Do Ventilation Systems Accomplish the Necessary Indoor Air Quality in Low Energy Houses?

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Abstract
The aim of the EU EPBD is to realize lower energy consumption in buildings, without neglecting the indoor air quality. A suggested measure is to improve the air tightness of the building, combined with a well designed ventilation system to guarantee a good indoor air quality. The research presented here analyzed the indoor climate of 71 recently built dwellings in Flanders, Belgium, ranging from standard execution over low energy up to even energy positive houses. These houses represent a wide range of air tightness levels and different types of ventilation systems. In each house, temperature, humidity and CO_2 concentration were monitored in living room, master bedroom and bathroom during 2 weeks in winter. These measurements were complemented with air tightness measurements. Results showed good to reasonably good indoor air quality in all houses, independently of the type of ventilation system. Also the internal humidity was very acceptable in almost all houses. Only in some dwellings with a natural ventilation system, the average indoor climate class in the living room reached a level ICC3 or ICC4. Furthermore, no correlation was found between air tightness and indoor air quality. Even in very air tight dwellings, good indoor air quality was achieved, also with natural or mechanical exhaust ventilation.

Keywords – low energy; indoor air quality; air tightness; ventilation system; internal humidity

1. Introduction

The challenge of climate change and the exhaustibility of fossil fuels made governments introduce energy performance regulations, such as the EU EPBD of 2002 [1] to avoid the construction of energy devouring buildings. These regulations are tightened regularly and will become very severe in the future, given the recast of the EU EPBD in 2010 [2] that imposes nearly zero energy performance for new buildings by 2021. However, individual builders do not wait for this tightening, but increasingly opt to build dwellings that perform better than the legal standard. In Flanders, Belgium, in 2006 at the introduction of the Flemish EPBD (called EPB), only 4.5% of all new dwellings performed at least 40% better than the then applicable legal standard, thereby meeting the legal requirements as they will be set in 2014. In 2010, already more than 35% of the new dwellings met the requirements of 2014. Also the ‘forerunners group’, individuals who build extremely low energy houses, is constantly increasing, from 0.8% in 2006 to 10.7% in 2010 [3].

One of the measures to increase the energy performance of dwellings, is by improving the air tightness of the building and thus reducing the infiltration losses. The Flemish EPB does not legally impose a certain air tightness level up to now, but stimulates measures to improve the air tightness, by letting a good air tightness, proved with an official blower door test, have a positive impact on the official energy performance certificate that has to be calculated for each new dwelling. As the analysis of the Flemish EPB certificates for new dwellings from 2006-2011 shows [3], there is a growing awareness of the importance of air tightness, with only 1.9% of all new dwellings having a blower door test in 2006, and already 21.6% in 2010 (29% for detached houses). The houses with blower door test have an average air tightness of 3.65 m^3/h per m^2 heat loss area (in contrast to the default air tightness value for the energy performance level calculation, being 12 $m^3/h.m^2$).

However, a low energy building without a good indoor air quality is a badly performing and unsustainable building, thus a good air tightness level should be combined with a well designed ventilation system in order to guarantee a good indoor air quality. Different ventilation systems are available, from natural ventilation with ventilation grids in the windows and a stack ventilation chimney in kitchen and bathroom over mechanical exhaust ventilation, with or without humidity or CO_2 based control systems, up to complete balanced ventilation with heat recovery. The installation of a well designed ventilation system has been imposed by the Flemish government since the introduction of the EPB in 2006. There is freedom of choice between the different ventilation types, but the design of the ventilation system has to occur in accordance with the ventilation standard CEN/TR 14788 [4]. However, as the legal requirements on energy performance become more severe, it is clear that application of balanced ventilation with heat recovery is increasing. The EPB certificates report [3] reveals that in 2006 18% of all new dwellings had natural ventilation, 52% exhaust ventilation and 25% balanced ventilation with heat recovery. In 2010, however, only 2% of the new dwellings had natural ventilation, whereas 55% opted for exhaust ventilation and 42% for balanced ventilation with heat recovery.

However, as the requirements on ventilation are imposed in order to guarantee a good indoor air quality in low energy houses, it is important to investigate whether these systems do provide a good indoor air quality in reality and to what extent the real indoor air quality depends on system and/or air tightness level. Therefore, in the frame of a larger ongoing research project on 'Reliable energy performances of dwellings – To a robust and occupant independent performance', a large monitoring campaign has been set up to monitor real energy consumption and indoor climate as well as perceived indoor climate in 71 recently built dwellings, ranging from standard over low energy and passive up to zero energy and energy positive houses. In this paper, the results of the monitoring campaign of the indoor air quality during winter will be presented. Firstly, in chapter 2, an overview of the dwellings will be given followed by a description of the applied methodology for monitoring and processing of the measurements. Then in chapter 3 and 4, the main results will be presented and discussed. Finally, in chapter 5 conclusions will be formulated.

2. Methodology

Description of the dwellings

All 71 dwellings are located in Flanders, Belgium, with a regular distribution over the Flemish territory. With regard to typology, 46 dwellings are detached, 23 semi-detached and 2 are attached houses. With regard to construction type, there are 45 massive constructions with brick cavity walls and 26 wood frame constructions. Fig. 1 gives the distribution of the dwellings according to insulation level (K-level) and energy performance level (E-level). The insulation level is determined by the overall mean U-value and the compactness (as ratio of heated volume and heat loss area). K45 represents a mean U-value of 0.45W/m²K for a compactness of 1m. Most passive houses have an insulation level between K10 and K20. The E-level is the ratio of the calculated primary energy consumption for heating, cooling, domestic hot water, pumps and fans (including the impact of renewable energy production) and the calculated reference primary energy consumption, depending on the compactness of the building. The lower the E-level, the better the energy performance. Depending on the presence of renewable energy systems, most passive houses have an E-level of E20-E60. Near-zero energy is represented by ±E0. In Fig. 1, also the legal requirements for K- and E-level since 2006 are given.

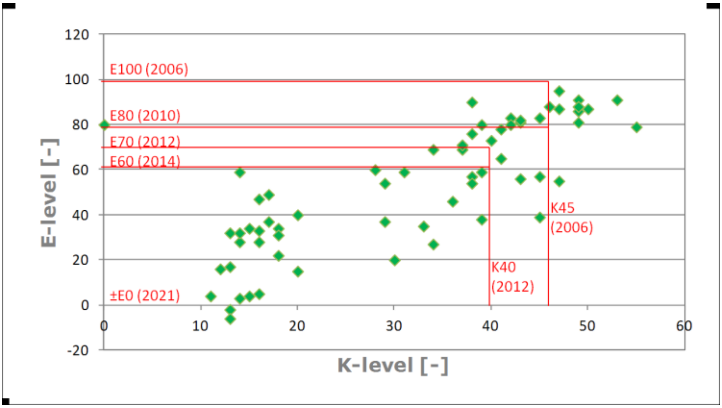

Fig. 1 Distribution of the dwellings according to their insulation level (K) and energy performance level (E) (dots) and legal requirements for K and E since 2006 (lines)

With regard to the heating system, 10 dwellings have a high efficiency boiler, 33 a condensing boiler, 14 a heat pump, 4 a wood boiler, 3 electrical heating of the ventilation air and 7 dwellings have no heating system. With regard to renewable energy systems, 6 dwellings have a thermal solar collector, 17 have photovoltaic panels and 10 dwellings have both.

With regard to ventilation, 14 dwellings have natural ventilation, 14 exhaust ventilation of which 2 with a humidity based control system and 43 have balanced ventilation with heat recovery. Fig. 2 presents the distribution of the ventilation systems according to insulation (K-level) and energy performance level (E-level).

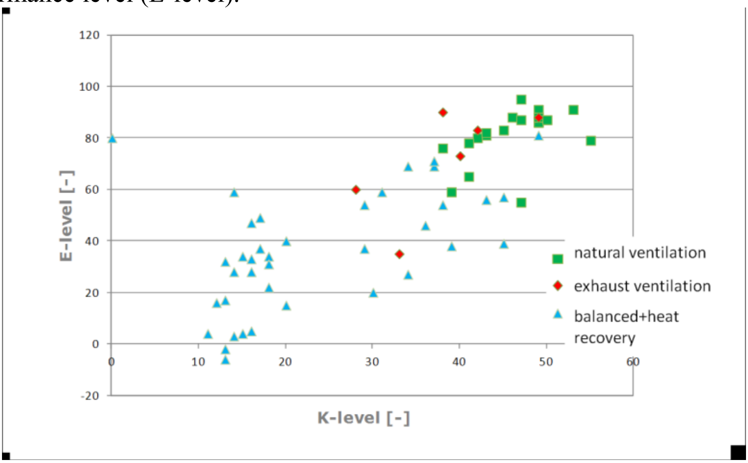

Fig. 2 Distribution of the dwellings according to the applied ventilation system in relation to insulation level (K) and energy performance level (E)

With regard to air tightness, 22 dwellings have an official passive house certificate and thus a proved n_{50} < 0.6/h and 9 dwellings got a blower door test without aiming for passive house standard. Further details on the achieved air tightness levels will be presented in the results.

Monitoring of indoor climate

In each dwelling, indoor climate in winter situation was monitored during at least 2 weeks in the period from November 2011 until April 2012. The indoor temperature and vapor pressure were measured every 15 minutes with an ONSET HOBO U12 logger in the living room, master bedroom and bathroom. In most living rooms and in 15 master bedrooms, also the CO_2 concentration was measured every 15 minutes with a Telaire 7001, coupled with a HOBO U12 logger. Due to the limited magnitude of the Flemish territory, the outdoor temperature and vapor pressure were measured at one central location, at 5-140km from the dwellings (on average 44 km).

Evaluation criteria for indoor air quality

The indoor air quality is assessed by means of the CO_2 concentration and the internal humidity. For CO_2 concentration, four indoor air quality levels are considered according to EN 13379 [5]: IDA1 (< 750ppm), IDA2 (750-950ppm), IDA3 (950-1350ppm) and IDA4 (>1350ppm). These levels are defined relative to the outdoor CO_2 concentration. Outdoor air contains about 350 to 400 ppm CO_2 [6]. Based on the value of the indoor CO_2 concentration in several dwellings outside occupation period, a general value of 350 ppm for the outdoor CO_2 concentration is used in the calculations. For a good indoor air quality, IDA1 or IDA2 level should be aimed for.

For internal humidity, the internal climate classes (ICC) according to EN 13788 (CEN 2001) [7] are used. The boundary conditions for ICC1 to ICC5 for the vapor pressure difference between indoor and outdoor ($p_i - p_e$) as a function of the monthly mean external temperature θ_{em} are shown in Table 1, together with the corresponding building types. In order to avoid problems of interstitial condensation and mould, level ICC3 or lower should be aimed for

Table 1. Boundary conditions for the indoor climate classes according to EN 13788

	p_i - p_e (Pa)		
	θ_{em} < 0°C	θ_{em} ≥ 0°C	Building types
ICC1	< 270	< 270 – 13.5 θ_{em}	Storage
ICC2	< 540	< 540 – 27.0 θ_{em}	Offices, shops
ICC3	< 810	< 810 – 40.5 θ_{em}	Buildings with low occupancy
ICC4	< 1080	< 1080 – 54.0 θ_{em}	Buildings with high occupancy
ICC5	≥ 1080	≥ 1080 – 54.0 θ_{em}	Special buildings, e.g. laundry, brewery,…

3. Results

Table 2 presents the cumulative percentage of time the CO_2 concentration is within an IDA class or better. The percentages are summarized per ventilation type and per type of room. Also the number of systems monitored per ventilation type and per type of room is given in table 2. For the living rooms, the whole monitoring period is taken into account, whereas for the bedrooms, only the night period between 1am and 5am is taken into account to guarantee that the bedrooms were occupied. Fig. 3 shows the cumulative distribution for each ventilation system separately for the 49 living rooms that have been monitored.

Table 2. Summarized cumulative percentage of time the CO_2 concentration in 49 living rooms and 15 master bedrooms is within an IDA class as a function of ventilation system

	IDA1	IDA2	IDA3	IDA4
Living rooms (during whole monitoring period)				
Natural ventilation (#=13)	57%	75%	92%	100%
Exhaust ventilation (#=12)	69%	87%	97%	100%
Balanced ventilation (#=24)	73%	90%	98%	100%
Bedrooms (during 1am-5am)				
Natural ventilation (#=2)	48%	61%	99%	100%
Exhaust ventilation (#=3)	19%	37%	80%	100%
Balanced ventilation (#=10)	17%	39%	78%	100%

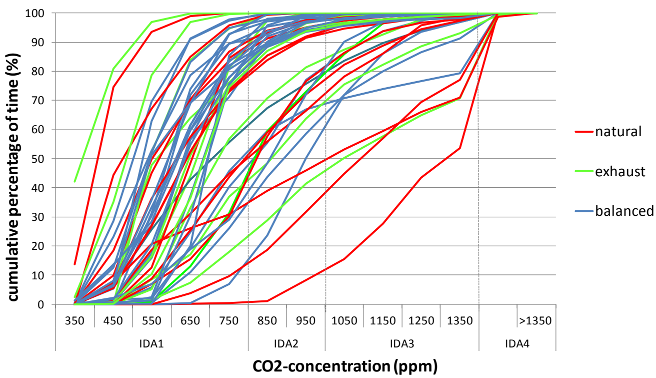

Fig. 3 Cumulative percentage of time the CO_2 concentration in 49 living rooms is within an IDA class as a function of ventilation system

Fig. 4 presents the mean value and the spread of the CO_2 concentration in 44 living rooms as a function of air tightness and ventilation type. As the blower door tests are still ongoing, only results are given for the dwellings of which air tightness level and CO_2 concentration have been measured. From these 44 dwellings, 13 have natural ventilation, 9 exhaust ventilation and 22 balanced ventilation with heat recovery.

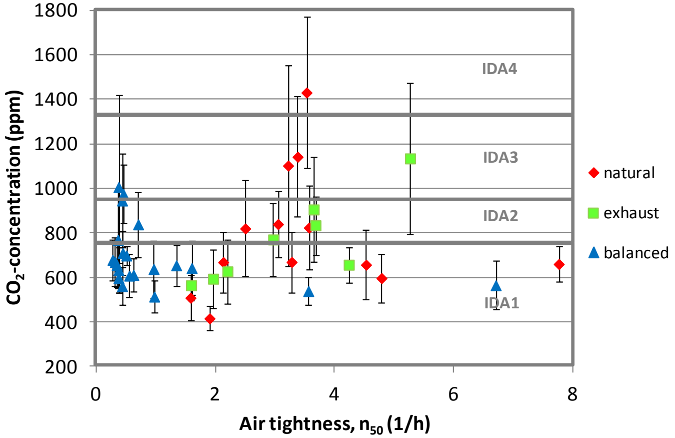

Fig. 4 CO_2 concentration in 44 living rooms as a function of air tightness and ventilation type

Fig. 5 gives the daily averaged vapor pressure difference per dwelling as a function of the daily averaged outdoor temperature and as a function of the ventilation system. The daily averaged vapor pressure differences are also volumetrically averaged values per dwelling based on the measured vapor pressures in and volumes of living room, master bedroom and bathroom.

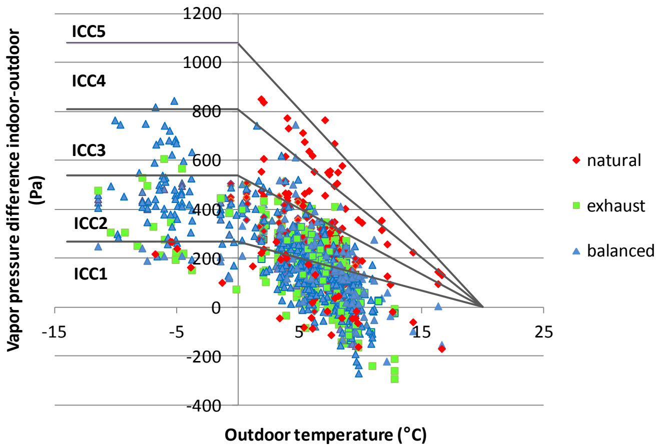

Fig. 5 Daily averaged vapor pressure difference in all dwellings as a function of the daily averaged outdoor temperature and of the ventilation system

Table 3 presents the number of dwellings for which the average indoor air quality in the living room and in the master bedroom can be qualified by a certain IDA-class and ICC. The type of ventilation system in these dwellings is notated through the abbreviation n (=natural), e (=exhaust) and b (=balanced). Per dwelling, the IDA-class and ICC have been calculated as an average for the whole monitoring period for the living room and for all monitored hours between 1am and 5am for the bedroom. The colors green, orange and red represent the zones of good, mediocre and unacceptable air quality.

Table 3. Number of dwellings within a certain IDA- and ICC-level with notation of their ventilation type (n=natural, e=exhaust, b=balanced).

	IDA1	IDA2	IDA3	IDA4
Living rooms (average over whole monitoring period)				
ICC1	3n-5e-12b	2e	1e-1b	
ICC2	4n-2e-7b	3n-1e-3b	1b	
ICC3			1n	1n
ICC4			1n	
Bedrooms (average over monitored periods from 1-5am				
ICC1	1n-1b	1e-1b	1n-2b	1e
ICC2		1b	5b	1b
ICC3				
ICC4				

4. Discussion

As Table 2 shows, most living rooms appeared to have a reasonably good CO_2 concentration during the monitored winter period. The percentage of time IDA4 level is achieved, is very limited: on average 8% of the time for dwellings with natural ventilation and 2-3% of the time for dwellings with exhaust or balanced ventilation. As appears from Fig. 3 and Table 3, for natural ventilation, this is mainly due to the bad performance of one natural ventilation system leading to IDA4 during almost 30% of the time and the mediocre performance of two other systems that are less than 50% in IDA1 and 2. In the sleeping rooms, however, the results are less positive. During almost 40% of the time IDA3 is achieved with all ventilation types and IDA4 during circa 20% of the time with the mechanical ventilation systems. In contrast to what could be expected, the natural ventilation systems are better performing in the sleeping rooms than the mechanical ventilation systems. However, some caution with regard to too positive assessment of natural ventilation is required, since only 2 bedrooms with natural ventilation have been monitored. Similarly, caution with the good performance of all systems is needed for the living rooms, since no information on effective presence of the occupants has been taken into account. This might be included in the future, as a high CO_2 concentration is only problematic when the occupants effectively are in the room. Nevertheless, 34 out of 49 monitored living rooms appeared to achieve IDA2 or better during more than 90% of the time and these 34 dwellings include all ventilation types: 7 with natural ventilation, 8 with mechanical exhaust ventilation and 19 with balanced ventilation.

Fig. 4 presents the CO_2 concentration in 44 living rooms with their corresponding air tightness and ventilation system. In Fig. 4 the air tightness ranges from n_{50} = 0.31/h to 7.77/h, but air tightness levels from n_{50} = 0.12/h to 11.25/h have been measured in 53 dwellings with an average n_{50} of 1.58/h; from these houses, 21 have an air tightness level n_{50} < 0.6/h, thus meeting the passive house standard for air tightness. From Fig. 4, it is clear that the air tightness as such does not have an impact on the CO_2 concentration. Furthermore, the results show that for most air tightness levels good indoor air quality can be achieved, regardless of the type of ventilation system. Only for very low air tightness levels (n_{50} < 1/h), no evidence for good indoor air quality with natural or exhaust ventilation can be shown, as these combinations are not present in our sample. However, in contrast to what is sometimes expected, these very low air tightness levels combined with a mechanical balanced ventilation system can perfectly result in sufficiently low CO_2 concentrations. Obviously, a good design and execution of the ventilation system and a proper use are important.

Fig. 5 shows that most days the indoor humidity in relation to the outdoor humidity remains below ICC4, especially with the mechanical ventilation systems (exhaust and balanced). This means that according to internal humidity, the majority of the houses performs as building with low occupancy. For some dwellings with natural ventilation, the internal humidity level was ICC4 for some days and even ICC5 for two days. However, since mould and interstitial condensation due to vapor diffusion need prolonged high humidity levels to occur, the risks for hygric problems appear to be very low in these dwellings.

Table 3 integrates both evaluation criteria on indoor air quality, as it shows the number of dwellings for which a combination of IDA-class and ICC can be found. This Table clearly shows that there is a larger spread on CO_2 concentration than on internal humidity level. Based on the average for the whole monitoring period, only one dwelling (with natural ventilation) is located in ICC4, thus performing as a building with high occupancy. All other dwellings perform very well with regard to humidity control, in the living rooms as well as in the bedrooms. Nevertheless, in despite of the larger spread on CO_2 concentration, it is also clear from Table 3 that the majority of dwellings is also performing well with regard to CO_2 concentration in the living room, as they are located in IDA1 or IDA2-class, without distinction between ventilation systems. Only for 6 dwellings the

CO_2 concentration in the living room is too high, with no clear distinction between the ventilation systems. For the bedrooms, however, the CO_2 concentration is less positive, since the majority is in IDA3, especially for the rooms with balanced ventilation. This might be due to the fact that only a very concentrated period in the bedrooms is considered. Nevertheless, it is also important to keep in mind that IDA3 does not represent problematic or unhealthy CO_2 concentrations, but simply is below good air quality.

5. Conclusions

With the upcoming strengthening of the energy performance regulations, it is important that newly built houses not only are energy saving, but also have a good indoor climate. Therefore an extensive monitoring campaign has been executed on 71 recently built dwellings in Flanders in order to investigate their indoor climate. Focus of this paper was the indoor air quality in relation to the applied ventilation system and the air tightness. The indoor air quality has been assessed by means of the CO_2 concentration (IDA-classes) and the internal humidity (internal climate classes ICC). From this research it can be concluded that all dwellings, except one, perform very well with regard to internal humidity control and that the majority of dwellings is also performing well with regard to CO_2 concentration. There is a larger spread on CO_2 concentration than on internal humidity, but there were no problematic or unhealthy situations found, regardless of the applied ventilation system or the air tightness level.

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