MONITORING THE ENERGY- & IAQ PERFORMANCE OF VENTILATION SYSTEMS IN DUTCH RESIDENTIAL DWELLINGS

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ABSTRACT

MONICAIR --MONItoring & Control of Air quality in Individual Rooms-- is a pre-competitive field research project of a broad consortium of Dutch ventilation unit manufacturers and research institutes, supported by the Dutch government. The aim is to investigate the indoor air quality (IAQ) performance and energy characteristics of 9 different mechanical ventilation solutions in dwellings that meet strict air-tightness standards and comply with current building regulations. Over a full year 62 residential dwellings were monitored, with in each habitable room sensors for occupancy, CO_2, relative humidity and air temperature. Energy consumption of the mechanical ventilation units and space heating boilers were also continuously monitored. The ventilation solutions included mechanical exhaust ventilation (MEV) systems (mechanical exhaust in the wet rooms, and with natural air supply in habitable rooms), systems with mechanical exhaust in all rooms, as well as local and central balanced (MVHR) systems with various types of control systems. Sampling and data evaluation were handled by specialists. The monitoring part of the MONICAIR project is nearing completion and the first results are now available.
The data show that (from the ventilation systems under investigation) systems with *mechanical* air supply and/or exhaust provisions for each individual room are more robust in maintaining certain IAQ-levels, whereas systems with only *natural* air exchange provisions in the habitable rooms show larger variations in IAQ and depend to a large degree on the number and behaviour of inhabitants. In dwellings with MEV-systems the CO_2 concentration in the average habitable room is 380 ppm above the limit value of 1200 ppm during 10% of the heating season (515 of 5088 hours). If inhabitants spend only half of the time at home, then 20% of this time the air exchange is insufficient. Looking at individual houses these percentages vary from 2% to over 50%. In dwellings with MVHR systems the CO_2 concentration in the average habitable room is 320 ppm above the limit value of 1200 ppm during 4.6% of the heating season (237 of 5088 hours). Again, if inhabitants spend half of the heating season indoors and at home, 9.2% of these hours have insufficient air exchange. Per dwelling this figure varies from 0.1% to more than 20%.
Looking at the energy performance of the ventilation systems under investigation, monitoring data show that also in this respect significant differences occur. The average primary energy consumption for mechanical ventilation without heat recovery is 125 MJ/m^2. For the ventilation systems with heat recovery the average primary energy consumption is 22 MJ/m^2.

KEYWORDS

Ventilation systems, Monitoring, IAQ-performance, energy-performance

INTRODUCTION

The built environment accounts for approximately 40% of the EU total energy consumption with space heating as the largest contributor (>50%). Not surprisingly, EU-legislation focuses on increasing the insulation levels and improving the air tightness of buildings. As a result, the contribution of air infiltration to Indoor Air Quality (IAQ) is reduced and ventilation systems become more and more the sole responsible for the IAQ. Relevant question in the light of this development is: “How well do ventilation systems perform in terms of IAQ and energy consumption in well insulated and air tight dwellings *in real life,* and how can their performance be further improved?” Past research has focussed on compliance with standards at nominal conditions -- and improvements are certainly necessary there [1] – but research on IAQ and energy performance at real life conditions is definitely scarce [2,3]. While housing stock is being improved in terms of insulation and air tightness as we speak, we do not know whether ventilations systems sufficiently perform and are capable to compensate for the reduced infiltration.

To answer these key questions, a consortium of manufacturers and specialized consultancy firms from the Dutch ventilation industry was established that initiated the long term monitoring project “MONICAIR” (MONItoring & Control of Air quality in Individual Rooms). MONICAIR is a 1,6 million euro research project, partly financed by the consortium members and partly by the Dutch Ministry of Economic Affairs within the framework of TKI (Top consortia for Knowledge & Innovation). One of the aims of the monitoring project is to assess the real life IAQ performance in all individual rooms during presence of the occupants and the related primary energy consumed by the ventilation system. The assumption is that with a full analysis of the acquired monitoring data, system parameters can be identified that can help the participating manufacturers further improve their ventilation systems on both the IAQ- and energy performance. This paper reports the first results from a full year monitoring, covering nine commonly used ventilation systems in Dutch residential dwellings. Before the start of the monitoring project, all ventilation systems were checked and – when necessary - adjusted according to building code practice, thus securing correct system specifications and ensuring that possible design- or installation errors do not influence performance.

SELECTION OF VENTILATION SYSTEMS AND DWELLINGS

Ventilation systems

The manufacturing partners in the MONICAIR consortium produce both type C (MEV) and type D (MVHR) ventilation systems. Most commonly used in the Netherlands is ventilation system type C (mechanical extraction in wet rooms combined with natural air supply vents in habitable rooms). Ventilation systems type D (mechanical air extraction and mechanical supply) are applied in the new built sector when the budget allows for more expensive ventilation systems. Both types of ventilation systems are selected for the monitoring study, both with their specific variants and combinations as described in Table 1. The table describes per type of ventilation system 1) the air exchange provisions in both the wet rooms (bathroom, kitchen, toilets) as well as the habitable rooms (living room, bedrooms), 2) whether heat recovery is applicable and 3) what type of controls are used for the exhaust and supply provisions. The system type numbers refer to classification used in the Netherlands Standard NEN 8088-1, 2011 [4].

Table 1: Type of ventilation systems selected for MONICAIR

System type	Section of house that is served	**Air exchange provisions**			**Controls**	
		Exhaust	Supply	Heat Recovery	Exhaust	Supply
Type C ventilation systems						
C.1	Whole house	Mech. extraction in wet-rooms	Stnrd nat.supply vents in hab.rooms	No	Manual 3-pos. switch	Manual
C.2c	Whole house	Mech. extraction in wet-rooms	wind contrl. nat. supply in hab.rooms	No	Manual 3-pos. switch	Manual
C.4a	Whole house	Mech. extraction in wet-rooms	wind contrl. nat. supply in hab.rooms	No	CO_2-sensor in living room	Manual
C.4c	Whole house	Mech. extraction in all rooms	wind contrl. nat. supply in hab.rooms	No	CO_2-control on all hab.rooms	Manual

Type D ventilation systems						
D.2	Whole house	Mech. extraction in wet-rooms	Mech. supply in hab.rooms	Yes	Manual 3-pos. switch	
D.5a	Whole house	Mech. extraction in wet-rooms	Mech. supply in hab.rooms	Yes	Manual 3-pos. switch with CO_2-contrl in 2 zones	
D.5b	Whole house	Mech. extraction in all rooms	Mech. supply in hab.rooms	Yes	CO_2 and RH -controlled ventilation rate in all rooms	
Combination of systems						
X1/C	Living section: D	Mech. extraction in hab.rooms	Mech. supply in hab.rooms	Yes	CO_2 and RH -controlled ventilation rate in living room	
	Sleeping section:C.2c	Mech. extraction in wet-rooms	wind contrl. nat. supply in bedrooms	No	Manual 2-pos. switch	Manual
X1/A	Living section: D	Mech. extraction in hab.rooms	Mech. supply in hab.rooms	Yes	CO_2 and RH -controlled ventilation rate in living room	
	Sleeping section: A	Nat. extraction in wet-rooms	wind contrl. nat. supply in bedrooms	No	No control	Manual

Dwellings

Selecting and finding suitable dwellings for the monitoring project proved to be challenging and could not have been done without the help of the housing corporations. The first requirement was to find groups of 5 to 6 identical clustered terraced houses with an air tightness of $q_{v;10} \leq 1.0$ $dm^3/s.m^2$, that all have the same system, which also had to be one of the ventilation systems selected for the project. Initially the air tightness requirements were set at a higher level, but blower door tests proved that – although dwelling specifications stated otherwise – these higher levels of air tightness were not always achieved. The second requirement was to find inhabitants that were prepared to allow sensors being installed in all rooms that monitor the IAQ and their behaviour for more than a year. The last requirement was that all dwellings needed to have the same condensing combi boiler that enable the monitoring of gas consumption for space heating and domestic hot water (dhw). In dwelling clusters that complied with the first two requirements but had a different combi boiler, the combi boilers were replaced. Eventually 62 families with as many dwellings were found prepared to participate in the MONICAIR project. Before the start of the actual monitoring, all ventilation systems were checked and adjusted to the latest building code requirements. The monitoring results can thus also be used to re-evaluate the existing building code requirements for ventilation.

DATA MONITORING SYSTEM

In every dwelling participating in the MONICAIR project the following sensors were installed:

- Sensors that monitor the CO_2 concentration, relative humidity and the air temperature in all habitable rooms (living room, kitchen, bedrooms, study and utility room (if applicable) every five minutes. As far as possible these sensors were mounted in the middle of the room approximately 1.5 m above the floor. The CO_2-sensor used is a non-dispersive infrared (NDIR) type sensor with an accuracy of ± 50 ppm.
- Presence sensors (PIR-type) in all habitable rooms.
- A sensor monitoring the relative humidity in the bathroom every five minutes.
- Sensors that monitor the power consumption of the mechanical ventilations units and kitchen hoods (and with it the corresponding airflow) every 10 minutes as well as every change within this period.

Apart from these room-specific sensors, the following appliances are monitored:

- The condensing combi boilers, monitoring the gas consumption for space heating and dhw through IM protocol, at least once in every six minutes.

- In dwelling clusters that use ventilation units equipped with rf-communication, their data on power consumption and airflow was also logged every five minutes.
- Finally, meteorological data on outdoor temperature, relative humidity, wind speed, wind direction and air pressure of the most nearby weather station was gathered.

Per cluster of dwellings all data of each house is gathered through rf-communication and stored on a local PC. Through an FTP connection the data stored on local PCs is regularly copied onto the centralized MONICAIR SQL database.

DATA ANALYSES

For a period of more than a year an enormous amount of data was gathered about the ventilation systems and their real life performance on indoor air quality and energy consumption, as well as data on consumer behaviour regarding the preferred temperature per habitable room, operation of ventilation units, use of kitchen hoods, and hot water consumption pattern. With these data various angles of data analysis are possible. Given the focus and resources related to the first part (WP1a) of the MONICAIR project, the analysis here is restricted to the IAQ- performance and the energy performance during heating season. At the moment four of the nine ventilation systems were analysed and will be discussed here.

Indicator for the IAQ performance

To assess the IAQ performance of ventilation systems the measured CO_2-concentration in the individual habitable rooms will be the leading parameter. The CO_2-concentration is generally accepted as the key indicator for the existing ventilation rate during presence [5] and consequently for the occurring IAQ levels. The following procedure is therefore used to assess the IAQ in the various habitable rooms:

a) Determine for each habitable room in each dwelling the number of hours per day that the CO2 concentration is above 1200 ppm in unit [hours/day]. The limit value of 1200 ppm corresponds to the IAQ category IV (= the lowest IAQ level) as described in EN 15251 [6].
b) Determine for each habitable room in each dwelling the average concentration with which the CO_2 limit of 1200 ppm is exceeded in unit [ppm/h].
c) Calculate the CO_2 excess dose per heating season in kppmh by multiplying the outcome of a) with the outcome of b) and then multiplying the result with the number of days in a heating season (212) and dividing it with 1000 to convert the ppm-figure to kppm.
d) Add all the CO_2 excess doses per habitable room per dwelling and divide it with the number of rooms of that specific dwelling to determine the average achieved IAQ level per dwelling.

(Note 1: The calculations for a) and b) are made with a resolution of five minutes and summarised to obtain either the number of hours per day or the excess value per hour. Note 2: This procedure is comparable to the methodology used in the declaration of equivalence of the VLA [7])

Indicator for the Energy performance

The indicator for the Energy performance of the ventilation systems is obtained according to the following procedure:

I) Determine the total average hourly mechanical ventilation rate of all ventilation units in the dwelling (kitchen hood excluded).
II) Determine the hourly average of the indoor temperatures and indoor humidity of the sleeping section and the living section separately and use these two values to calculate the average indoor climate conditions.
III) Determine the hourly average of the outdoor climate conditions, in casu air temperature, relative humidity and air pressure (data from the Royal Netherlands Meteorological Institute)

IV) Calculate the thermal energy exchange per hour on the basis of I), II) and III) in relation to the hourly temperature difference between indoors and outdoors ($\Delta T_{in\text{-}out}$).
For systems with heat recovery this energy figure is corrected with the heat recovery efficiency as determined according to EN 13141-7 and -8.

V) Calculate the total daily thermal energy exchange in relation to the daily average $\Delta T_{in\text{-}out}$.

VI) Calculate the total primary energy consumption for mechanical ventilation for an average heating season by multiplying the daily average thermal energy exchange (the value corresponding to the annual average $\Delta T_{in\text{-}out}$ of 13°C) by 212 days (duration of the heating season) and divide this figure by the average system efficiency of 85% (for condensing heating system with limited distribution losses); add to this figure the total power consumption of all ventilation units during heating season, after converting it to primary energy.

VII) Divide the outcome of VI) with the total heated surface area of the dwelling to obtain the average energy consumption of the mechanical ventilation system per m^2 during heating season.

Note : Energy consumption related to cross ventilation (air that enters the dwelling through infiltration or airing on one façade and leaves through another façade) is not included; also internal and solar gains are not included in this assessment of the energy performance.

RESULTS

IAQ-performance

So far, data of four ventilation systems have been analysed on IAQ performance and energy performance. The following graphs give an overview of the results.

Ventilation system C.2c

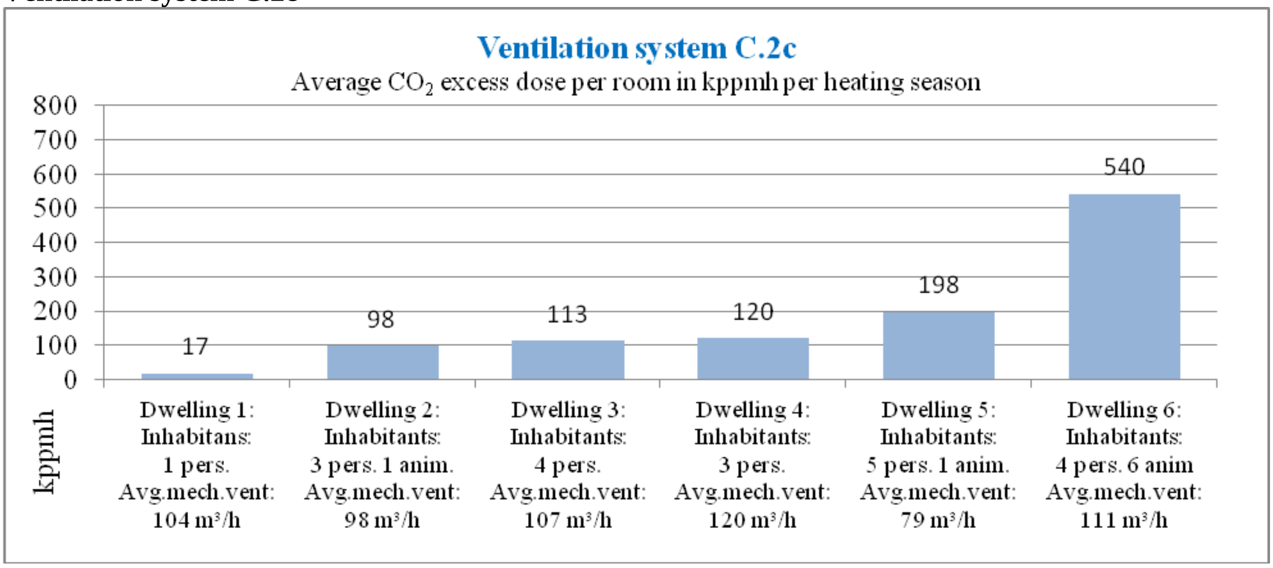

Figure 1. IAQ performance of ventilation system C.2c in six comparable dwellings

The arithmetic mean of the IAQ performance of these six houses with ventilation system C.2c is 181 kppmh. This average is very much influenced by dwelling number 6. The qualitative data that was gathered through face-to-face interviews before the start of the monitoring project however show, that there are valid reasons for the high kppmh figure. The intake interview reveals that, compared to the other dwellings, people in house nr. 6 stay at home for much longer periods per day, they keep the vents in the bedrooms closed during presence and airing of the room is less frequent than in the other houses.

Ventilation system C.4a

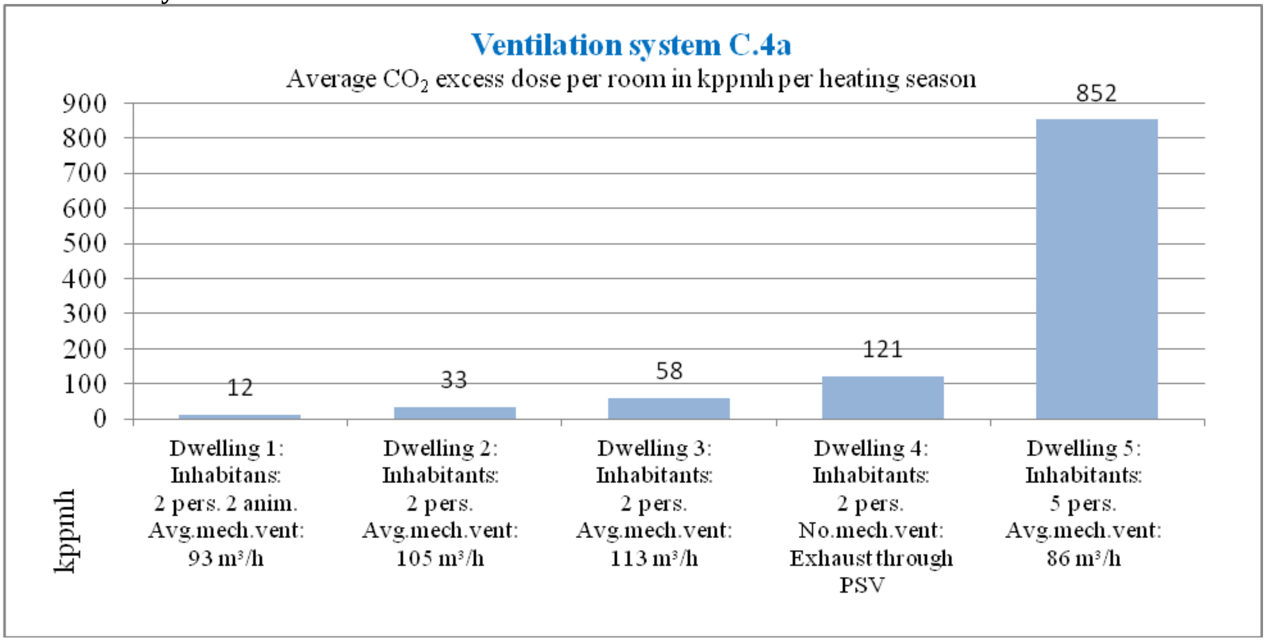

Figure 2. IAQ performance of ventilation system C.4a in five comparable dwellings

The arithmetic mean of the IAQ performance of these five houses with ventilation system C.4a is 215 kppmh. Without dwelling nr.4 (Passive Stack Ventilation (PSV) system) the mean value is 238 kppmh. Also in this cluster the average is largely influenced by dwelling nr. 5 where people also stay at home for much longer periods per day. The inhabitants state in the intake interview that the air vents in the bedrooms are open, but the CO_2 concentrations of the bedrooms suggest that they are closed when people are present.

Ventilation system D.2

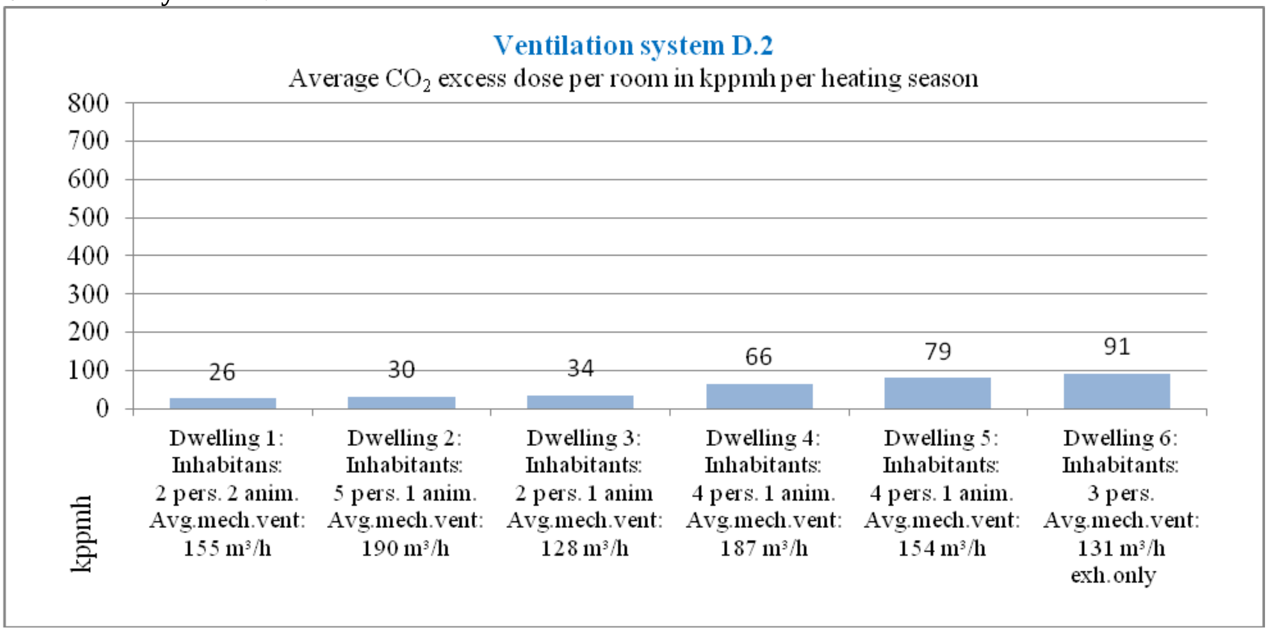

Figure 3. IAQ performance of ventilation system D.2 in six comparable dwellings

The arithmetic mean of the IAQ performance of these six houses with ventilation system D.2 is 54 kppmh.

Ventilation system D.5a

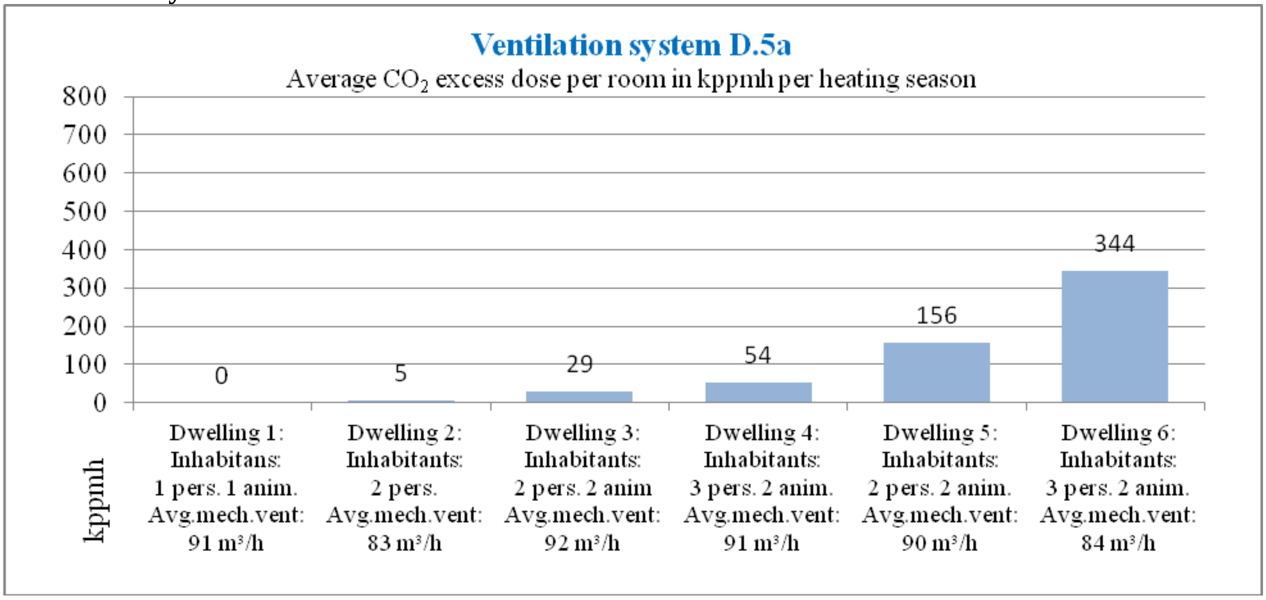

Figure 4. IAQ performance of ventilation system D.5a in six comparable dwellings

The arithmetic mean of the IAQ performance of these six houses with ventilation system D.5a is 98 kppmh. In dwelling 6 the size of the air supply opening in bedroom 3 was reduced after the start of the project, resulting in a higher CO_2-excess dose for that particular room and consequently for the whole dwelling.

Energy performance

The energy performance of each ventilation system is determined according to the method described under the paragraph ‘Data analyses’, and presented in the graph below. The electricity consumption of the mechanical ventilation units during a heating season is displayed separately from energy related to the air exchange.

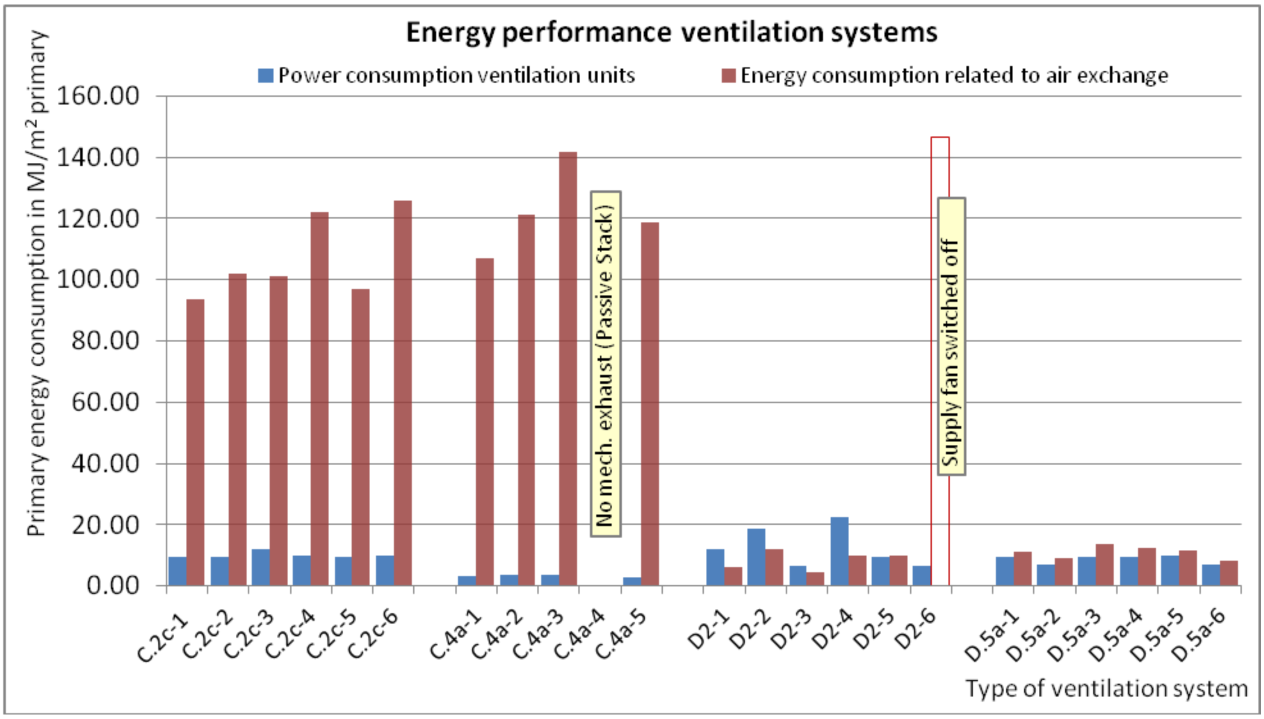

Figure 5. Energy performance of the ventilation systems

CONCLUSIONS

Data analyses will continue for the other five ventilation systems (thirty-nine dwellings), but based on the results of the four systems analysed so far, it can already be concluded that there are significant differences in both the real-life IAQ- and energy performance of ventilation systems.

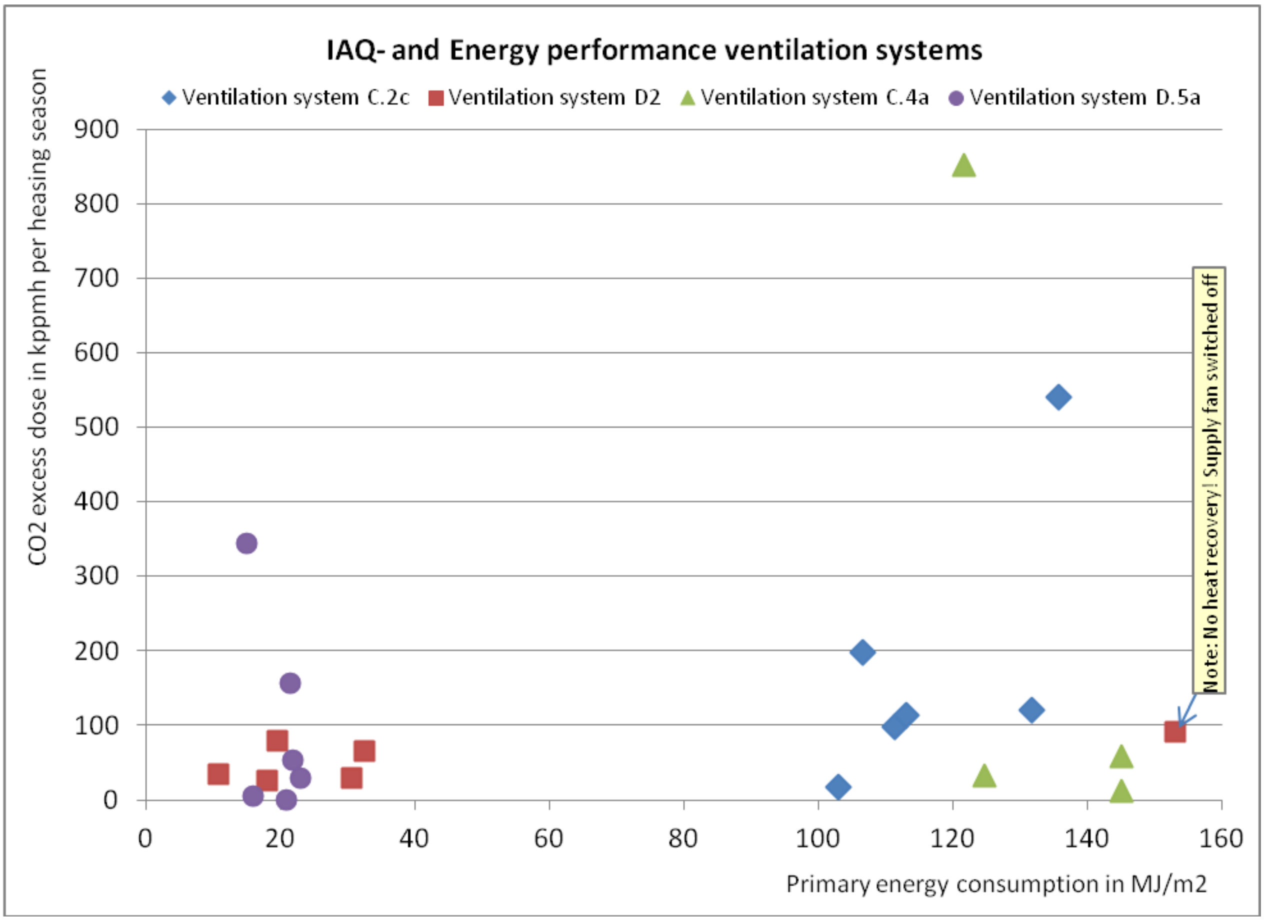

Figure 6. IAQ- and energy performance of the ventilation systems

The differences in energy performance are evident. For the average EU-heating season (ΔT_{in-out} = 13°C) the average primary energy consumption for ventilation is 22 MJ/m^2 for systems with heat recovery and 125 MJ/m^2 for systems without heat recovery. Further analysis will be necessary to determine if the use of IAQ-sensors has an effect on the energy performance.

The preliminary analyses furthermore suggest that systems with mechanical air supply and/or exhaust provisions in each room are more robust in maintaining a certain IAQ- performance compared to systems that use only natural air exchange provision in habitable rooms. Systems with natural air exchange provisions in habitable rooms achieve an average CO_2 excess dose of 196 kppmh in each habitable room per heating season, whereas systems with a mechanical component serving either the air supply and/or exhaust in each room achieve 76 kppmh.

In terms of time spent in rooms with insufficient air exchange, this means that:

- In dwellings with MEV-systems combined with only natural air exchange provisions in habitable rooms, the CO_2 concentration in the average habitable room is 380 ppm above the limit value of 1200 ppm during 10% of the heating season (515 of 5088 hours). Since inhabitants are not continuously at home, this percentage will be higher when related to the actual time spent at home. If the occupants are only 12 hours per day at home (2544 hours per heating season), then 20% (515/2544) of this time the air exchange is insufficient. Looking at individual houses these percentages vary from 2% over 50%.

- In dwellings with MVHR-systems the CO_2 concentration in the average habitable room is 320 ppm above the limit value of 1200 ppm during 4.6% of the heating season (237 of 5088 hours). Again, if inhabitants spend half of the heating season indoors and at home, 9.2% of these hours have insufficient air exchange. Per dwelling this figure varies from 0.1% to more than 20%.

DISCUSSION

Current practice is that ventilation systems are primarily selected on the basis of their purchase- and installation costs. Building codes determine the minimal level of air exchange rates that must be installed as well as its minimal energy performance level (EPBD-legislation). But whether ventilation systems actually deliver the required air exchange rates in the right rooms at the right times is not a topic or a criterion in selecting ventilation systems. More monitoring studies will certainly be necessary but the preliminary results argue in favour of an approach that looks more specifically at the *real-life* IAQ-performance of the various systems, especially with a building stock that is becoming more insulated and more air tight. Furthermore, like with all other energy using products, the energy performance of ventilation systems can only be compared between systems that have equal IAQ-performance. Without an IAQ assessment we are comparing apples with oranges. Further discussion on the method for determining the IAQ-performance will be necessary as well as discussions on the limit values and IAQ- classes than can be set as guidelines.

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