Improving Effective Energy-Efficient Commercial Package Dedicated Outside Air Systems Located in Hot-Humid Climate Zones

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ABSTRACT

Mechanically distributing an appropriate amount of outside air (OA) ventilation throughout a commercial building with variable occupancy can be challenging without over-ventilating, and can have significant energy costs associated. This particularly tests engineers that seek to optimize energy-efficiency with effective variable OA throughout different zones.

Conditioning OA in hot-humid climates takes special consideration due to the very high latent loads that must be removed. 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 can result in high indoor humidity during periods of low cooling load. It may also result in over-cooling if the setpoint is lowered to increase dehumidification, particularly with conventional packaged and split HVAC systems.

Using a dedicated outside air system (DOAS) to handle 100% of the ventilation air has been part of the solution to improve moisture control and over-cooling issues. This improves comfort control by dedicating systems properly sized solely for heating and air conditioning (HAC) loads, and dedicating DOAS specifically sized for the OA ventilation load. It can also make it easier to distribute variable amounts of OA to different zones. While DOAS help improve control, there are still challenges to managing energy-efficient OA conditioning and distribution in buildings with variable cooling loads and occupancy. Many packaged DOAS use air distribution fans that operate at constant speed and vary airflow by simply using air damper controls. Fixed-flow designs have more limitations to energy savings potential than variable supply flow DOAS.

The advancement of variable speed fan motors and variable refrigerant flow technologies have made their way into space conditioning systems and offer good energy savings potential as they can operate very efficiently at varying load levels. These advancements had recently been developed and applied to a package DOAS, and a field study was completed through third-party evaluation. The variable-capacity DOAS was put into a field trial at a high school cafeteria. Testing showed that the unit was able to deliver 55°F-60°F (12.8°C-15.6°C) dewpoint supply air under a variety of weather conditions and at variable ventilation rates. Analysis indicated a potential 77% reduction in annual DOAS energy when a schedule-based controlled fixed-flow DOAS (EER=10) was replaced with the variable capacity DOAS unit using CO^2 demand-based control. Demand control accounted for about 36% of the total savings.

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INTRODUCTION

It is not uncommon for interior spaces to experience comfort complaints involving over-cooling or elevated humidity, particularly with conventional packaged and split HVAC systems. The simplest solution has been to size the 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. Such 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 apply 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 (V) 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 air flow (VAF) DOAS. Even newer variable flow DOAS must still be carefully designed to match evaporator coil limitations within an expected range of airflow and wide range of entering air conditions.

Variable refrigerant flow (VRF) technology has advanced significantly in recent years. This along with variable air flow (VAF) fans offers new possibilities for DX-DOAS with substantial energy savings potential when coupled with occupancy demand control ventilation (DCV). Different manufacturers have begun offering DX-DOAS with these features, and rating standards such as Air Conditioning, Heating, and Refrigeration Institute (AHRI) Standard 920-2015 have been developed to provide a basis of performance comparison which have been incorporated into ASHRAE 90.1-2016 minimum efficiency Tables 6.8.1-15 and 6.8.1-16.

One manufacturer developed a package DX-DOAS design that used a combination of VRF, VAF, and a unique evaporator coil geometry allowing variable capacity (VC) conditioning. Figure 1 shows an exterior view of this DX-DOAS. The designation, VC DX-DOAS, will be used to refer to this unit throughout this paper. Figure 2 shows some detail of the unique inside coil arrangement that helps maintain leaving air conditions at different flowrates.

Figure 1. Exterior view of a new VC DX-DOAS located outside a high school cafeteria.

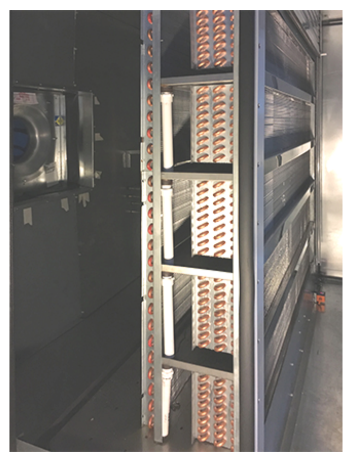

Figure 2. Inside view of five individual coils; entering air on the right side and supply fan on left.

The VC DX-DOAS tested in this research was an air-cooled system without energy recovery. Energy recovery was not required for replacement of the pre-existing DX-DOAS, and there was not enough time to account additional efficiency features. The VC DX-DOAS had five independent and separate evaporator coils each with an independent electronic expansion valve (EEV), to provide the necessary cooling capacity during changing loads through the day. The EEV are located on the opposite side in Figure 2 out of view. The VAF fan is on the left side of Figure 2 and has an airflow station. Staged damper control blocked air flow through inactive coils. Figure 2 shows the coil arrangement with the slide gate damper fully open exposing all coils. With lower load and lower demand ventilation, the slide damper moved downward isolating unused coils. This feature allowed a variable speed compressor to operate with variable refrigerant flow rather than simply perform on/off operation or two-stage cooling operation. The prototype design goal was to meet the minimum required ventilation flow with supply air at 55°F (12.8°C) dpt and increase potential energy savings especially at partial-load conditions. Currently available VC DX-DOAS now use a 52°F (11.1°C) leaving supply air dewpoint target. This paper will discuss test results of the VC DX-DOAS system and compare the potential energy-saving features to a fixed-flow two-stage cooling capacity DX-DOAS.

TEST DESCRIPTION

A study was conducted by a third-party to compare the performance of an existing fixed-flow DX-DOAS to the new VC DX-DOAS design during the summer and fall of 2016. A test site was chosen that had a variable occupancy schedule, an existing fixed-flow DX-DOAS that could be replaced, and that could accommodate a retrofit within the time constraints of the study period. The study was completed at an existing older Orlando high school cafeteria with an open plan. The 5,000 ft^2 (465 m^2) cafeteria had a design occupancy of 200 students at the time of the study. The design ventilation rate required 2,400 cubic feet per minute (cfm) (1,180 L/s) according to ASHRAE 62.1-2016.

Ventilation was distributed through a supply duct that ran down the center of the cafeteria along the long-axis of the building with well-distributed supply grilles about 12 ft (3.7 m) above finish floor. This duct was not connected to central space conditioning ducts. 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.). Interior temperatures were set at 71°F (21.7°C) during school hours to be able to keep indoor temperatures from rising beyond 78°F (25.6°C) during peak cooling load periods. Night setback was 78°F (25.6°C).

A certified efficiency rating was not available for the original fixed-flow DX-DOAS, but the site-measured energy efficiency ratio was found to be approximately 10 (Btu/h)/W with outdoor air at 95°F (35°C). This was the first field test of the new DOAS design. A certified efficiency rating for the new VC DX-DOAS was also not available. ASHRAE 90.1-2016 ISMRE efficiency requirements were not in place at this time of manufacture and installation.

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 carbon dioxide (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 any 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 were rare and would only occur if a sensor was malfunctioning or due to an unexpected environmental factor. Temperature, relative humidity and pressure-based airflow sensors were checked against portable sensors with NIST traceable calibration at the beginning of the project and found to be working within manufacturer specifications.

RESULTS

The primary objective of testing was to compare energy use of two different DX-DOAS designs and evaluate the energy savings potential of the new VC DX-DOAS system. Energy results are shown in two ways. The first compared direct measured energy during similar summer conditions. The second compared annual predicted energy use based upon simulation using measured data as input. The annual simulation predicted energy savings potential possible from DCV, higher efficiency DX-DOAS, and any periods of economizer operation. The summer day comparison indicates measured savings from DCV and higher efficiency DX-DOAS.

Savings potential from DCV is directly proportional to the decrease in occupancy from design occupancy as well as how much time the degree of reduced demand occurs. Figure 3 shows the measured VC DX-DOAS ventilation supply flowrate (proportioned to CO^2 demand) for five consecutive schooldays under a dashed line set at the design flowrate. Data is shown at 1 minute interval. The supply flow was changing in response to the variable occupancy demand. The measured CO^2 difference between indoor and outdoor was used. Outdoor CO^2 was typically about 400 ppm. Figure 3 shows that not only did ventilation demand significantly decrease from design, but each day could vary from another. Whle the CO^2 measured by the VC DX-DOAS was used in DCV, it was not recorded as part of the monitoring effort. Independent monitoring early in the project was used to verify the DOAS CO^2 accuracy.

Figure 4 shows measured data from a school day during occupied period from 6 a.m.-6 p.m. Data shown here is at 1 minute interval. This particular day may have slightly exceeded the indicated design occupancy based upon DOAS flow rate slightly exceeding 2,500 cfm (1,180 L/s) for some short durations. The VC DX-DOAS had a maximum flow of about 3,000 cfm (1,416 L/s), so if demand called for more than the calculated 2,500 cfm (1,180 L/s), then the airflow would increase beyond "design". Power and temperatures of the new VC DX-DOAS are shown on the left axis with the ventilation supply air flow shown on the right. The potential period of time for DCV savings is when the measured flow was less than about 2,500 cfm (1,180 L/s). This potential is shown in the shaded regions of Figure 4 that lie between the 2,500 cfm (1,180 L/s) design (orange dash line) and the measured supply flow (solid orange line). Figure 4 shows the supply air temperature dewpoint (SAT dpt) near 60°F (15.6°C) during lower flowrates and at about 55°F (12.8°C) near design flow rates. Two SAT dpt anomalies occurred around 4 and 5 p.m. where the SAT dpt rose above 60°F (15.6°C) for several minutes each time corresponding to a drop in energy use. The cause of this is unknown. Generally the unit provided cool dry air under a variety of entering conditions. The elevated periods of SAT dpt indicate perhaps some modification could help maintain SAT dpt closer to the 55°F (12.8°C) desired target or even lower as design requirements dictate.

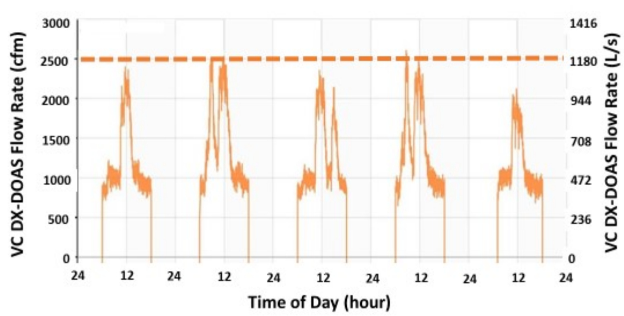

Figure 3. VC DX-DOAS CO^2 DCV flowrate over a school week.

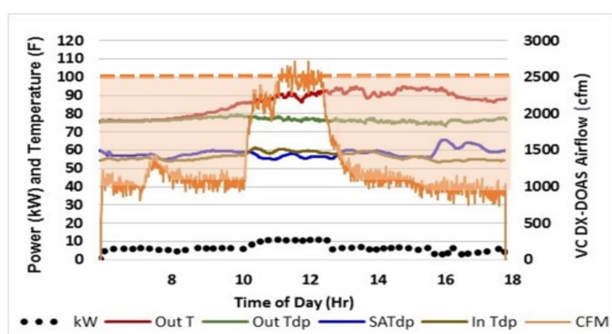

Figure 4. Hot-humid day with VC DX-DOAS flow, SATdpt, power use, outdoor conditions, and indoor Tdpt.

Package VC DX-DOAS Operations During Variable Weather Conditions

Figure 5 shows daily measured total energy of the new VC DX-DOAS vs daily average outdoor temperature. The daily total cooling data showed good correlation (R^2=0.91). Data points have been differentiated to identify cooling only from cooling and heating with some economizer operation. Economizer operation did not occur most of the time due to unsuitable outdoor conditions, although the economizer function appeared to function adequately during suitable periods. No cooling energy (economizer mode) was observed when the outdoor dpt was less than 56°F (13.3°C) dpt, and no heating was observed if outdoor temperature was greater than 54°F (12.2°C) db. During the testing period, economizer operation with at least 1 period of operation happened with outdoor temperatures between 64°F (17.8°C) to 70°F (21.1°C).

The lowest energy use shown happened on November 16, when the economizer operation occurred for all but about 15 minutes. The energy use was only 7.2 kWh (24.6 kBtu) for this 24 hour period. It is expected that the daily total energy (without heating or cooling) would bottom out at about 7 kWh (23.9 kBtu) for days with 100% economizer operation. According to the energy monitoring data, economizer supply fan operation (including electronics and other misc. power) varied from about 0.23 kW (785 Btu/h) at 1,000 cfm (472 L/s) up to about 0.50 kW (1,708 Btu/h) at 2,500 cfm (1,180 L/s) (5 minute data average).

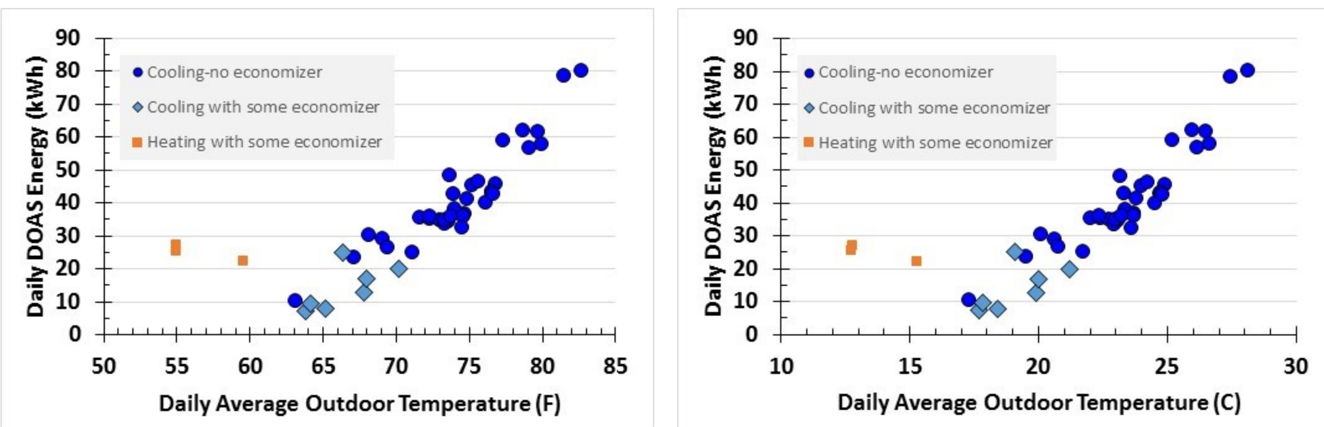

Figure 5. Daily energy use of VC DX-DOAS plotted against the daily average outdoor temperature.

Daily Summer Day Energy Comparison

The pre-retrofit monitoring period limited energy analysis to cooling energy use during hot summer weather. This is because the monitoring opportunity did not begin until June and retrofit had to occur before the start of the new school year in August. Direct comparison of daily total energy use of each DOAS was compared by selecting sets of school days with similar outdoor weather conditions. After selecting the site it was discovered that the existing DX-DOAS had a supply flowrate of about 5,000 cfm (2,360 L/s), exactly double the amount required. It is unknown why it was designed to be this high since the cooking area with exhaust fans and exhaust make-up air were in an adjacent wing separated by doors. This would obviously indicate much more savings largely in part to gross over-ventilation, which was not an intention of this project. This system was monitored and adjustments were made to summer comparison analysis to allow a more equitable comparison to the new properly sized VC DX-DOAS. Assuming the same efficiency and entering air conditions in an appropriately sized fixed-flow DX-DOAS, half the airflow would require half the energy as measured at the 5,000 cfm (2,360 L/s) flowrate. This can be confirmed through psychrometric calculation. The existing DX-DOAS energy at a fixed-flow of 2,500 cfm (1,180 L/s) was determined by using half the measured energy of the existing DX-DOAS at 5,000 cfm. This allowed a simple comparison during a typical Florida summer day. Results are shown in Table 1 and are representative for a summer day with daily average outdoor conditions of 80°F (26.7°C) and 75°F (23.9°C) WB for DX-DOAS. Results are also specific to 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 new VC DX-DOAS set at a fixed-flow rate of 2,500 cfm (1,180 L/s) as well as for the new unit with ASHRAE 62.1-2016 CO^2 demand-based control implemented. The CO^2 control was based upon the measured CO^2 differential between indoors and outdoors.

Energy savings are shown relative to a fixed-flow DX-DOAS. Operating the new VC DX-DOAS at fixed-flow allowed an opportunity to differentiate savings from improved efficiency of the VC DX-DOAS and savings associated with DCV. The second row shows benefit of the more efficient VC DX-DOAS design. The third row shows the combined benefit of efficient mechanical operation combined with energy conservation that occurs through CO^2 control. The daily comparisons between the existing fixed-flow DX-DOAS and VC DX-DOAS operated at fixed-flow show that the new DOAS design used 26% less daily energy. The new design combined with DCV resulted in a combined total energy reduction of 53%. The DCV alone accounted for about 38.4 kWh/day energy reduction (104.9 kWh – 66.5 kWh=38.4 kWh) which represented a 27% energy decrease from the replaced fixed-flow DOAS summer daily energy use.

Table 1. Measured DOAS Summer Daily Energy for High School Cafeteria

Test	Test Description	Energy Use	Savings Compared to Test 1	Savings (%)
1	Replaced DX-DOAS fixed-flow at 2,500 cfm (1,180 L/s)	141.3 kWh (482 kBtu)	---	---
2	VC DX-DOAS forced to fixed-flow at 2,500 cfm (1,180 L/s)	104.9 kWh (356 kBtu)	36.4 kWh (124 kBtu)	25.8%
3	VC DX-DOAS with CO^2 DCV	66.5 kWh (227 kBtu)	74.8 kWh (255 kBtu)	52.9%

Predicted Annual Energy Comparison

The VC DX-DOAS unit was able to be monitored for about 3 months allowing a performance model to be developed that could be used with typical meteorological year data for Orlando (TMY3 Orlando) data to predict hourly energy use over an entire year. This was compared to an annual simulation of a fixed-flow DX-DOAS using EnergyPlus (DOE 2017 A).

The replaced fixed-flow DX-DOAS unit was not able to be monitored long-enough to develop a model suitable for a whole year simulation. Instead, 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 DX-DOAS with fixed-flow at 2,500 cfm (1,180 L/s) and EER=10 (Btu/h)/W. 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. The same days and schedule were also used for the VC DX-DOAS annual energy prediction. The EnergyPlus simulation also called for space conditioning according to the actual monitored cafeteria indoor temperatures. The daytime school day setpoint was 71°F (21.7°C) with nighttime set-back at about 78°F (25.6°C). The fixed capacity DX-DOAS was sized to meet the ventilation load. Independant space conditioning systems with qualities mentioned earlier were used in the simulation to provide space conditioning to meet building cooling loads.

Energy models were developed for the VC DX-DOAS using measured energy, supply airflow, along with outdoor dry bulb and dewpoint temperature data. A least-squares best-fit regression analysis was used to create equations developed from the measured data. A simple least-squares best-fit regression of daily energy versus outdoor temperature worked well for daily analysis (Figure 5), but was not suitable for hourly simulation.

Multiple linear regression (MLR) least-squares analysis was utilized to develop an equation that could be used at hourly intervals. MLR correlation coefficient was 0.80 with standard error of 1.21 kW. This mode of operation represented 74% of the annual school schedule hours based on TMY3 Orlando weather data. The equations were then used with TMY3 Orlando hourly data to predict annual energy use. The new unit with CO^2 DCV energy model accounted for occupancy variability based on a composite supply flow schedule developed from monitored data. The composite cafeteria DOAS ventilation supply flow shown in Table 2 was used for each school day of the predicted energy calculation.

Table 2. Composite Hourly Average DOAS Demand Ventilation Supply Flowrate

	Time- Hour of Day											
	7	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**
Airflow ft^3/m	617	1028	1382	1262	1481	2063	1941	1261	1119	1086	922	900
Airflow L/s	291	485	652	596	699	974	916	595	528	513	435	425

Annual energy calculations of the new DOAS also included hourly periods when economizer operation would occur. Economizer mode of operation represented 21% of the annual school schedule hours based on TMY3 Orlando weather. DOAS heating use is minor for an area like Orlando representing only about 5% of annual school schedule hours. There was inadequate heating hour data to develop a statistically valid heating model, therefore, heating energy was not included. A separate period of measured performance was also performed with the VC DX-DOAS set to a fixed-flow at 2,500 cfm (1,180 L/s) (no CO^2 DCV). This enabled the energy savings from DCV to be separately evaluated from the efficient technology design. Two equations used with TMY3 Orlando data follow.

For new VRF/VAF DOAS cooling operation when outdoor Tdb≥ 54°F and Tdpt ≥ 56°F:

(1) kWh = (supply cfm * 4.3761E-05 + out Tdb (°F) * 1.67E-03 – 0.1288)*60

For new VRF/VAF DOAS economizer operation when outdoor Tdb≥ 54°F and Tdpt < 56°F:

(2) kWh = (supply cfm * 3.0521E-06 + 8.5E-04)*60

Results of the calculated annual DX-DOAS energy are shown in Table 3. The energy includes total DX-DOAS energy use except during any heating hours. Energy savings are shown relative to a fixed-flow DX-DOAS unit. Operating the VC DX-DOAS at fixed-flow allowed an opportunity to differentiate savings from improved efficiency design from savings only associated with DCV. The second row shows benefit of the more efficient VC DX-DOAS design. The third row shows the combined benefit of efficient mechanical operation combined with energy conservation that occurs through CO^2 DCV control.

Results in Table 3 show that the VC DX-DOAS design without DCV used 41% less annual energy. The new design combined with DCV resulted in a total annual energy reduction of 77%. The DCV alone accounted for about 8,790 kWh/yr energy reduction (14,354 kWh – 5,564 kWh) which represented a 36% energy decrease from the pre-existing replaced fixed-flow DX-DOAS annual energy use. Greater percent savings should be expected for annual evaluation compared to savings during an average summer day. This is due to the benefit of economizer function in the new VC DX-DOAS design and more efficient operation at part-load conditions that occur particularly during cooler and drier times of the year.

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

Test	Test Description	Energy Use	Savings	Savings (%)	Savings $/design cfm
1	DX-DOAS fixed-flow at 2,500 cfm (1,180 L/s)	24,503 kWh (83.6 MBtu)	---	---	---
2	VC DX-DOAS forced to fixed-flow at 2,500 cfm (1,180 L/s)	14,354 kWh (49.0 MBtu)	10,149 kWh (34.6 MBtu)	41.4%	$0.41/cfm
3	VC DX-DOAS with CO^2 DCV	5,564 kWh (19.0 MBtu)	18,939 kWh (64.6 MBtu)	77.3%	$0.76/cfm

Savings $ /design flow of 2,500 cfm based on simplified rate of $0.10/kWh

The results in Table 3 have also been shown as $ saved per design cfm. This can be a way to compare one application to another. There are currently no known published results of measured energy comparisons between package VC DX-DOAS with DCV and fixed-flow package DOAS completed in hot and humid climate zones. Studies completed in the Midwest U.S. indicate savings value of about $0.60/design cfm and payback between 2-5 years (Hackel et al. 2015) and (Crowther 2015). The Hackel 2015 DCV study of 6 buildings that implemented DCV into large VAV systems had a median $0.50/design cfm with a range of $1.14-0.35/cfm and payback 4-8 yr. The cost per cfm of the VRF/VAF package DOAS is around the range of other studies. There was no cost yet assigned to the first generation field VRF/VAF DOAS evaluated in this paper so no further economic analysis is made here.

CONCLUSION

A new package variable capacity DX-DOAS was designed and tested to evaluate the performance and energy savings potential in a real application located in a hot humid climate zone. Variable air flow makes it easier to modulate ventilation according to demand. The key to doing this is to maintain good moisture and temperature control of the supply air. This was accomplished by having the appropriate amount of cold evaporator coil exposure across a wide range of ventilation air flow rates. This also means that one does not want air flow across any warm evaporator coil surfaces which diminishes dehumidification performance, and could re-evaporate moisture off of a warm wet coil back into the supply air. The VC DX-DOAS incorporated VRF and VAF along with proportional coil exposure control. This design demonstrated that such a design not only works, but has large energy savings potential compared to fixed-flow package DX-DOAS. It also has good dehumidification control across a wide range of airflow from about 20% of full design flow up through 100% of design flow.

This study compared the energy of an existing fixed-flow packaged DX-DOAS with two-stage compression to a new package VC DX-DOAS design at an existing high-school cafeteria. The pre-existing fixed-flow DX-DOAS was found to be delivering twice the required ventilation rate, which would have indicated twice the savings of an appropriate sized DX-DOAS. The study was not intended to evaluate savings from higher design flowrate than required so pre-existing DX-DOAS measured energy was decreased 50%. The new VC DX-DOAS was tested at both fixed design flow and with CO^2 DCV. The VC DX-DOAS with DCV resulted in daily summer energy reduction of 53%. About half of the reduction was associated with DCV and the other half with higher operational efficiency.

Simulation was used to predict annual potential savings. Annual energy percent savings were greater compared to summer day savings due to the benefit of economizer function of the VC DX-DOAS and more efficient operation at part-load conditions. The VC DX-DOAS with DCV resulted in an annual energy reduction of 77%. Operational efficiency accounted for 41% of total savings and DCV accounted for the other 36% annual savings. This study was conducted in a space with a wide variability in ventilation demand. Savings from CO^2 DCV in other applications will vary according to the range of demand. DCV may not be suitable for some applications where design occupancy variability is limited.

Testing of a unique first-generation design showed that VRF/VAF can be implemented in packaged DX-DOAS successfully and is capable of delivering suitably conditioned ventilation air under diverse occupant demand with high savings potential compared to fixed-flow package DX-DOAS in hot humid climates.

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