EXHAUST VENTILATION UNDER 5 VENTILATION STANDARDS : A PERFORMANCE ASSESSMENT

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ABSTRACT

Sizing rules in residential ventilation standards lack uniformity in both methodology and resulting design flow rates. Additionally, mere comparison of design flow rates is case sensitive and, due to effects of infiltration, adventitious ventilation and occupancy, ill-suited to assess performance of an exhaust ventilation system with regard to the achieved indoor air quality and energy cost in terms of heat loss. This paper presents a multi-zone simulation based performance assessment of residential mechanical exhaust ventilation systems, using five common dwelling typologies and the sizing rules put forward in the Belgian, British, Dutch, French and ASHRAE residential ventilation standards. The performance of the different cases proved to be substantially different, with an occurrence of poor perceived air quality in 5% or less of the occupation time for the Belgian, Dutch and French standard, and about 15% for the British and ASHRAE standard. When the trade-off between indoor air quality and heat loss is considered, the cases with the Dutch and ASHRAE standard did not achieve pareto-optimal performance.

KEYWORDS

Standard, Exhaust Ventilation, Residential, Simulation, IAQ

INTRODUCTION

The 1970's oil crisis caused the first wave of energy conservation campaigns in buildings. Improved airtightness of newly built dwellings and intensive weatherisation actions considerably reduced the amount of fresh air infiltration. As an unintended consequence of this, the incidence of indoor mould problems peaked and reports on high prevalence of occupants complaining of a wide variety of symptoms or physical discomfort, baptised 'sick building syndrome', emerged.

As a reaction to these problems with indoor air quality, ventilation standards were established in most western countries. Unfortunately, this did not happen on an internationally coordinated level, giving way to the introduction of a wide range of sizing rules. As there is no common methodology, like the one that was developed for non-residential buildings by CEN [1], that is used for the different standards, the flow rates proposed in them can't be compared easily. AIVC listed the requirements of 15 standards without attempting to analyse their performance [2]. the sizing rules to a reference dwelling and found that the design air change rate in the majority of standards is around 0.5 ACH.

In the moderate climate region of West-Europe, especially in Belgium, the Netherlands, France and the UK, simple exhaust mechanical ventilation systems dominate the residential ventilation market [3-5], while heat recovery ventilation and natural ventilation are the most common residential ventilation systems in northern and southern Europe respectively. Such simple exhaust systems are composed of a mechanical exhaust fan, ducted to a series of vent holes in the different ‘wet’ spaces in the dwelling such as kitchens, toilets, bathrooms and service rooms, combined with externally (trickle ventilators) and internally (transfer grilles) mounted air transfer devices [6]. Since the introduction of ASHRAE 62.2, this kind of ventilation system is also rapidly achieving a dominant position in the US residential ventilation market, although the use of trickle ventilators is usually omitted and not treated as such in the standard. The sizing rules for the trickle ventilators in the standards of the 4 European countries also demonstrate little uniformity, requiring the design flow rate, which itself is different for all standards, to be achieved at a different design pressure difference across the ventilator, ranging between 1 and 20 Pa.

The total air change rate achieved by simple exhaust ventilation systems can be considerably different from the flow rate of the fan due to adventitious ventilation and infiltration [7]. The importance of the extra flow rate is mainly related to the sizing of the trickle ventilators relative to the flow rate of the fan [8]. Therefore, the ventilation heat loss of exhaust ventilation systems can’t be assessed comprehensively by simple comparison of the design flow rates. In addition, the air flow in the system is controlled by the mechanical flow rate only in the ‘wet’ spaces, whereas the flow rate in the rest of the dwelling, which comprises the main living spaces, is governed by much less stable driving forces such as wind and buoyancy. Since the occupants spent the vast majority of time in the livings spaces [9], the indoor air quality (IAQ) achieved in these spaces will be the dominant contributor to perceived air quality [10]. Again, the design flow rates will not be a good metric for assessing the performance of simple mechanical exhaust ventilation systems.

Presenting the results from a multi zone simulation based performance assessment of simple mechanical ventilation systems sized in accordance with the Belgian [11], British [12], Dutch [13], French [14, 15], and ASHRAE [16] residential ventilation standards, this paper aims to provide a comprehensive analysis of the performance of the ventilation systems proposed in the standards. The 4 european countries are chosen because of the dominance of exhaust ventilation in their ventilation market and their geographical clustering. Although exhaust ventilation historically also represents a large part of the residential ventilation market in the Nordic countries, their cold climate [7] and recent market evolutions favour heat recovery ventilation. Therefore they were not included. The ASHRAE standard was chosen for its large geographical applicability and it’s authority in HVAC design. Additional motives include the fact that it’s promotion of exhaust ventilation is novel in the US and it’s recent publication. The sizing rules of each standard are applied to 5 common dwelling typologies and monte carlo analysis is used to consider the sensitivity of the results to the boundary conditions used.

SIZING IN THE STANDARDS

As was explained in the introduction, the sizing rules for simple exhaust residential ventilation systems put forward are different in the Belgian, Dutch, French, UK and ASHRAE standards. In this section, the specific rules found in each of the standards are summarized. If different sizing rules are provided for continuous and demand controlled systems, only those for continuous systems are considered.

Belgium

The Belgian standard requires a design flow rate of 1 l/s*m² for each occupied space. For the main living space, this design flow rate should be at least 21 l/s and can be limited to 42 l/s, while for bedrooms, studies… the minimum value is 7 l/s and the design flow rate can be limited to 20 l/s. For kitchens, bathrooms and service rooms, a minimum design flow rate of 14 l/s should be taken into account, while it can be limited to 21 l/s. The design flow rate for a toilet is 7 l/s.

The occupied spaces and the wet spaces should be connected to each other or via circulation spaces by transfer grilles sized at 7 l/s at 2 Pa pressure difference, which corresponds to 70 cm², except for the kitchen, in which the transfer grille should be sized twice as large. Each living space, bedroom, study… should be connected to the outdoor environment by a trickle ventilator sized at the design flow rate for that space at 2 Pa pressure difference.

The Netherlands

With a design flow rate of 0.9 l/s*m²for each occupied space and minimum design flow rates of 7 l/s in bedrooms, studies and toilets and 14 l/s in bathrooms and service rooms , the Dutch standard's sizing rules are quite similar to those in the Belgian standard. The minimum design flow rates for the kitchen, however, is set at 21 l/s instead of 14 l/s, while in the main living space, only 7 l/s is required as opposed to 21 l/s in the Belgian standard. Furthermore, Trickle ventilators should be sized at the design flow rate at 1 Pa pressure difference and transfer grilles should have a free face area of 12 cm² multiplied by the design flow rate for that space. As a consequence, the size of the trickle ventilators and transfer grilles is larger compared to the Belgian standard's sizing rules.

France

The design flow rate for each of the 'wet' spaces in the French standard depends on the number of 'main' spaces in the dwelling, eg. living spaces, bedrooms, studies.... The design flow rates of the trickle ventilators in the remaining spaces are also defined as a function of the number of 'main' spaces. For dwellings with only 1 or 2 'main' spaces, the design flow rate is increased for higher total design flow rates in the 'wet' spaces.

The trickle ventilators should be sized to the design flow rate at 20 Pa pressure difference, while the transfer grilles should be sized to the design flow rate at 5 Pa and 2.5 Pa for 'wet' and 'main' space grilles respectively. As a consequence, the size of components is typically smaller compared to the Dutch and Belgian standard's sizing rules.

The UK

Simple exhaust ventilation is denominated 'extract ventilation' in the British standard. Design flow rates of 13, 8 and 6 l/s are required for kitchens, bathrooms and toilets respectively. Service rooms are treated as bathrooms. In addition to these design flow rates per space, the total extracted flow rate should not be less than 9 l/s, increased with 4 l/s for each bedroom.

The equivalent, referenced to a round sharp edged opening, free face area of transfer grilles is set at 76 cm², that of the trickle ventilators at 25 cm².

ashrae

The design flow rate for kitchens proposed in the ASHRAE standard is 5 ACH, while 10 l/s is required for bathrooms. The total design exhaust flow rate for a dwelling is at least 0.05 l/s*m², increased with 7 l/s for the first bedroom and 3.5 l/s for each additional bedroom. No requirements for trickle ventilators or transfer grilles are included.

SIMULATION MODEL

The results presented in this paper are based on airflow simulations. These were executed in the multi-zone airflow simulation package Contam [17], which takes effects of buoyancy, wind and fan pressure into account and is used in numerous ventilation studies [eg. 18, 19].

Building Geometries

To assess the quality of the sizing rules in the standards discussed above, simple exhaust residential ventilation systems have been designed is accordance with the different standards for five different dwelling typologies. Their size and layout is based on an extensive survey of 200 dwellings in Belgium built in the 1990’s [20]. Their characteristics have been checked regularly with the evolution of newly built dwellings and still correspond well with current building practise. Four dwellings are single family houses, one is a flat. All dwellings have the same useful floor area corresponding to the mean from Belgian national statistical figures. All houses comprise a living room, 3 bedrooms, kitchen, bathroom, toilet, service room, and hall way, with a total net floor area of about 150 m². The detached, semi-detached and terraced house hold a separate study. The dwellings differ in building compactness, ranging from a detached bungalow to a flat in a 6-floor apartment building. The compactness is defined as the ratio of the volume to the heat loss area (Table 1).

	Bungalow	Detached	Semi-detached	Terraced	Flat
Compactness	0.9 m	1.3 m	1.6 m	2.1 m	3.8 m
Heated volume	557.3 m³	528.7 m³	521.0 m³	493.6 m³	450.0 m³
Heat loss area	611.3 m²	395.4 m²	330.1 m²	231.9 m²	118.4 m²
Number of floors	1	2	2	3	1 (of 6)

Table 1. Geometrical characteristics of reference dwellings.

Building envelope and ventilation system model

The airflow in the dwellings has been modelled taking into account both the ventilation system and leakage. Overall leakage, 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 [21], 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 [22]. In the results presented, a specific airleakage (v_{50}) of 3 m/h is used, representing the best quartile of measured airtightness values in a measurement campaign in Flanders in the late 90’s [21]. A recent measurement campaign [23], shows a tendency towards this level of airtightness in newly built dwellings.

The design exhaust flow rate for the wet spaces in the dwellings according to the different standards are listed in Table 2. Since the design exhaust flow rates in most standards are size independent, the flow rates are mostly the same for all 5 dwellings. If this is not the case, the range of the design flow rates for that space in the 5 dwellings is mentioned. Since trickle ventilators are sized with respect to different reference pressure differences in the five standards, the flow coefficient at 1 Pa pressure difference, assuming a flow exponent of 0.5 and a simple power law flow profile, for the trickle ventilators in the various living spaces of the dwellings according to the different standards are listed in Table 3. Note that the ASHRAE standard does not require the installation of trickle ventilators.

Space	Belgium	France	Netherlands	UK	ASHRAE
Kitchen	14 l/s	38 l/s	21 l/s	13 l/s	33 - 48 l/s
Bathroom	14 l/s	8 l/s	14 l/s	8 l/s	10 l/s
Service room	14 l/s	4 l/s	14 l/s	8 l/s	10 l/s
Toilet	7 l/s	8 l/s	7 l/s	6 l/s	-
Total exhaust flow rate	49 l/s	58 l/s	56 l/s	35 l/s	53 - 68 l/s

Table 2. Exhaust flow rates in the different standard.

All mechanical exhaust vents were modelled as constant volume flow rate components in the respective zone node, while transfer grilles and trickle ventilators were modelled with single direction power law flow components with a flow exponent of 0.5 [24]. All systems were modelled with windows and internal doors closed, in order to simulate the performance of the systems as such, without user interaction.

Space	Belgium	France	Netherlands	UK	ASHRAE
Living room	20 - 29 l/s/Pa	3 l/s/Pa	26 - 40 l/s/Pa	2 l/s/Pa	-
Master bedroom	11 - 14 l/s/Pa	2 l/s/Pa	14 - 21 l/s/Pa	2 l/s/Pa	-

Table 3. Trickle ventilator flow coefficient in living room and master bedroom in the 5 standards.

Boundary conditions and Monte Carlo

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 [21]. The test reference year for Ukkel, Belgium was used as the outdoor climate for all simulations, with hourly mean values for temperature, humidity, wind speed and direction.

The production of CO_2 within the model is only related to the occupants' metabolism and corresponds to their whereabouts. A constant outdoor background concentration of 350 ppm is assumed.

For most of the other boundary conditions, a Monte-Carlo (MC) approach, as proposed by Van Den Bossche et al. [25, 26], has been used in this study. In this approach, instead of fixing 1 value for each input data, a distribution is determined for the key parameters and multiple simulations are carried out with different values of these parameters. The following input variables are considered with a probabilistic approach (Normal distributions are mentioned as N(mean, standard deviation):

- Façade orientation - interval [0°; 359°]
- C_p coefficients - interval of the 6 AIVC tables [27]
- Terrain roughness α , partially correlated with the C_p coefficients – interval [0.149 – 0.377]
- Sunday is the ...th day of the year - interval [1;7]
- Moisture production from domestic activities - normal distribution (see below)
- Production of moisture and carbon dioxide by occupants - normal distribution (see below)
- Number of occupants - specific distribution
- Weekday / weekend occupancy schedules - specific distribution

The number of parameters can be considered to be small, so 100 datasets will be used to perform the simulations. Moisture production for domestic activities is based on data available in the EU technical report on design and dimensioning of residential ventilation systems [28]. The production in the bathroom is N(0.5, 0.05) l/s, in the service room cloth drying is N(1, 0.05)l/s and 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, which varies for each activity (eg. N(0.8, 0.05) Met for sleeping, N(2, 0.1) Met for cooking). Based on EN 15251[29], 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.

Assessment parameters

Through the correlation between excess CO_2 concentration and mean percentage of dissatisfied [30], excess CO_2 concentration is now widely accepted as a proxy for perceived indoor air quality [1], especially if the main pollution sources are related to the human metabolism. In contrast to the basic model, steady state conditions are rarely applicable to real ventilated environments. CO_2 concentrations are inherently transient, due to changes in environmental boundary conditions. Additionally, the relevant CO_2 sources tend to constantly move around in the multi-spaced dwelling, introducing discontinuous sources and further increasing the transient character of the indoor air quality. The amount of time an occupant spends in an environment within the different IDA classes [1] and the heating season averaged CO_2 concentration to which an occupant is exposed were selected as IAQ metric for this study. The best IDA class, IDA 1, corresponds to exposure lower than 400 ppm excess CO_2, while the lowest class, IDA 4, exposure to concentrations in excess of 1000 excess CO_2, is considered to correspond to poor perceived indoor air quality.

The total, heating season averaged, convective heat loss through the combination of intended ventilation, adventitious ventilation and infiltration is used to assess the energy performance of the different sizing rules. 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. This trade-off is addressed by means of the concept of pareto optimality. Pareto optimal cases are cases where none of the other standards achieve better results on both indoor air quality and heat loss.

RESULTS AND DISCUSSION

Exposure to carbon dioxide

Table 4. lists the time fractions spent in the different IDA classes considering all 334 occupants from the 100 simulations in the monte-carlo analysis for all 5 standards in all 5 geometries. The Belgian, Dutch and French standard consistently achieve similar indoor air quality, at a level that is considerably higher than that achieved by the British standard. The performance of the systems sized according to the ASHRAE standard, relative to the other standards, is much more prone to variation due to the fact that the flow rate is mainly concentrated in the kitchen and expressed as a function of its volume. Although the flow rates are similar in magnitude to those prescribed in the French standard, the lack of transfer grilles in the ASHRAE standard prevents a good distribution of this flow rate through the rest of the dwelling. Position and size of the kitchen relative to the other spaces therefore has a large influence on the achieved performance.

		Belgium	**France**	**Netherlands**	**UK**	**ASHRAE**
Flat	IDA 1	0.662	0.757	0.670	0.430	0.701
	IDA 2	0.184	0.185	0.162	0.221	0.114
	IDA 3	0.133	0.055	0.140	0.236	0.174
	IDA 4	0.021	0.002	0.028	0.114	0.010
Terraced	IDA 1	0.714	0.724	0.679	0.391	0.527
	IDA 2	0.164	0.130	0.151	0.191	0.197
	IDA 3	0.098	0.136	0.125	0.252	0.150
	IDA 4	0.024	0.011	0.046	0.166	0.127
Semi-Detached	IDA 1	0.695	0.702	0.719	0.452	0.634
	IDA 2	0.162	0.185	0.152	0.195	0.182
	IDA 3	0.116	0.106	0.118	0.227	0.161
	IDA 4	0.027	0.008	0.011	0.126	0.024
Detached	IDA 1	0.696	0.705	0.706	0.429	0.509
	IDA 2	0.163	0.142	0.148	0.183	0.185
	IDA 3	0.102	0.128	0.097	0.238	0.175
	IDA 4	0.039	0.025	0.048	0.149	0.131

Bungalow	IDA 1	0.719	0.666	0.693	0.436	0.482
	IDA 2	0.171	0.180	0.161	0.190	0.173
	IDA 3	0.103	0.144	0.137	0.215	0.205
	IDA 4	0.006	0.010	0.010	0.158	0.140

Table 4. Time fractions spent in the different IDA classes considering all 334 occupants from the 100 simulations in the monte-carlo analysis for all 5 standards in all 5 geometries.

Air change rates and ventilation heat loss

The median as well as first and third quartile values of the air change rate for all dwellings and all standards are listed in table 5. A clear distinction is seen between the Belgian and Dutch standard on the one hand and the British, French and ASHRAE standard on the other. The air change rate in the latter group is much less susceptible to variation due to changing boundary conditions due to the smaller sizing of trickle ventilators or the absence thereof compared to the Belgian and Dutch standard that require relatively large trickle ventilators. The Belgian, Dutch, French and ASHRAE standard all achieve median air change rates close to 0.5 ACH, that, as was mentioned in the introduction, can be considered a consensus value for residential buildings, while the system sized according to the British standard consistently renders about 40% lower values.

Figures 1 shows the cumulative distribution of the ventilation heat loss for both the detached house for all 5 standards, taking into account both intended and adventitious ventilation as well as infiltration. The same conclusions as with the air change rate apply.

		Belgium	**France**	**Netherlands**	**UK**	**ASHRAE**
flat	median	0.58	0.69	0.66	0.42	0.80
	Q1	0.57	0.68	0.65	0.41	0.79
	Q3	0.59	0.69	0.67	0.42	0.80
terraced	median	0.50	0.51	0.54	0.31	0.50
	Q1	0.46	0.51	0.50	0.31	0.50
	Q3	0.68	0.52	0.72	0.32	0.50
semi-detached	median	0.47	0.48	0.54	0.29	0.53
	Q1	0.42	0.47	0.48	0.29	0.53
	Q3	0.66	0.50	0.72	0.32	0.54
detached	median	0.64	0.59	0.72	0.39	0.55
	Q1	0.54	0.57	0.61	0.36	0.53
	Q3	0.85	0.67	0.96	0.45	0.61
bungalow	median	0.55	0.53	0.61	0.36	0.59
	Q1	0.47	0.51	0.54	0.33	0.57
	Q3	0.75	0.61	0.80	0.45	0.66

Table 5. Median, first quartile and third quartile air change rate from the 100 simulations in the monte-carlo analysis for all 5 standards in all 5 geometries.

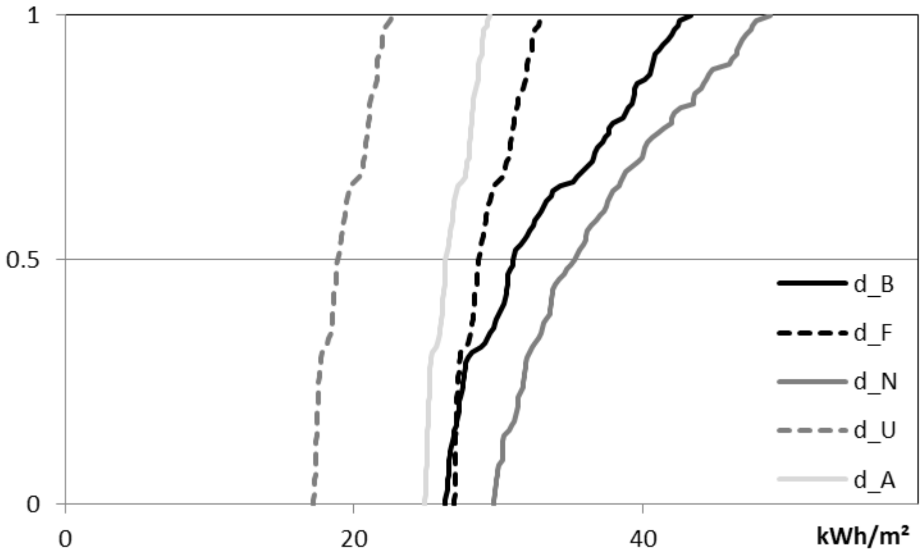

Figure 1. Cumulative distribution of ventilation heat loss in the detached dwelling for all 5 standards.

Trade-off ventilation heat loss and indoor air quality

If the trade-off between heat loss and indoor air quality is considered (Figure 2), using the average ventilation heat loss for the former and the average carbon dioxide to which the occupants are exposed as the criterion for the latter, the French and British standard provide pareto optimal solutions for each dwelling, although the fact that the indoor air quality achieved by the British standard is to be considered ‘poor’ 15% of the time is a cause of concern. Compared to the French standard, for example, the exposure to carbon dioxide of the cases using the ASHRAE standard is on average 40% higher, with higher or comparable heat losses (+16 to -8 %). Similarly, the ventilation heat loss in 4 cases using the Dutch standard is on average 20 % higher than that in the cases with the French standard for higher or comparable carbon dioxide exposure (+10 to -5%). In the flat, the heat losses using the French standard were comparable to those using the Dutch standard (+4%) with lower exposure to carbon dioxide (-26%).

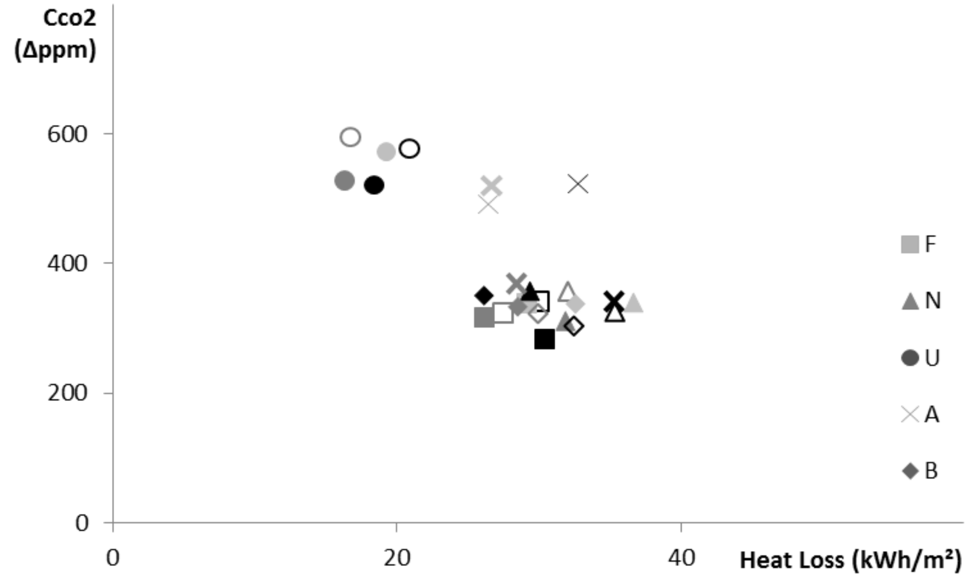

Figure 2. Heating season averaged ventilation heat loss traded-off against average carbon dioxide concentration to which occupants are exposed during the heating season for all 5 standards in all 5 dwellings (flat – black solid

fill, terraced – grey line, semi-detached – dark grey solid fill, detached – light grey solid fill, bungalow – black line, symbols correspond to the standards, as shown in the legend)

CONCLUSION

Sizing rules in residential ventilation standards lack uniformity in both methodology and resulting design flow rates. Mere comparison of design flow rates is case sensitive and, due to effects of infiltration, adventitious ventilation and occupancy, ill-suited to assess performance of an exhaust ventilation system with regard to the achieved indoor air quality and energy cost in terms of heat loss. A performance assessment of residential mechanical exhaust ventilation systems using five common dwelling typologies and the sizing rules put forward in the Belgian, British, Dutch, French and ASHRAE residential ventilation standards in multi-zone simulations with Monte-carlo based sensitivity analysis presented above showed that the performance of the different cases proved to be substantially different. An occurrence of poor perceived air quality in 5% or less of the occupation time for the Belgian, Dutch and French standard, and about 15% for the British and ASHRAE standard was found.

The spread observed in the performance of the cases using the ASHRAE standard can be attributed to the larger impact of geometrical parameters on the system design in this standard.

The total air change rate was close to or greater than the consensus value of 0.5 ACH in most cases, except in the cases using the British standard, where it was consistently about 40% lower. The cases using the Belgian and Dutch standards, with relatively large trickle ventilators, rendered the air change rates most sensitive to changes in boundary conditions. When the trade-off between indoor air quality and heat loss is considered, the cases with the Dutch and ASHRAE standard did not achieve pareto-optimal performance.

Considering the performance spread observed, harmonization of residential ventilation standards is to be recommended. The design philosophy of the French standard proves to be a good basis for exhaust ventilation design with high occurrence of good perceived air quality, minimized ventilation heat loss and robust performance. It's combination of moderately high exhaust flow rates, large transfer devices and small trickle ventilators should explored further when new, more uniform standards are developed.

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