Performance of natural, exhaust, demand controlled exhaust and heat recovery residential ventilation systems as prescribed by the standards in 5 European countries.

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ABSTRACT: Over the last decades, residential ventilation standards have been integrated in most of the buildings codes of European countries. Contrarily to the consolidation effort in the development of the non-residential ventilation standard EN 13779, most of the residential ventilation standards have been drafted in a prescriptive way, with disparate sizing prescriptions in the different countries. Due to these differences in ventilation requirements, the reference levels for ventilation heat loss and associated indoor air quality is different in each country. The energy saving potential for demand controlled systems is therefore different in each country as well.

In this paper, the performance of natural, exhaust and mechanical residential ventilation as prescribed by the standards of 5 European countries with moderate climate is assessed with regard to perceived air quality and odour spread as well as heating season integrated ventilation heat loss using multi zone simulations with local climate data. These results are then used to calculate the energy saving potential of a demand controlled exhaust ventilation system based taking into account the trade-off between indoor air quality and heat loss.

With results showing that about 50% of ventilation heat loss reductions can be achieved at equivalent indoor air quality levels, we conclude that demand controlled exhaust ventilation has a good potential for reduction of building energy use in moderate climates.

1 INTRODUCTION

Advances in several disciplines of knowledge such as the growing understanding of global warming (IPCC, 2007) and its effects on our environment, the increasing evidence of the limited nature of our major energy supply and the large cost, both economical and human, of air pollution related illnesses are dramatically altering the goals of innovations in building technology. The focus is shifted towards ‘green’ or sustainable buildings, seeking concepts that allow to maintain or even further increase the comfort level that we are accustomed to, while significantly reducing the associated energy use in every aspect of human life.

In a moderate climate, infiltration, adventitious and intended ventilation combined represent about 50% of the total heat loss in well insulated buildings, while space heating accounts for about 26% of all final energy consumption in the EU (Bosh et al., 2007, IEA, 2008). Consequently, this field represents a massive gross energy saving potential. Simply reducing ventilation rates, however, will deteriorate the indoor air quality and therefore sort unwanted effects such as an increase in the incidence of respiratory illness (Seppanen and Fisk, 2004, Kovesi et al., 2009) and loss of productivity (Seppänen et al., 2006) or adequate decision making (Satish et al., 2012).

Two main strategies exist in contemporary building practice that allow to reconcile these opposing interests, namely the use of heat recovery units and the implementation of demand controlled ventilation. With different approaches to demand controlled exhaust ventilation, substantial energy savings can be achieved at equivalent indoor air quality (Laverge et al., 2011). Over the last decades, residential ventilation standards have been integrated in most of the buildings codes of European countries. Contrarily to the consolidation effort in the development of the non-residential ventilation standard EN 13779, most of the residential ventilation standards have been drafted in a prescriptive way, with disparate sizing prescriptions in the different countries. Due to these differences in ventilation requirements, the reference levels for ventilation heat loss and associated indoor air quality is different in each country. The energy saving potential for demand controlled systems is therefore different in each country as well.

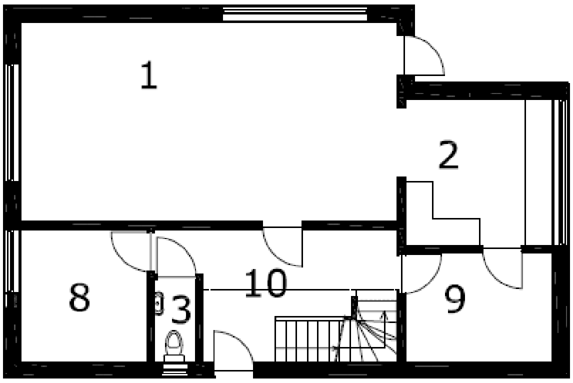
In this paper, the performance of natural, exhaust and mechanical residential ventilation as prescribed by the standards of 5 European countries with moderate climate is assessed with regard to perceived air quality and odour spread as well as heating season integrated ventilation heat loss using multi zone simulations with local climate data. With these systems as a reference, this paper focuses on the performance of two demand control strategies for mechanical exhaust ventilation in residences on a system level with respect to the performance of the continuous flow reference systems proposed in the ventilation standards of 5 countries in the moderate climate zone of western Europe, taking total ventilation heat loss and perceived indoor air quality in to account. The robustness of the performance of these control strategies is assessed by sensitivity analysis based on Monte-Carlo techniques.

2 MODELING

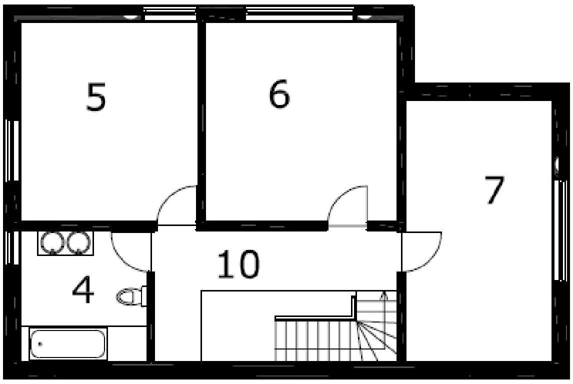
The results presented in this paper are based on airflow simulations. These were executed in the multi-zone airflow simulation package Contam (Dols, 2001). The validation of multi-zone ventilation models against e.g. tracer gas measurements is well documented in literature (Emmerich, 2001, Emmerich, 2003, Delsante and Aggerholm, 2002, Bossaer et al., 1995). Multi-zone simulation models typically assume well mixed air in every room (simulated as a single node in the model). As a result, these models are not suited for detailed analysis of the distribution of contaminants in a single room. However, this is not the scope of this paper. In contrast to a typical office setting, no specific occupied zone can be defined in a residential setting. To assess the energy use related to hygiene ventilation, only the bulk fresh airflow in the building is relevant. As Contam is a ventilation model only, it cannot calculate transient room or duct temperatures. Therefore, for simplicity, the temperature inside the building and all ducts has been set to 18 °C, the inside temperature fixed by the Belgian EPBD calculation procedure , which corresponds to the average temperature measured in Belgian dwellings (Bossaer et al., 1998). In this section, the implementation of the building geometry in the model will be discussed, followed by a description of the two implemented demand control strategies.

2.1 *Building model*

The geometry used in the model is based on a detached house that is statistically representative for the average Belgian dwelling. It has been designed for and used in several previous research projects (Verbeeck, 2007, Verbeeck and Hens, 2005, Verbeeck and Hens, Verbeeck and Hens) and is currently used to assess the performance of residential ventilation systems in the EPBD framework in Belgium (Van Den Bossche et al., 2007, Savin and Laverge, 2011, Janssens et al., 2009). Table 1. lists the dimensions (m^2) of the spaces in the building model. Figure 1. shows the floor plan of the ground floor and 1st floor of the dwelling.



groundfloor



2nd floor

Figure 1. Floor plan of the reference dwelling.

The airflow in this dwelling has been modelled through the introduction of system components and leakage.

Overall airtightness, characterized by the v_{50} value, is modelled by means of cracks in the roof and wall surface. The v_{50} value is the ratio of the air leakage rate at 50 Pa pressure difference and the building envelope heat loss area. According to observations by Bossaer (Bossaer et al., 1998), the specific leakage rate through roof and walls has a 2/3 ratio, which has been implemented in the model. Each wall is fitted with two cracks, one at 1/4 of its height and the second one at 3/4. The internal doors are simulated with additional cracks in the walls. For the indoor walls, a fixed specific leakage value is assumed. This methodology is in agreement with guidelines given in EN 15242 (CEN, 2007a). In the results presented, a specific airleakage (v_{50}) of 0.6, 3 or 6 m/h is used, representing the state of the art in envelope leakage control, the best quartile of measured airtightness values in a measurement campaign in Flanders in the late 90’s (Bossaer et al., 1998) and the median found in a recent measurement campaign in Flanders (Laverge et al., 2010) respectively. Results from other countries (Pan), shows a tendency towards these levels of airtightness in newly built dwellings throughout Europe.

A natural ventilation system, a simple exhaust ventilation system and a fully mechanical ventilation system are implemented. The non-mechanically driven components (internal transfer devices and, depending on the system type, trickle ventilators and/or exhaust vents) are modelled to represent self-regulating trickle ventilators (Karava et al., 2003) according to the EN 13141-1 standard (CEN, 2004).

Table 1. floor area (m²) of the spaces of the reference dwelling in the building model

Ground Floor	Area
Living room	35.7
Office	8
Kitchen	10.2
Service room	7.7
Toilet	1.7
Hallway	28.1
1st Floor	Area
Bedroom 1	17
Bedroom 2	18.2
Bedroom 3	18.3
Bathroom	8
Hallway	28.1

2.2 *Demand Control*

Two different demand control strategies were implemented on the basic exhaust ventilation system.

The first control strategy interacts with an economiser in the vent of each ‘wet’ room (kitchen, toilet, service room and bathroom) and is based on the relative humidity measured in the extracted air. A minimal flow rate of 15 % of the design flow rate for each vent hole is maintained at all times. The flow through the vent hole is increased to the design flow rate if the measured relative humidity is higher than 80 % or if an increase in relative humidity of more than 2 % is observed over 5 minutes. The fan is electronically controlled to operate at constant pressure difference, within the range of its flow capacity. The 70 % setpoint is chosen because it is a marker for elevated mould risk on typical thermal bridges (Viitanen et al., 2010, Isaksson et al.). An EMPD model (Janssen and Roels, 2009) is used to simulate moisture buffering in the spaces.

The second strategy has exactly the same features, with additional exhaust vent holes and dampers in each of the spaces with trickle ventilators. The flow rate through these is determined by the CO_2 concentration measured in the extracted air. If the CO_2 concentration is below the setpoint of 450 ppm above the outdoor concentration, the opening size is reduced to 10% of the original size. Between 450 and 550 ppm, the flow rate is linearly increased to the design flow rate of 30 m^3/h, aiming to keep the indoor air quality within the limits of IDA 2 as defined in EN 13779 (CEN, 2007b).

3 ASSESSMENT METHOD

Three parameters are used to assess the performance of the selected control strategies. Two of them concern indoor air quality, whereas the 3rd deals with the ventilation heat loss. For the assessment of the level of indoor air quality the occupants are exposed to, the exposure to excess carbon dioxide concentration is used along with the exposure to a tracer gas.

Through the correlation between excess CO_2 concentration and mean percentage of dissatisfied (CEN, 1998) and Fanger’s Perceived Air Quality approach (Fanger, 1988), excess CO_2 concentration is now widely accepted as a proxy for perceived indoor air quality (CEN, 2007b), especially if the main pollution sources are related to the human metabolism. In this paper, the mean excess CO_2 concentration to which an occupant is exposed during his time of residence in the dwelling over the course of the heating season and the dose of CO_2 over 1000 ppm excess CO_2 are used as a performance indicators. From all performance criteria proposed in EN 15665 (CEN, 2009), these are assumed to be best fit to represent the ability of the system to dilute occupant related pollutants for comparison to other systems. The average concentration represents the mean perceived indoor air quality achieved by the system, while the doses represent exposure to below average and poor indoor air quality peaks. The production of CO_2 within the model is only related to the occupants’ metabolism and corresponds to their whereabouts. The production rate is, in accordance with EN 15251 (CEN, 2005a), fixed at 19 l/h for an adult performing light work and 12 l/h for an adult at rest. A background outdoor concentration of 350 ppm is assumed.

In dwellings, however, non-metabolism related pollution sources are present in the sanitary units such as toilets and bathrooms. Consequently, the mean exposure to a tracer gas with sources in these specific rooms only is used to assess the efficiency of the ventilation system in removing this specific type of pollutants. The simulated tracer source is active every time an occupant is present in the toilet or bathroom, for the first 5 minutes of occupancy and at a fixed rate.

Exposure to emissions originating from building materials and their secondary effects can be reduced effectively with source control measures (Knudsen and Wargocki, 2010, Kurnitski and Seppanen, 2008). Therefore, it is not considered as a performance indicator for the ventilation systems in this paper.

As a measure for the energy saving potential of the demand controlled configurations, the total, heating season averaged, convective heat loss through ventilation for each demand controlled configurations is compared to that of the reference systems with continuous flow rates. Fan power was not taken into account because it is very system specific. Since heat loss and exposure reduction are opposing interests, they have to be trade off against each other (Laverge and Janssens, 2010, Becker et al., 2007). Several authors have proposed using weighted sums of these different criteria (Ncube and Riffat, 2012, Johansson, 2009). The definition of these weighting coefficients, however, lacks scientific evidence. Compared to these combined references, demand controlled systems should achieve better results on both indoor air quality (IAQ) and heat loss.

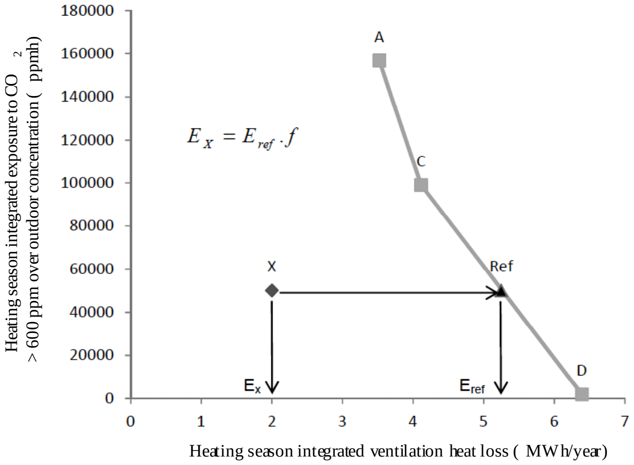


Figure 2. Reference and energy saving coefficient calculation for a ventilation system X.

Therefore, the trade-off is addressed by means of interpolation between the reference systems (natural ventilation, simple exhaust ventilation and mechanical ventilation), taking the level of IAQ that is attained by the application of the demand controlled system into account to determine an energy saving coefficient. The coefficient is defined as the ratio of the heating season integrated ventilation heat loss and a reference. This reference is determined by interpolating between the heat loss levels of the 2 reference systems from that produce an IAQ level just higher and lower respectively than the system under review, based on the IAQ level attained by the latter system. The process for the determination of the reference and the energy saving coefficient for a system ‘X’ is demonstrated in Figure 2.

4 SIZING IN THE STANDARDS

As was explained in the introduction, the sizing rules for residential ventilation systems put forward are different in the Belgian, Dutch, French, German and UK standards. In this section, the specific sizing prescribed for the reference dwelling by each of the standards are summarized in Table 4. It lists the design flow rates for supply, transfer devices and exhaust for all spaces for natural ventilation, simple exhaust ventilation and mechanical ventilation. Local weather data for the capital is used for each simulation. In France, Germany and the UK, a second set is used to take the climate variations on their large territory into account. These extra locations are Lyon, Munich and Aberdeen respectfully.

5 MONTE CARLO

A sensitivity analysis has pointed out that the building airtightness, wind related factors such as wind velocity and wind reduction parameters (Costola et al., 2009) and the number of inhabitants and their occupancy schedules have the biggest influence on the overall performance of the ventilation system (Van Den Bossche et al., 2007).

The input variables considered with a probabilistic approach and their distributions are listed in Table 2.

Table 2. Input variables and their distribution in the probabilistic approach. For interval distributions (I), minimal and maximal values are mentioned, for normal distributions (N), the mean and standard deviation are given.

Variable	Unit	Type		
Orientation	°	I	0	359
Terrain roughness	-	I	0.149	0.377
Sunday n^{th} day	-	I	1	7
$P_{moisture}$	l/s	N		
Showering			0.5	0.05
Drying clothes			1	0.05
Metabolism	met	N		
Cooking			2	0.1
Sleeping			0.8	0.05

The number of parameters can be considered to be small, so 100 datasets are used to perform the simulations. The wind pressure coefficients provided by the AIVC (Liddament, 1996) are used, with interval distribution between the 6 tables. Moisture production for domestic activities is based on data available in the EU technical report on design and dimensioning of residential ventilation systems (CEN, 2005b). For cooking, a half hour cycle of N(0.6, 0.05) l/s, N(1, 0.1) l/s and N(1.5, 0.1) l/s for 10 minutes each is used. The production of moisture and carbon dioxide by occupants is modelled as a linear function of the metabolism. Based on EN 15251(CEN, 2005a), the production rate is 11.875 l/h/met for CO_2 and 34.375 g/h/met for moisture. The number of occupants and the occupancy schedules are considered with a specific distribution based on the social demography and time use studies in Belgium. Based on the available data, 100 different data sets were compiled with different occupancy schedules. The number of occupants in the building varies from one to six (1: 3%, 2: 21%, 3: 31%, 4: 32%, 5: 10%, 6: 3%), with an average of 3.34 persons per building.

6 RESULTS & DISCUSSION

In this section, the results for the different countries and the different system configurations will be reported. First, the ventilation heat loss associated with the different sizing options and system approaches is presented. Then the impact on the achieved indoor air quality is discussed. Finally, the energy saving coefficient is calculated for the 2 demand controlled systems in all countries.

6.1 *Ventilation heat loss*

The cumulated ventilation heat loss for the heating season for the Belgian sizing is shown in Figure 3. As a consequence of inconsistent sizing rules for the different system approaches or due to inaccurate assumptions in the standards on the average pressure drop at non mechanical components such as trickle ventilators and transfer devices, substantial differences in average flow rate for the different system approaches. Self-evidently, this is immediately translated in substantial differences in ventilation heat loss. Mechanical ventilation, simple exhaust ventilation and the first demand control strategy (DC.1) have a very similar sensitivity to the envelope leakage level, while the second demand control strategy (DC.2) manages to slightly limit excessive leakage losses and natural ventilation is more sensitive to the leakage level. For all other countries and climates, virtually the same ranking of systems and qualitative sensitivities are found.

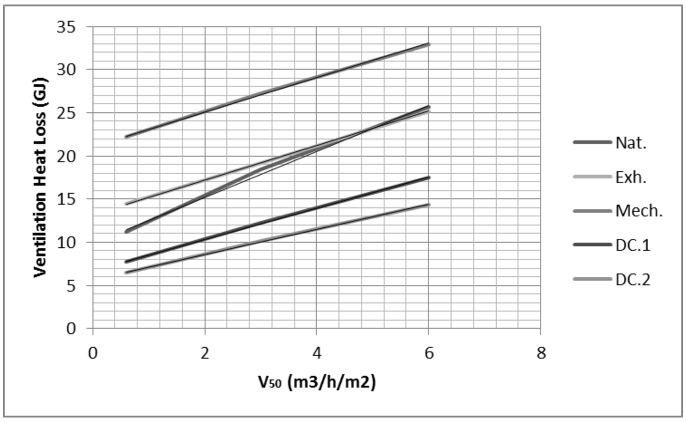


Figure 3. Ventilation heat loss for the 3 reference systems and 2 demand controlled systems in Brussels under different leakage levels.

In addition to the differences between the different reference systems found for each country, the performance of a single system also varies widely from country to country, as is shown for mechanical ventilation systems in Figure 4. Three distinct groups can be observed: the Dutch and Belgian sizing options generate the largest ventilation heat loss. The German and British standards form a middle group and the French standard comes in lowest.

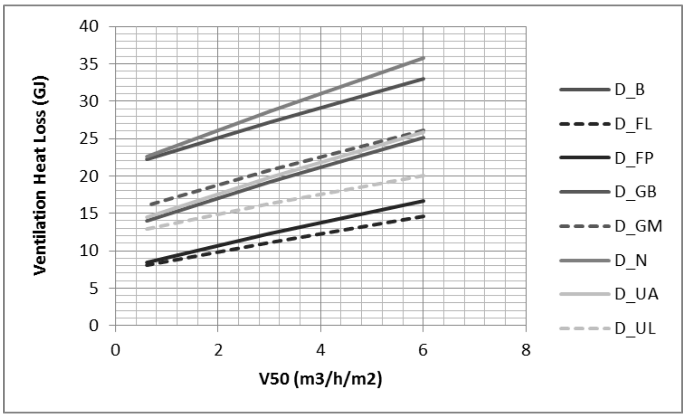


Figure 4. Ventilation heat loss for the mechanical ventilation systems sized in accordance with the five standards (8 weather conditions) under different leakage levels.

6.2 *Exposure to carbon dioxide*

For the reference system, the magnitude of the average flow rate is inversely correlated to the average exposure of the occupants to excess carbon dioxide. This is can be seen by comparing Figure 5 to Figure 3. The order of the flow rates of the reference systems in Germany is the same as in Belgium. The demand controlled systems achieve better indoor air quality than the natural ventilation system at lower flow rates. They therefore effectively address the heat loss – exposure trade off associated with ventilation that was discussed in section 3. Due to its control strategy, the second demand control option is very effective at limiting peak exposure to carbon dioxide, with results close to those achieved by mechanical ventilation for all cases.

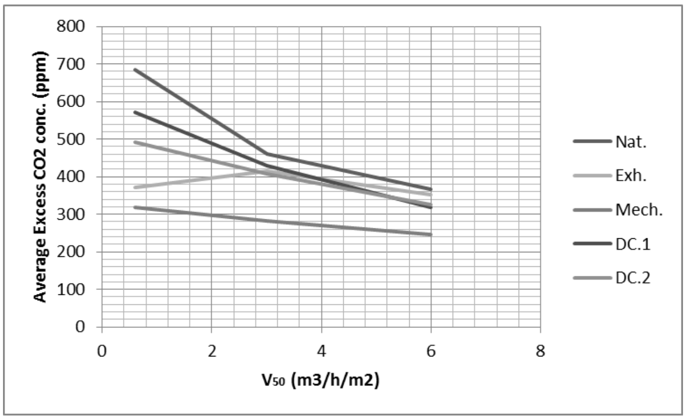


Figure 5. Average exposure to excess carbon dioxide during occupancy for the 3 reference systems and 2 demand controlled systems in Berlin under different leakage levels.

An interesting characteristic of exhaust ventilation systems observed in all cases except in the Netherlands is that at very strict leakage levels, the average exposure decreases with decreasing average flow rates. This is shown in Figure 6.

This is can be attributed to the increased under pressure generated by the fan in airtight dwellings. This in turn increases the stability of the air flow rates through the trickle ventilators under variable wind and buoyancy conditions, especially on the first floor.

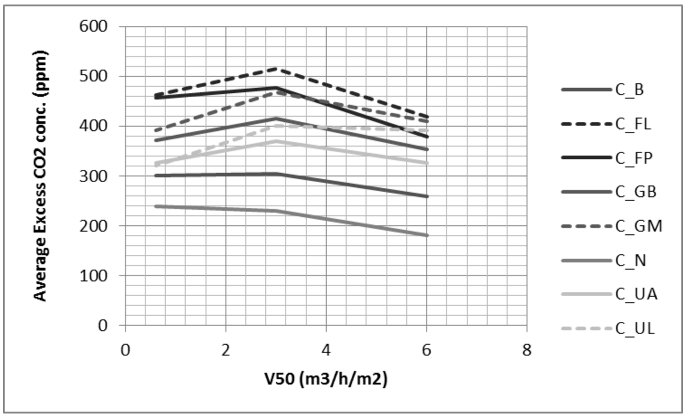


Figure 6. Average exposure to excess carbon dioxide during occupancy for the exhaust ventilation systems sized in accordance with the five standards (8 weather conditions) under different leakage levels.

6.3 *Exposure to odours*

The exposure of the occupants to odours generated in the bathroom and toilet is mainly controlled by size and the sense of the exhaust flow rate in these spaces. For simple exhaust and mechanical systems, this flow rate is continuously guaranteed by the operation of the fans. Envelope leakage therefore has virtually no influence on this exposure. In natural ventilation cases, however, the envelope leakage will determine part of the pressure differences throughout the dwelling and therefore influence the exhaust flow rate. In Figure 7, this effect is clearly seen.

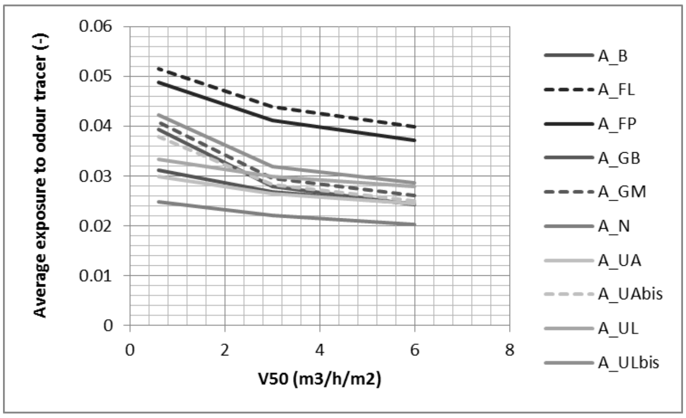


Figure 7. Average exposure to odour tracer during occupancy for the natural ventilation systems sized in accordance with the five standards (8 weather conditions) under different leakage levels.

6.4 *Energy saving coefficient*

The energy saving coefficient of both demand control options was calculated according to the method detailed in section 3 for each of the cases, for 3 $m^3/h/m^2$ of envelope leakage and for both average and peak exposure to carbon dioxide. The trade-off between ventilation heat loss and exposure for the Paris case is shown in Figure 8. as an example.

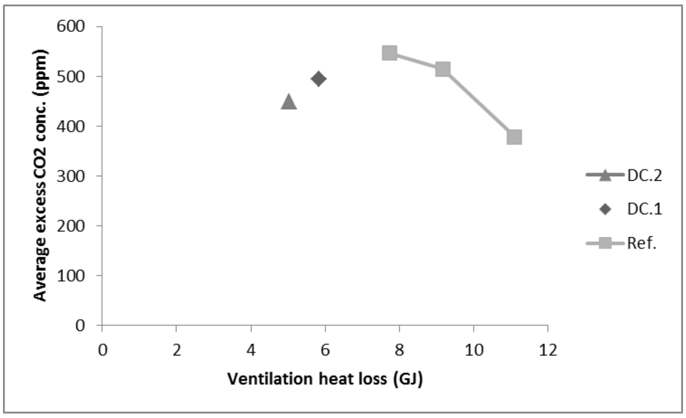


Figure 8. Average excess carbon dioxide exposure of the occupants vs. ventilation heat loss for the 3 reference systems and 2 demand controlled systems in Paris for an envelope leakage of 3 $m^3/h/m^2$.

All results are listed in Table 3. The average coefficient for the first option is 0.60 based on both average and peak exposure. For the second option, this is 0.51 and 0.45 respectively. For Aberdeen, the coefficient could not be calculated for the first demand control option due to the peculiar sizing definitions for natural ventilation in the British standard.

Table 3. Energy saving coefficient for both demand control options for all cases for an envelope leakage of 3 $m^3/h/m^2$ based on average (A) and peak (P) exposure to carbon dioxide

Case	DC.1A	DC.1P	DC.2A	DC.2P
Brussels	0.62	0.55	0.53	0.39
Paris	0.63	0.64	0.52	0.49
Lyon	0.62	0.64	0.50	0.46
Berlin	0.60	0.60	0.51	0.43
Munich	0.57	0.58	0.46	0.38
Amsterdam	0.69	0.67	0.59	0.53
London	0.49	0.48	0.42	0.41
Aberdeen	-	-	0.58	0.47

7 CONCLUSIONS

In this paper, the performance of natural, exhaust and mechanical residential ventilation as prescribed by the standards of 5 European countries with moderate climate is assessed with regard to perceived air quality and odour spread as well as heating season integrated ventilation heat loss using multi zone simulations with local climate data. These results are then used to calculate the energy saving potential of a demand controlled exhaust ventilation system based taking into account the trade-off between indoor air quality and heat loss.

With results showing that about 40-55 % of ventilation heat loss reductions can be achieved at equivalent indoor air quality levels, we conclude that demand controlled exhaust ventilation has a good potential for reduction of building energy use in moderate climates.

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Table 4. Design flow rates at 1 Pa for system components in the reference dwelling. Mechanical flow rates are marked in *italics*.

		Belgium			The Netherlands			France			Germany			UK		
		Nat.	Exh.	Mech.	Nat.	Exh.	Mech.	Nat.	Exh.	Mech.	Nat.	Exh.	Mech.	Nat.	Exh.	Mech.
Supply	Living room	90.8	90.8	*128.4*	115.7	115.7	*115.7*	14.2	4.7	*21.0*	9.8	15.9	*45.0*	99.2	7.1	*63.8*
	Study	20.4	20.4	*28.9*	25.9	25.9	*25.9*	9.5	4.7	*21.0*	4.9	8.1	*23.0*	42.5	7.1	*14.3*
	Bedroom 1	43.2	43.2	*61.1*	55.1	55.1	*55.1*	9.5	4.7	*21.0*	6.7	10.6	*30.0*	42.5	7.1	*30.4*
	Bedroom 2	46.4	46.4	*65.6*	59.0	59.0	*59.0*	9.5	4.7	*21.0*	6.7	10.6	*30.0*	42.5	7.1	*32.5*
	Bedroom 3	46.5	46.5	*65.8*	59.3	59.3	*59.3*	9.5	4.7	*21.0*	6.7	10.6	*30.0*	42.5	7.1	*32.7*
transfer	Living room	17.7	17.7	17.7	115.7	115.7	115.7	22.4	22.4	22.4	43.0	36.7	19.6	21.5	21.5	21.5
	Study	17.7	17.7	17.7	25.9	25.9	25.9	22.4	22.4	22.4	21.0	18.8	13.1	21.5	21.5	21.5
	Bedroom 1	17.7	17.7	17.7	55.1	55.1	55.1	22.4	22.4	22.4	29.0	24.5	19.6	21.5	21.5	21.5
	Bedroom 2	17.7	17.7	17.7	59.0	59.0	59.0	22.4	22.4	22.4	29.0	24.5	19.6	21.5	21.5	21.5
	Bedroom 3	17.7	17.7	17.7	59.3	59.3	59.3	22.4	22.4	22.4	29.0	24.5	19.6	21.5	21.5	21.5
	Kitchen	35.4	35.4	35.4	75.6	75.6	75.6	44.7	44.7	44.7	48.0	41.6	22.9	21.5	21.5	21.5
	Service room	17.7	17.7	17.7	24.9	24.9	24.9	22.4	22.4	22.4	27.0	22.9	22.9	21.5	21.5	21.5
	Bathroom	17.7	17.7	17.7	50.4	50.4	50.4	2.3	2.3	2.3	48.0	41.6	22.9	21.5	21.5	21.5
	Toilet	17.7	17.7	17.7	25.2	25.2	25.2	22.4	22.4	22.4	27.0	22.9	22.9	21.5	21.5	21.5
Exhaust	Kitchen	35.4	*50.0*	*50.0*	75.6	*75.6*	*75.6*	14.2	*45.0*	*45.0*	42.3	*47.0*	*51.0*	34.0	*64.5*	*64.5*
	Service room	35.4	*50.0*	*50.0*	24.9	*24.9*	*24.9*	4.7	*15.0*	*15.0*	42.3	*26.0*	*28.0*	34.0	*39.7*	*39.7*
	Bathroom	35.4	*50.0*	*50.0*	50.4	*50.4*	*50.4*	9.5	*30.0*	*30.0*	42.3	*47.0*	*51.0*	34.0	*39.7*	*39.7*
	Toilet	17.7	*25.0*	*25.0*	25.2	*25.2*	*25.2*	4.7	*15.0*	*15.0*	42.3	*26.0*	*28.0*	34.0	*29.8*	*29.8*