Taylor, 2007, Fisk 2010). This affects the validity of the reading.

Many manufacturers now offer long warranties on CO_2 sensors and this will potentially reduce the impact of CO_2 sensors not being reliable. There is not a lot of evidence in existing buildings operating for a reasonable period that this has been effective in making CO_2 sensors more reliable.

Whether CO_2 sensors work or not in real life is very important to analysis. As shown above, more detailed software techniques allow CO_2 to be monitored in an energy model and used as a real-life version of control. However if CO_2 sensors in real-life are not accurate then the energy and ventilation performance results in a thermal model will not be correct either.

CONCLUSIONS

The first conclusion of this paper is that it is very easy for energy models looking at VAV systems in large and diversely loaded buildings to underventilate high occupancy center zone spaces.

This in turn could be leading to inaccuracies in energy results where those buildings incorporate ventilation controls such as CO_2 monitoring to prevent those zones from being underventilated (if those controls work).

The paper has reviewed analysis software and found that although many simulation tools offer demand control ventilation, the controls in these simulation tools do not always prevent underventilation from happening because they only vary the amount of Outside Air coming into the AHU, not the actual Outside Air delievered to each space or the turndown at each zone. Furthermore the modeling controls in most analysis tools do not match controls in practice.

It would be extremly beneficial to have the ability to check ASHRAE 62.1 compliance based on hourly ventilation rates and outdoor air fractions at the AHU. This could then be used as a design tool increasing the operational hours in which all spaces are achieving

targeted ventilation rates while minimizing unnessary over ventilation.

There are tools that allow proper consideration of CO2 monitoring. These tools are not as widely used, arguably because the level of detail needed for their use is more than is typically applied by many energy analysts.

In real life, there is evidence that buildings are both under-ventilated and over-ventilated. This possibly means that the analysis results are correct and that it is a design and code issue that causes some zones to be underventilated.

However in buildings with CO2 sensors, the question is then whether they are working or not. If they are working, but were not incorporated into the original energy model, it is likely that energy use is higher in real life than in the energy model.

If CO2 sensors are not working, then it is worth asking the question – is there a better way to control ventilation in buildings and also, should VAV systems be designed to service so many zones, especially center and perimeter zones from a single AHU?

For overhead VAV system controls, a better way both in analysis and real life might be to track occupancy using a different method, such as an occupancy sensor and then allow a more significant reduction in OA delivery to the zone if it is unoccupied. If this were applied, energy consumption predictions in energy analysis would also need to be corrected to reflect this sort of operating proceedure rather than assuming that OA rates can modulate according to partial occupancy (which cannot be measured if CO2 sensors are not doing the job properly).

The ideal solution is the analysis and real life control with CO2 sensors. However until it is proven that CO2 monitoring systems can be routinely and successfully implemented through all phases of design, analysis, construction, commissioning and operation, it is likely that energy analysis for these systems is going to be inaccurate comparing modeled vs actual performance.

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