

THE EFFECT OF VENTILATION AND ECONOMIZER ON ENERGY CONSUMPTIONS FOR AIR SOURCE HEAT PUMPS IN SCHOOLS

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ABSTRACT

The study discusses the applications of CO₂-based demand-controlled ventilation DCV strategy integrated with the economizer for air source heat pumps in schools, investigates their impact on the annual heating, cooling and total energy consumption, also determines the potential savings achieved in different USA locations. The study includes detailed energy analysis on an existing middle school through whole building simulation energy software. The simulation model is first calibrated and checked for accuracy using actual monthly utility data. This model is then used for savings calculations resulted from a combination of air-side economizer and CO₂-based DCV and with various occupancy profiles and locations. The results show that a significant saving could be obtained as compared to the actual operating strategy implemented in the existing system and this saving depends mainly on the actual occupancy profile and building locations.

Key words: HVAC Systems, Ventilation Control, Heat Pump, CO₂ Concentration, Economizer

1. INTRODUCTION

Ventilating the building with a fresh air to maintain a proper Indoor Air Quality (IAQ) is one of the major loads added to the HVAC system (Chao and Hu, 2004; Shan *et al.*, 2012). School buildings have much more concerns about IAQ due to the fact that children spend 12% of their life time in classrooms (Santamouris *et al.*, 2008). Controlling ventilation is recommended to maintain the minimum airflow rate that is specified by ASHRAE (2010) and avoid over ventilation and thereby reduce energy consumption in buildings (Wang and Xu, 2002; Nassif, 2012; Shan *et al.*, 2012). Many ventilation control strategies are proposed for HVAC system (Nassif *et al.*, 2005; Lu *et al.*, 2011; Mysen *et al.*, 2007; Ng *et al.*, 2011). CO₂-based Demand Control Ventilation (CO₂-DCV) is one of the strategies that could

lower energy use by reducing over ventilation of buildings (Nassif, 2012; Taylor, 2006; Stanke, 2006). Most DCV strategies are based on flow rate per person, which may not necessary comply with the new ventilation requirements of ASHRAE (2010). As the new standard requires two ventilation rates, one intended to dilute the contaminants generated by occupants and other for building-related sources, the required space CO₂ concentration or the indoor-outdoor difference is no longer constant, making any CO₂-based DCV strategy hard to apply (Stanke 2006; Murphy, 2005; Nassif, 2012). In this study, two control methods (1) proportional control and (2) single set point control are presented for the CO₂ control. The study also discusses the applications of CO₂-based demand-controlled ventilation DCV strategy integrated with the economizer operating strategy for air source heat pumps in schools,

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investigates their impact on the annual energy consumption and determines the potential savings achieved in different USA locations. The methodology used in this study includes (1) modeling an existing middle school building located in North Carolina, equipped with a total of forty nine wall mounted air source heat pumps, using the whole building simulation energy software eQuest, (2) comparing the energy consumption simulated by the model with the actual monthly energy data collected over five years for model calibration and testing for the accuracy and (3) running the validated model with CO₂-based demand-controlled ventilation DCV and economizer for different occupancy profiles and USA ASHRAE climate zones to estimate the energy savings as compared to the actual operating strategy applied in the investigated system.

2. CO₂-BASED DEMAND CONTROLLED VENTILATION AND ECONOMIZER

A middle school building with a 133,200 ft² located in US is used for this study. There are two types of HVAC system the first is single zone system with a total of forty nine wall mounted air source heat pumps located in classrooms. The capacities of heat pumps vary from 2 to 4 tons, with airflow rates ranging from 800 to 1400 cfm. There are 27 direct-expansion DX coil units supplying conditioned air to offices, gyms and other general areas. The airflow rates of those units range from 600 and 8000 cfm. A fixed amount of fresh is supplied to the space based on design number of students. There is no economizer applied in this system. Thus, this study will investigate the energy benefits of using the CO₂-based DCV integrated with economizer operation, which can be done by installing modulated damper, CO₂ sensor and controller as shown in **Fig. 1**.

The temperature or enthalpy control strategy could be applied for economizer operation. In this case, the outdoor air temperature and/or relative humidity readings should be also available for the controller. The CO₂ sensor can be installed on the wall in the class room, just like the thermostat. The controller will use the CO₂ signal to control and modulate the position of outdoor air damper and thereby provide the space with the proper amount of ventilation air. Two possible CO₂ control approaches could be used (a) proportional control based on the calculations in Appendix A of the ASHRAE 62.1-2010 user's manual

(ASHRAE Standard 62.1 2010) or (b) single set point control as described by Murphy (2005). Those control approaches are discussed below.

The ASHRAE Standard 62.1-2010 prescribes two ventilation rates, one intended to dilute the contaminants generated by occupants (R_p) and other for building-related sources (R_a).

For a single zone, the required minimum outdoor air rate V_{oz} as a function of the number of zone occupants P_z and the zone floor area A_z is given:

$$V_{oz} = \frac{R_p \times P_z + R_a \times A_z}{E_z} \quad (1)$$

The R_p and R_a are determined from the table in standard 62.1 based on the occupancy type. The zone outdoor air rate needs to be adjusted to account for the supply diffuser and return grill location, supply air temperature and other factors by including the space air distribution Effectiveness E_z.

ASHRAE Standard 62.1 provides the mass balance equation to predict the difference between indoor CO₂ Concentration (C_z) and outdoor CO₂ concentration (C_o) at steady-state conditions (the air supplied to the space is assumed to be well mixed and the efficiency:

$$V_{oz} = \frac{N_z}{(C_z - C_o)} \quad (2)$$

The N_z is the CO₂ generation rate and it is a function of people number (N_z = C×P_z); where the C is a constant value related to the occupancy activities, level, diet, health and etc. The space CO₂ concentration C_z is given (using Equation 2 and 1, E_z = 1):

$$C_z = C_o + \frac{N_z}{V_{oz}} = C_o + \frac{C \times P_z}{R_p \times P_z + R_a \times A_z} \quad (3)$$

As indicated in Equation 1, because of those two different ventilation rates, the required space CO₂ concentration is no longer constant as it was in ASHRAE Standard 62.1 2001 and making any CO₂-based DCV strategy hard to apply and comply exactly with the recommendations of the Standard 62.1 2010. Thus, two control approaches “proportional control” and “single set point control” are presented for the single zone CO₂ control.

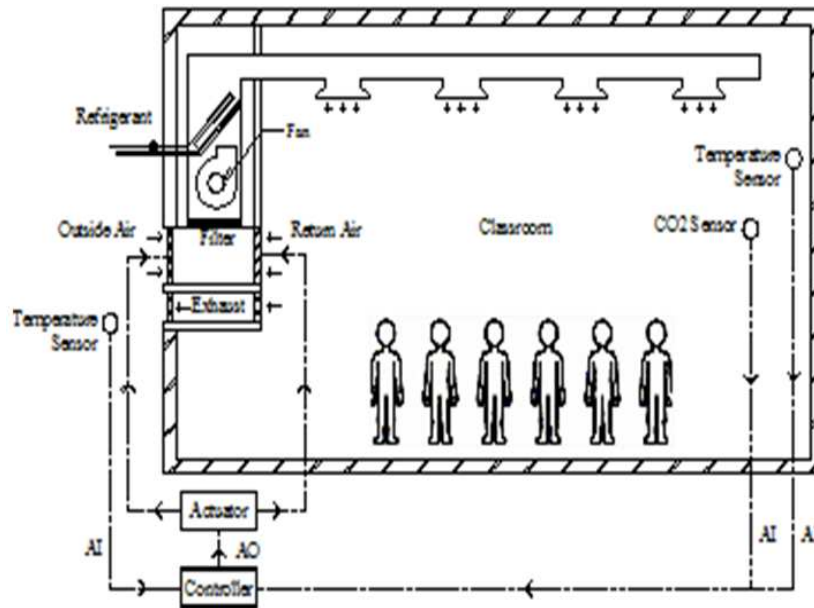


Fig. 1. Schematic of air source heat pump located in the classroom when integrate DCV and economizer.

In the proportional control, the outdoor airflow rate supplied to the space ($V_{oz-supply}$) is determined by the following proportional control Equation 4:

$$V_{oz-supply} = \frac{C_{z-actual} - C_{z-min}}{C_{z-design} - C_{z-min}} (V_{oz-design} - V_{oz-min}) + V_{oz-min} \quad (4)$$

The required CO_2 concentrations at the design full occupancy ($C_{z-design}$) and at the minimum occupancy (C_{z-min}) and the required fresh air based on the design population $V_{oz-design}$ and on the minimum occupancy V_{oz-min} are determined as the following:

- The required CO_2 concentration at the design occupancy $C_{z-design}$ is determined by Equation 3 and using P_z at design occupants ($P_z-design$).
- The required CO_2 concentration at the minimum occupancy C_{z-min} is determined by the same equation but by using P_z-min , e.g., 40% of design occupants (adjustable)
- The required fresh air based on the design zone population $V_{oz-design}$ is determined by Equation 1 and using P_z at the design occupancy ($P_z-design$)
- The required fresh air based on the minimum occupancy V_{oz-min} is determined by Equation 1 and by using minimum P_z-min (40% of design occupant)
- The control adjusts the outdoor airflow rate $V_{oz-supply}$ supplied to the space proportionally

between V_{oz-min} and $V_{oz-design}$ when the actual space CO_2 concentration $C_{z-actual}$ (measured) is between C_{s-min} and $C_{s-design}$

This proportional control strategy is easy to implement and yields an outdoor air flow supplied to the space ($V_{oz-supply}$) that equals or exceeds the requirements (V_{oz}) (Murphy, 2005) but it needs two limits and outdoor airflow measurement.

In a single set point control, the modulated outdoor damper is controlled to maintain the CO_2 concentration $C_{z-setpoint}$ at a value calculated by Equation 2 and based on the required fresh air at the minimum occupancy (V_{oz-min}) as a follow.

As described by Murphy (2005), the single set point approach results in outdoor airflow provided to the space that equals or exceeds the ventilation rate required by ASHRAE 62.1. The strategy is simple to implement and it requires a modulating outdoor air damper and the controller needs only one outdoor air damper set point (V_{oz-min}) and one CO_2 set point (C_{s-min}) rather than two limits and outdoor air flow measurement.

3. MODELLING

An energy simulation software eQuest is used for the energy performance analysis. The detailed information on building and system was entered into the software and then the model outputs are compared with the actual data from utility bills of five years. The model was first

calibrated using the data of year 2009 and then tested for other four years (2007, 2008, 2010 and 2011). **Figure 2** shows the comparison between the simulated and utility data for 2009. A calibration process began in order to reduce the error between the actual data and model outputs. Detailed information on schedule, equipment, lighting, etc. was collected and readjusted. The main adjustment was related to various occupant and equipment schedules due to different days and seasons. As example, different schedules are considered for summer, winter, holiday, weekday, weekend and so on. Our stopping criteria are to obtain an error of 5% or less. The error resulted by comparing annual consumption between the

model and utility data is 0.6%. However, as shown in **Fig. 2**, by comparing the energy consumption per season, the errors are still within the 5%, for instance, 1.2% in winter, 4% in spring, 2.4% in summer and 3.5% in fall.

After the model was calibrated using the utility data of 2009, the model is then tested for other four years (2007, 2008, 2010 and 2011). **Figure 3** shows comparison between the simulated and utility data for five years. The model errors are 2.3% for 2007, 8.2% for 2008, 0.6% for 2009 (calibrated period), 9% for 2010 and 6.5% for 2011. Thus, the model uses in next section for energy saving calculations.

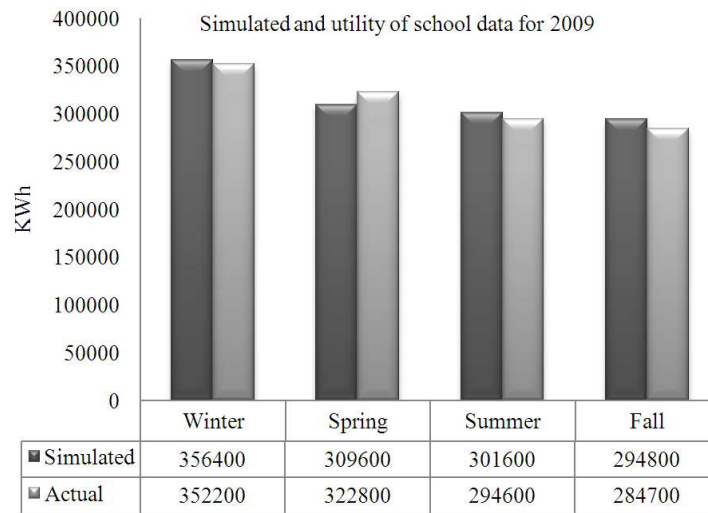


Fig. 2. Comparison between the simulated and utility data for 2009

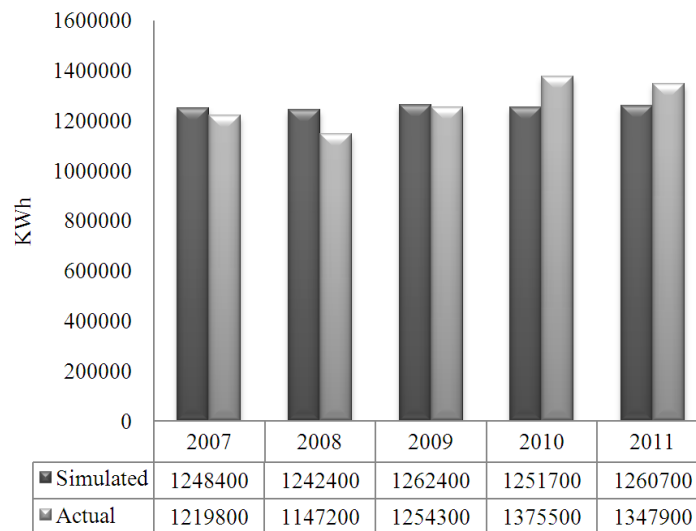


Fig. 3. Comparison between the simulated and utility data for five years

4. RESULTS AND DISCUSSION

The calibrated model developed by eQuest and discussed before is used for estimating the energy savings that could be resulted by implementing the CO₂-based DCV along with the economizer on heat pumps located in the classrooms and the offices. As they are currently installed in the investigated school, the outdoor air intake provides a fixed amount of fresh air based on design number of students. Even if the outside air is suitable for free cooling, the system always provides this amount of air as there is no modulated damper and associated control installed. To demonstrate the energy saving from implementing the DCV, it is assumed that the occupancy profile varies from 100% as low as 50%. The enthalpy control for economizer is used in this study. **Figure 4** shows the annual cooling, heating and total energy consumptions when both DCV and economizer are implemented with different occupancy profiles (100, 90, 80, 70, 60 and 50% of design occupancy profile). The simulation is done for Greensboro, NC. The fan power is not included in the cooling and heating energy consumption as shown in **Fig. 4** but the fan power is included in the total energy consumption. The baseline represents the case when the economizer and DCV are not implemented. When the occupancy is always at design condition as indicated by 100%, the saving resulted is only due to the economizer

operation and there is no saving obtained from DCV. In this case, the total energy consumption drops from 1,258,300 to 1,170,600 kWh, a saving of about 7% due to the economizer operation only. However, when the occupancy is less than design condition for example, 90, 80, 70, 60 and 50%, the savings result due to both economizer and DCV. When the DCV and the economizer are integrated into the heat pump design, both energy cooling and heating consumptions drop significantly. As example, when the actual occupancy is 50% less than design one, the energy use drops from 315,700 to 217340 kWh for cooling, from 118,900 to 65,590 kWh for heating and from 1,258,300 to 965,720 kWh for total annual building energy use.

The simulations are repeated for various USA locations covering most ASHRAE climate zones. **Figure 5** shows the energy consumption and **Fig. 6** shows energy saving obtained by implementing the DCV and economizer in various USA locations. However, **Table 1** shows the percentage of the annual energy saving resulted first from DCV only and second from both Economizer (ECO) and DCV combined. Again, the baseline represents the case when the economizer and DCV are not implemented. As shown in **Fig. 5 and 6**, if the actual occupancy is 50% less than design value, the energy consumption drops of about 304, 600 kWh, with saving of 23% in Las Vegas, for instance. While in Miami the drop is about 255,800 kWh and the saving is 15% of total energy use.

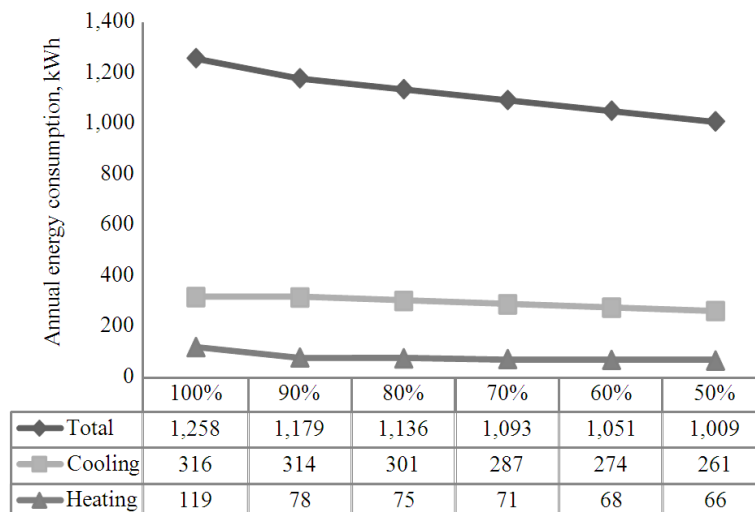


Fig. 4. Annual cooling, heating and total energy consumptions when both DCV and economizer are implemented with different occupancy profiles (Greensboro, NC)

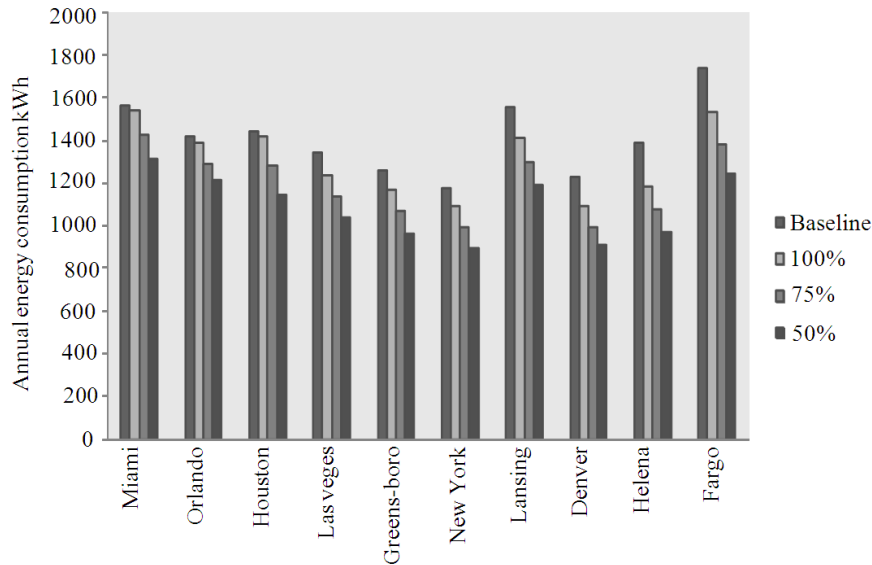


Fig. 5. Energy consumption due to the DCV along with economizer in various locations

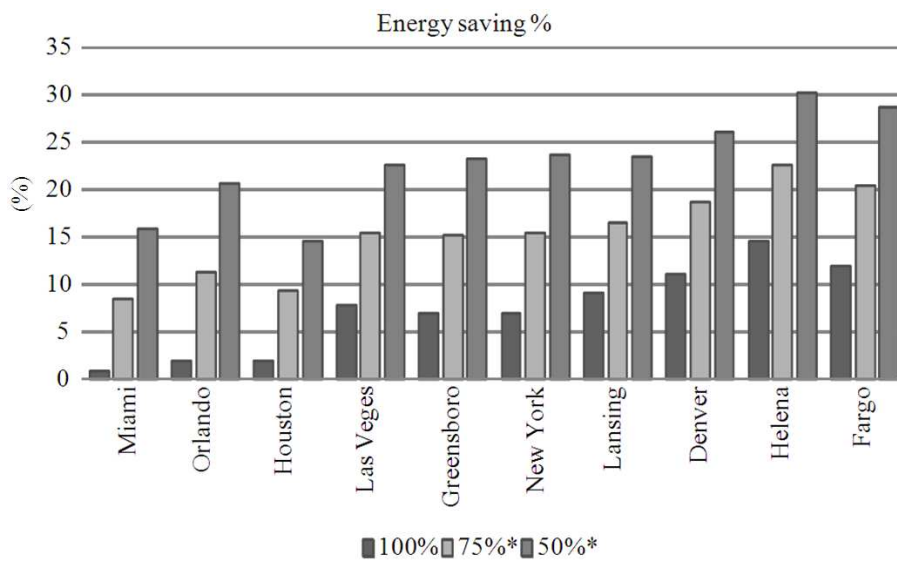


Fig. 6. Energy saving percentage due to the DCV along with economizer in various locations

The energy saving due to the economizer varies with location's climate weather and the energy saving due to the DCV varies with locations and actual occupancy changes.

As indicated in **Table 1**, when the occupancy is always at 100% there is no saving associated with DCV and the saving is resulted only from the economizer and it is clear that saving from the economizer operation is higher in Las Vegas (Climate Zone 5B and dry) than

Orlando (Climate Zone 2 A, Hot-Humid). A substantial energy saving is resulted by implementing the DCV. The saving increases as the actual occupancy becomes less than design value. If the actual occupancy becomes 50% of design value, the saving is 19% for Orlando and this saving amount varies with the locations. However, in **Table 2**, the percentage of saving in energy use for the annual cooling heating and total resulted from both DCV and economizer.

Table 1. Percentage of the annual energy saving resulted from first the DCV only and second from both Economizer (ECO) and DCV combined

	Orlando		Las Vegas	
	DCV %	DCV& ECO%	DCV	DCV& ECO%
ECO	0	2	0	8
DCV 75% Occ.	9	11	11	15
DCV 50% Occ.	19	21	19	23
	New York		Denver	
	DCV %	DCV& ECO%	DCV	DCV& ECO%
ECO	0	7	0	11
DCV 75% Occ.	12	16	15	19
DCV 50% Occ.	21	24	22	26

Table 2. Percentage of the annual cooling heating and total saving in energy use resulted from both DCV and economizer

%Occ. profile		Cooling saving (%)	Heating saving (%)	Total saving (%)
Orlando	100	4	0	2
	75	15	23	11
	50	27	39	21
LV	100	17	0	8
	75	25	23	15
	50	31	43	23
NY City	100	13	0	7
	75	22	11	16
	50	30	22	24
Denver	100	28	0	11
	75	35	7	19
	50	41	13	26
Fargo	100	11	0	8
	75	20	8	17
	50	27	18	25

5. CONCLUSION

The study discussed the applications of CO₂-based demand-controlled ventilation DCV strategy integrated with the economizer for air source heat pumps in schools, investigates their impact on the annual energy consumption and determines the potential savings achieved in different USA locations. A 133,200 ft² (12375 m²) middle school located near the city of Greensboro is used for this study. The school heating and cooling system includes a total of forty nine wall mounted air source heat pumps located in classrooms. In order to estimate the energy savings by implementing the DCV and the economizer, the school was first modeled using the whole building simulation energy software eQuest. The model is then calibrated using utility data of year 2009 and tested on other utility data covering four years. The calibrated and tested results showed that the model produces accurate estimations and the error is less than 5%. The model error drops to less than 3% by

adjusting to the major energy conservation measures that was applied to the school.

The exciting heat pump control supplies a fixed amount of fresh to the space based on design number of students and no economizer is applied. A substantial energy saving could be attained by implementing the economizer and ventilation control strategies. Two control methods (1) proportional control and (2) single set point control were proposed. Those control strategies require installing modulated damper, CO₂ sensor and controller. The controller uses the CO₂ signal to control and modulate the position of outdoor air damper and thereby provides the space with the proper amount of ventilation air. To investigate the energy benefits of using the CO₂-based DCV integrated with economizer operation, the calibrated model were used. The simulated results show that by implementing the DCV and economizer, a significant energy saving can be achieved. The savings could vary from 19 to 26% depending on the

locations and actual occupancy profile drifted from the design occupancy.

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