Demand controlled ventilation in residential buildings

Huijuan Chen[1] and Caroline Markusson[1]

[1] RISE, Research institutes of Sweden, Göteborg, Sweden
Huijuan.chen@ri.se
Caroline.markusson@ri.se

The energy use for ventilation (heating and fan electricity) accounts for a large part of the energy use in residential buildings. For residential buildings, in many cases the building is occupied only part of the day, and further the pollution and moisture load generated by household activities varies during a day. Using demand controlled ventilation (DCV) has a great energy saving potential both regarding fan and heating energy. However, it is important how the ventilation is controlled in order to ensure an adequate indoor air quality, thermal comfort and avoid damages on the building.
In this study different control strategies, control parameters, number of sensors and placing of sensors, number of zones are tested by modeling a single family house. Conclusions from the study are that the size of the energy saving depends on control strategy and system design and it is important to design and choose appropriate control strategy to obtain a good indoor environment.

Keywords: Demand controlled ventilation, DCV, Control strategies, Energy saving

1 Introduction

The role of a ventilation system is to provide an acceptable indoor air quality (IAQ) and thermal comfort for occupants in buildings. The energy use for ventilation, both for heating and fan electricity, accounts for a large part of energy use in residential buildings, varying form 15% to 45%, depending on the type of ventilation system and building[1,2,3]. According to Swedish building regulation [4], the ventilation flow rate required is 0.35 l/s per m^2; it is allowed to be reduced to a minimum flow rate of 0.1 l/s per m^2 if no occupants are at home.

For residential buildings, in many cases the building is occupied only for part of the day, and further the pollution and moisture load generated by household activities varies during a day [5, 6]. Use of demand controlled ventilation (DCV) has a great energy saving potential both regarding fan and heating energy. The ventilation flow rate can be controlled by the demand of IAQ and temperature. However, it is important how the ventilation is controlled in order to ensure adequate indoor air quality, thermal comfort and avoid damages on the building. Further the size of the energy saving depends to a great extent on control strategy and ventilation system design.

The performances of DCV have been investigated previously for office buildings [7], schools [8] and residential buildings [9, 10] etc. For office and schools, demand is commonly measured by CO_2 or presence. While for residential buildings, the demand is more complex. Choice of control strategy, control parameters, e.g., temperature (T), relative humidity (RH), carbon dioxide (CO_2), difference of the CO_2 concentration between indoor and outdoor (ΔCO_2), difference of the moisture content between indoor and outdoor (Δx) or combination of several variables, as well as the their respective threshold values are important to demand controlled ventilation.

Nielsen and Drivsholm [11] tested demand controlled ventilation for a single family house where all sensors and controls are located in the air handing unit. In their study, ΔCO_2 and Δx between the exhaust air and outdoor are used as control parameters and are set with different limits in the range of 100-200 ppm and 1-2 g/kg, respectively. It is found that with the setting of the maximum value of 150 ppm for ΔCO_2 and 2 g/kg for Δx, the highest saving on heat (23%) and fan energy (35%) is achieved among all cases tested in their study. However, sensor placement and control strategy are also important aspects of DCV. Most of the previous studies have been focused on demand controlled ventilation where the demand is measured in the exhaust air and the flow rate is switched between a high and low flow rate. Other strategies, such as individual room control, can be more energy efficient and needs to be evaluated.

In this study different control strategies, control parameters, number of sensors and placement of sensors, number of zones are tested by modeling a low energy single family house with a ventilation system with heat recovery.

Further, saving on space heating is modelled for additional three cases; 1. for a cold climate- Kiruna, 2. for a conventional house with an overall heat transfer coefficient typical for Swedish single family houses and finally 3. for a single family house with only exhaust ventilation. All simulations are based on the same model (the low energy house model), this by moving the house to another climate zone (Kiruna) or reducing the insulation layer and increasing thermal bridges or by changing ventilation system design to an exhaust ventilation system.

The low energy house is modelled in IDA ICE with the aim to test and evaluate demand control ventilation with different control strategies and system designs, including control parameters, number of sensors and placing of sensors (see below for examples). The study discuss how the size of the energy saving depends on control strategy and system design and it is important to design and choose appropriate control strategy to obtain a good indoor environment.

Control parameters evaluated in project are:

- temperature
- carbon dioxide
- relative humidity
- difference in absolute humidity indoor and outdoor

Sensor placings evaluated in the project are:

- centrally sensor placing, one or more sensors are placed centrally, e.g. in exhaust duct
- multiple sensor placing, one or more sensors are placed in each zone of the building

Different divisions/zoning of the house evaluated in the project are:
- every room is a zone
- every floor is a zone
- the building is a single zone

2 The reference house

In the project a reference house is used for the model. The house, situated at RISEs premises in Borås (Fig 1), Sweden, is a low energy single family house (average heat transfer coefficient, $U_{average}$=0.16 W/m^2 K) with a total floor area of 155 m^2 and two floor levels. The ventilation system is a balanced mechanical ventilation system with heat recovery, the design supply flow rate is 60 l/s and the design exhaust flow rate is 66 l/s. The efficiency of the heat exchanger is, according to manufacturer data, 82%.

3 Method

3.1 The model

A model of the single family house is created in IDA ICE, and the construction and the configuration corresponds to the reference house situated in Borås (see Fig. 1). Result from the model for the heating demand is compared with measurements from the reference house and show good agreement [12].

The program of IDA Indoor Climate and Energy (ICE) 4.6 is used to test and evaluate the DCV system with different control strategies. IDA is a dynamic simulation tool for studying indoor climate in the zones as well as energy use in the zones and the entire building for general-purpose. It models buildings, systems and its controllers, and it provides user interface to define, build up and simulate different cases which makes it possible to simulate a wide range of system designs and configurations [13].

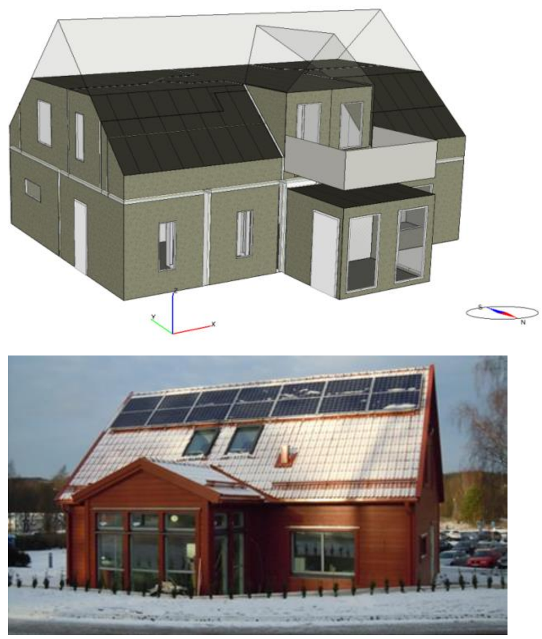

Fig. 1. The IDA model (above) and the reference house (below).

Input data to the model climate and load profiles are important. The climate data used in the model is for Gothenburg-Landvetter, which is fairly representative for Swedish conditions with a yearly average temperature of 8°C. The weather data files are available in the IDA program and they are derived from integrated surface hourly weather data originally archived at the national climate data center [13].

The load profiles used in the IDA model include heat emission, CO_2 generation and water vapor generation. The internal heat load (i.e. heat generated by lighting and other equipment) of 30 kWh/m^2 is used, suggested by SVEBY [14] as a standard value for residential building energy simulation. The internal heat load is distributed to the rooms with specific schedules and unevenly distributed over the year i.e., higher household electricity use in the winter and lower in the summer.

The generation rate of CO_2 and moisture by occupants depends on metabolism varying for each activity, which is modelled to be linearly varying with metabolism in this study. According to EN 15251[15], the generation rate is 11.875 l/h/met for CO_2

and 34.375 g/h/met for moisture for an adult. In this simulation, 0.8 met is considered for sleeping, 1.0 met is for resting and 1.5 met is for cooking. The ambient air CO_2 level is assumed to be 400 ppm.

The total daily moisture production designed in the IDA modelling is about 4 kg/day for weekdays and 5 kg/day for weekends, which is within the range reported by Mattsoon [16]. The moisture production is considered due to household activities of showering, preparing food, washing and drying cloths, dishwashing, as well as the occupants themselves.

Further, three additional cases have been modeled to obtain result for colder climate and for typical Swedish single family house. The model of the reference house has been moved or modified to obtain result for a:

1. cold climate, this by moving the modelled reference house to Kiruna which is situated in a cold climate.
2. conventional Swedish single family house with balanced ventilation and heat recovery, this by changing the average heat transfer coefficient to 0.28 $W/m^2 \cdot K$ by decreasing insulation layer and increasing thermal bridges.
3. conventional Swedish single family house with exhaust ventilation, this by changing the average heat transfer coefficient to 0.28 $W/m^2 \cdot K$ and changing ventilation system design to an exhaust ventilation system.

3.2 Modelled control strategies and sensor placements

Four different ventilation control strategies are designed and implemented in the IDA model including multiple-zone control, two-zone control, one-zone control and exhaust duct control, see Table 1. Four parameters are chosen as control parameters: CO_2, RH, T, and Δx between indoor and outdoor. A short description of those control strategies and threshold values for control parameters are presented in Table 1.

The reference case is the existing ventilation system with constant air volume with supply flow rate of 60 l/s. In the case of demand control ventilation the maximum ventilation flow rate is 60 l/s and the minimum flow rate corresponds to 0.1 $l/s/m^2$.

The demand ventilation flow rate is determined by proportional integral (PI) control. The total supply flow rate is balanced with exhaust flow rate, by feeding back the signal from supply to exhaust if there is a demand for increasing the supply flow rate, and vise versa if there is a demand for increasing the exhaust flow rate.

The maximum CO_2 concentration is set to be 1000 ppm which is a typical value considered giving an acceptable IAQ. A threshold of 2.5g/kg in absolute humidity between indoor air and outdoor air is used for ensuring adequate removal of the moisture produced in the house, as recommend by Public health agency of Sweden [17].

Notice, Table 1, that threshold for exhaust control is set differently compared to the other cases in order to give adequate IAQ. With the setting of high- and low-limits for CO_2 of 400-600ppm, a good indoor environment could be maintained based on IDA simulation results.

Table 1. Description of the modelled cases using different control strategies, sensor placement and zoning

Strategy	Sensor placement	Threshold	Description
Multiple-zone control	Living rooms, kitchen, bed rooms, laundry room and bathroom	CO_2: 700-1000 ppm RH: 20-75% T: 25 °C Δx:2.0-2.5 g/kg	Every room is a zone. Each zone has its own control signal.
Two-zone control	See above	See above	Every floor is a zone. The control signal is the maximum signal among the rooms connected to each floor level.
One-zone control	See above	See above	The building is single zone. The control signal is the maximum signal among all rooms inside the house.
Exhaust duct control	Exhaust duct	CO_2: 400-600 ppm RH: 20-75% T: 25 °C Δx:2.0-2.5 g/kg	The building is a single zone. The control signal comes from the exhaust duct.

4 Results

4.1 Energy saving

Simulation results from different ventilation control strategies in Table 1 are compared with the reference case (constant air volume system), and results are summarized in Table 2. The multiple-zone control strategy gives the highest ventilation flow rate reduction of 57% and space heating of 25%, while the exhaust duct control yields the least saving potential, i.e., 32% for flow rate and 14% for space heating. The space heating includes the total heating demand of the house.

The flow rate reduction and fan electric energy saving is much higher in the winter time than in the summer, as the ventilation fan is almost always on full speed in the summer months due to overheating.

Table 2. Simulation results in terms of ventilation flow rate and space heating energy for the low-energy single family house (Gothenburg)

Case	The average ventilation flow rate during the year (l/s)	Reduction of ventilation flow rate (%)	Space heating demand (kWh/m^2 year)	Reduction of space heating in kWh/m^2 and in %	Fan electrical energy (kWh)	Reduction of the fan electrical energy (%)
Reference case	60	/	16	/	1090	/
Multiple-zone control	26	57	12	4 and 25	84	92
Two-zone control	29	52	12	4 and 23	126	88
One-zone control	38	37	13	3 and 17	284	74
Exhaust duct control	41	32	13	3 and 14	350	68

In Table 3 space heating demand is presented for the additional three cases;

1. reference house in a cold climate (Kiruna)
2. conventional single family house ($U_{avarage}$=0.28 $W/m^2 \cdot K$) with balanced ventilation and heat recovery
3. conventional house ($U_{avarage}$=0.28 $W/m^2 \cdot K$) with exhaust ventilation.

As the ventilation flow rate is nearly the same for all cases, only the space heating demand is presented in Table 3.

The saving in heating demand in kWh/m^2 will of course be much higher when the reference house is placed in a cold climate of Kiruna compared to when the reference house is placed in Gothenburg, Table 3 and Table 2. The saving potential for multiple zone control is 7 and 4 kWh/m^2 for the reference house placed in Kiruna and Gothenburg respectively. For the single-zone control the saving is 4 and 3 kWh/m^2 for the reference house placed in Kiruna and Gothenburg respectively. The house area of 155 m^2 will give a total saving per year, for heating, for the multiple-zone control of 1085 and 620 kWh for the reference house placed in Kiruna and Gothenburg respectively.

If comparing the reference house placed in Gothenburg with a conventional house ($U_{avearge}$=0.28 $W/m^2 \cdot K$) with balanced ventilation and heat recovery also placed in Gothenburg the result for the saving is similar for the two cases, this since both cases has the same ventilation system design and performance.

If comparing the reference house and conventional house ($U_{avearge}$=0.28 $W/m^2 \cdot K$) with balanced ventilation and heat recovery with a conventional house with only exhaust ventilation the difference is significant. For a conventional house with only exhaust air the saving potential for heating is for multiple zone control 26 kWh/m^2 and for single-zone control 17 kWh/m^2. When considering a house area of 155 m^2 the saving is 4030 and 2635 kWh per year for multiple-zone and single-zone control respectively, see Table 3.

Table 3. Simulation results of space heating energy for another climate and a conventional single family house

	Low energy house (Kiruna)		Conventional house with balanced ventilation (Gothenburg)		Conventional house with exhaust ventilation (Gothenburg)	
Case	Space heating demand	Absolut reduction of space heating	Space heating demand	Absolut reduction of space heating	Space heating demand	Absolut reduction of space heating
			kWh/m^2 year			
Reference case	43	/	30	/	68	/
Multiple-zone control	36	7	26	4	42	26
One-zone control	39	4	28	2	51	17

4.2 Control parameters

Results from the simulation shows that during the winter months the CO_2 and Δx are the most important control parameters for living spaces (living room, kitchen, bed room etc.). Simulations from multiple-, two-zone and one-zone control show that Δx is even more important than CO_2, and suggest that Δx could work as single control parameter for living spaces during winter months for those control strategies. However, this depends to a great extent to choice of moisture load, which is indata in the model, and need to be investigated further with field measurements in real conditions. If only CO_2 is used, the limit for Δx will be exceeded for example during preparation and cooking of food.

For the bathroom during wintertime the Δx is always the only needed control parameter. If instead the relative humidity is preferred as a control signal one has to be attentive regarding threshold/limits used for the control and to be aware that the often used limits for RH (e.g. 75 %) will not work properly.

During summertime temperature alone is the most (and only) important control parameter due to high temperature indoor. This is especially true for this house, since the house is a low energy house. Due to the high temperatures in the living spaces during summertime the supply flow rate controlled by the temperature is already at maximum at all times and thus the control signal from dx or RH in the bathroom can-not change flow rate. In Table 4 the parameters which are important for each season and living area are summarized.

Table 4. Summary of parameters are important for each season and living area

	Living spaces (living room, kitchen, bed room)		Bathroom	
	summer	winter	Summer	winter
CO_2		x		
Temperature	x		x*	x
Δx		x	x*	x
RH		possibly		possibly

*will be override by temperature signal from living space due to overtemperatures.

4.3 IAQ and demand control

For all results presented in Table 2, the IAQ and thermal comfort as well as the humidity level in all rooms including bathrooms is controlled and within the limits (Table 1) at all time.

Regarding IAQ and thermal comfort all the three cases where the sensors/control signal are placed in each room (multiple-zone control, two-zone control, one-zone control) will give more or less the same result.

Since exhaust duct control is more easily implemented in reality both regarding cost and technical installation results from this case will be presented more thoroughly below in Fig. 2 and Fig. 3. Fig. 2 shows the CO_2-level in the exhaust duct and the control signals from exhaust duct. Fig. 3 shows the IAQ and ventilation flow rate for kitchen, master bedroom and bathroom. According to Fig. 3(a, c and d), IAQ in the living room and kitchen, master bedroom and bathroom is maintained at an acceptable level: the maximum CO_2 concentration and RH is about 820 ppm and 40%, respectively, which are below the maximum limits. The common supply and extract air is continuously adjusted by the control signal from the exhaust duct and divided into the rooms, Fig. 3(b, d, f).

Comparing the CO_2-levels in Fig. 2a and Fig. 3c one can see that the CO_2 concentration in the exhaust duct (Fig. 2a) is lower than that in the rooms (Fig. 3a,c,e) when the house is occupied, this is due to that the air in the exhaust duct is diluted as all exhaust air from all the rooms are going through the exhaust duct. During the midnight, the CO_2 concentration in exhaust air is about 550 ppm while in the bedroom is about 800 ppm. This means that the control signal from the exhaust duct seldom reaches levels above the set point which results in an insufficient ventilation flow rate.

In a larger houses the total air flow rate will be higher (as the flow rate is based on square meter) resulting in an even larger discrepancy between the actual room levels and the level in the exhaust duct. If exhaust duct control is to be installed and used in buildings this has to be considered and a method for calculating correct set point for the exhaust duct control is needed.

Thus when placing control sensors in the exhaust duct the flow rate is reduced mainly during unoccupied hours, while when many zones can be individually controlled the air flow will be reduced continuously depending on demand for each zone yielding a higher energy saving.

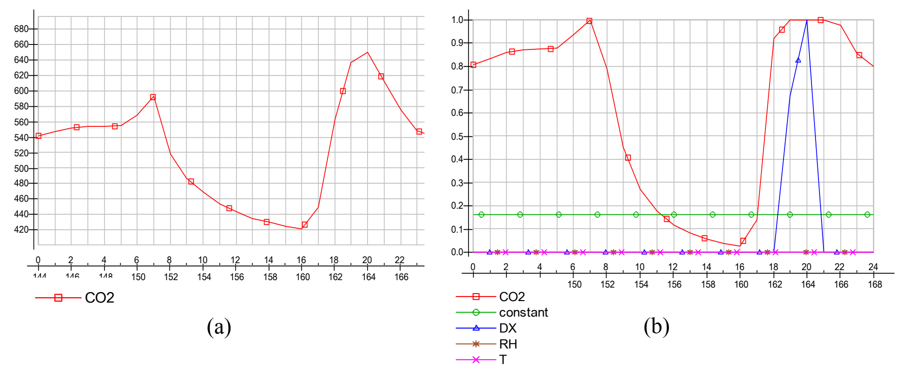

Fig. 2. Exhaust duct control for a winter day (2015-01-07): (a) CO_2 concentration in the exhaust duct and (b) control signals.

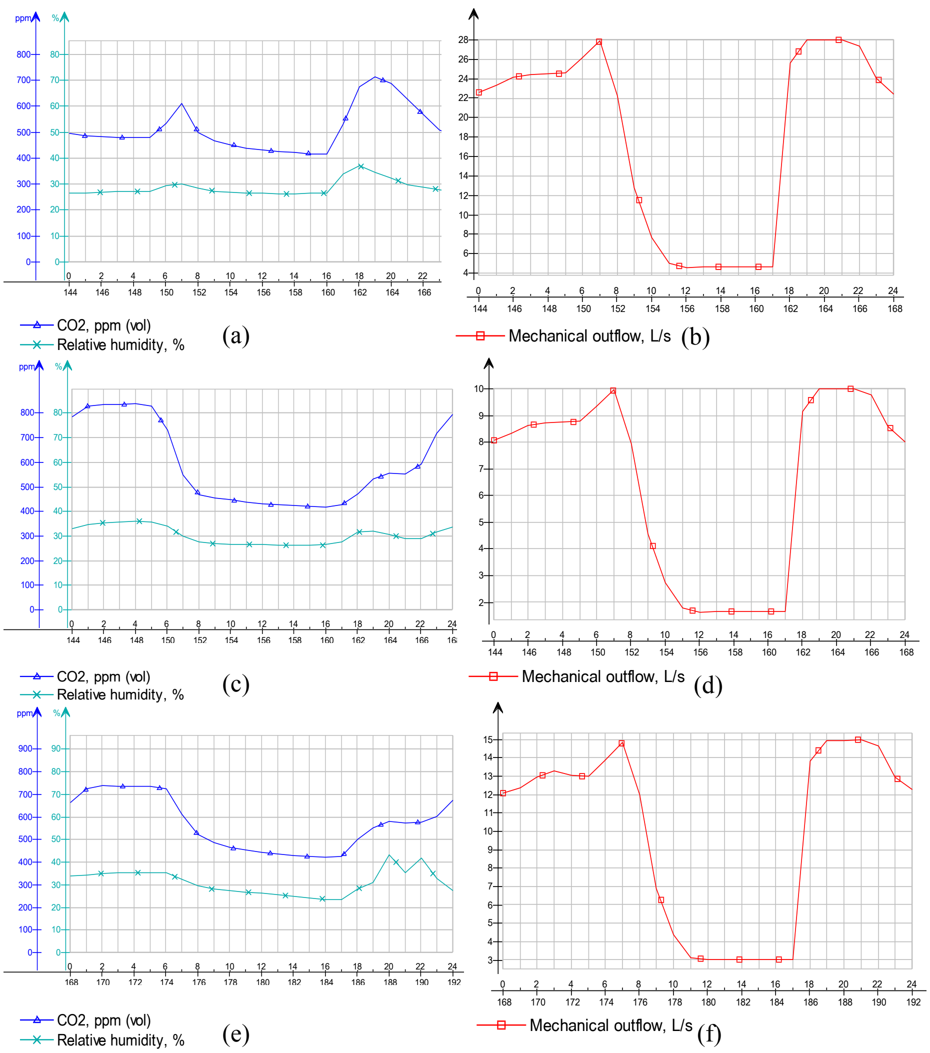

Fig. 3. IAQ and ventilation flow rate for several selected rooms for a winter day (2015-01-07). Living room and kitchen: (a) IAQ and (b) ventilation flow rate; master bedroom: (c) IAQ and (d) ventilation flow rate; bathroom: (e) IAQ and (f) ventilation flow rate.

5 Conclusions

Different strategies of demand controlled ventilation have been tested for a single family house by performing IDA simulations. The program IDA has been shown to be a useful tool for testing demand control strategies and detecting problems. It is concluded that there is an energy saving potential in using demand control ventilation without impairing IAQ in residential buildings. However, it is important to design and choose an appropriate control strategy including control parameters and sensor placing to obtain a good indoor environment, thermal comfort and avoiding damages on the building. Further, the energy saving depends to a great extent on how many zones the building is divided into, also depends on the climate zone and ventilation system design. The multiple zone control will always yield a higher saving potential, however this system is much more complex both in terms of number of mechanical devices as well as control strategy, and thus will be more expensive and require more maintenance compared to single zone control systems. For residential houses with balanced ventilation and heat recovery, the saving potential in kWh is small for both multiple and single zone control and the investment needed for demand control ventilation can be hard to justify. In residential houses without heat recovery the saving potential is much higher and demand control ventilation can be an option.

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