Meeting the Variable Needs of Energy-Efficient Mechanical Ventilation When and Where You Need It

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Introduction

Effectively providing mechanical ventilation in commercial buildings can be challenging especially when the minimum requirement for ventilation varies throughout the day due to variable occupancy. Mechanical ventilation can be treated and delivered into commercial buildings using different equipment. Providing ventilation through package space heating and air conditioning equipment (HVAC) is a common method and will be the focus of this paper. This creates challenges to provide acceptable comfort and the appropriate amount of ventilation at the same time in different locations as loads and ventilation needs change. The simplest solution has been to size the package HVAC system to meet the space design load as well as the load of the maximum design ventilation rate. This results in a large capacity system that is much larger than needed most hours of the year.

It is not uncommon for spaces to experience comfort complaints involving over-cooling or elevated humidity, particularly with conventional package HVAC systems. Simple HVAC systems must constantly operate the supply fan to meet ventilation requirements even if indoor comfort temperature has been met. This method of operation results in high indoor humidity during cooling operation or overcooling if the setpoint is lowered to increase dehumidification.

One solution to improve comfort and ventilation control has been to use a dedicated outside air system (DOAS) to handle 100% of the ventilation air. This improves comfort control by dedicating a system properly sized solely for heating and air conditioning (HAC), while a DOAS is sized for the ventilation load. Each system conditions air independent from the other creating the potential for the DOAS to be optimized for reduced energy and improved comfort (Murphy 2006). However, DOAS that operate at constant fixed-flow can have more limitations than variable supply flow DOAS.

Variable Occupancy Creates Challenges for Energy-Efficient DOAS Operation

If your occupancy varies during the day, a fixed-flow DOAS will provide more ventilation than the minimum requirement resulting in wasted energy. The longer the duration that occupancy is below design and the greater the amount the occupancy is less than design, means there is more potential to reduce energy consumption. Demand-based ventilation control is a method of varying the ventilation rate to meet the minimum ventilation need at the time. Ventilation can be varied based on scheduled demand, accumulated carbon dioxide (CO_2) levels in a space (surrogate demand), or potentially by other acceptable means of accounting for occupancy.

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Scheduled demand is simple and varies the flow according to a set time of day, but it cannot adjust for actual change in occupancy. CO_2 demand-based control is currently the most common control used to vary ventilation in direct response to actual changing occupancy. Occupants exhale carbon dioxide and indoor CO_2 concentrations increase as occupancy increases at specific ventilation rates. A CO_2 sensor in a ventilation zone can be used to control ventilation flow rates as needed. As occupancy increases, CO_2 increases and the DOAS is called to deliver more ventilation. As occupancy decreases, CO_2 decreases and the DOAS begins to decrease ventilation.

Meeting variable needs of ventilation can become more complicated if different ventilation zones need to be supplied by the same DOAS. Different spaces can require different rates of ventilation based not only on actual occupancy, but also the area, use of space, and activity levels. Consider the potential range of ventilation needs in a school cafetorium. Effectively conditioning wide ranging ventilation flows can be challenging under such conditions even when using a DOAS.

A New Variable Capacity DOAS Technology

Variable refrigerant flow technology has advanced in recent years. This along with variable flow fans offers new possibilities for packaged DX DOAS with substantial energy savings potential when coupled with CO_2 demand-based ventilation control. Addison HVAC has developed an exclusive DOAS package design that uses a novel combination of variable refrigerant flow (VRF), variable air flow (VAF), and Active Coil Exposure™. This design results in energy-efficient ventilation with the potential to meet diverse requirements without over- or under-ventilating. This new Addison 100% DOAS is known as the LC unit. LC stands for Linear Capacity™, an innovative variable capacity solution.

The current LC unit design is equipped with 5 independent and separated evaporator coils, by means of 5 independent EEVs, to provide the necessary cooling capacity during changing loads through the day. The LC unit can vary the amount of active evaporator coils. This feature allows for the compressor to operate on a variable refrigerant flow rather than simply perform on/off operation or basic two-stage operation. Thus the unit works only at the required rate allowing for substantial savings especially at partial-load conditions.

Varying the coil surface as supply air flow varies avoids lowering coil face velocities and having laminar flow at the coil boundaries that drastically affect the coil performance. In addition, since the evaporator surface is not fixed, the compressor does not have to work to keep the full evaporator surface at the desired supply air dew point in order to maintain the dehumidification process, resulting in reduced energy consumption.

Case Study

During the summer and fall of 2016, a study[2] was conducted by the Florida Solar Energy Center to compare the performance of an existing fixed-capacity DOAS to the Addison LC unit with CO_2 demand-based control (Withers 2016). A test site was chosen that had a variable occupancy schedule, an existing fixed-flow DOAS that could be replaced, and that could accommodate a retrofit within the time

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[2] Addison, Inc. contracted with the Florida Solar Energy Center, a research institute of the University of Central Florida, to oversee monitoring installation, as well as collect and analyze performance data from two different types of DOAS.

constraints of the study period. The study was completed at an Orlando private high school cafeteria building. The 5,000 ft^2 cafeteria had a design occupancy of 200 students at the time of the study. At maximum occupancy, the design ventilation rate required 2,500 cubic feet per minute (cfm) according to ASHRAE 62.1-2016.

Figure 1. Interior view of cafeteria shows ventilation duct at center with space conditioning supply ducts on each side.

Figure 1 shows an interior view of the cafeteria. Ventilation supply air was distributed through a central duct down the center of the space. Space conditioning was provided by two separate 7.5 ton heat pumps each with an ARI rating of 10.4 EER and 3.2 COP (high-temp.). The existing DOAS was found to be designed and functioning at twice the required ventilation flowrate. A certified energy rating was not available, but the site-measured energy efficiency ratio was found to be approximately 10 Btuh/w with outdoor air at 95°F. A photo of the new LC unit that replaced the existing DOAS is shown in Figure 2.

Power meters, temperature, relative humidity and airflow sensors were installed to monitor performance of each DOAS. Energy use and air flow of the cafeteria heat pumps and interior temperature, relative humidity and CO_2 concentration were also monitored. Data were collected and stored at 1 minute intervals, then transferred via cellular modem from the datalogger to a secured university research data account. The incoming data were scanned for missing or erroneous values. Data errors were tagged and the database management system could notify the analyst of which data were affected and when. Such errors are rare and may only occur if a sensor was malfunctioning or due to an unexpected environmental factor.

Figure 2. Addison LC 100% outside air package unit shown after installation at a high school cafeteria.

Temperature, relative humidity and pressure-based airflow sensors were checked against sensors with NIST traceable calibration at the beginning of the project and found to be working within manufacturer specifications.

Case Study Results

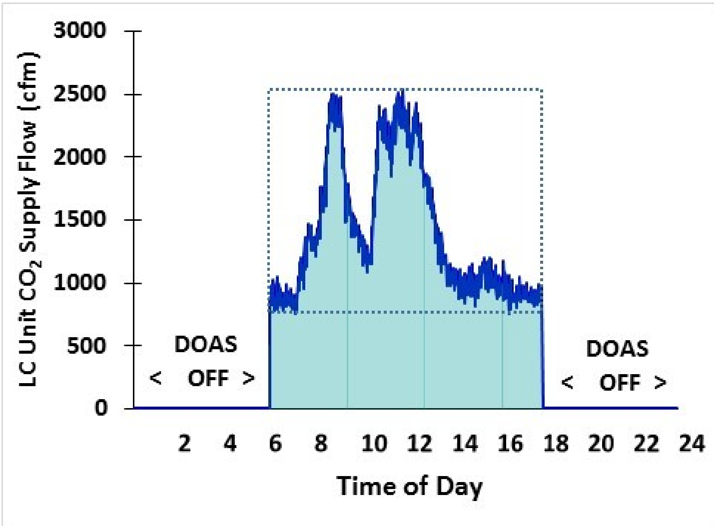

Figure 3. Supply flowrate of LC Unit with CO2 control during a school day. White space within rectangle indicates periods when ventilation was reduced from the fixed-flow at 2,500 cfm.

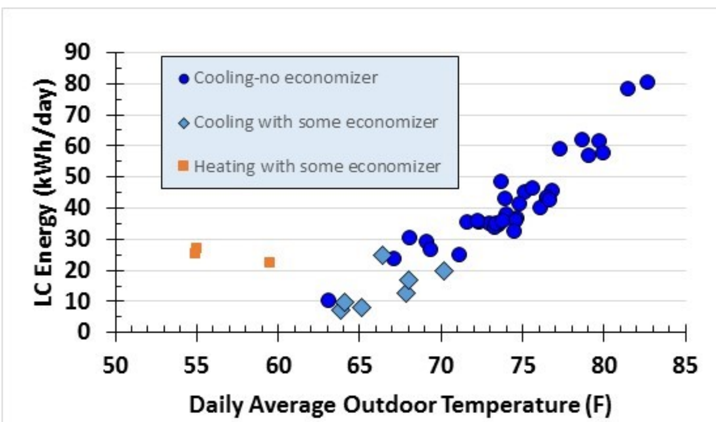

Figure 4. LC Unit with CO2 control daily total energy use plotted against the daily average temperature.

Figure 3 shows the measured supply ventilation flowrate of the LC unit using CO_2 demand-based control during a school day. The flowrate varies up and down in direct response to occupancy measured indirectly through CO_2 measurements in the cafeteria compared to CO_2 outside. The white space within the rectangle with dashed lines indicates periods when CO_2 control was able to reduce ventilation and conserve energy compared to if the DOAS was set to fixed-flow at 2,500 cfm the entire 12 hour business day. The LC unit maintained at least a minimum flowrate of about 900 cfm to satisfy minimum ventilation requirements during business hours.

Figure 4 shows measured LC unit with CO_2 control energy plotted against the daily average outdoor temperature. Here it can be seen that there were only three days when heating was necessary, and when it was, it only occurred for a few early morning hours before the economizer operation took over. Economizer operation provided the necessary ventilation without heating or cooling outdoor air when desirable outdoor conditions were met. No cooling or dehumidification energy use was observed if outdoor air dewpoint was less than 56°F. No heating energy use was observed if outdoor temperature was greater than 54°F.

The monitoring period and available weather conditions limited energy analysis to cooling energy use. Analysis of the existing DOAS energy use was limited to summer cooling conditions since replacement had to occur before the start of the new school year in August. The existing DOAS had a supply flowrate of about 5,000 cfm exactly double the amount required. This system was monitored and adjustments were made in analysis to allow a more equitable comparison to the properly sized LC unit.

Assuming the same efficiency and entering air conditions in an appropriately sized fixed-flow DOAS, half the airflow would require half the energy as measured at the 5,000 cfm flowrate. The existing DOAS energy representative at a fixed-flow of 2,500 cfm was determined by using half the measured energy of the existing DOAS at 5,000 cfm. Table 1 results are representative for a summer day averaging outdoor conditions of 80°F and 75°F WB for DOAS in a building with the same occupancy schedule as this high school cafeteria operated from 6 a.m. to 6 p.m. Daily energy use is shown for the LC unit set at a fixed-flow rate of 2,500 cfm as well as for the LC unit with ASHRAE 62.1 CO_2 demand-based control implemented. The CO_2 control is based upon the differential between indoors and outdoors.

Measured Daily DOAS Cooling and Fan Energy Use During Summer Conditions

The savings shown in Table 1 are based on each LC unit test configuration compared to an existing DOAS with fixed-flow at 2,500 cfm. Operating the LC unit at a fixed-flow of 2,500 cfm indicates about 26% savings that would be primarily contributed by the combined impact of more efficient qualities of the LC unit without conservation from using demand control. The combined impact of LC equipment efficiency and conservation measures of CO_2 demand control resulted in about a 53% reduction of summer daily energy use compared to the existing fixed-flow DOAS.

Table 1. Daily DOAS Energy Use for a High School Cafeteria Operated 12 Hours Per Summer Day

Test Configuration	Energy Use kWh/day	Savings kWh/day	Savings %	Savings $/day*
Existing DOAS fixed-flow @ 2,500 cfm	**141.3**	**---**	**---**	**---**
LC unit fixed-flow @ 2,500 cfm	**104.9**	**36.4**	**25.8**	**$2.80**
LC unit with CO_2 demand control	**66.5**	**74.8**	**52.9**	**$5.76**

* $ savings based on $0.077/kWh simplified commercial rate including demand and energy use charges.

Space Conditioning Energy Use

Space conditioning energy use provided independently from DOAS may also be impacted from a DOAS replacement or retrofit. The gross over-sizing of the existing DOAS in this study did not allow fair comparison of space conditioning and DOAS energy between two different DOAS with the same design maximum flow. The best available data for comparing space conditioning impacts came from the LC unit set at fixed-flow and with CO_2 control. This allowed an evaluation of CO_2 control during summer conditions.

Space conditioning energy should also be considered in the total energy impact of a DOAS retrofit from fixed-flow to CO_2 demand control. This is because a fixed-flow DOAS, depending upon design and conditions, may reduce the cooling load of the space conditioning. Effective CO_2 control will result in less ventilation supply air and potentially less supplemental cooling to the space. As a result the cooling load on the space conditioning systems increases. In the case where a fixed-flow DOAS operated at the same efficiency as the space conditioning systems, the shift of cooling load from the DOAS to recirculation systems would not detract from the DOAS energy savings.

In the test case using the LC unit, the LC unit fixed-flow efficiency was greater than the space conditioning systems. The space conditioning energy increased nearly as much as the LC unit DOAS energy reduction with CO_2 control, resulting in only about a 1% net decrease in daily energy during hot summer conditions. This occurred as the CO_2 control resulted in less space cooling thereby increasing the load on the low efficiency space conditioning heat pumps.

In cases where a fixed-flow DOAS operated at the same efficiency as the space conditioning systems, the shift of cooling load from the DOAS to recirculation systems after implementing CO_2 control would not detract from the DOAS energy savings. This case is more likely during a retrofit when existing equipment is replaced.

DOAS Power Reduction

The potential benefits of power demand reduction should also be considered. Table 2 compares the power use between a fixed-flow DOAS and the LC system. Since the flowrate affects the fan and compression power usage, the power shown in Table 2 is when both systems have the same maximum design flowrate set at 2,500 cfm. These results occurred with outdoor conditions of about 95°F and 78°F WB. The LC unit used about 1.6 less kW (13% reduction) than the pre-existing DOAS. This reduction represents a utility customer value of about $16 per month in demand charges for an account that is charged $10.28 / kW demand. The demand reduction also represents value for utility rebate programs that may offer incentives towards DOAS replacement. Actual energy demand reduction will vary by design airflow and operational efficiency of the DOAS being replaced. The value of demand reduction can vary widely depending upon the utility and customer rate structure. A customer with time-of-use demand rate may experience greater demand savings than indicated here if the CO_2 control is implemented and occupancy is low during the highest time-of-use peak rates.

Table 2. Comparison of Electric Power Usage.

Test Configuration	kW	Delta kW	% kW saved
Existing DOAS fixed-flow @ 2,500 cfm**	**12.1**	**---**	**---**
LC unit fixed-flow @ 2,500 cfm	**10.5**	**1.6**	**13.2%**

*****Determined as 50% of the measured existing DOAS @5,000 cfm.***

Annual DOAS Cooling and Fan Energy Use Predictions

Previously the daily energy use of three different DOAS was compared based on an average summer day summarized in Table 1. Testing schedules were not long enough to collect a full year of energy data for each test configuration. An annual energy use prediction is made in this section for the same three test configurations discussed previously regarding daily energy comparisons.

Two different methods were used to calculate annual energy use. The preferred choice of calculation was based on using measured data to develop models that could predict energy based on outdoor conditions and occupancy. This approach was able to be used for the LC unit calculations. Since the testing period of the existing fixed-flow DOAS unit did not experience an adequate range in environmental conditions required to develop a suitable model, the EnergyPlus energy simulation program was used with guidance from ASHRAE 90.1 and supporting material (DOE 2017 A, DOE 2017 B, ASHRAE 2013, ASHRAE 62.1 2016). The simulation used a building with equipment, schedules and loads similar to the high school cafeteria. The simulation used a package DOAS with fixed-flow at 2,500 cfm with an EER=10. This DOAS was only scheduled to operate according to a school schedule of 180 days per year on weekdays from 6 a.m. to 6 p.m. Cooling was called on when the interior temperature was greater than 71°F similar to the existing control before replacement with the LC unit. This DOAS was sized to meet the ventilation load, and supplemental space conditioning systems provided conditioning to meet building loads.

LC unit energy models were developed using measured energy, supply airflow, along with outdoor drybulb and dewpoint temperature data. A least-squares best-fit regression analysis was used to create equations developed from the measured data. The regression models were then used with Orlando TMY3 hourly data to predict annual energy use. The LC unit with CO_2 control energy model accounted for occupancy variability based on a composite supply flow schedule developed from monitored data. Energy use of the LC unit was also limited to 180 days per year from 6 a.m. to 6 p.m. The LC CO_2 demand control annual calculations included economizer energy operation.

Results of the calculated annual DOAS energy is shown in Table 3. The energy includes all cooling and fan energy without heating energy. DOAS heating use would be very minor for an area like Orlando representing approximately 5% or less of DOAS annual energy use. Energy savings are shown relative to a DOAS fixed-flow unit scheduled for replacement. Operating the LC unit at fixed-flow allowed an opportunity to evaluate the benefits of the LC unit efficiency impacts without the added conservation of using CO_2 control. The LC unit with CO_2 control test shows the combined benefit of efficient mechanical operation combined with energy conservation that occurs through CO_2 control.

The LC unit energy set at fixed-flow had an estimated annual energy reduction of 41.4% worth approximately $781 per year. An average cost of energy of $0.077/kWh is assumed. The energy cost of $0.077 is a simplified assumption incorporating commercial demand and energy charges together. Actual rates will vary depending upon commercial plan, actual peak demand throughout the year, as well as energy use. Replacing an existing fixed-flow DOAS with the LC unit using CO_2 demand control had a predicted annual reduction of 77.3% with an estimated annual savings of $1,458.

Table 3. Predicted Annual DOAS Cooling and Fan Energy for a High School Cafeteria

Test	Energy Use kWh/yr.	Annual Savings kWh	Annual Savings %	Annual Savings $*
Existing DOAS fixed-flow at 2,500 cfm	**24,503**	**---**	**---**	
LC DOAS fixed-flow at 2,500 cfm	**14,354**	**10,149**	**41.4%**	**$781**
LC DOAS with CO_2 control	**5,564**	**18,939**	**77.3%**	**$1,458**

* $ savings based on $0.077/kWh simplified commercial rate including demand and energy use charges.

Based on results shown in Table 3, the savings solely from CO_2 demand control are 8,790 kWh/year (61.2%) when used with the LC unit. This equates to an estimated annual savings of $677. The energy reduction and percent savings from implementing CO_2 control will vary depending upon the DOAS that utilizes CO_2 control.

Conclusion

Incorporating variable speed fans, variable refrigerant flow technologies, and Active Coil Exposure™ into a package DOAS offers new opportunities for meeting the needs of variable ventilation requirements energy-efficiently. Such a product was evaluated at a high school cafeteria in Orlando, Florida.

The Addison LC unit with CO_2 control evaluated in the field study demonstrated significant energy savings potential towards replacement of existing fixed-flow DOAS. The key findings able to be drawn from this study are as follows:

- There is a potential annual DOAS cooling and fan energy savings of 18,939 kWh per year representing a 77% reduction when an existing DOAS (EER=10) operated at fixed-flow is replaced with an LC unit using CO_2 demand control. These savings are based on a school cafeteria schedule operating only 180 days per year, 12 hours per day in Orlando, Florida.

  - Potential annual savings from the LC unit will decrease with less required annual DOAS operational hours or as occupancy tends to stay closer to the maximum design occupancy.
- Measured summer daily energy savings of about 75 kWh/day (53% reduction) were indicated from replacing an existing DOAS with an LC unit using CO_2 demand control. Annual savings were expected to be higher than daily summer savings since the LC unit energy use dropped substantially during part cooling-load conditions that occur throughout much of the year.
- Space conditioning energy can be impacted when retrofitting from a fixed-flow DOAS to CO_2 demand control.
  - In a case where a fixed-flow DOAS operated at the same efficiency as the space conditioning systems, the shift of cooling load from the DOAS to recirculation systems, after CO_2 control was implemented, would not detract from the DOAS energy savings.
  - A shift of cooling load from the DOAS to recirculation systems after CO_2 control was implemented, could detract from the DOAS energy savings if the existing fixed-flow DOAS efficiency was greater than the efficiency of the space conditioning equipment before retrofit.
- Further effort is needed to evaluate DOAS heating energy and total annual energy impacts in climate regions outside IECC Climate Zones 1A and 2A.
- Power reduction was compared with both systems set at the maximum design flow with outdoor temperature of 95°F. The LC unit used about 1.6 less kW (13% reduction) than the pre-existing DOAS with both operating at 2,500 cfm. A reduction of 1.6 kW could have a value of about $16 per month.
  - The value of demand reduction can vary widely depending upon the utility and customer rate structure. A customer with time-of-use demand rate may experience greater demand monetary savings than indicated here if the CO_2 control is implemented and occupancy is low during the highest time-of-use peak rates.
- Utility rebate programs should consider offering rebates towards DOAS replacement.

The performance of the first generation Addison LC unit with CO_2 demand control was evaluated for several weeks from mid-September into December 2016. During that time it demonstrated the ability to vary airflow to meet variable ventilation demand of a single ventilation zone, and deliver the air at comfortable dry conditions. This system demonstrated the ability to deliver 55°F-60°F dewpoint supply air under a variety of weather conditions. The LC unit also demonstrated an ability to automatically transition between economizer, heating, and cooling operations.

The wide range in LC unit conditioned supply airflow (900 cfm-2,500 cfm) demonstrated the suitability towards serving one large ventilation zone with variable occupancy. While it was not evaluated in this project, the LC unit was designed to be used to serve multiple ventilation zones having different airflow requirements with an appropriately designed ventilation distribution system and sequence of operation.

Acknowledgments

The author would like to thank Addison and the Addison engineering team for their support of this study. The author would also like to acknowledge Dr. Bereket Nigusse, of the Florida Solar Energy Center, for contributing his expertise in annual energy modeling and analysis.

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