Measured and Simulated Economizer Performance with Demand-controlled Ventilation in an Institutional Building

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Abstract

The ASHRAE 62.1 ventilation standard stipulates minimum outdoor air (OA) requirements for commercial buildings. The standard includes provisions for lower OA supply with demand-controlled ventilation (DCV). Air-side economizers (ASE) increase the OA flow beyond minimum requirements to reduce use of mechanical refrigeration when weather conditions permit. Economizer performance data were collected over a two-year period to evaluate EE4-DOE2 simulation of hybrid DCV-ASE in two systems in a 12,000 m^2 building in Calgary.. The results show the DCV hours predicted in the model were three times greater than the actual operation. The results were consistent with those from a calibration study carried out with the same EE4-DOE2. The analysis showed that the OA damper position relative to the OA temperature can be used to estimate DCV use and is a helpful first indication of the validity of a model both as a reality check and a calibration aid.

1 Introduction

Demand-controlled ventilation (DCV) can reduce the large energy use for both sensible heating and humidification of OA in cold regions, because the relative humidity of outdoor air drops as it is heated. While Liu et al. (2012) wrote "No case studies of [multiple zone] implementations using CO_2-based DCV were found," a couple do seem to have been reported for cold climate buildings. Janssen et al. (1982) found a 20% reduction in heating of outdoor air for a 4-zone system. Raatschen (1990) reported a 40% reduction for a 4700 m^2 office building in Finland, but gave few. According to Hong (2010), DCV is less advantageous with a low fraction of OA in the supply air (SA). Before deciding on DCV implementation details such as sensor location, designers must evaluate financially viability and environmentally soundness for a specific application.

The potential energy use reduction with DCV depends on a couple of factors. One is net internal loads that vary with building envelope thermal exchanges, occupancy type, activity pattern, etc.. Another factor is potential for air-side economizer (ASE) use. ASEs cool buildings by increasing the fraction of unconditioned OA in the SA when outdoor temperatures permit (core areas of large buildings typically require year round cooling, even in very cold climates). A hybrid DCV-ASE system can further reduce energy use (Rock and Wu 1998). Since OA dampers are opened above the low temperature setpoint with free cooling, DCV should be deactivated to avoid increased energy use (Brandemuehl and Braun 1999). This explains the reason reported DCV studies assess performance outside the free cooling range (Nassif and Zaheer-uddin 2007, Sun et al. 2011). Simulation studies of hybrid DCV-ASE in various climates have been published for single-zone systems (Brandemuehl and Braun 1999, California Energy Commission 2002) and multiple-zone systems (MZS) (Hong 2010). In cold climates, DCV has greater energy efficiency potential in buildings with large heat losses where there is less opportunity for air-side economizer (ASE) use (Brandemuehl and Braun 1999), also known as free cooling. However, there has been little empirical verification. Lau et al’s (2013) report on DCV control for MZS, including consideration of DCV-ASE interactions, was limited to simulation.

Maxwell et al. (2004) reported validation of economizer simulation (no DCV) with DOE2 and TRYNSYS for two variable air volume (VAV) overhead mixing MZS with terminal reheat in an 850 m^2 test building in Iowa. The TRNSYS time step was 0.005 h (DOE2 is limited to 1 h steps) for accurate simulation of the VAV box proportional-integral controllers. The two paired MZS (designated A and B) each served four 25 m^2 test rooms (adjacent east, south, west and core spaces); while a third system served the remaining spaces. Internal loads were constant, safe for some daylight-responsive control of electric lighting. Twelve days of tests occurred in late March to early May; system B was used as a constant OA control. One hour averages of 1 min data were used for simulation and analysis; the report lacked any discussion of variability (e.g., of damper position) within the 1 h periods. Maxwell et al. found discrepancies in their initial air flow rate measurements. Fisk et al. (2004a) used a specialized lab rig to evaluate OA flow measurement systems. They noted that, to achieve even 20% accuracy in AHUs with ASE, the OA intake would require two parallel sections, each with an OA damper, for flow velocities sufficient for accurate measurement. Maxwell et al. resorted to a dual high and low flow measurement system to address this. Fisk et al. (2008) found that using electronic probes at the intake dampers worked, with calibration required for each damper type and velocity sensor location.

Given the paucity of reported ASE verification, ASE was evaluated in comparison with results from the literature and from a simulation model of hybrid DCV-ASE. Data collected in the course of other investigations such as (Gestwick and Love 2013) were used for this purpose.

2 The Child Development Centre

The study building was the University of Calgary Child Development Centre (CDC) in Calgary, Alberta (Figure 1), which is in ASHRAE climate zone 7 (very cold) (ASHRAE Standard 90.1 (2010)).

Figure 1 - Child Development Centre

The CDC is a 12,000 m^2, four-storey, Leadership in Energy and Environment Design (LEED) Platinum certified building. The CDC officially opened in 2007, before which an EE4-DOE2 (Natural Resources Canada 2008) model of the building was created for LEED ` peer review. Because the fitout design of some portions of the interior remained unknown in 2007, these were modelled according to EE4 modelling procedures. Tian et al. (2009) provide many additional details on the EE4-DOE2 model used for the CDC.

2.1 Mechanical Systems

The CDC has two main recirculating VAV air handling units (AHUs) equipped with CO_2 DCV, with sensors in all high occupancy density rooms. AHU1 serves level 1 and part of level 2 (higher occupant density spaces), while AHU2 serves the remaining, lower occupant density spaces; both AHUs have air- and water-side economizers (the latter for additional summer cooling). All room supply is via stratified ventilation systems (Table 1). This paper focuses on AHU2, with total and OA flows of 2.2 L/s m^2 and 0.4 L/s m^2, respectively.

Table 1 - Mechanical System Summary

- Zone-level and AHU level CO_2- DCV
- Dry-bulb air- and water-side economizers
- Level 1: VAV recirculating displacement ventilation – low wall diffusers
- Level 2 - 4: VAV recirculating ducted underfloor air distribution
- Overhead radiant cooling for south perimeter zones
- Baseboard heating for perimeter zones (hydronic, condensing gas-fired boilers)
- Exhaust air heat recovery

2.2 Occupancy Type

The CDC is used for multiple purposes, which determined the configuration of its spaces and systems. The main floor houses mainly multi-occupant spaces, including a childcare centre and a school for children with severe developmental disabilities. Other than a common public area on the second floor east mezzanine, where occasional large gatherings may occur, the second floor houses a mix of medical assessment rooms, meeting rooms and offices. The third and fourth floors were largely unoccupied large open spaces in 2010 and 2011 when data were collected. 1600 m^2 of the third floor was occupied by a foundation in 2011.

2.3 Occupancy Schedule

DCV benefits depend on occupancy patterns and fan schedules; spaces where population varies greatly provide the most DCV benefit. During this study, the CDC fans were scheduled ON 6:00 to 18:00 while occupants were typically present 8:00 to 16:30. Since 1) continuous monitoring of occupants was beyond resources available to the project and 2) there was no way of knowing the representativeness of a sample from a spot check,, occupant numbers were based on the literature (Huang and Franconi 1999). For offices, this is typically about half the number assumed for design purposes.

3 Methods

Subtracting the yearly ASE use hours from the total number of occupied hours gave the annual number of potential DCV hours. This section explains the approach used to determine the number of hours the system was operating in 1) free cooling mode and 2) DCV mode. Background information about theoretical ASE operation is first provided, followed by details on the data collection procedure. Finally, the number of DCV hours predicted by the EE4-DOE2 model was compared to the measured data.

3.1 Issues in Comparing Economizer Model Estimates with Measured Values

The CDC AHUs lacked the dual OA system described by Fisk et al. (2005b) (see section 1) and the time and resources available precluded installation and calibration of an intake flow rate measurement system (Fisk et al. 2008). AHU2 has SA and return air RA) flow sensors, but lacks OA and exhaust sensors. AHU2 is very close to the building envelope with exhaust and intake duct cross sections varying between the air handler and the envelope, another important error factor identified by Fisk et al. (2004b). Given these impediments, the damper position (fraction of opening) was compared with the fraction of outdoor air in this preliminary analysis. In future work, the SA, RA, and OA DBTs could be used to calculate air flow rates. This could be checked with SA, RA, and OA CO_2 concentrations.

A potential issue with economizer studies is system variability relative to simulation time step. The Building Automation System (BAS) logged instantaneous damper position at 30 min intervals. The two main measurements used for this research were the OA DBT and the OA damper position (% open); the hourly medians of 30 min interval data points were used. The median interval to interval differences in damper opening for the first 6 mo of 2010 during normal operation (see section 4 regarding hours excluded from analysis) was 1% of opening with a median absolute deviation of 1%. In other words, large, sudden changes during normal operation were rare.

3.2 Theoretical Air-side Economizer Logic

ASEs can either be based on enthalpy or dry-bulb temperature (DBT) measurements (sensible ASE). In a dry climate such as Calgary's, enthalpy-based economizers are seldom used because of their added initial and maintenance costs and negligible advantage over sensible economizers (Rock and Wu 1998).

A sensible ASE typically has a high-limit and a low-limit shutoff temperature as shown in Figure 2 (Rock and Wu 1998, Stanke and Bradley 2006).

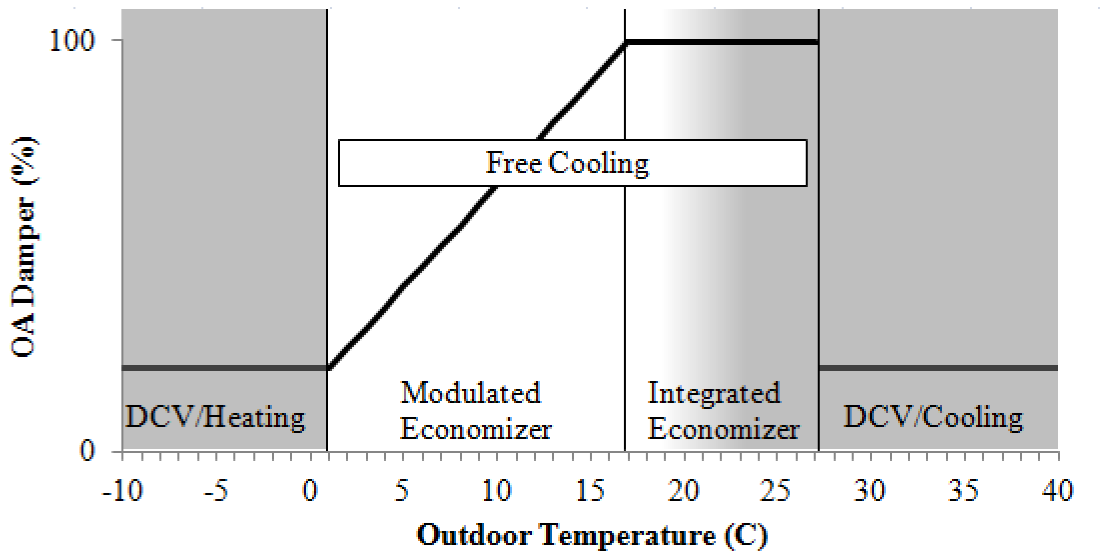

Figure 1 – Theoretical economizer and DCV operation

The low-limit shutoff point can be a fixed temperature or vary with the building heating load, but is usually -12.2°C to 4.4°C (Rock and Wu 1998). If the shutoff point varies, the ASE should turn off when the AHU heating coil must warm the SA. DCV will then be used to ensure only the real-time OA requirement is being introduced. The ASE is said to be in "modulated" mode when the cooling load can be met simply by modulating the OA dampers (when OA temperature is about 0 to 15 °C). In "integrated" mode, 100% OA is introduced and the cooling coils provide additional cooling capacity (about 15 to 24 °C OA temperature). Typically, the ASE high-limit shutoff temperature, or temperature at which free cooling is not used, is set to a temperature recommended by ASHRAE Standard 90.1 (ASHRAE 2010). DCV is used when OA temperatures (OAT) reach or exceed the high-limit shutoff temperature.

3.3 AHU1 Air-side Economizer Logic

AHU1 is equipped with a heat recovery wheel (HRW). The building mechanical system control sequences (Direct Energy Business Services (SNC-Wiebe Forest) 2008) show that the CDC HRW only operates when the ASE is not in use. The HRW was set to work at OAT below 11ºC or above 26 ºC during the study period, limiting the DCV use to a statically set range.

3.4 AHU2 Air-side Economizer Logic

The focus of this study was AHU2, which had a floating low-limit shutoff that varied with the building internal loads and no high-limit shutoff temperature (Figure 3), as specified by the mechanical documents. Lack of a shutoff temperature in Calgary would have little impact on the energy use of a building, but may have a substantial positive impact on indoor air quality. For the purpose of this work, AHU2 was observed operating as shown in Figure 3.

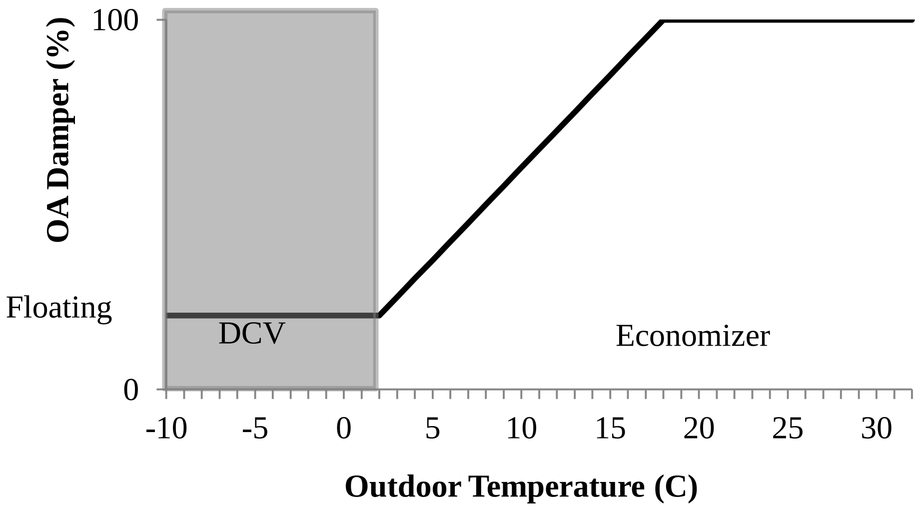

Figure 2 – AHU2 air-side economizer and DCV operation

The low-limit shutoff temperature was set arbitrarily in Figure 3 since, as noted it was its exact value was obtained by analysing measurements.

In order to determine the DCV hours for AHU2, the OA damper opening was plotted relative to the OAT. The OAT was rounded to whole values and the average damper opening for each temperature was calculated and plotted on a second graph. The inflection point on the curve where the OA damper opening was constant was determined using MATLAB and was considered the low-limit shutoff temperature. The number of fan operation hours below this shutoff temperature was totalled to determine the number of DCV hours for AHU2. A second order polynomial curve fit was done with the 30 min interval BAS damper position data; the R^2 was 0.62 for 2010 data and 0.80 for 2011 data, so DBT was the dominant influence.

3.5 EE4-DOE2 Model Air-side Economizer Logic

Although whole building simulation programs with more advanced features (e.g., subhourly intervals, underfloor air distribution module) have been developed, DOE2 is still a widely used simulation engine and was used in Maxwell et al.’s (2004) economizer validation study. The CDC EE4-DOE2 model ASE logic is shown in Figure 4. The only difference from Figure 3 is that the model high-limit shutoff temperature was 21°C (as noted in 3.3 AHU2 lacked a high-limit shutoff temperature.) The number of hours when the OA DBT was below the average low-limit shutoff temperature was summed to determine the potential DCV hours.

The EE4 interface lacks the capacity to modify DOE2 parameters related to DCV, so the DOE2 file generated by EE4 was used directly. The DOE2 custom hourly report facility was used to extract information such as OA fraction and DBT.

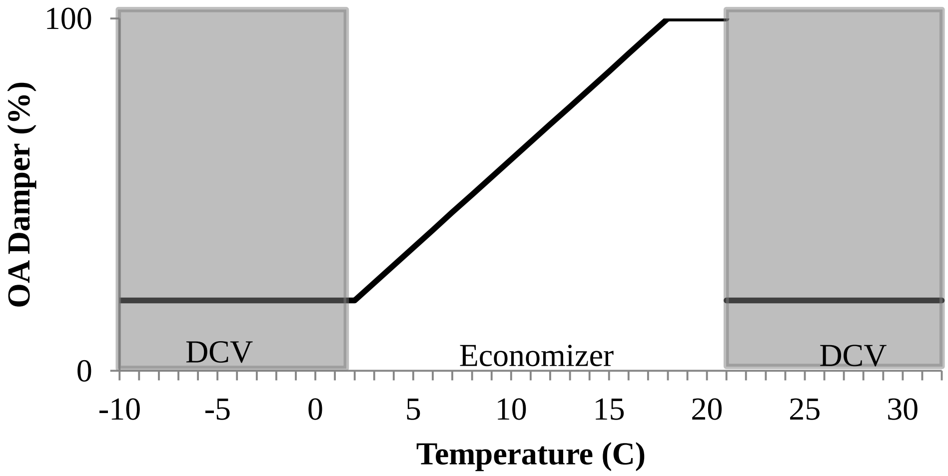

Figure 3 - CDC EE4-DOE2 model air-side economizer and DCV control regions

4 Results

Based on the fan schedule (section 2.3) and working day dates, the CDC fans were on for approximately 3120 AHU2 annual operating hours. More precisely, data were collected for 2992 h in 2011 and 2973 h in 2010. Missing data were due to 1) issues with seasonal time changes (discussed in section 4.2) and 2) data being overwritten due to a retrieval interval exceeding the BAS data storage capacity.

4.1 Typicality of the weather

The typicality of the outdoor temperature conditions was assessed by comparing 2010 and 2011 at AHU2 OA DBT with those in the Calgary CTMY2. Different approaches can be taken for climate comparison such as heating degree-days (HDD) and mean annual temperature. Of the factors affecting ASE use (internal gains, envelope thermal exchanges, and OA DBT), DBT has the most variable effect on ASE operation in Calgary, since diurnal temperature swings are larger than for most locations in Canada due to the 1100 m altitude and sunny climate. This is supported by the typically small interval to interval economizer adjustments discussed in 3.1. While the solar radiation affects OA DBT, the CDC has a low window-to-wall-ratio of 0.21 and the south-facing windows are extensively shaded; combined with the deep floor plate, this reduces sensitivity of net interior loads to solar radiation. Model sensitivity to various parameters is discussed further in (Gestwick and Love 2013). Given the influence of OA DBT, this analysis was based on counting hours below the threshold OA DBT. Therefore, the years were compared based on the number of hours each OA DBT was represented. The resulting graph is shown in Figure 5.

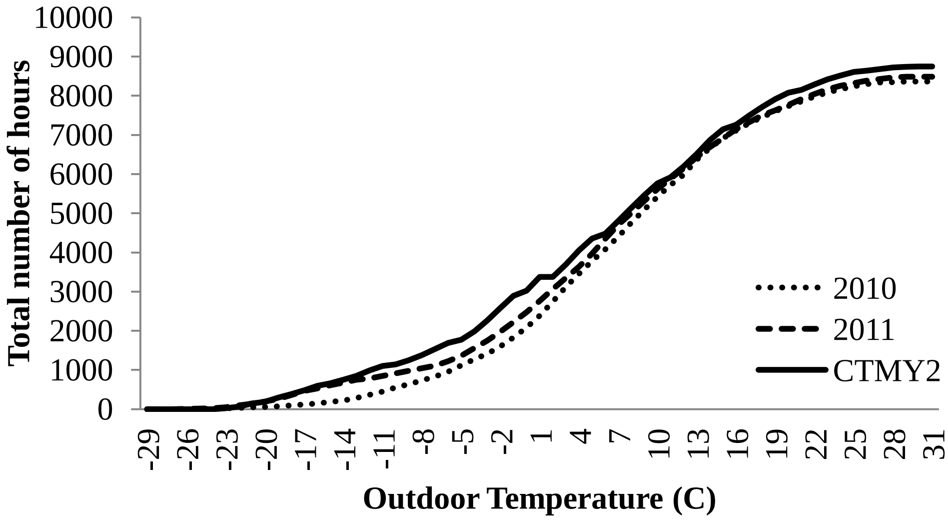

Figure 4 - Cumulative hours above outdoor temperature thresholds

All three years showed a similar pattern. The h total for each year differed as some points were missing from the collected data for various reasons, as noted above. In 2010, 2011 and CTMY2, the totals were 8366, 8488 and 8760 h, respectively. At the largest gap between the three curves on Figure 5, 29% of the h recorded was below 1°C in 2010 compared with 39% in CTMY2, a 25% difference. This difference is important to bear in mind when results are compared.

4.2 AHU2

The opening of the OA damper for each occupied hour was graphed relative to the OAT for the years 2010 and 2011. The distribution of data would be expected to resemble Figure 3.

4.2.1 2010 Measurements

Figure 6 shows the distribution of hours for data collected in 2010 at AHU2 which resembles the theoretical curve of Figure 3.

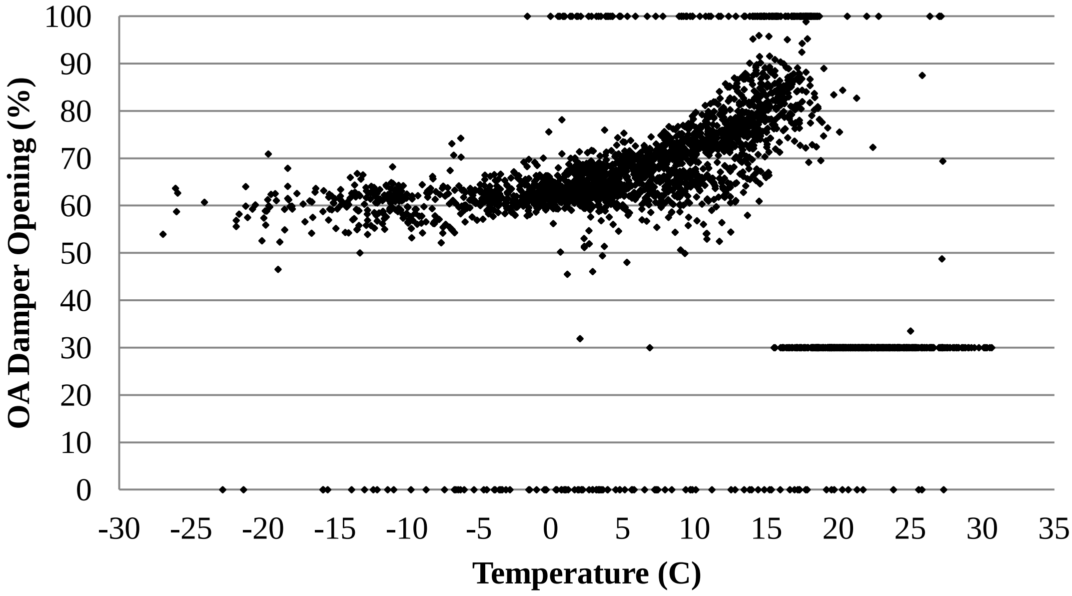

Figure 5 - 2010 AHU2 actual OA damper opening relative to OAT

In 2010, between 15°C and 30°C, the system reverted to a 30% opening of the OA damper. This situation was rectified in 2011 as can be seen in Figure 8. It was also observed that the OA defaulted to 10% for 1 h at morning startup and would close dampers completely for the last daily hour. Since extensive data was available, it was possible to retain a very large number of points after dropping the outliers. The 6:00 – 7:00 am and 17:00 – 18:00 pm points were therefore excluded to find the average opening of the dampers. Even though these points were excluded, some outliers of 0% and 10% were still observed. It was found that, in 2010, the system failed to revert to normal time when Daylight Saving Time (DST) ended. These irregular points were removed from the data set.

In February 2010, the OA damper was completely opened with temperatures below 0 ^{o}C. Data showed this was the case for only 1 wk (February 2 to February 9 2010). It can therefore be assumed that either the system was defective and subsequently fixed or it was intentional as work was being performed at the building site around these dates. These points were also removed. Once all points previously mentioned were removed, the median damper opening by ^{o}C was extracted and plotted as shown in Figure 7.

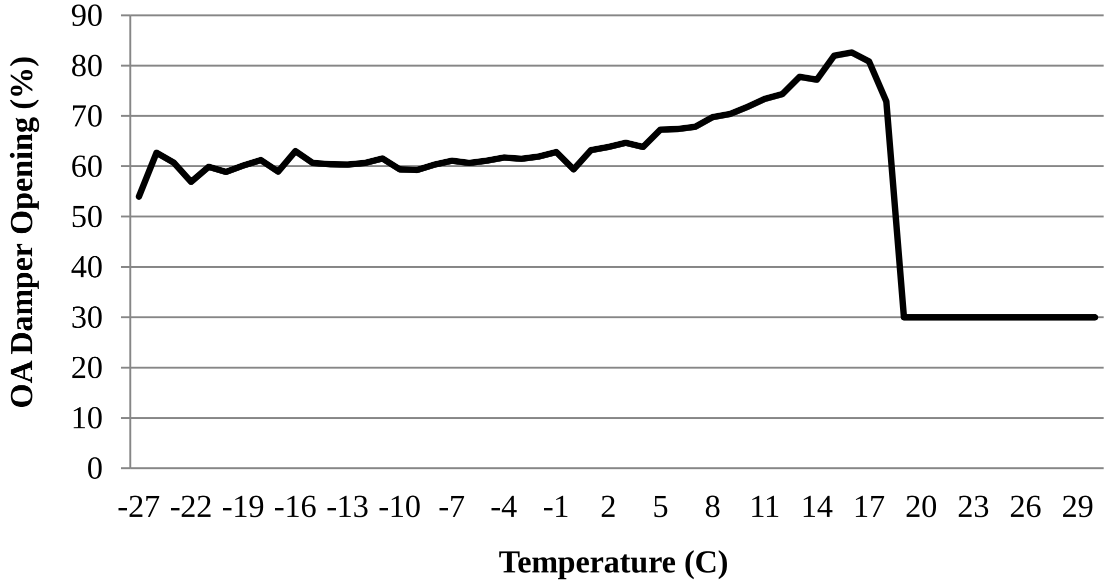

Figure 6 - 2010 average AHU2 OA damper opening at each OAT

Based on Figure 7, the minimum OA for the building appeared to be around 60%. The point where the curve reached a null slope was determined using MATLAB and was considered the low-limit shutoff temperature. The same analysis was repeated with 2011 data.

4.2.2 2011 Measurements

In 2011, most 2010 defects appeared to have been resolved as shown in Figure 8. Some points around -15°C to -20°C fell outside the general trend of 30% to 90% opening. These points were all from February 17 and 18. The data for these dates showed anomalous OA damper behaviour. Once more, a temporary defect or maintenance work was assumed as performance normalized after those two days. There were also additional points at 10% when DST ended in November. The situation was fixed within less than a week; these few 10% and 0% points were removed from the data set. The median hourly OA damper opening for the remaining data points is shown in Figure 9.

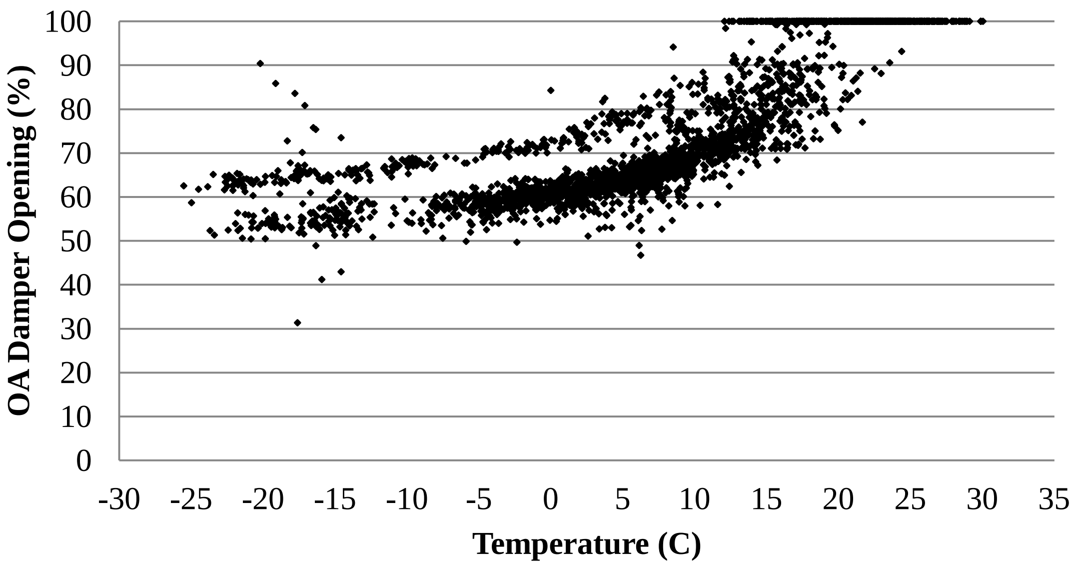

Figure 7 - 2011 AHU2 OA damper opening relative to OAT

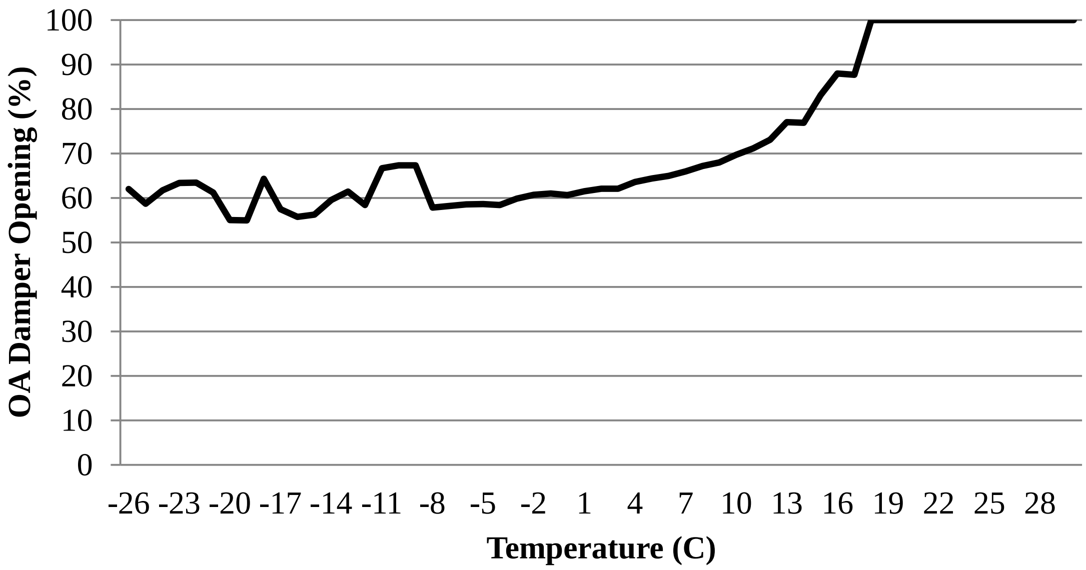

Figure 8 - 2011 average AHU2 OA damper opening at each OAT

Figure 9 closely reflects the theoretical curve shown in Figure 3. As observed in 2010, the average minimum OA opening appeared to be around 60%. The transition point between free cooling and DCV in Figure 9 was located approximately at -2°C. The difference from 2010 could partially be attributed to the weather difference noted in section 4.1.

4.3 DOE2 Model

The hourly AHU2 OA fraction position versus DBT was determined with the DOE2 code generated by the EE4 interface as shown in Figure 10.

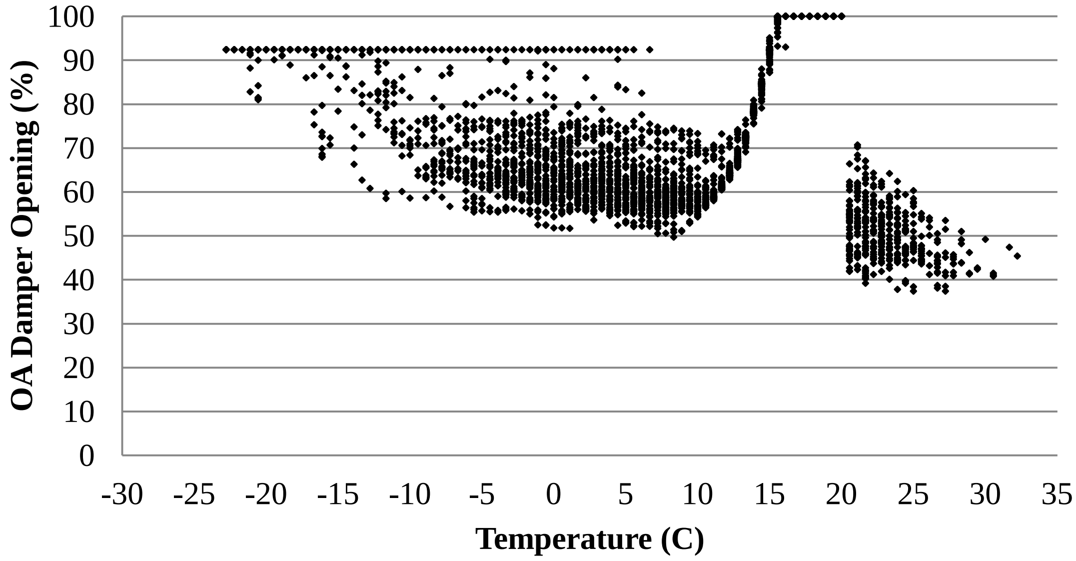

Figure 9 –AHU2 OA damper opening relative to OAT from DOE2 code generated by EE4 interface.

The distribution would be expected to resemble Figure 4. Values representing closed OA dampers were removed from the data set as they represented either weekends or times when fans were off. Doing so resulted in exactly 13 h of operation, five days a week for 52 weeks or 3993 h. The curve of hourly median is shown in Figure 11.

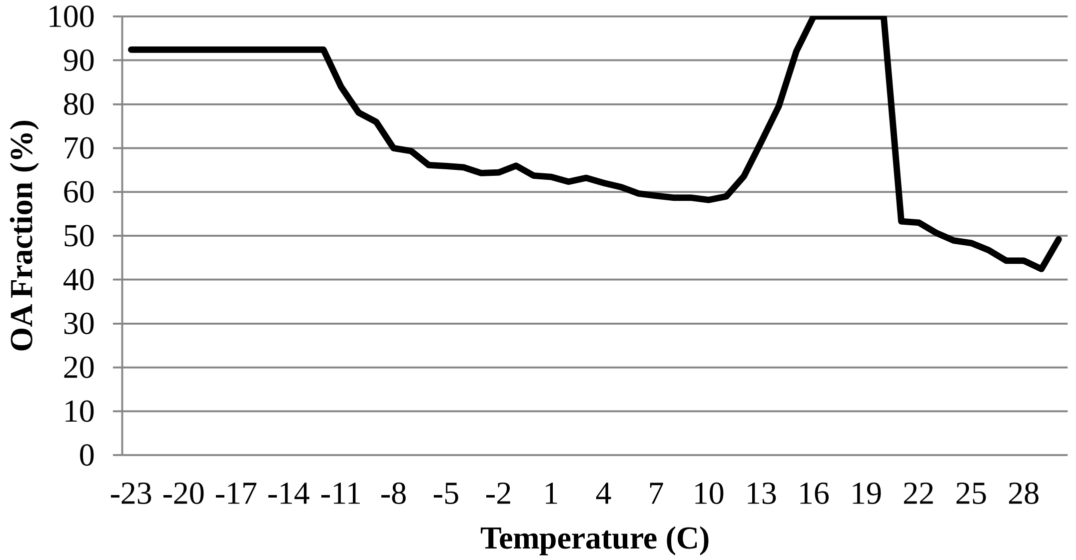

Figure 10 –AHU2 OA fraction relative to OAT from DOE2 code generated by EE4 interface.

In Figure 11, the high fraction of OA at low temperatures is due to AHU2 VAV going to a low SA flow rate, while the OA flow remained constant. The OA fraction would be constant at lower temperatures when the VAV system reaches its minimum flow. There were about 400 h with DBT below -14 ^{o}C when the OA fraction was above 0.90 or about 13% of AHU2 operating hours. The simulated ASE lower shutoff point was approximately 11°C (the minimum OA fraction) substantially higher than the measured values. The simulated free cooling range was therefore much smaller than the actual. While DOE2 has an economizer lower limit temperature parameter, this was left unspecified by the EE4 interface. DOE2 documentation such as the Engineers Manual (LBL 1982) lacked any discussion of the lower limit calculation when unspecified; presumably it minimizes heating energy use while meeting minimum outdoor air requirements, which would be consistent with Figure 11. Possible explanations include 1) the stratified ventilation system (due to higher return air temperatures than with a mixed condition), 2) higher internal gains than modelled, and 3) lower net envelope losses than modelled. Further investigation is required to determine the cause. The simulated building internal loads controlled the damper position only when in economizer mode, between 11°C and 21°C. When in economizer mode, the model OA fraction matched the theoretical curve shown in Figure 4. Below 11°C and above 21°C, the OA fraction corresponded to the design minimum OA requirements of the building or the time when DCV would be used. It is important to note that DCV can only be simulated in EE4 by manually modifying ventilation schedules.

4.4 Model and site measurement graph comparison

The theoretical curve of Figure 4 is for a constant air volume (CAV) system, where the minimum OA fraction is constant. The simulation model OA fraction in Figure 11 increased as temperatures decreased, due to the CDC having a variable air volume (VAV) distribution system. In theory, as cooling loads decrease, VAV flows are reduced to a minimum setpoint (where heating is handled by a perimeter hydronic heating system, as is typical in cold climates) and the OA fraction must increase to maintain the zone minimum OA requirements. The recorded OA damper opening would also be expected to increase as outside temperatures decrease for the same reason. However, Figure 9 shows that the OA damper opening was constant as temperatures decreased. The CDC data showed the supply air CO_2 levels occasionally reached 900 parts per million (ppm), because of the near constant damper opening at low temperatures. Supply air CO_2 levels typically hovered around 500 ppm during milder weather. The cause of the flat damper response requires further study, but understanding whether the CO_2-DCV system functions properly at the CDC would not affect the extent of DCV use.

4.5 DCV use summary

The ratios of occupied hours below the shutoff temperature are summarized in Table 2.

Table 2 - Percentage of DCV use in Calgary AB

		AHU2	
Source	**Weather**	**DCV Use**	**Free Cooling Range**
Measured Data	**2010**	18%	Above -2 °C
Measured Data	**2011**	17%	Above -4 °C
Model	**CTMY2**	61%	11-21 °C

The AHU2 DCV use in the model was 3 times greater than that determined from the measured data. The model was finalized for certification near the end of design when much information about actual conditions remained to be determined. For example, the tenant fit out for levels 2 to 4 was unknown as was that for the Renfrew Centre area on level 1. The model used specified reference conditions (Natural Resources Canada 2007). During 2010 and most of

2011, AHU2 served only level 2 of the building (levels 3 and 4 had yet to be fitted out and occupied). The data for both years 2010 and 2011 were consistent showing AHU-2 typically used DCV for approximately 20% of yearly fan operating hours.

5 Discussion

As noted above, the AHU2 service area was only partially occupied when data were collected in 2010 and 2011. Further studies on the free cooling range should be done as building occupancy increases (by the end of 2012, level 4 was fully occupied and level 3 about 50% occupied). The 2010 and 2011 results for the partially occupied building showed DCV was used approximately 20% of AHU2 operating h, which was consistent with the simulation results reported by Rock and Wu (1998) for Madison, WI, the closest climate to that of Calgary. Rock and Wu (1998) modelled a single-zone system, much simpler than the CDC MZS. The CDC uses new energy saving technologies such as radiant cooling, for which DOE2 lacks specific modules, which may have affected the results as explained by Tian et al. (2009). A calibrated model would provide more accurate results about free cooling. Calibration of simulation based on field studies provide a better understanding of building operations and make it possible to use more representative procedures during design. Until more is known about the operations of the AHU2 area (e.g. the effects of partial occupancy), it is necessary to be cautious about the reliability of the simulation model. We know that increasing the number of occupants will decrease the heating load and therefore increase the free cooling range. The results presented in this study can therefore be considered the best case scenario for AHU2 and should provide some guidance for other similar building types in a similar climate.

Originally, the OA damper position was analyzed in this research to determine the number of hours that DCV could be used. This approach was inspired by the work of Rock and Wu (Rock and Wu 1998) and could easily be reused for other building case studies. Plotting the OA damper versus the OAT proved to provide much more information than expected both for the actual building and the EE4 model. Based on measurements, the graph gave important insight about the operation of the building over the past few years. The graph even revealed potential mechanical issues with the system at very low OAT. The graph of damper position relative to OAT also showed the model free cooling range was atypical based on Rock and Wu's work (1998). The model low-shutoff temperature was found to be higher than the measured value, as discussed in section 4.3. Calibration of the model (with level 2 fit out design added) was attempted by Gestwick and Love (2013). They found the discrepancies between the model estimates and actual values fell outside the acceptable range, due to electricity and heating energy use being higher than simulation estimates. With regard to heating, possible factors could have been higher than modelled infiltration, higher than modelled ground heat loss and lower than modelled boiler efficiency; the former two of these cannot be readily measured on an ongoing basis. More research is required to determine how the CDC model could better represent the actual building. Ensuring the modeled and the actual OA damper operation are within similar and typical ranges should be considered an important step in the building calibration process.

Further assessment of the discrepancy between AHU2 modeled OA fraction and actual damper position was done by inspecting the simulated OA fraction as the modeled internal loads were increased by doubling space lighting power density. Results showed the low-shutoff temperature to then be around 0 ^{o}C, a result closer to what would be expected based on the literature. Since the lighting power density was verified by Gestwick and Love (2013), other factors such as the building envelope may require scrutiny to improve accuracy. At this stage, it is impossible to tell if there was an issue with the model or with the simulation software. Further work would be required to determine the exact root of this discrepancy.

6 Conclusion

Prior to the study reported here, the only empirical verification of MZS ASE performance was limited to 12 days of tests in an experimental building with almost constant loads. This study provides complementary analysis based on 2 years of cold climate field measurements. Site measurements showed DCV for an AHU with an ASE with no set high-limit shutoff temperature, no HRW and VAV underfloor air distribution system (AHU2) could be used approximately 20% of annual AHU operating hours in Calgary. In contrast, AHU1 equipped with an HRW and ASE used DCV close to 60% of AHU1 operating hours. For AHU2, results agreed with those from a simulation model of a single zone system in a cold climate (Rock and Wu 1998). It was also found that the CDC simulation model finalized near the end of design represents OA fraction poorly, because 1) it was done before all building fitout details were completed and 2) the simulation tool lacked specific modules for some innovative systems (e.g., stratified ventilation). The simulated free cooling range was therefore much smaller than for the actual range. Possible explanations include 1) the stratified ventilation system (due to higher RA temperatures than with a mixed condition), 2) higher internal gains than modelled, and 3) lower net envelope losses than modelled. Further investigation is required to determine the cause.

Further work is required to understand the discrepancy between the modeled OA flow and actual OA damper opening, including finding better ways to determine the actual OA flow. Possibilities include using electronic flow measurement systems (Fisk et al. 2008) and determination of air flows analytically based on SA and RA air flows, temperatures, and CO_2 concentrations. Future work should include simulation with a program that has more advanced capabilities, such as subhourly time steps and underfloor air distribution module. Assessment of net internal gains and their effect on ASE operation by using monitored SA and RA flows and temperatures should be studied. Use of actual weather files would enhance the assessment. It would also be useful to carry out the same study for mixing ventilation systems.

An important finding was that tracking the OA damper opening has proven to be a convenient tool to understand a building's operation and potentially a helpful tool for building fault detection.

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