Indoor air quality in mechanically ventilated residential dwellings/low-rise buildings: A review of existing information

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ABSTRACT
Mechanical ventilation has become a mandatory requirement in multiple European standards addressing indoor air quality (IAQ) and ventilation in residential dwellings (single family houses and low-rise apartment buildings). This article presents the state of the art study through a review of the existing literature, to establish a link between ventilation rate and key indoor air pollutants. Design characteristics of a mechanical ventilation system such as supply/exhaust air flow, system and design of supply and exhaust outlets were considered. The performance of various ventilation solutions was assessed by comparing reported ventilation rates, concentrations of CO_2 and total volatile organic compounds (TVOC) to minimum requirements defined by the latest version of the European Standard EN 15251:2007. Based on the literature review of these parameters, the authors noted that whenever the whole-house ventilation rate was reported below $0.5h^{-1}$ or 14 l/s·person in bedrooms, the concentrations of the pollutants elevated above minimum threshold limits (CO_2>1350 ppm; TVOC > 3000 μg/m^3) defined by the standard. Insufficient or non-existent supply of air was related to significantly higher pollutant concentrations. The authors additionally noted that the literature frequently reported the role of improper maintenance and use on deterioration of IAQ in residential dwellings. The summarized data and comments may provide useful information for future guidelines related to ventilation strategies designed for high IAQ in residential dwellings.

KEYWORDS

Mechanical ventilation, residential dwellings ventilation rates, pollutants, indoor air quality

1. INTRODUCTION

Due to the tightly insulated building envelope, the provision of sufficient fresh air becomes more important than ever in residential dwellings for better indoor air quality (IAQ). In this case, natural ventilation is often unable to provide adequate ventilation for odour or contaminant removal, and mechanical ventilation (MV) is necessary to achieve minimum ventilation rates (Dimitroulopoulou, 2012). Still, nowadays only a few European national standards regarding IAQ in residential dwellings either recommend MV for ventilation system selection (Belgium and Germany) or stipulates that MV must be installed in dwellings as the only ventilation solution (Denmark and Poland). Other standards (France, Sweden and UK) allow flexibility in the selection between natural and MV systems (Kunkel, 2015). Although all the standards provide guidance on whole-house ventilation rates, calculation tools for ventilation rates vary from standard to standard depending on whether the ventilation rate is regulated based on the number of persons, type of room or floor area. When mechanical ventilation is required, virtually every code specifies that a certain volume of air must be exhausted from wet-rooms (bathroom, kitchen and toilets), however few codes (Denmark, Poland and Belgium) have requirements for distributing fresh air throughout other, so called dry saces where people spend most of their time. Several European national standards (France, UK, Germany and Sweden) do not include any requirements on ventilation rates for bedrooms, where people spend one-third of their life while sleeping: 12–14 h/day during infancy and 7–8 h/day during adulthood (Strøm-Tejsen et al., 2016). In addition, different requirements for building airtightness imposed by different national standards (Kunkel, 2015) make it even more difficult to harmonise the wide range of sizing rules for an adequate comparison across countries for assessing IAQ in mechanically ventilated dwellings. The first version of the standard addressing ventilation requirements for IAQ in residential buildings on a European level was published in 2007 as EN 15251:2007and current representative of European standards for residential buildings. This standard is currently under revision and its last draft dates back to 2014. EN 15251:2007 offers three methods for defining the minimum ventilation rates (Table 1.).

Table 1. Ventilation rates defined by EN 15251:2007

		Supply Airflow							Exhaust Airflow		
Class	Expected percentage of dissatisfied	Total Ventilation Rate including Air Filtration(1)		Airflow per person	Air flow based on perceived IAQ for adapted persons		Airflow Bedroom level		Kitchen	Bathrooms	Toilets
	(%)	(l/s·m^2)	ACH	(l/s·per)	q_p (l/s·pers)	q_b (l/s·m^2)	Master Bedroom (l/s)	Other Bedrooms (l/s)	(l/s)		
I	15	0.49	0.7	10	3.5	0.25	20	10	28	20	14
II	20	0.42	0.6	7	2.5	0.15	14	8	20	15	10
III	30	0.35	0.5	4	1.5	0.1	8	4	14	10	7
IV	40	0.23	0.4	N/A	N/A	N/A	5	2.5	10	6	4

The supply ventilation rates is based on one of the three following criteria: total ventilation rate for the dwelling, supply airflow for bedrooms and supply airflow based on assumed number of occupants. EN 15251:2007 instructs to select the highest value from the three calculated methods for supply flow rate, compare it to the prescriptive total exhaust flow rate and select the higher of the latter two as the minimum design value for the total ventilation rate. Beside ventilation rates and air quality classes, pollutant limit values for two common air pollutants are also indicated in EN 15251:2007. Requirements for limiting carbon-dioxide (CO_2) and total volatile organic compound (TVOC) levels in residential buildings as defined by different air quality classes (AQC) are presented in Table 2.

Table 2. Limit values of CO_2 and TVOC as given by EN 15251:2007

Air Quality Class	CO_2 (ppm)		TVOC (μg/m^3)	Level
	Bedrooms	Other rooms		
I	780	950	300	Very low polluting building
II	950	1200		
III	1350	1700	1000	Low polluting building

2. METHODOLOGY

The objective of this review is to:

1. Assemble, and summarize existing measurement data on ventilation rate, CO_2 and/or TVOC in mechanically ventilated European dwellings
2. By comparing assembled data to the existing standard for IAQ (EN 15251:2007) - identify and summarize direct and indirect relationships between characteristics of mechanical ventilation systems in residential dwellings/buildings and pollutant concentrations

Previous literature reviews on the relationship between a reduced risk of allergic manifestations among children in a Nordic climate and whole-house ventilation rates above 0.5 ACH (Wargocki 2002, Sundell 2011).To verify whether ventilation requirements stipulated by the current classes in prEN 15251:2007 are sufficient to reduce the pollutant concentrations, the results from previous research studies based on field experiments that reported CO_2 and TVOC concentrations in mechanically ventilated residential dwellings and low rise buildings are analysed and compared to limits indicated by EN 15251:2007.
Beside ventilation rate and airflow distribution through rooms in dwellings, the characteristics also include type of MV system (MEV- mechanically exhaust ventilation system, MES – mechanically supply ventilation system MVHR – mechanically ventilation system with heat recovery) and type of airflow control strategy (CAV – constant air volume systems, DCV) – demand control ventilation system). Since the main focus of the study was to analyse the relationship between the ventilation rate and CO_2 and TVOC concentrations, the keywords used for the search were: *mechanical ventilation, ventilation rate, residential dwellings/buildings, and indoor air quality.* Science direct and Google scholar engines were used to search the literature. The literature peer-reviewed publications: journals papers, conference proceedings. The classification process was based on whether the source article was *relevant and informative* – providing sufficient information on ventilation rates and pollutant levels of at least CO_2 or TVOC concentrations; or *relevant but non-informative*– containing incomplete information concerning ventilation rates or the indoor air pollutants.

3. RESULTS

In total, twenty articles were identified and those containing studies of residential dwellings including quantitative evaluations of ventilation rates and data of at least concentration levels of CO_2 or TVOC. Seven papers were excluded and judged as relevant but non-informative. The main reason for exclusion was that data on ventilation rates and IAQ pollutants in mechanically ventilated dwellings were lumped into the same ventilation category as natural ventilation systems. Thirteen papers were found to be informative and relevant for this study and the paper originated from eight European countries: Sweden (3), UK (3), France (2), Austria, Belgium, Finland, Netherlands and Norway. Three papers addressed both CO_2 and TVOC concentrations, eight only CO_2 concentrations and two only TVOC concentrations along with ventilation rates. The articles were published from 2007 to 2016. Summarized information on the objective, number of dwellings, type of ventilation and control system, year of construction, airtightness, ventilation rates, CO_2 and TVOC concentrations are presented in Table 3.

3.1. CO_2 concentrations

A Swedish study (Hesaraki, 2015) analyzed four different ventilation rates (Figure 1) in a recently renovated single house in Sweden equipped with mechanical exhaust ventilation. The mean CO_2 concentrations measured showed that increasing the whole house ventilation rate from 0.14 ACH to 0.3ACH (both < AQC IV EN 15251) decreased the CO_2 levels from over 1300 ppm (AQC II) to less than 1000 ppm (AQC I).

While the CO_2 concentrations were mostly kept within AQC III in ten new-built mechanically ventilated French dwellings ($<0.6 m^3/h \cdot m^2$), the limit levels were frequently exceeded in bedrooms due to low whole house ventilation rates <0.5 ACH (Figure 2). The same study (Guyot, 2015) also reported bad doors undercut as a reason for high CO_2 concentrations in main bedrooms.

A study from the UK (Mcgill, 2015) reported lower ventilation rates (< 4 l/s·person – below AQC III EN 15251) and average CO_2 concentrations exceeding 1000 ppm in bedrooms of two of four new built dwellings (airtightness level $< 5 m^3/h \cdot m^2$@50 Pa) with MVHR ventilation. Inadequate ventilation rates less than 11 l/s (< AQC II) were observed in all bedrooms during night. None of the cases complied with AQC I or II of EN15251 for minimum CO_2 concentrations in bedrooms (Figure 3).

Author(s)	Objective	Dwellings	Type of Mechanical Ventilation	Control system	Construction/Renovation year	Airtightness	Measurement Method	CO2 concentrations (ppm)	TVOC (µg/m3)	Ventilation Rate
Berge et Mathisen 2016	The indoor climate in a high-performance multifamily building was evaluated based on a user survey and measurements (Norway)	4(A)	MVHR (n=4)	CAV	2008 ©	< 0.6ACH @50 Pa	CO2 concentrations were measured continuously in the period May 2013–April 2014 using Wisensys WS-DLC sensors.	85% of the time < 750 2,2 % of the time > 1200	N/A	24-52 m3/h (bedroom)
Derbez et al. 2014	Indoor air quality and comfort in seven newly built, energy-efficient houses (France)	7(H)	MVHR (n=7)	CAV	2008-2009 ©	0.06-0.41 m3/h.m2@4 Pa 0.29 -3.33 ACH @ 50 Pa	CO2 concentrations were measured during three weeks in summer and winter using a non-dispersive infrared probe/ TVOC measurements were done using a photoionization detector	351-881 (median range for all houses)	6 - 276 (range winter) 128-569 (range summer)	0.10–1.30 ACH (whole house)
Fischer et al. 2014	Indoor air measurements were conducted in one unoccupied apartment of a NZE residential building with wooden construction (Sweden)	1(A)	MVHR (n=1)	N/A	2010 ©	<0.6 ACH@50 Pa	TVOCs were collected using the Field and Laboratory Emission Cell (FLEC) with a flow rate of 0.0036 m3 /h during 60 min.	N/A	150±20 (average + SD)	0.53 ACH (whole house)
Guyot et al. 2015	Ventilation performance and indoor air pollutants diagnosis in low energy homes (France)	10 (H)	MVHR (n=10)	CAV/DCV	N/A	6 m3/hr/m2 @50Pa	CO2 concentrations were measured using a data logger with an infrared dispersive sensor for 7 days	661-1442 (mean - living room); 728-2351 (mean - bedroom)	N/A	0.13-0.79 ACH (whole house)
Hesaraki et al. 2015	To analyse the influence of different ventilation levels on indoor air quality and energy savings: a case study of a single-family house (Sweden)	1(H)	MEV (n=1)	CAV	1950s	N/A	CO2 concentrations were measured using the 'Testo 480 IAQ Probe' for three days per ventilation rate case	586-1337 (range)	N/A	0.14-1.0 ACH (whole house)
Holstejin et al. 2016	Monitoring IAQ in 62 Dwellings for 12 months (Netherlands)	62(H)	MEV in wet rooms; MEV in all rooms; MVHR with various types of controls	CAV/DCV	N/A	10 ± 1.0 dm3/s.m2	The CO2 concentrations were monitored for more than one year.	1399-1971 (mean)	N/A	37-52 m3/h (per person)
Mcgill et al. 2015	Bedroom environmental conditions in airtight mechanically ventilated dwellings (UK)	19 (H)	MVHR (n=17); MEV (n=2)	N/A	2010-2013	< 5 m3/hr/m2 @50Pa	CO2 concentrations were measured continuously during July–August 2013 and November 2013–January 2014 using a Wohler data logger.	630-1289 (mean - summer); 929-1291 (mean - winter)	N/A	3.53-16.84 l/s·per person (summer); 3.74-5.38 l/s·per person - (winter)
Järnström et al. 2006	Eight new residential buildings investigated for IAQ (Finland)	8(A)	MES (n=3); MEV (n=5)	N/A	1999-2002	< 4 ACH @50 Pa	TVOCs were collected on Tenax TA adsorbent at the air flow rate of ~100 ml min−1 for 120 min	N/A	397 (mean) in MES 1098 (mean) in MEV	0.95 ACH (whole house)
Langer et al. 2015	20 new passive houses and 21 new conventionally built houses monitored for IAQ (Sweden)	5(H)	MVHR (n=5)	CAV	2010-2013	< 0.6ACH @50 Pa	CO2 was sampled in the bedroom using a Q-trak Indoor Air Quality Monitor for a one week period time/The TVOCs were sampled onto radial diffusive tubes (Radiello®) with an exposure time of 7 days	6% of the time >1000	10 (median winter) 9.2 (median spring) 8.0 (median summer) 7.3 (median autumn)	0.68 ACH (whole house)
Laverge et al. 2015	Monitoring CO2 in the exhaust spaces of 36 old, 39 standard and 39 low energy dwellings (Belgium)	78 (H)	MVHR (n=39); MEV (n=39)	CAV	2007-	0.5 - 3 ACH @50 Pa	CO2 concentrations was monitored using a non-dispersive infrared logger for 9 days.	<750 (living rooms); < 1250 (bedrooms)	N/A	0.26 ACH (whole house)
Ridley et al 2013	Monitoring the performance of the first new London dwelling certified to the Passive House standard (UK)	1 (H)	MVHR (n=1)	CAV	2010	0.44 ACH @ 50 Pa	The CO2 concentrations were monitored for a one year period using Eltek wireless data logging and monitoring system.	< 700 ppm (living room); 78% of time < 1000 (bedroom)	N/A	0.48 ACH (whole house)
Sharpe et al. 2014	To asses indoor environmental quality in bedrooms of low energy houses (UK)	4(H)	MVHR(n=4)	N/A	N/A	2.45 m3 /h m2@50Pa	CO2 was collected using a Wireless Sensor Technology (WIST) during three different sample months in summer, spring and autumn	600-1100 (range) 858 (average winter)	N/A	9.76 l/s (bedroom)
Wallner et al. 2015	To investigate IEQ in 123 mecanically ventilated buildings (Austria)	62 (70% H, 30% A)	MVHR(n=62)	CAV	2010-2012	N/A	The CO2 concentrations were measured continuously for one week using method Wohler data logger/TVOCs were sampled by pumping air through charcoal tubes	1280-1360 (median)	120-300 (median)	20 to 25 m3/h per person 11% -21% of time (bedroom)

Table 3. Summary of papers providing background information about ventilation rates and indoor air pollutants

The graphical representation of indoor pollutant concentrations vs ventilation rates from articles presenting individual measurements in dwellings are based on the different metrics used for ventilation rates (Figure 1-3).

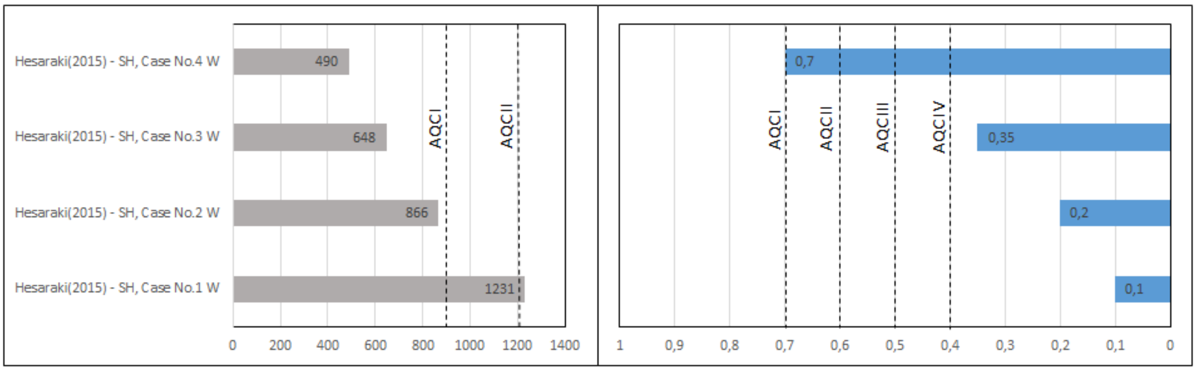

Figure 1. Average CO_2 concentrations (ppm) vs whole house-ventilations rates (ACH) compared to air quality classes defined by EN 15251 (Hesaraki, 2015)

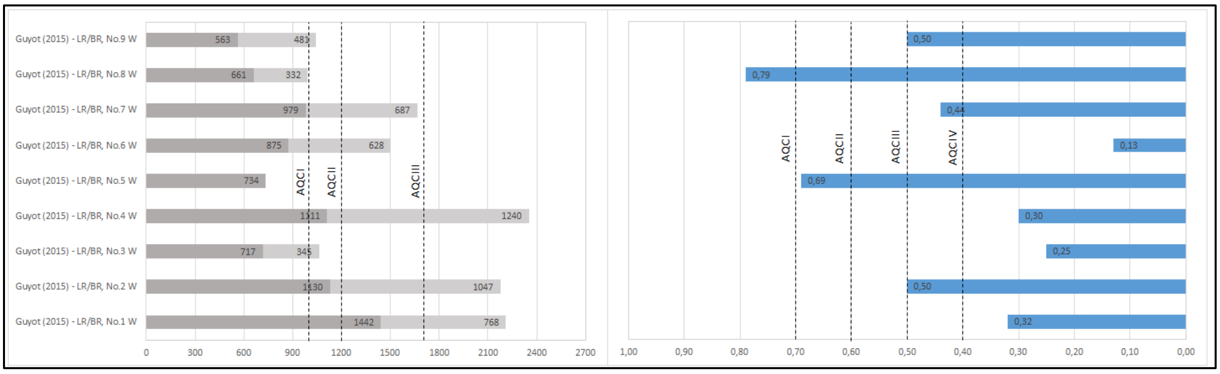

Figure 2. Average CO_2 concentrations in living rooms and bedrooms (ppm) vs whole house ventilation rates (ACH) compared to air quality classes defined by EN 15251 (Guyot, 2015)

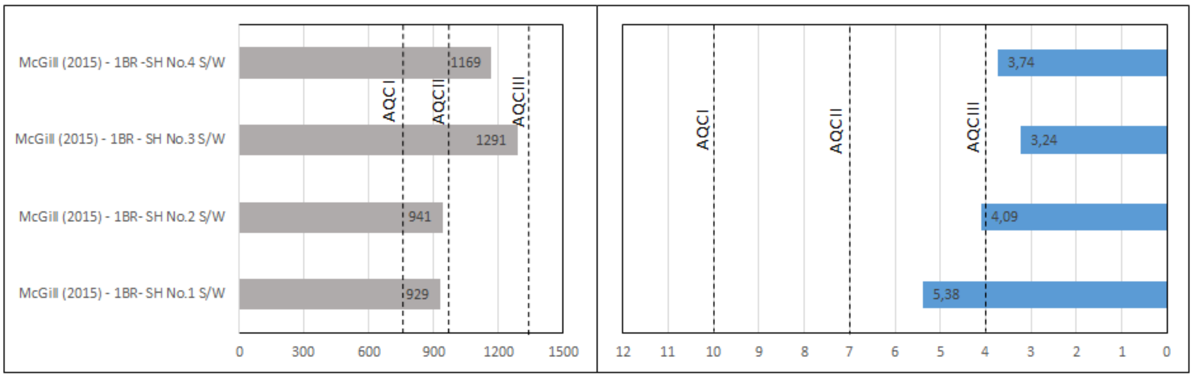

Figure 3. Average CO_2 concentrations (ppm) in bedrooms vs ventilation rates per person (l/s·person) compared to air quality classes defined by EN 15251 (Mcgill, 2015)

A French study (Derbez, 2014) found that the median CO_2 concentrations measured using tracer gas method were lower than 1000 ppm in six highly airtight French houses (< 0.6m^3/h·m^2@4 Pa) equipped with MVHR ventilation systems. Concentrations ranged from 360 to 2030 ppm in winter conditions and from about 290 to 1950 ppm in summer conditions. The reasons for the maximum CO_2 concentrations exceeding the EN 15251 AQC III is that the MVHR systems were reported to be frequently switched off due to high noise levels

The maximum hourly average CO_2 concentrations reported in bedrooms of 62 Austrian homes (air tightness ≤0.6h^{-1}) with MVHR systems built between 2010 and 2012 were above 1000 ppm (AQC I) in 52 of the houses about three months after the residents moved in and in 55after about one year (Wallner, 2015). The same study reported that CO_2 concentrations in 39% of the bedrooms were exceeding 1400 ppm, indicating they were at least temporarily at a level of lower indoor air quality according to AQC III EN 15251. The high values of CO_2 levers were coincident with low ventilation rates: only 11% and 21 % of the bedrooms were supplied with airflow rates higher than 5.5 l/s·person (AQC III) in the first group and second group of measurements respectively.

Assessing the performance of a MVHR equipped highly insulated (airtightness≤0.44h^{-1}) London dwelling; (Ridley, 2012) reported peak CO_2 concentrations in the living room of 815ppm, while the bedroom CO_2 concentrations exceeded 1000 ppm (AQC II) 22% of the time. As the internal doors were opened all time, the main reason reported for poorer indoor air quality in the bedroom was the lowest possible ventilation rate operated (0.43h^{-1} – AQC IV).

The median CO_2 concentration levels in bedrooms of 5 passive houses built between 2010 and 2013 (Langer, 2015) were 540 and 660 ppm respectively. The CO_2 concentration exceeded 1000 ppm during 6% of the measured time. The median ventilation rates for the two types of houses were 0.60 and 0.68h^{-1} respectively (AQC II).

In five of the twenty-six houses monitored with MVHR systems (average airtightness 3m^3/h·m^2@50 Pa), (Sharpe**,** 2014) reported average CO_2 rates in bedrooms of 858 ppm while three of the bedrooms measured CO_2 levels above 1000 ppm during 30 % of the time. The latter figure were attributed to family size as the houses where CO_2 concentrations did not exceed 1000 ppm for more than 30 % of the time had 1-2 occupants compared to the other group with 4-5 occupants. The average ventilation rate was 6.61 l/s (ACQ IV for main bedrooms and ACQ III for other bedrooms).

In four apartments in newly built low-rise residential buildings (3m^3/h·m^2@50) equipped with MVHR system and delivering fresh air to every bedroom, it was reported CO_2 levels below 750 ppm 85% of the time and levels 900-1200 ppm 5% of the time (Berge, 2016**)**. Although none of the master or other bedrooms was supplied with enough volume of air to comply with minimum requirements set by EN 15251 AQC II, CO_2 levels above 1200 ppm (AQC II) were measured only 2.2% of the time.

A very recent study on indoor air quality in Dutch residential buildings (Holsteijn, 2016) found that in apartments with only mechanical extraction in wet rooms had significantly higher CO_2 levels exceeding 1200 ppm (7.62-12.42 h/day) compared to apartments with mechanical supply and/or exhaust systems in all rooms (2.65-4.40 h/day). The apartment equipped with mechanical extraction in all rooms and CO_2 and humidity sensor but without heat recovery unit had lower CO_2 values than in all other apartments with MVHR except for one room. The average ventilation rate in all apartments ranged from 10.3-14.4 l/s·person, satisfying the minimum requirements defined by AQC I EN 15251.

A Belgian study **(**Laverge, 2015) measured the CO_2 and humidity levels for four groups of dwellings equipped with different ventilation systems: 36 with natural ventilation, 39 with exhaust-only ventilation and two types of MVHR: 23 for low energy houses and 16 extremely airtight passive houses. The average CO_2 concentrations, measured in living rooms and bedrooms, was found to be in the same range for all groups. Although more stable concentrations over time were reported in dwellings with MVHR, the reason for relatively high CO_2 levels is attributed to the fact that the ventilation system was operated with an average value of $0.26h^{-1}$ (AQC IV EN 15251).

3.2. TVOC concentrations

Derbez, et al. 2014) reported highest concentrations of TVOCs were found in the house (1042 μg/m^3) where painting activity generated air pollution and in house (3087 μg/m^3) where besides painting, presence of occupants and ventilation system switched off. In other houses in preoccupancy conditions, without painting and with ventilation system turned on, the measured TVOCs ranged from 130-525 μg/m^3.

It's reported median TVOC concentrations of 300 μg/m^3 in the first group of measurements and an increase of 17% in the second group (Wallner, 2015). Only 3% of the rooms with mechanical ventilation reported TVOC values exceeding 3000 μg/m^3 while in the follow-up measurements there were no houses exceeding 3000 μg/m^3.

Langer, 2015 reported significantly higher median TVOC concentrations (272 μg/m^3) in Swedish passive houses than in conventional houses (145 μg/m^3), despite the former group having lower ventilation rates.

Fischer, 2014 evaluated the IAQ in an unoccupied apartment in a multi-story wooden passive building equipped with mechanical ventilation in Sweden. The average TVOC concentrations reported were 150 ± 20 μg/m^3 while the reported AER was $0.53h^{-1}$.

Järnström, 2006 measured the TVOC concentration in apartments in Finnish buildings with mechanical supply and exhaust ventilation and showed the TVOC level was significantly lower than in buildings with mechanical exhaust ventilation. The mean TVOC concentration was 780 mg/m^3 in the newly finished buildings while the reported AER of 0.95 ACH was higher than AQC I as defined by EN 15251.

4. DISCUSSION

Highly insulated houses rely upon controlled ventilation for good indoor air quality. In these dwellings mechanical ventilation systems are needed. This review aimed to characterize the relationship between indoor air polllutants and ventilation rates in mechanically ventilated dwellings. The majority of papers reporting CO_2 and TVOC concentrations were built in mechanically ventilated dwellings with low levels of airtightness (<10m^3/h·m^2@50) or very low leakage levels required by passive house standard (≤$0.6h^{-1}$@50Pa). It is difficult to adequately characterize indoor CO_2 concentrations only as a function of ventilation rate as they also vary with time and occupancy. Another disadvantage for generalisation of existing data is a great variability in the methods used to characterize the CO_2 concentrations in the papers identified. Short-term measurements may be inadequate to provide information on the long-term ventilation conditions in mechanically ventilated residential dwellings. Different metrics used for reporting average pollutant values (median vs. mean) and measurement time makes it more difficult to make absolute comparison between different studies. In most of the reports from field measurements the ventilation rate concentrations were above the minimum requirements for whole-house ventilation (>0.4 ACH) defined by EN 15251:2007. Generally, papers reporting ventilation rates of at least air quality class III (>0.5 ACH) as defined by EN 15251:2007 and that comply with class II for bedrooms (14 l/s·person) reported lowest average or median CO2 concentrations. Still, the CO2 concentrations exceeded frequently the EN 15251:2007 minimum levels (>1350 ppm for bedrooms; >1700 ppm for other rooms) for at least some of the measurement time. The main reason reported was poor use of the ventilation system by occupants. The most common behavior was changing the power settings of the MV system due to noise nuissance. Very few measurements of TVOCs are reported in the literature for mechanically ventilated dwellings. For Europe, only four papers were found which reported TVOC measurements and neither reported a prominent influence of the ventilation rate compared to other building characteristics.

5. CONCLUSION

The available measurements of ventilation rates and CO_2 concentrations in schools suggest that, based upon the current EN15251:2007 ventilation standard, many new-built airtight residential dwellings are not adequately ventilated.Low ventilation rates were reported due to insufficient ventilation capacity, incorrect use of the control system and incorrect maintenance; the ventilation rates were frequently reported to be reduced or switched off by users because of high noise levels or poor occupant understanding of how to use the ventilation system.

6. REFERENCES

EN 15251:2007. Indoor environmental input parameters for design and assessment of energy performance of buildings. Brussels: European Committee for Standardization (CEN), 2007.

Berge M., Mathisen H.M.(2016) Perceived and measured indoor climate conditions in high-performance residential buildings, Energy Build. 127:1057-1073.

Derbez M., Berthineau B., Cochet V., Lethrosne M., Pignon C., Riberon J., et al., (2014). *Indoor air quality and comfort in seven newly built, energy-efficient houses in France*. Build. Environ.;72:173-187.

Dimitroulopoulou, C. (2012). Ventilation in European dwellings: a review. *Building and Environment*, 47,109-125.

Fischer A., Langer S., Evert Ljungstrom E., (2014) Chemistry and indoor air quality in a multi-storey wooden passive (low energy) building: formation of peroxyacetyl nitrate. *Indoor Built Environ*, 23,485-496.

Guyot G., Bailly A., Bernard A.M., Perez G., Coeudevez C-S., et al. (2015). Ventilation performance and indoor air pollutants diagnosis in 21 French low energy homes. *36th AIVC Conference " Effective ventilation in high performance buildings", Madrid, Spain, 23-24 September 2015.*

Hesaraki A., Myhren J.A.,Holmberg S.,(2015) Influence of different ventilation levels on indoor air quality and energy savings: a case study of a single-family house, *Sustain. Cities Soc*., 19, 165–172.

Holstejin van R.C.A, Li W., Harm J.J., Kornaat W., (2016*) Improving the energy and IAQ performance of Ventilation systems in Dutch dwellings.Int.J.Vent.,*14(4), 363-370.

Järnström, H., Saarela, K., Pasanen, A-L., Kalliokoski, P., (2006). Reference values for indoor air pollutant concentrations in new, residential buildings in Finland. *Atmospheric Environmen,t* 40, 7178–7191.

Kunkel, S.; Kontonasiou, E.(2015). Indoor air quality, thermal comfort and daylight policies on the way to nZEB—Status of selected MS and future policy recommendations. *In Proceedings of the ECEEE Summer Study, First Fuel Now, Belambra Les Criques, Toulon, France*.

Langer S., Ramalho O., Derbez M., Riberon J., Kirchner S., Mandin C., (2016) Indoor environmental quality in French dwellings and building characteristics, *Atmos. Environ*, 128, 82-91.

Laverge J., Delghust M., Janssens A., (2015). Carbon Dioxide Concentrations and Humidity Levels Measured in Belgian Standard and Low Energy Dwellings with Common Ventilation Strategies. *International Journal of Ventilation*, 14 (2), 165-180.

McGill, G., Oyedele, L.O., McAllister, K., (2015). Case study investigation of indoor air quality in mechanically ventilated and naturally ventilated UK social housing. (2015), *Int. J. Sustain*. *Built Environ*. 4, 58-77

Ridley I., Clarke A., Berec J., Altamiranod H., Lewis S.,Durdev M.,Farr A., (2013). The monitored performance of the first new London dwelling certified to the Passive House standard, *Energy and Buildings*, 63, 67–78.

Sharpe T.R., Porteous C.D.A., Foster J., Shearer D., An assessment of environmental conditions in bedrooms of contemporary low energy houses in Scotland, (2014). *Indoor Built Environ*. 23 (3), 393–416.

Strøm-Tejsen P., Zukowska D., Wargocki P., Wyon D.P. (2016). The effects of bedroom air quality on sleep and next-day performance. *Indoor Air.*

Sundell, J., Levin, H., Nazaroff, W.W., Cain,W.S., Fisk, W.J. et al. (2011). Ventilation rates and health: multidisciplinary review of the scientific literature. *Indoor Air,* 21, 191–204.

Wallner P., Munoz U, Tappler P., et al. (2015). Indoor environmental quality in mechanically ventilated, energy-efficient buildings vs. conventional buildings. *International Journal of Environmental Research and Public Health*, 12, 14132-47.

Wargocki, P., Sundell, J., Bischof, W.,Brundrett, G., Fanger, O., et al. (2002). Ventilation and health in non-industrial indoor environments, Report from a European multidisciplinary scientific consensus meeting, *Indoor Air,* 12, 113–128.