Performance of a demand controlled mechanical extract ventilation system for dwellings

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Abstract

The main aim of ventilation is to guarantee a good indoor air quality, related to the energy consumed for heating and fan(s). Active or passive heat recovery systems seem to focus on the reduction of heating consumption at the expense of fan electricity consumption and maintenance. In this study, demand-controlled mechanical extract ventilation systems of Renson (DCV1 and DCV2), based on natural supply in the habitable rooms and mechanical extraction in the wet rooms (or even the bedrooms), was analysed for one year by means of multi-zone Contam simulations on a reference detached house and compared with standard MEV and mechanical extract ventilation systems with heat recovery (MVHR).

To this end, IAQ, total energy consumption, CO_2 emissions and total cost of the systems are determined. The results show that DCV systems with increased supply air flow rates or direct mechanical extract from bedrooms can significantly improve IAQ, while reducing total energy consumption compared to MEV. Applying DCV reduces primary heating energy consumption and yearly fan electricity consumption at most by 65% to 50% compared to MEV. Total operational energy costs and CO_2 emissions of DCV are similar when compared to MVHR. Total costs of DCV systems over 15 years are smaller when compared to MVHR due to lower investment and maintenance costs.

Key Words:

Demand, controlled, ventilation, assessment, procedure, model, simulation.

AD F – Approved Document F

IAQ – Indoor Air Quality

DCV – Demand-Controlled Ventilation

MEV – Mechanical Extract Ventilation Systems

MVHR – Mechanical Ventilation with Heat Recovery

PSV – Passive Stack Ventilation

1. Introduction

On continental Europe, demand-controlled ventilation (DCV) is considered today as a particularly relevant alternative to other mechanical extract ventilation systems (MEV), and especially for mechanical extract ventilation systems with heat recovery (MVHR). For the moderate climate zone of Western Europe, with about 2500–3000 heating degree days, the pay-back time for investments in heat recovery ventilation is long, especially in buildings with relatively low air change rates such as dwellings.

Due to its competitive price setting as well as due to reports in popular media and scientific literature about possible health risks associated with heat recovery systems[i,ii], simple central MEV dominates the residential ventilation market in this region[iii, iv]. The great variability of a dwelling occupancy in time and place enhances the potential of DCV. By applying DCV, heating energy related to ventilation is reduced by 20% to 50%, while electricity consumption is similarly reduced[v-xvii].

In the UK, due to no recognition of such an advanced system either under Part F of the Building Regulation or under Appendix Q of the Standard Assessment Procedure (SAP), with the Code for Sustainable Homes tightly tied to SAP, DCV has little or no chance on the market[i,xviii, xx].

The aim of this paper is to assess theoretically the energy saving potential of DCV and the indoor air quality (IAQ) to which the occupants of the dwelling are exposed, compared to normative ventilation systems. Two different demand-controlled mechanical extract ventilation (DCV) systems (DCV1 and DCV2) in comparison with passive stack ventilation (PSV), MEV and MVHR were investigated. In addition, an overall comparison was made between the different ventilation systems concerning annual primary energy consumption, annual CO_2 exhaust, annual energy cost for ventilation heat losses and fan(s) consumption, and net present value (NPV) over 15 years.

2. Methodology

The three reference ventilation systems (PSV, MEV and MVHR) and the two DCV systems (DCV1 and DCV2) were designed on a detached dwelling, on the one hand according to the British ventilation regulation (approved document F) and on the other hand according to the Belgian ventilation regulation (NBN D 50-001). The resulting design air flow rates are shown in Table 1.

In contrast to other countries, the design supply air flow rates according to AD F vary strongly among the different ventilation systems. Since different design flow rates have a substantial influence on the performance of a ventilation system, simulations for the UK were also carried out based on the same design supply rates of MVHR. Similar optimisation changes were carried out by Palmer et al (2009)[xviii].

In practice, it is also found that the fan(s) of a MEV or MVHR system is often set on the intermediate operating speed (or even the low

Table 1 – Supply and extract design air flow rates (l/s) of the ventilation systems simulated according to the British and Belgian standard

	PSV		MEV		MVHR		DCV1		DCV2	
	UK	BE	UK	BE	UK	BE	UK	BE	UK	BE
Living	28	36	2	36	18	36	2	36	2	36
Office	12	8	2	8	4	8	2	8	2	8
Bedroom 1	12	17	2	17	8	17	2	17	2 (supply) 8 (supply)	17 (extract) 8 (extract)
Bedroom 2	12	18	2	18	8	18	2	18	2 (supply) 8 (supply)	18 (extract) 8 (extract)
Bedroom 3	12	18	2	18	8	18	2	18	2 (supply) 8 (supply)	18 (extract) 8 (extract)
Kitchen	12000 mm^2	13889 mm^2	18	14	18	28	18	14	18	14
Bathroom	12000 mm^2	13889 mm^2	11	14	11	28	11	14	11	14
Toilet	12000 mm^2	6944 mm^2	8	7	8	14	8	7	8	7
Utility Room	12000 mm^2	13889 mm^2	11	14	11	28	11	14	11	14
Hall	–		–		–		–		–	

operating speed) instead of the high operating speed on which the design air flow rates are reached. Therefore, the MEV reference system was also simulated with half of the design extract rates as listed in Table 1.

In this study, two Renson demand-controlled mechanical extract ventilation systems of (DCV1 and DCV2) based on natural supply via trickle vents in the habitable rooms and mechanical extraction in the wet rooms (such as kitchen, bathroom, sanitary accommodation (toilet) and laundry (utility)) or even the bedrooms (DCV2) were analysed (see Figure 1). Direct mechanical extraction

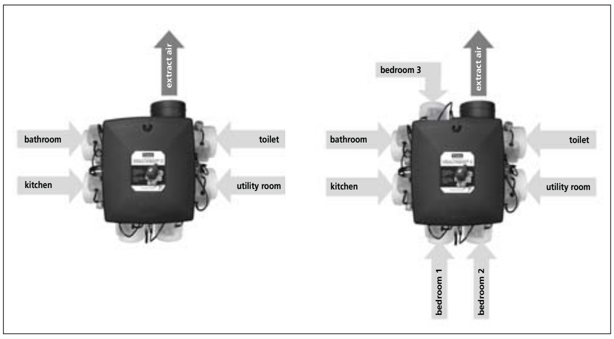

Figure 1: Configuration of DCV 1 (left side) and DCV 2 (right side)

from bedrooms can reduce the exposure to gaseous pollutants in bedrooms as studied by Laverge et al[xxi].

By means of the Belgian assessment procedure for DCV[xiv,xv], the ventilation heating energy consumption, the yearly fan electricity consumption and the realised IAQ were calculated and compared for three locations. For the UK, two locations (London and Aberdeen) with the corresponding climate were considered, Brussels was chosen as the location in Belgium. In that way, the effect of demand control in combination with the impact of the ventilation standard and the climate zone could be analysed. The effect of heat recovery used within MVHR was not considered in these simulations.

Furthermore, based on the previously-calculated energy consumptions, an overall comparison was made between MEV, DCV1, DCV2 and MVHR regarding annual primary energy consumption, annual CO_2 exhaust due to energy consumption, annual energy cost for ventilation heat losses and fan(s) consumption, and net present value (NPV) over 15 years. In that way also the effect of heat recovery was taken into account.

2.1 Simulation tool and parameters

Both DCV systems under review and the three reference systems (PSV, MEV and MVHR) were assessed through numerical simulations with the multi-zone airflow model Contam, developed by NIST, and used within the Belgian assessment procedure for

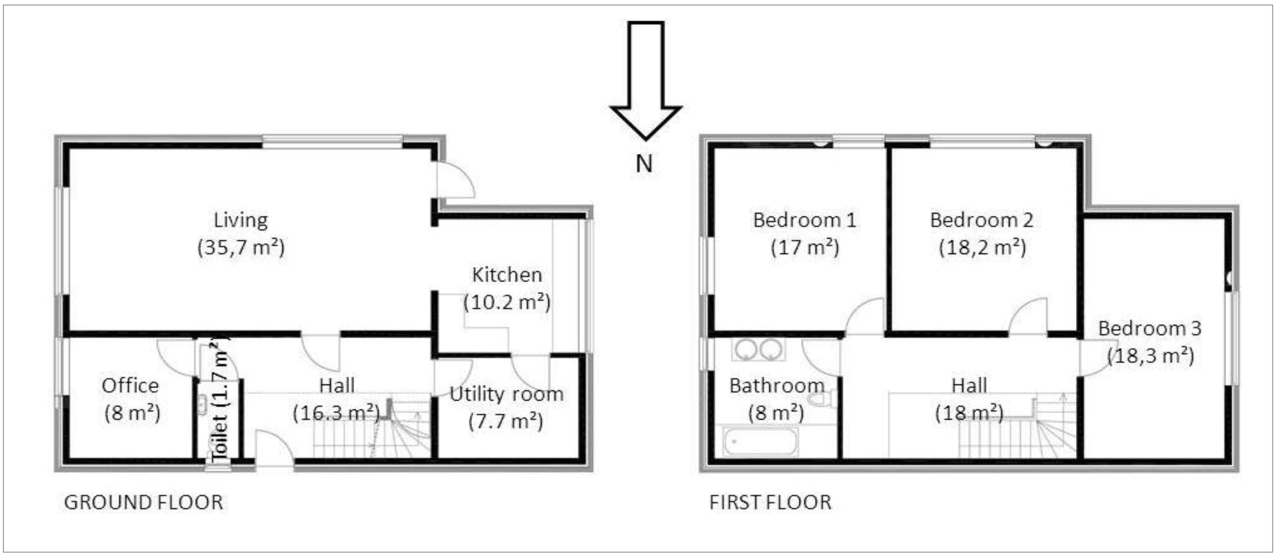

Figure 2 Geometry of the reference building used in the equivalence procedure

DCV. A similar model was used by Palmer et al. (2009)[xviii] to investigate the IAQ obtained with different ventilation systems, without looking to the energy performance.

The geometry used in this model is based on a detached house with a ground and a first floor (Figure 2). Simulations performed on other types of dwelling (semi-detached, apartment) showed that the average effect of DCV is best approached by the detached house[xix].

The three climate zones of Brussels, London and Aberdeen with the hourly average outdoor temperature (mean outdoor temperature during heating season of London: 6.6°C; Aberdeen: 5.6°C; Brussels: 6.3°C), wind speed (mean wind speed during heating season of London: 3.3 m/s; Aberdeen: 5.2 m/s; Brussels: 5.1 m/s) and wind direction were distinguished. Climate data reveals the difference between those locations. A constant indoor air temperature of 18°C in all habitable and functional rooms was considered. A four-person family (two parents, child and baby) with a given occupancy schedule during week and weekend is considered. Internal pollutant emission scenarios were also implemented. Windows and internal doors remained closed, while a hood was operating during cooking (56 l/s). More details about the model can be found in[xiv-xvi].

The impact of uncertainty on the previous input data can be limited by using a Monte-Carlo approach as described by Laverge et al[xiv]. Due to the significant higher simulation time of this MC approach – keeping in mind the objective of this study to show the relative potentials of DCV rather than the absolute – this approach was not used.

The ventilation heating losses were determined over the heating season from 1 October to 15 April, while the yearly electricity consumption due to mechanical ventilation systems was derived from the fan power consumption of the DCV system. The fan power as a function of airflow rate for an external static pressure of 120 Pa – which is the case for well-designed ductwork – is shown in Table 2. The same power consumption was supposed for the MEV and, in the case of the MVHR, twice the electricity consumption was taken into account.

Simulations were performed for five building air tightness levels (0.6; 1; 3; 6 and 12 $m^3/(h.m^2)$). The ventilation and leakage heat losses for these different air tightness levels were extrapolated to a perfect airtight building (0 $m^3/h.m^2$) to isolate the ventilation losses. The performance of the demand-controlled system with respect to IAQ was assessed on three parameters, namely exposure to carbon dioxide, exposure to odours and the humidity level: –

- The average cumulative CO_2 concentration (in kppm.h) for the five building airtightness levels was chosen as a marker for indoor air quality to compare ventilation systems;

Table 2 – Power consumption as a function of airflow rate per fan for the MEV, MVHR and DCV systems at an external static pressure of 120 Pa

Air flow rate (l/s)	0	7	14	21	28	35	42	49	56
Consumption per fan (W)	11.3	12.8	14.4	16	18	20.3	23.3	26.9	30.4

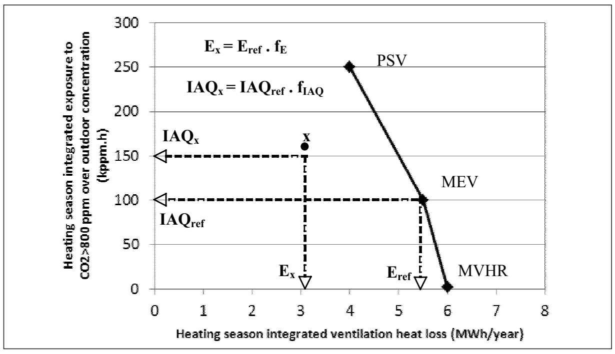

Figure 3: Heating energy and IAQ factor calculation for a ventilation system 'x' with respect to reference systems

- The monthly average relative humidity level on a thermal bridge with a temperature factor of 0.7 must be lower than 80%, in order to limit the risk on condensation and mould;
- Furthermore, the exposure to odours must be lower or equal to that of the worst-performing reference system to be accepted as equivalent.

If performance of the DCV system under review is equal to that of the worst-performing reference system (PSV, MEV or MVHR) for each of these parameters, it is accepted as equivalent and a heating energy factor (f_E) and IAQ factor (f_{IAQ}) (as defined below and demonstrated in Figure 3 for a system 'x') is determined.

- The heating energy factor (f_E) of a DCV is defined as the ratio of the heating season integrated ventilation heat loss of the system (E_x) and that of the reference MEV system (E_{ref});
- The IAQ factor (f_{IAQ}) of a DCV is defined as the ratio of the IAQ of the system (IAQ_x) and that of the reference MEV system (IAQ_{ref}).

2.2 Overall comparison between ventilation systems

For the location of London, MEV, DCV1, DCV2 and MVHR, with an average heat recovery efficiency η of 80%, were compared with respect to:

- Annual primary energy consumption (kWh/year);
- Annual CO_2 exhaust due to energy consumption (CO_2/year);
- Annual energy cost for ventilation heat losses and fan(s) consumption (£/year);
- Net present value over 15 years (£).

Conversion factors to primary energy were 1 for natural gas and 2.5 for electricity. CO_2 emission factors based on secondary energy consumption of 0.202 kg CO_2/kWh gas and 0.543 kg CO_2/kWh electricity were used[xxii].

The net present value or global cost C_G was calculated according to EN15459:

$$C_G(\tau) = C_I + \Sigma [\, \Sigma (C_{a,i}(j) \times R_d(i)) - V_{f,\tau}(j)]$$

The following assumptions were made:

- The initial investment costs C_I are listed in Table 3;
- The annual energy cost $C_{a,i}$ (energy) and the annual maintenance cost $C_{a,i}$ (maintenance) were determined for the four systems.

The annual energy cost is calculated based on the Contam simulations, taking into account the assumed user energy prices for 2013 in [xxiii] of 0.035 £/kWh gas and 0.15 £/kWh electricity. The annual maintenance cost was assumed to be a percentage of the investment cost and is listed in Table 3;

- The discount rate R_d was based on an inflation rate of 2% and a market interest rate of 3%;
- The final value of components $V_{f,\tau}(j)$ was assumed to be zero;
- The calculation was done over a period equal to 15 years.

This results in the following formula:

$$C_G(\tau) = C_I + \Sigma\,(C_{a,i}\,(\text{energy}) \times R_d(i)) + \Sigma\,(C_{a,i}\,(\text{maintenance}) \times R_d(i))$$

Table 3 – Initial investment cost and annual maintenance cost for the different systems

	MEV	DCV1	DCV2	MVHR
Initial investment cost C_I (£)	800	1200	1400	2800
Annual maintenance cost $C_{a,i}$ (maintenance) (£)	16 (2% C_I)	30 (2.5% C_I)	35 (2.5% C_I)	84 (3% CI)

3. Results

3.1 Ventilation heat losses and IAQ

Figure 4 illustrates the average cumulative CO_2 levels against the ventilation heat losses for the three references and the two DCV systems for the three locations of Brussels, London and Aberdeen according to current Belgian and British standards. The heating energy factor (f_E) and the IAQ factor (f_{IAQ}) of both demand-controlled ventilation systems (DCV1 and DCV2) are shown in Figure 5.

The impact of the different ventilation regulations in Belgium and the UK on the IAQ and the ventilation heat losses is obviously illustrated in Figure 4. The smaller air supply rates of all UK-designed ventilation systems and the smaller extract rates of MVHR, especially explain the lower heat losses and the worse IAQ of UK-designed systems.

As can be seen in Figure 4, the IAQ of PSV and MEV is always worse with respect to that of MVHR. Due to variable wind and thermal forces on the building, airflow rates are less controlled and cross ventilation can occur, especially in the case of PSV, which causes higher CO_2 concentrations, especially in the bedrooms.

The ventilation heat loss of reference system MEV and MVHR (η = 0%) is not equal to each other, since the ventilation heat loss is determined by extrapolating the ventilation heat loss at different building air tightness levels to an air tightness of 0 m³/h.m², and not by simulating for a building air tightness of 0 m³/h.m². In that way the impact of the building air tightness on the ventilation heat losses is, to a certain extent, taken into account.

Outdoor climate differences between London and Aberdeen have a particular impact on PSV which is most affected by thermal and

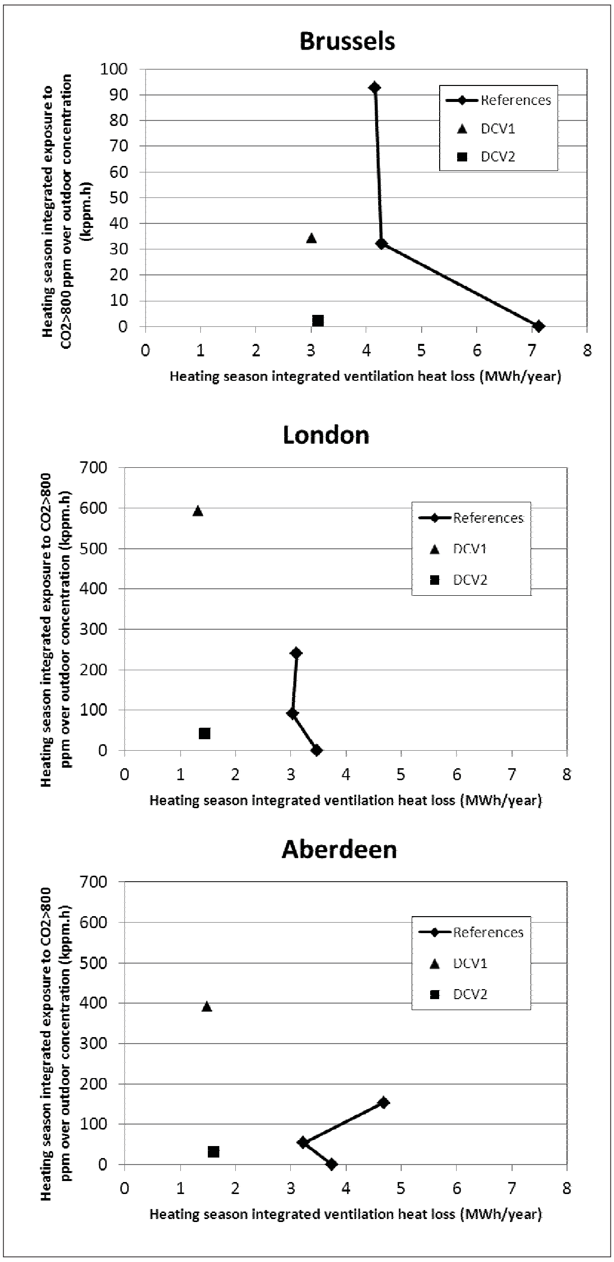

Figure 4: Average cumulative CO_2 concentrations (kppm.h) above 800 ppm over outdoor CO_2-concentration against ventilation heat loss (MWh/year) for the reference and the DCV1 and DCV2 ventilation systems for the three locations according to current Belgian and British standards

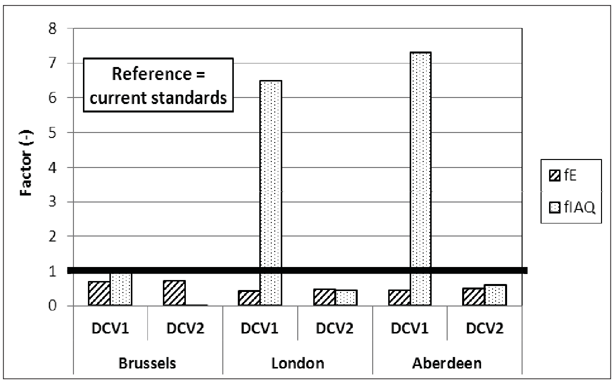

Figure 5: Heating energy (f_E) and IAQ factor (f_{IAQ}) for DCV1 and DCV2 for the three locations according to current Belgian and British standards

wind-driven forces. Due to the lower outdoor temperatures and higher wind speeds in Aberdeen, ventilation heat losses are obviously higher for Aberdeen, while IAQ is better when compared with London.

When looking to DCV1 and DCV2 in Figure 4 and Figure 5 for a given location, it is clear that both DCV systems have a similar impact on the ventilation heat losses, but huge differences are observed concerning exposed IAQ.

In the case of Brussels, DCV1 realises a similar IAQ compared to MEV (f_{IAQ} = 1.07), while the CO_2 concentration exceeds of DCV2 are very small. This means that DCV2 approaches closely the IAQ of MVHR. DCV1 and DCV2 reduce the ventilation heating energy by 30% and 27%, respectively, compared to MEV. When expressed compared to MVHR (η = 0%), a heating energy reduction of 48% and 46% for a DCV1 and DCV2 system, respectively, is found. Common residential MVHR realise a heat recovery efficiency of 70% to 85%, if well designed and maintained.

The situation is different for the locations of London and Aberdeen. DCV1 has an unacceptable IAQ factor (6.5-7.3) when compared to the reference system MEV, while the IAQ factor of DCV2 (0.47-0.60) is acceptable and situated in the middle between that of MEV and MVHR. The heating energy reduction of DCV1 and DCV2 for the two locations compared to MEV is in the range of 50% to 57% and 58% to 62% when compared to MVHR (η = 0%).

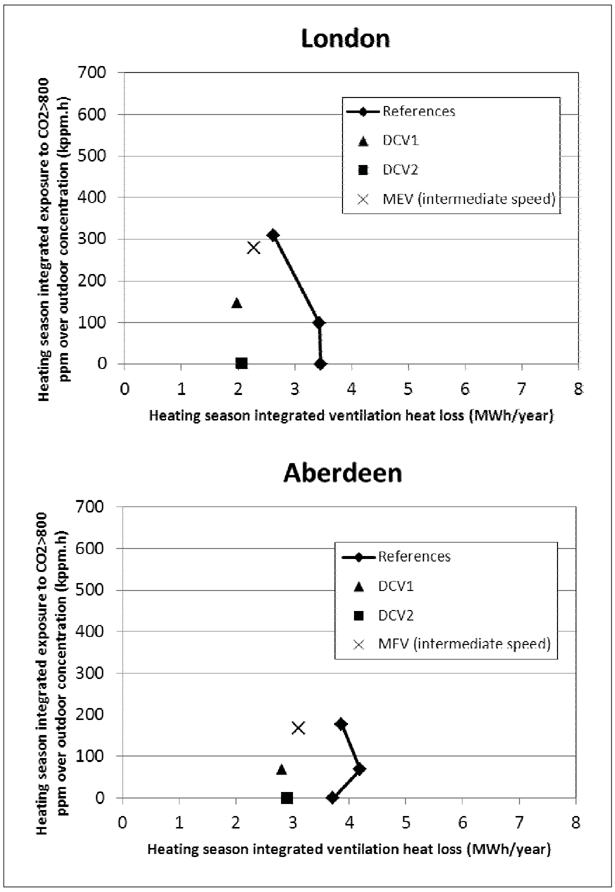

Figure 6: Average cumulative CO_2 concentrations (kppm.h) above 800 ppm over outdoor CO_2 concentration against ventilation heat loss (MWh/year) for the reference and the DCV1 and DCV2 ventilation systems with supply air flow rates equal to MVHR for London and Aberdeen

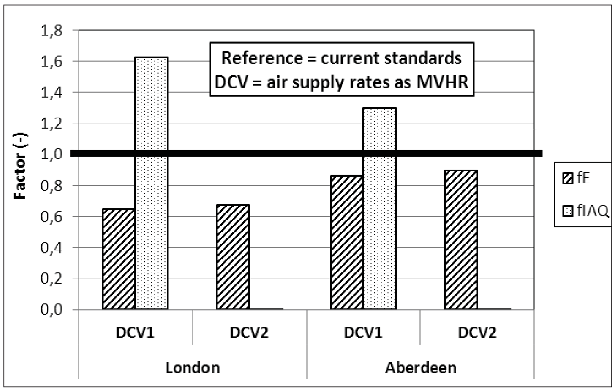

Figure 7: Heating energy (f_E) and IAQ (f_{IAQ}) factor for DCV1 and DCV2 for London and Aberdeen with adapted DCV air supply rates

With the exception of DCV1, all systems comply with the humidity and odour criteria. The question arises if design airflow rates affect considerably the realised IAQ and energy savings of a DCV system compared to reference systems. Therefore, a second set of simulations was carried out with identical air supply rates (namely the air supply rates of MVHR) for all ventilation systems under consideration for the locations of London and Aberdeen, as can be seen in Figure 6. As can be deduced from Table 1, this means that design air supply rates of PSV are reduced while those of MEV, DCV1 and DCV2 are considerably increased. Furthermore, since in practice the extract fan of a standard MEV often runs on the intermediate operating speed, this configuration was also simulated.

Comparing Figure 6 with Figure 4 points out that – in case of PSV with lower design air flow rates – the IAQ deteriorates and ventilation heat losses decrease as can be expected. While the higher design supply rates of MEV induce higher ventilation heat losses, they also lead to a slight decrease of the IAQ. This is due to interactions between constant mechanical and variable natural pressures that mean that room airflow rates are increasing or decreasing. Higher design supply rates on a windward façade increase the actual air flow rate, causing higher ventilation heat losses and lower CO_2 levels. The opposite occurs on leeward façades. DCV can therefore offer a solution since actual airflow rate is taken into account by measuring IAQ.

As illustrated in Figure 6, a MEV running on the intermediate operating speed has an IAQ level which is at least twice as bad when compared with a MEV working on the design airflow rates. This configuration also failed on the odour criterion. The ventilation heat losses are reduced by 33% to 25%.

Due to higher design air flow rates, the IAQ factor of DCV1 is considerably improved from 6.5 to 1.6 and from 7.3 to 1.3, for respectively London and Aberdeen as can be seen when comparing Figure 7 with Figure 5. All factors in both figures are expressed to the references calculated according to current UK standard.

The IAQ levels of DCV1 are considerably lower than those of PSV and are therefore acceptable. In the case of DCV2, the IAQ becomes equal to that of MVHR systems, since an IAQ factor of zero is obtained, instead of 0.5 to 0.6.

With respect to ventilation heat losses for the location of London, the energy losses of DCV1 and DCV2 with higher air supply rates increase by about half, resulting in a heating energy factor of 0.65 to 0.68 respectively, instead of 0.43 to 0.48 in the first set of simulations. This means that heating energy reduction for DCV1 and DCV2 becomes 35% and 32% compared to MEV and about 40% when compared to MVHR without heat recovery.

Due to the more severe climate in Aberdeen, heating energy losses almost double due to the higher design supply rates, giving rise to a heating energy factor of nearly 0.9 for both DCV systems. Higher design airflow rates are for this case less or not justified. Applying a better zone-controlled DCV2 is advisable.

For the second set of simulations, with the exception of the MEV running on the intermediate operating speed, all systems comply with the humidity and odour criteria.

3.2 Fan(s) consumption

Furthermore, the annual fan(s) electricity consumption of the several mechanical ventilation systems under consideration is illustrated in Figure 8. One is designed according to AD F and one with adapted air supply rates equal to those of a MVHR system, for the location of London at a building airtightness of 3 m³/h.m². The impact of the design supply rates on the fan consumption is negligible. Only in the case of DCV, the fan consumption is slightly decreased when design supply airflow rates are higher. Due to more natural ventilation by means of cross ventilation, the average extract rate is slightly decreased.

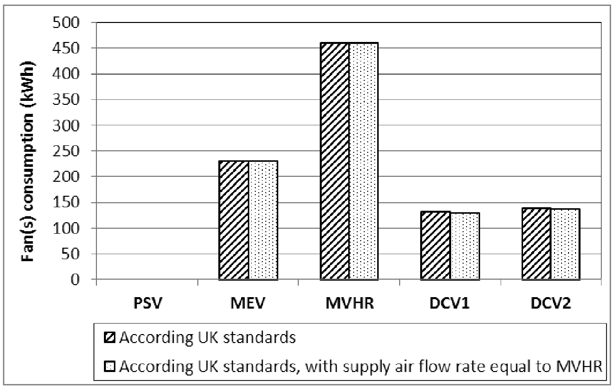

Figure 8: Annual fan(s) electricity consumption for the several mechanical ventilation systems for the location of London at a building air tightness of 3 m³/h.m², according to UK standards (left) and with adapted air supply rates (right)

The annual electricity consumption of MVHR (460 kWh) is twice that of MEV (230 kWh), since it was supposed that the specific fan power of MVHR was double of MEV. In reality, due to the presence of a heat exchanger and filters, fan consumption of MVHR can significantly be higher than supposed. By means of demand control, the average extract rate of DCV1 was reduced by about 66%, resulting in an auxiliary energy reduction of about 40%. In the case of DCV2, the average airflow rate was somewhat higher, resulting in a slightly higher electricity consumption when compared with DCV1.

3.3 Overall comparison between ventilation systems

For the location of London, MEV, DCV1 (with supply rates equal to MVHR), DCV2 and MVHR (average heat recovery efficiency η of 80%) were compared in Figures 9, 10, 11 and 12 with respect to:

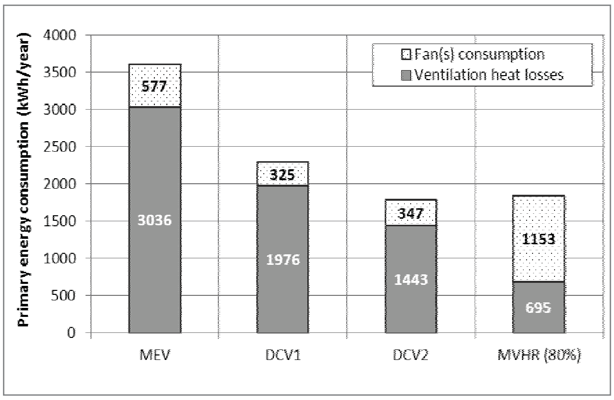

Figure 9: Annual primary energy consumption (kWh/year) of MEV, DCV1, DCV2 and MVHR(η = 80%)

- Annual primary energy consumption (kWh/year);
- Annual CO_2 exhaust due to energy consumption (kg CO_2)
- Annual energy cost for ventilation heat losses and fan(s) consumption (£/year);
- Net present value over 15 years (£).

As illustrated in Figure 9, primary energy consumption of MVHR is about half that of MEV without demand control. MVHR has a higher primary energy consumption for operation of the fans than for compensating the ventilation heat losses. Fan consumption of MVHR is quite high due to double fans and higher air resistance due to the heat exchanger and the filters.

Demand control on MEV can considerably decrease primary energy consumption, and even give rise to a primary energy consumption similar to that of MVHR. This reduction is caused by smaller ventilation heat losses in combination with smaller fan consumption. The primary energy consumption to compensate for ventilation heat losses is about three to two times higher for DCV1 and DCV2 respectively, when compared to MVHR. However, the primary fan consumption of DCV1 and DCV2 is about 30% when compared with MVHR.

The annual CO_2 exhaust related to the energy consumption of the several ventilation systems shows a similar trend as can be seen in Figure 10. Demand control reduces strongly the CO_2 exhaust of MEV to an equivalent CO_2 level of that of MVHR.

The annual total energy cost of the ventilation systems was compared in Figure 11. Due to high electricity prices compared with natural gas per kWh, DCV systems have similar and even lower total energy costs when compared with MVHR, for acceptable or similar levels of IAQ. The annual energy cost of DCV and MVHR ranges between £75 and £100. This cost is about 10% of the total annual energy costs of a one-family dwelling of £800 to £1000.

Figure 12 clearly illustrates that the energy cost to ventilate cannot be considered separately from the total cost of a system, including investment (product and installation cost) and maintenance cost (cleaning, sensors, filters). MEV systems with or without demand control show the lowest net present value, which is about half that of MVHR systems. Saving on the investment and maintenance cost of MVHR is done in practice at the expense of IAQ and acoustic comfort.

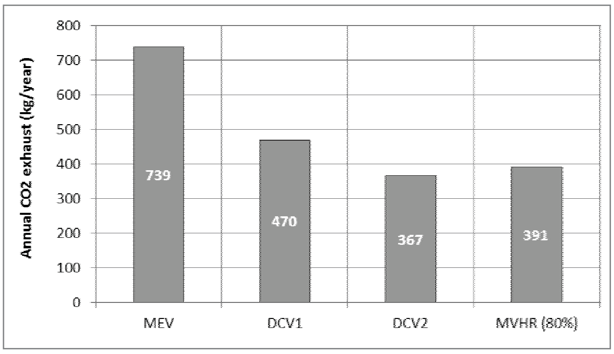

Figure 10: Annual CO_2 exhaust (kg/year) of MEV, DCV1, DCV2 and MVHR(η = 80%)

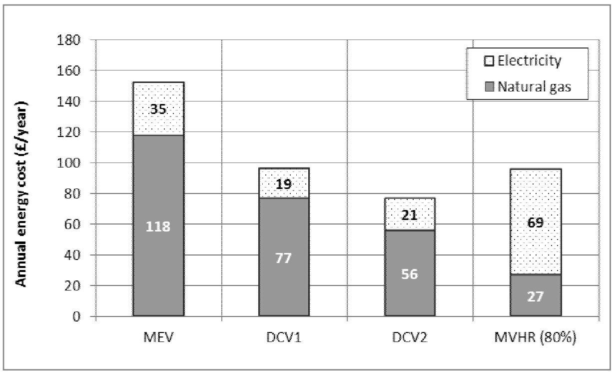

Figure 11: Annual energy costs of MEV, DCV1, DCV2 and MVHR(η = 80%)

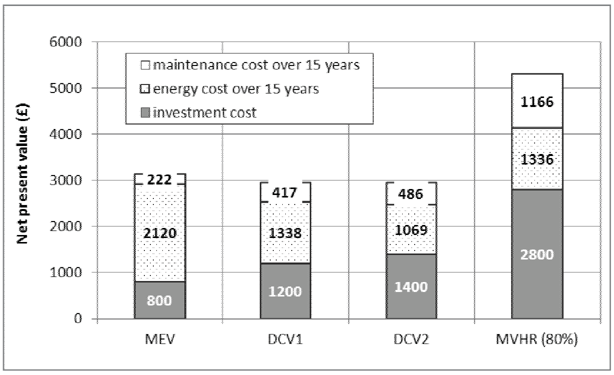

Figure 12: Net present values over 15 years of MEV, DCV1, DCV2 and MVHR(η = 80%)

4. Conclusions

By means of simulations the significant effect of demand control on the performance of a MEV system was illustrated and discussed. From the simulations, it is clear that outdoor climate can be an important parameter to take into account. The less controlled the system, the higher the impact of the outdoor climate (temperature, wind speed and wind direction) and vice versa. Under more severe climate conditions such as Aberdeen, controlling the air extraction from the bedrooms is advisable as realised within DCV2. Under certain circumstances, higher design airflow rates are needed to obtain similar IAQ levels as MEV and MVHR systems, since reference supply airflow rates of MEV are small in the UK (Table 1).

When extracting and controlling airflow rates from all functional rooms and also from the bedrooms, IAQ is good, while ventilation heat losses are more than halved when compared with MEV or MVHR, without increasing supply airflow rates. Due to the automatic control of DCV systems, the guarantee on good IAQ when applying a DCV system should not be lower than using a fully-mechanical MVHR system that is manually operated.

Demand control can bring a standard MEV system to a similar level as MVHR when considering IAQ, CO_2 exhaust, primary energy consumption and energy costs. Besides, due to the automatic detection of the IAQ in the different rooms, the guarantee on good IAQ is higher when compared with a manually-operated mechanical system without sensors. The total cost or net present value of qualitative MEV systems with or without demand control is nearly half that of a qualitative MVHR system, due to the higher investment and maintenance cost of the latter.

Further research should focus on the embedded carbon of the system and the impact of regular filter cleaning and replacement in the case of HR, optimising the DCV system with respect to design airflow rates, and control algorithms. A Monte-Carlo approach can be applied to eliminate the uncertainties on input parameters and the effect of other UK climate zones on the performance of DCV can be analysed.

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