Natural ventilation in single-family houses during the summer

Energy and Climate

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strategic research centre for
ZERO ENERGY BUILDINGS

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INSTITUTE

Title: Natural ventilation in single-family houses during the summer

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Energy and Climate

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March 2015
1st printing, 1st edition, 2015

ISBN: 978-87-93250-03-1
ISSN: 1600-3780

Front page: EnergyFlexHouse at the Danish Technological Institute
UK: www.dti.dk/inspiration/25348
DK: www.teknologisk.dk/projekter/energyflexhouse

Preface

The report concludes the work carried out by Danish Technological Institute, Energy and Climate on natural ventilation in single-family houses during the summer. The work has been carried out within the Strategic Research Centre for Energy Neutral Buildings (www.zeb.aau.dk) and financed by the Strategic Research Programme Commission on Sustainable Energy and Environment – project no. 2104-08-0018.

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A special thanks to the occupants of the six private homes for allowing us to measure the room temperature, relative humidity and CO_2 concentration during a longer period of time in different rooms of their houses/apartments.

Summary

Several investigations in existing low energy buildings point out that there may be problems with the indoor environment – too low ventilation rates and too high temperatures. However, these problems occur in none low-energy buildings as well.

The Research Centre, therefore, carried out a study with the aim of investigating how natural ventilation during the summer months may solve these problems in single-family houses. The investigations were carried out during the summer of 2013 in the EnergyFlexHouse Lab at Danish Technological Institute.

Several ventilation and control strategies were investigated and compared with a compact mechanical ventilation system. The comparisons between control strategies were possible as the occupants of the house were artificial in the form of barrels emitting heat, humidity and CO_2 in a controlled way leading to repeatable results.

Main results of the investigation are:

- mechanical ventilation dimensioned according to today's standard results in high CO_2 concentration in the bedrooms with closed doors. Higher than the three comfort classes in EN 15251 in a two person bedroom and just within comfort class III in a one-person bedroom

- compact mechanical ventilation systems with an efficient heat exchanger and without bypass lead to overheating in the summer period

- natural ventilation (and solar shading) may in most cases eliminate overheating problems when the max ambient temperature is a few degrees below the comfort limit

- it is difficult to maintain comfort class II for both temperature and CO_2 – especially during the night where the temperature in the house may drop below 20°C in some rooms, if the aim is a low CO_2 level in the bedrooms

- highest CO_2 concentrations are normally obtained in occupied bedrooms during the night

- it is possible with both balanced mechanical ventilation and natural ventilation to obtain reasonable CO_2 concentrations. However, more care should be taken when designing natural ventilation

- doors to the bedrooms should be left ajar during the night with a gab of 50-100 mm in order to decrease the CO_2 level. This goes for both natural and mechanical balanced ventilation

- it is easier to obtain high air change rates that are less influenced by the wind conditions in a two-storey house than in a one-storey house due to the higher buoyance effect in the former

The conclusions are from experiments carried out in EnergyFlexLab at Danish Technological Institute for the given control strategies and weather conditions. The experience from other houses with different control strategies may differ considerably. However, the conclusions obtained in this report may be used as inspiration when designing the control of natural ventilation. Nevertheless, care should be taken with respect to the actual conditions.

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1 Introduction

The realization of the Danish vision of a society independent of fossil fuels by 2050 requires considerably energy savings in all parts of the society. The building sector is central in this respect, as the energy use in buildings accounts for one third of the end energy use in Denmark and because the saving potential is identified to be up to 80%. One way to decrease the energy demand of especially new buildings is to tighten the requirements of the building code. At the moment, we look towards Building class 2020 (Danish Building Regulations 2010), which is aimed to be the Danish requirements for nearly zero-energy buildings requested by the European Energy Performance of Buildings Directive (EPBD, 2010).

Building class 2020 not only requires a low gross energy demand, it also has focus on a good indoor climate. The reason for the latter is that a low energy demand is often obtained at the expense of the indoor climate. However, it is important to point out that some of the problems with low energy houses are also present in none low-energy buildings. For instance, the problem with overheating is well-known, but the problem is more distinct with low energy houses as the houses heat up very quickly. Thus, even though many details and good solutions in the houses have been considered, problems can still arise.

Several sources report that overheating is often a problem in low energy houses, - e.g. (Larsen, 2011a and 2011b) but also in none low-energy homes as seen in chapter 7 of the present report. However, other sources report on solutions for this problem, - e.g. (Christensen et al, 2012), from where the below figures are obtained. Figure 1.1 shows the room temperature in EnergyFlexFamily (Appendix A) during a warm period, where nothing is done to prevent overheating, - i.e. no solar screening and only ventilation via the mechanical ventilation system. Figure 1.2 shows a comparably warm period where solar screening was introduced combined with excess natural ventilation (the mechanical ventilation system was switched off). The figures show that overheating problems can be reduced/eliminated via passive means.

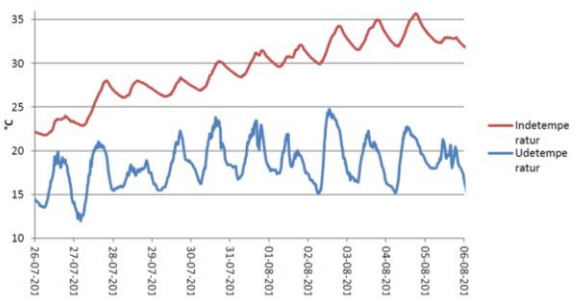

Figure 1.1. Room temperature in EnergyFlex-Family without prevention of overheating (Christensen et al, 2012).
room temperature
ambient temperature

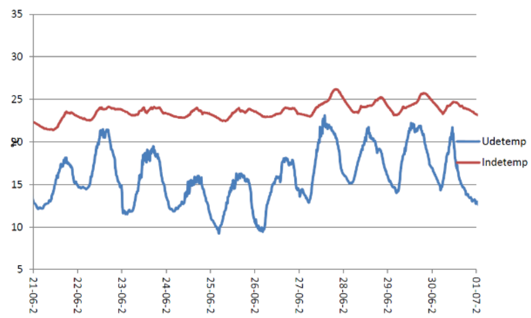

Figure 1.2. Room temperature in EnergyFlex-Family with prevention of overheating (Christensen et al, 2012).
room temperature
ambient temperature

The CO_2 concentration of the indoor environment has not been in focus in the residential sector, - only in the commercial and educational sector due to a reduction in efficiency and the learning at increased levels of CO_2 concentration. It was not believed that the influence of the CO_2 concentration on people, e.g. while sleeping, was critical. However, new research at the Technological University of Denmark (Strøm-Teisen, 2014a and 2014b) indicates that a CO_2 concentration of 2,500 ppm decreases the quality of sleeping leading to increased sleepiness and lower concentration during the day. CO_2 concentration levels above 2,500 ppm in a bedroom are very common in both new and existing buildings, as well as in mechanical and natural ventilated buildings as reported in (Larsen et al, 2012a-e) and shown in chapter 7 of the present report.

The purpose of the work described in the present report was, therefore, to investigate different control strategies for natural ventilation during the summer, which both decrease overheating in the house during the day and reduce the CO_2 concentration in the bedrooms during the night. The investigations were carried out in EnergyFlexHouse (EnergyFlexLab) with a similar control system as applied in EnergyFlexFamily (Christensen et al, 2012). However, EnergyFlexLab is better instrumented than EnergyFlexFamily. The investigated control strategies for natural ventilation were compared with a balanced mechanical ventilation system.

2 EnergyFlexHouse

EnergyFlexHouse consists of two single-family houses with two storeys. each with a total heated gross area of 216 m². In principle the two buildings are identical. However, while one of the buildings acts as a technical laboratory (EnergyFlexLab), the other building can be occupied by typical families who test the energy services of the building (EnergyFlexFamily). Each family lives in EnergyFlexFamily for 3-5 months at a time. In principle, everything in the two buildings can be changed: the thermal envelope, heating system, ventilation system, renewable energy, etc. The buildings were put into operation during the autumn of 2009. More details about EnergyFlexHouse can be found in Appendix A and on the website of EnergyFlexHouse: www.dti.dk/inspiration/25348. The houses are energy neutral, which means that the houses produce as much energy as they use including plug loads over the year due to a large PV area.

The front page of this report shows a picture of the two houses. The experiments described in the following have been carried out in EnergyFlexLab (hereafter EFHlab) shown to the left on the front page. Figure 2.1 shows a cross section of the house while figures 2.2 and 2.3 show the floor plans of the two stories of the houses. Table 2.1 explains the types of the 11 rooms in the house.

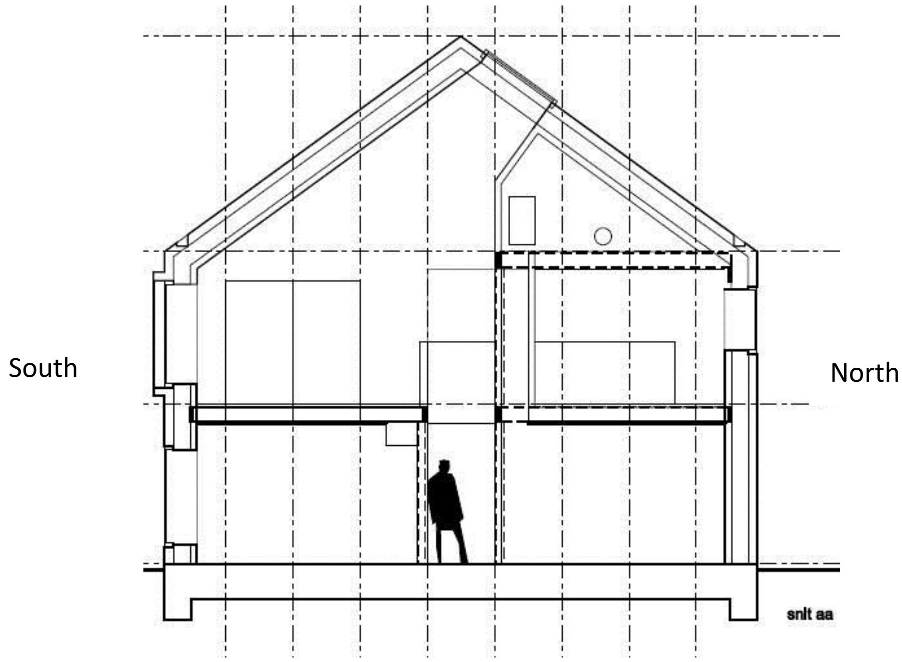

Figure 2.1. Gross section of EnergyFlexHouse.

	Room number	Type of room
Ground floor	1	Master bathroom
	2	Bedroom
	3	Children’s room
	4	Second bathroom
	5	Bedroom
	6	Parents’ room
	9	Storage room below staircase
	10	Aisle
	11	Technical room
First floor	7	Kitchen
	8	Living room

Table 2.1. The type of rooms shown in figures 2.2-3. Measurements have been carried out in the highlighted rooms.

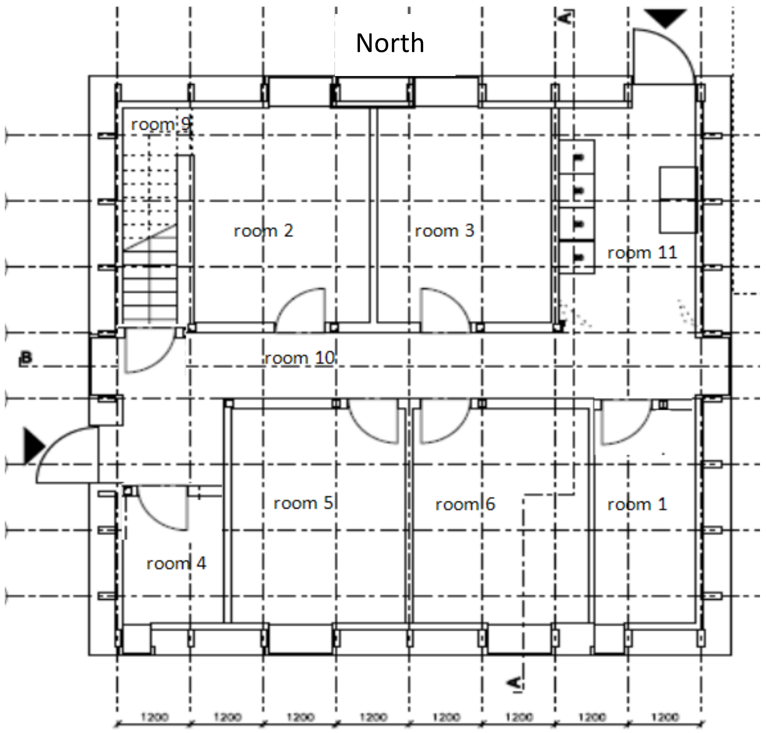

Figure 2.2. Floor plan for the ground floor of EnergyFlexHouse.

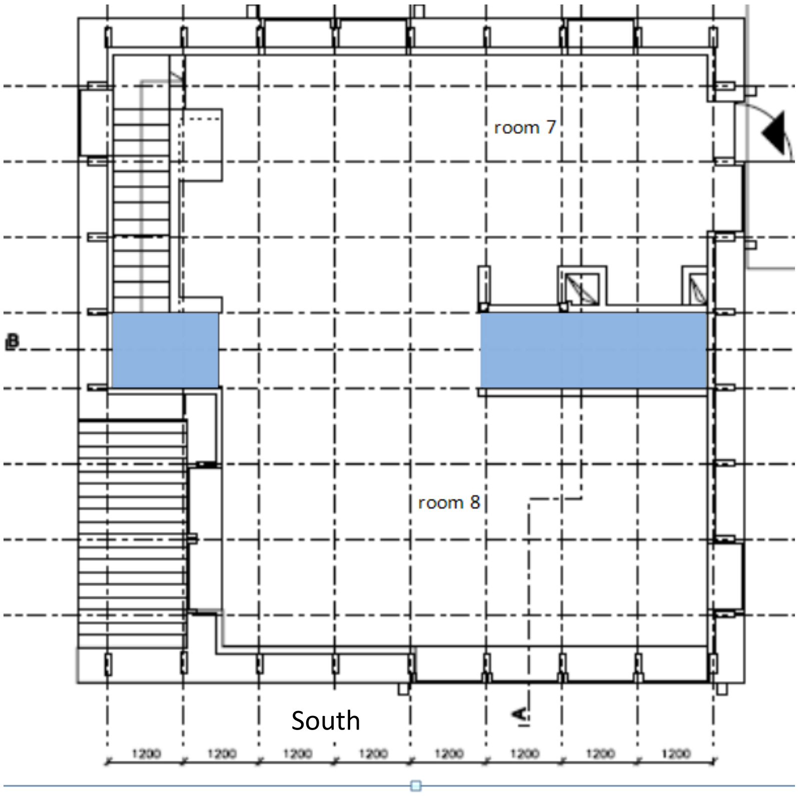

Figure 2.3. Floor plan for the first floor of EnergyFlexHouse. The two blue areas are openings between the ground floor and first floor. These openings can be closed in order to separate the ground floor from the first floor. A door at the staircase can be closed as well.

Since the partition openings between the ground floor and the first floor (figure 2.3) can be closed and a door at the staircase can be closed as well, it is possible to separate the two floors from each other. In this way, both a two-story building and a single storey building can be investigated. This feature has been utilized in the following experiments.

2.1 Natural ventilation

EFHLab has several automatically controllable openings in order to create natural ventilation - as illustrated in figures 2.4-7:

- roof windows
- small windows in each end of the aisle at ground floor
- fresh air valves in the bedrooms and on the first floor

Furthermore, windows and external doors may be opened manually at both ground floor and first floor. It is possible to open a natural exhaust duct from the master bathroom to above roof level. The internal doors at the ground floor have a gab of 30-35 mm between the door and the doorstep. Table 2.2 shows the flow areas of the windows, doors and fresh air valves

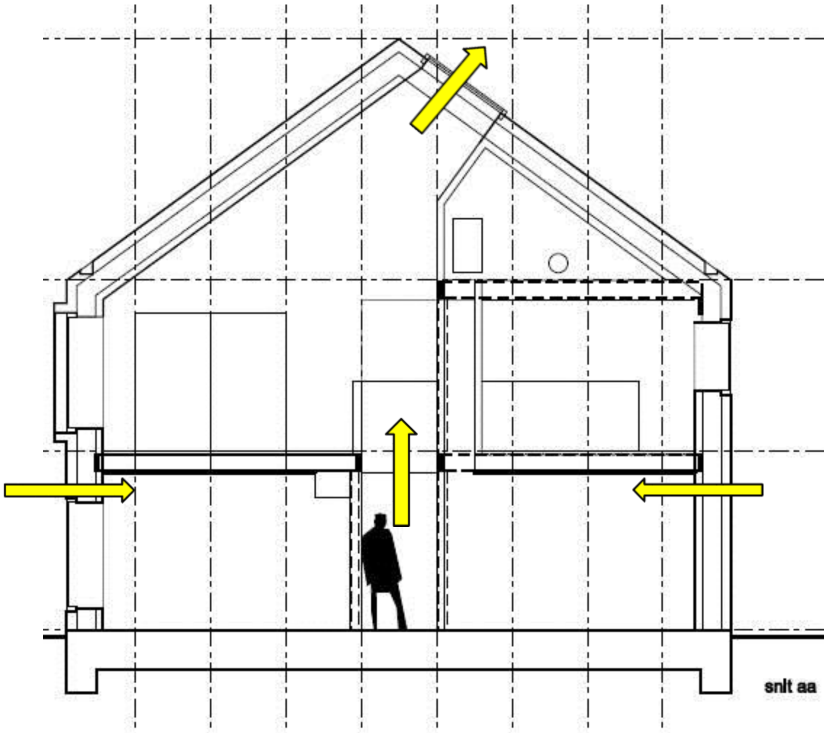

Figure 2.4. The principle of buoyancy driven natural ventilation in EFHlab when the blue areas in figure 2.3 are open.

Figure 2.5 shows the fresh air valves in one of the bedrooms. Figure 2.6 shows the roof windows, while figure 2.7 shows the automatically operable windows in the aisle.

If not stated directly, only the two roof windows, the two aisle windows and the fresh air valves in the bedrooms have been operated in the following described experiments with natural ventilation. During the experiments with natural ventilation the exhaust duct from the master bathroom was open at all times.

In order to have a reference case to compare the natural ventilation against, experiments with balanced mechanical ventilation were also carried out.

Room	Type	Orientation	Total flow area m²	Manually	Automatically
1 Master bathroom	window	South	0.73	X	
	exhaust duct to above roof	-	0.018	X	
2 Bedroom	fresh air valve	North	0.0027		X
3 Children's room	fresh air valve	North	0.0027		X
4 Second bathroom	window	South	0.73	X	
5 Bedroom	window	North	1.65	X	
	fresh air valve	North	0.0027		X
6 Parents' room	window	North	1.65	X	
	fresh air valve	North	0.0027		X
8 Living room	roof win-dow	North 50° slope	0.21		X
	roof win-dow	North 50° slope	0.35		X
10 Aisle	window	East	0.21		X
	window	Vest	0.21		X
	window	East	1.37	X	
	window	West	1.37	X	
	door	West	1.97	X	
10 Technical room	door	North	1.97	X	

Table 2.2. Operable windows, doors and fresh air valves at the ground floor of EFHlab as well as the roof windows. The total flow area is when fully open or open as much as possible. The windows in the north facing children's room/bedroom cannot be opened.

Figure 2.5. One of the operable fresh air valves seen from the outside and the inside.

Figure 2.6. The two roof windows seen from the outside and the inside.

Figure 2.7. The two small operable windows in each end of the aisle.

In EFHlab, the roof and aisle windows as well as the fresh air valves can be controlled arbitrary based on measurements in the house.

2.2 Mechanical ventilation

In the following the results from the experiments with natural ventilation are compared with measurements from experiments with balanced mechanical ventilation with heat recovery. Table 2.3 shows the airflow to and from the rooms during mechanical ventilation.

Measured air-flow rates during experiments with mechanical ventilation				
supply			exhaust	
Room	m³/h			m³/h
8 living room[1]	54		7 kitchen[2]	52.5
8 living room[1]	54		7 kitchen[2]	53.5
2 bedroom	30		4 second bathroom	33.5
3 children's room	28		1 master bathroom	50.5
5 bedroom	34		11 technical room	43.5
6 parents' room	40.5			
Total	240.5		Total	233.5

Table 2.3. Measured supply and exhaust air-flow rates in EFHlab with balanced mechanical ventilation.
[1]air is supplied to the living room at two locations.
[2]air is exhausted from the kitchen at two locations.

According to the Danish Building Regulation 2010 the ventilation flow rate should be:

1 in occupied residential rooms: 0.3 l/s/m²
2 from kitchen: 20 l/s
from bathrooms and toilets: 15 l/s and
from utility rooms/cellars: 10 l/s

In EFHlab, 1) gives a flow rate of 233 m³/h, while 2) gives 216 m³/h. Thus, the flow rate in the experiments was a little above the requirements. Furthermore, the flow rate was not balanced between the four bedrooms at the ground floor: the fresh air inlet to the parents' room was 19-45 % higher than the inlet of fresh air to the three other bedrooms. The reason for this is that two people were sleeping in the parents' room during the experiments, while only one person was sleeping in the children's room (the two other bedrooms were unoccupied as explained later).

The ventilation unit was a compact unit with heat recovery of around 80 %, but without summer bypass. This means that the fresh air was always heated by the exhaust air all year round.

2.3 Infiltration

The EnergyFlexHouses are made very airtight. The infiltration has been measured to be 0.059 l/s per m² (Danish Technological Institute, 2012), which is less than half the allowed infiltration of 0.13 l/s per m² in the existing Danish Building Regulation 2010.

This means that the infiltration was negligible compared to both the flow rates created by the mechanical ventilation system and by natural ventilation.

2.4 Solar screening

It is a well-known fact that solar radiation through windows may lead to overheating especially during warm periods. Unfortunately EFHLab was not equipped with automatically shading devices – the shading devices on the south windows and the south facing roof windows – see figure 2.8 - are manually operated. However, houses with a risk of overheating should have some sort of solar screening – manually or automatically. In order to simulate the presence of solar screening, the solar shading devices were left 2/3 down on the south facing windows, as seen in figure 2.8, while the solar screens on the two south facing roof windows was fully closed.

Figure 2.8. The movable solar screening on the south façade and south facing roof.

3 Experimental setup

It is difficult to measure the influence of natural ventilation in ordinary houses as people behave more or less differently from day to day – and very differently when comparing working days with weekends. Thus, long measuring sequences are necessary in order to obtain statistically significant results. It is, therefore, not feasible to try out and compare a large number of natural ventilation strategies within a short period of time in occupied houses.

In the experiments carried out in EHFlab, this problem was overcome by letting artificial persons move into the house. Artificial persons in the sense of barrels, which can emit heat, humidity and CO_2 in a controlled way. The artificial persons/barrels – as is seen in figure 3.1 – were developed at Danish Technological Institute and they can be programmed to emit heat, humidity and CO_2 equal to one or two persons. Furthermore, they can be programmed to emit according to a timetable in order to emulate that the persons are in different places in the house in different times or out of the house for work or school.

Figure 3.1. An artificial person in the form of a barrel and a bucket with water for the humidifier. The artificial persons were supplied with CO_2 from a common gas cylinder through plastic tubes.

The experiments simulated that three persons lived in EFHlab: two parents and one child. The timetable used for the persons present in the house is shown in table 3.1. Table 3.1 also includes a row for showers (DHW) in the master bathroom. Here, the unit is litre hot water at around 50°C. The water from the showerhead did hit the shower curtain in order to create a realistic moisture load in the master bathroom. EFHlab has no kitchen, so a moisture and heat load from cooking were not simulated. However, as seen in figure 2.4, there is a high ceiling in the living room creating a large space which are less influenced by the moisture and heat load when cooking.

	room	hour of the day																							
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Person present	First floor	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	2	3	3	2	2	2	2	2
	Parents' room	2	2	2	2	2	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2
	Children's room	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	1	1	1
DHW	Master bath-room	0	0	0	0	0	0	70	0	0	0	0	0	0	0	0	0	0	0	0	0	35	0	0	0

Table 3.1. Timetable for persons present in three different rooms. The number in each cell of the table states the number of persons present. The last row shows the actual amount of tapped hot water in litre during showers at that specific hour. Periods when persons are present or taking showers are highlighted in yellow.

The artificial persons were programmed to emit per person:

heat: 100 W
humidity: 1 l/day
CO_2: 20 l/h

3.1 Experiments

In total 11 experimental sequences were carried out in EFHlab during a period of almost three month: June 25 to September 22, 2013. Table 3.2 shows the main characteristics of the 11 experiments, while table 3.3 shows more details.

The experiments were divided into two groups: experiments with balanced **mechanical ventilation** (*experiment 1 and 11)* and experiments with **natural ventilation** (*experiments 2-9)*.

The ventilation was either carried out in a **two story building**: *experiment 1-5 and experiment 10 and 11*, or in a **single story building**: *experiment 6-9*.

Control strategies:

Experiment 1 and 11: fixed flow rates at all times

Experiment 2: opening of roof windows and windows in aisle based on the room temperature on the first floor

Experiment 3: opening of roof windows and windows in aisle based on the room temperature on the first floor and the CO_2 level in the parents' room

Experiment 4: opening of roof windows, windows in aisle and fresh air valves in bedrooms based on the room temperature on the first floor and the CO_2 level in the parents' room

Experiment 5 and 10: opening of the roof windows and windows in the aisle based on the room temperature on the first floor as well as opening of the roof windows and fresh air valves in the bedrooms based on the CO_2 level in the parents' room. The CO_2 control had first priority

Experiment 6-8: opening of the windows in the aisle and the fresh air valves in the bedroom based on the room temperature and CO_2 level in the parents' room.

Experiment	Period	Mechanical ventilation	Natural ventilation	2 floor building	1 floor building	Closed doors to bedrooms	Doors to bedrooms ajar	Open doors to bedrooms	Opening of roof windows	Opening of Aisle windows	Opening of fresh air valves	Control based on tempera-ture at first floor	Control based on tempera-ture in parents's room	Control based on CO_2 in par-ents's room	Opening of windows in south facing bedrooms	Opening of external doors in aisle
1	25/6-1/7	X		X		X										
2	1/7-7/7		X	X		X		X	X	X	X	X				
3	8/7-13/7		X	X		X		X	X	X		X		X		
4	15/7-22/7		X	X		X		X	X	X	X	X		X		
5	23/7-29/7		X	X		X		X	X+O	O	X	O		X	X	
6	29/7-5/8		X		X	X		X		X	X		X	X		
7	5/8-14/8		X		X	X		X		X	X		X	X	X	
8	14/8-21/8		X		X		X			X	X		X	X	X	
9	21/8-4/9		X		X	X	X	X		X			X	X		X
10	4/9-16/9		X	X			X	X	X+O	O	X	O				
11	19/9-22/9	X		X		X	X									

Table 3.2. Synthesis of the experiments carried out in EFHlab.
X+O for experiments 5 and 9 mean that the opening of the roof windows and the aisle windows was controlled by the temperature on the first floor, while the opening of the roof windows and the fresh air valves was control by the CO_2 level in the parents' bedroom. CO_2 had first priority.

The number listed in the column Day in table 3.3 refers to the night between the given day (Day) and the day before, - i.e. Day 179 is the night between day number 178 and 179.

Experiment	Day	Control system	Closed bedroom doors	Fully open bedroom doors	55 mm bedroom doors	114 mm bedroom doors	Only closed doors to bed-room 2 and 5	Theft-proof open windows in south facing bedrooms	Open doors in aisle	Open windows in south fac-ing bedrooms	Controllable fresh air valves
1	179	1	X								
	180		X								
	181		X								
	182		X								
2	183	2	X								
	184		X								
	185			X							
	186			X							
	187			X							
	188			X							
3	190	3		X							
	191			X							
	192		X								
	193			X							
	194			X							
4	197	4		X							X
	198			X							X
	199		X								X
	200		X								X
	201		X								X
	202		X								X
	203		X								X
5	205	5	X								X
	206		X					X			X
	207			X				X			X
	208			X							X
	209			X							X
	210			X							X
6	211	6	X								X
	212		X								X
	213		X								X
	214			X							X
	215			X							X
	216			X							X
	217			X							X
7	218	6		X				X			X
	219			X				X			X
	-										X
	225		X					X			X
	226		X					X			X

Experiment	Day	Control system	Closed bedroom doors	Fully open bedroom doors	55 mm bedroom doors	114 mm bedroom doors	Only closed doors to bed-room 2 and 5	Theft-proof open win-dows in south facing bed-rooms	Open doors in aisle*	Open windows in south facing bedrooms*	Open fresh air valves
8	227	6			X						X
	228				X						X
	229					X					X
	230					X					X
	231					X					X
	232					X					X
	233					X		X			X
9	234	7				X		X			X
	235					X					
	236					X					
	237					X					
	238					X					
	239			X							
	240			X							
	241			X					8:20 —	9:20	
	242			X			X				
	243			X			X				
	244			X			X				
	245			X			X				
	246		X								
	247		X								
10	248	2		X							X
	249			X							X
	-										X
	253			X							X
	254			X							X
	255			X							X
	256			X							X
	257					X					X
	258					X					X
	259					X					X
11	260	1	X								
	261		X								
	262			X							
	263			X							
	264					X					
	265					X					

Table 3.3. Details of the experiments carried out in EFHlab. The number in the column Day can be translated into dates by comparing with table 3.2.
* the windows in the south facing bedrooms and the external doors of the aisle were open 500 mm for one hour during day 241.

Experiment 9: opening of the windows in the aisle (the fresh air valves were sealed except for the first day) based on the room temperature and CO_2 level in the parents' room.

The aim of the temperature control was to maintain the temperature in the living room during experiments 2-5 and 10 and in the parents' room during experiments 6-9 rom within class I in EN 15251 – i.e. between 23.5 and 25.5°C. See chapter 5.

The aim of the CO_2 control was to maintain the CO_2 level in the parents' room in experiment 3-10 within class II in EN 15251 – i.e. between 750 and 900 ppm. See chapter 5.

With the combined temperature and CO_2 control, the windows/fresh air valves would stay open for as long as it was required by either the temperature control or the CO_2 control. As the CO_2 level often exceeded the class II level for longer periods this may lead to very low room temperatures in the house. For this reason the windows/fresh air valves closed when the temperature in the living room (experiments 2-5 and 10) and the temperature in the parents' room (experiments 6-9) dropped below 20°C.

During the 11 experiments, tests have been carried out with the opening degree of the doors to the bedrooms on the ground floor shown in table 3.3: closed, fully opened or slightly opened with an air gap of either 55 or 114 mm.

The windows in the south facing bedrooms have been left open in theft-proof mode during several days. Opening of the windows in the south facing bedrooms together with the external doors in the aisle (all opened 500 mm) was carried out during one hour of day 241.

Finally, the influence of open doors to the parents' bedroom and the children's bedroom has been tested, while the doors to the two other bedrooms were closed.

The characteristics of the different experiments is also mentioned under the results of the different experiments.

4 Data acquisition system

The two EnergyFlexHouses are extremely well monitored with approx. 700 sensors and meters. Only a few of these sensors including a couple of additional sensors have been utilized in the described experiments.

The data acquisition system and sensor set in EnergyFlexHouse are briefly described in Appendix A. In the following, only the sensor set applied in the experiments will be described.

Figure 4.1 shows the sensor locations on the ground floor, while figure 4.2 shows the sensor locations on the first floor.

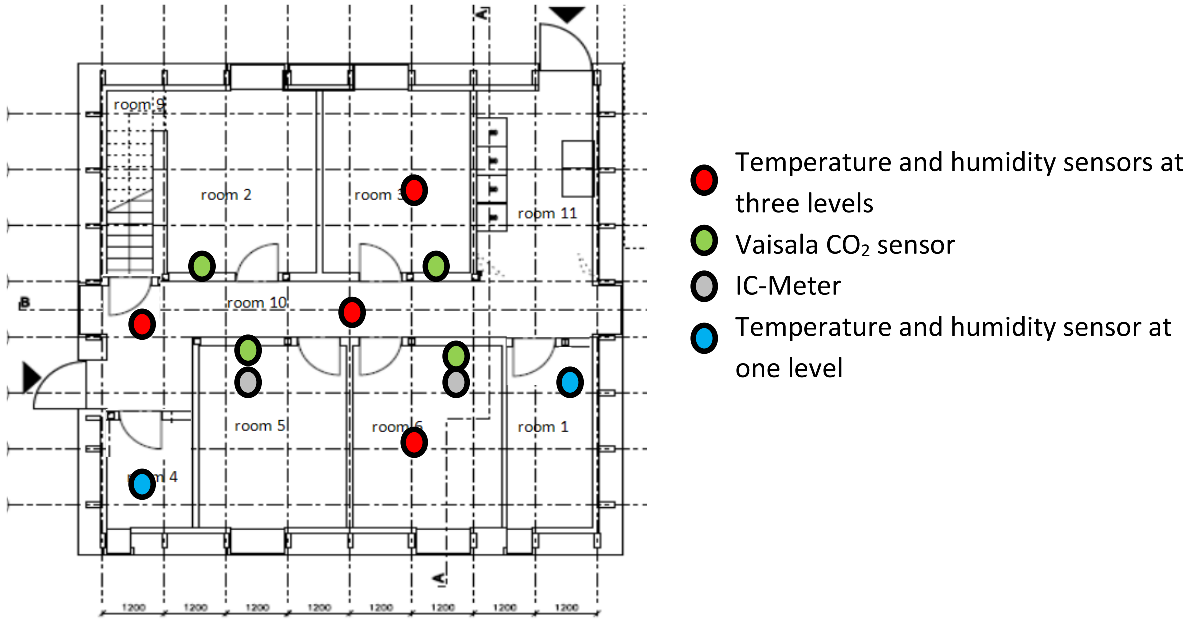

Figure 4.1. Temperature, humidity and CO_2 sensors on the ground floor.

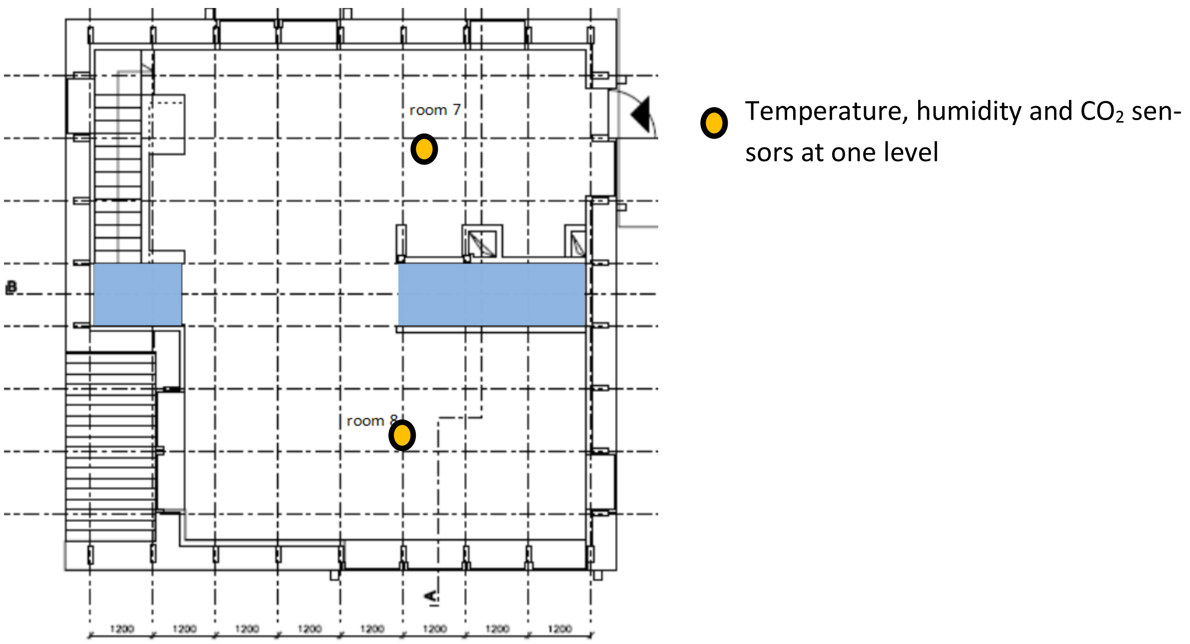

Figure 4.2. Temperature, humidity and CO_2 sensors on the first floor.

4.1 Sensors in the bedrooms and the aisle

The temperature and humidity were measured at three levels in the parents' room, the children's room and the aisle with a combined temperature and rh sensor from Rense, type PC-521-xx-HTC[1]. The three levels of the measurements were 0.3, 1.2 and 2.2 m above the floor. The stand with the sensors in the parents' room is seen in figure 3.1 and the stands in the aisle are seen below in figure 4.3.

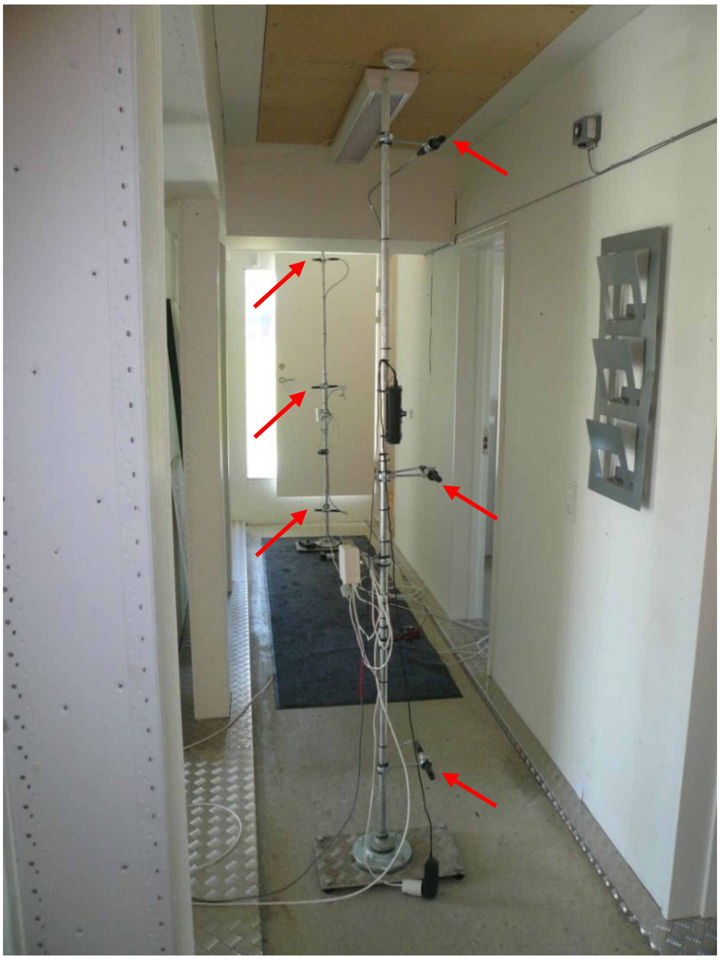

Figure 4.3. The stands with three combined temperature and rh sensors (at the arrows) in the aisle.

Figure 4.4 shows the two types of CO_2 sensors: one type from Vaisala and one type from IC-meter. The sensors from Vaisala, type GMW115[2] are part of the permanent sensor set of EFHlab. However, their max reading was set to 2000 ppm. Thus, from experiment 3 and onwards a IC-meter[3] was installed in the parents' room and in the children's room as the CO_2 level often got well beyond 2000 ppm in these rooms.

The two sensors were located 2.11 cm above the floor close to the partition wall to the aisle.

Figure 4.5 shows an example of the CO_2 concentration measured by the Vaisala sensors and the IC-Meters in the parents' room and the children's room.

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[1] www.michell.com/us/documents/pc-series-mini-us.pdf

[2] www.instrumart.com/assets/GMW115-Datasheet.pdf

[3] www.ic-meter.com

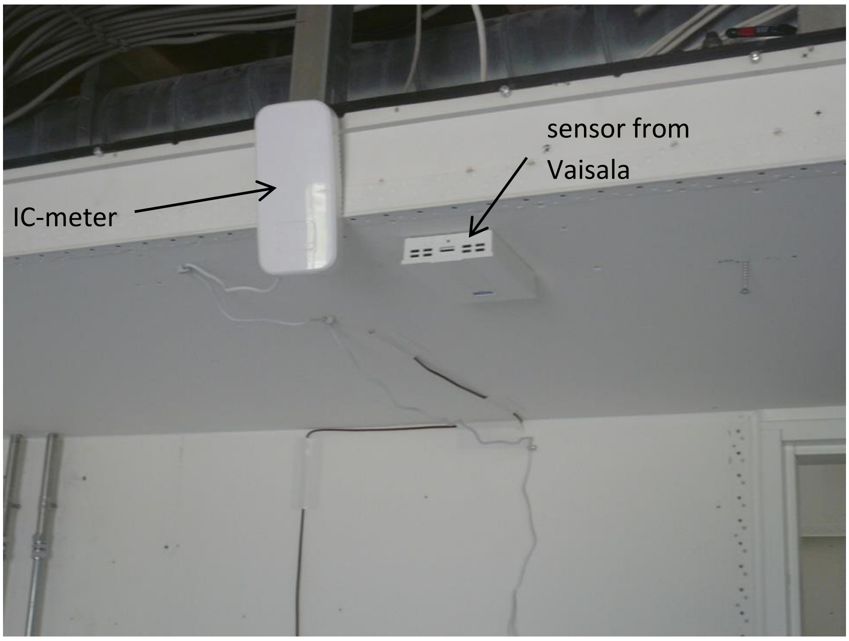

Figure 4.4. The two CO_2 sensors in the children's room.

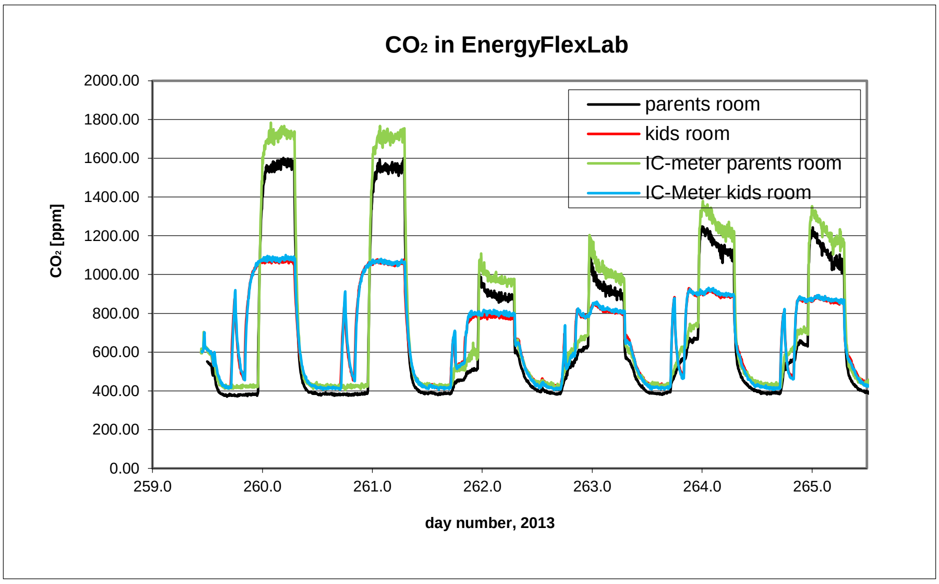

Figure 4.5. The CO_2 concentration in the parents' room and the children's room during experiment 11 measured with the Vaisala sensors and the IC-Meters.

Figure 4.5 shows that the measurements of the CO_2 concentration with the two instruments in the children's room are almost identical, while the Vaisala sensor in the parents' room measured a CO_2 concentration, which was around 10 % lower that the concentrations measured by the IC-Meter. From figure 4.5 it is seen that the two IC-Meters and the Vaisala sensor in the children's room give almost identical readings at the low CO_2 level around 400 ppm, while the Vaisala sensor in the parents' room give readings that are approx. 10 % below. Based on this it is judged, that the readings from the IC-Meter in the parents' room are more correct than the readings from the Vaisala sensor.

It is not possible to plot the readings from of the Vaisala sensors against the IC-Meters because of the difference in intervals, i.e. the two types of sensors provide four-minutely measurements and five-minutely measurements, respectively.

4.2 Sensors in the bathrooms

The sensors in the two bathrooms were combined temperature and rh sensors from Vaisala, type HMW83[4].

4.3 Sensors on the first floor

The sensors on the first floor were CO_2 sensors from Vaisala (identical to those used in the bedrooms) and combined temperature and rh sensors also from Vaisala (identical to those used in the bathrooms). The sensors were located 1.13 m above the floor – see figure 4.6.

Figure 4.6. The Vaisala CO_2 sensor and Vaisala temperature/rh sensor in the kitchen on the first floor.

4.4 Weather data

The EnergyFlexHouse facility is well equipped with sensors for measuring the surrounding weather:

- global and horizontal diffuse solar radiation at the ridge of the roof of EFHlab by a combined pyranometer from Delta Devices SPN1[5]
- total solar radiation in a plane equal to the orientation and tilt of the PV panels and solar collectors: tilted 50° and facing south. CMP 21 pyranometer from Kipp & Zonen[6]. The pyranometer is shown in figure 4.7.
- vertical total solar radiation at the east, south and west facade of EFHlab using CMP 21 pyranometers from Kipp & Zonen. A photo of one of the pyranometers is shown in figure 4.7
- weather data at 10 m height using Vaisala Weather Transmitter WXT520[7]
  The instrument measures: ambient temperature, ambient relative humidity, wind speed, wind direction, rain and air pressure

[4] http://www.transcat.com/PDF/HMW83.pdf

[5] http://www.delta-t.co.uk/product-display.asp?id=SPN1%20Product&div=Meteorology%20and%20Solar

[6] http://www.kippzonen.com/Product/14/CMP-21-Pyranometer#.U4W8N3KSzms

[7] http://www.stevenswater.com/catalog/products/weather_sensors/datasheet/WXT520.pdf

- ambient temperatures at the four facades of EFHlab measured with shielded and natural ventilated temperature sensors: type T thermocouples from Ametek. Photos of a shield is shown in figure 4.7.

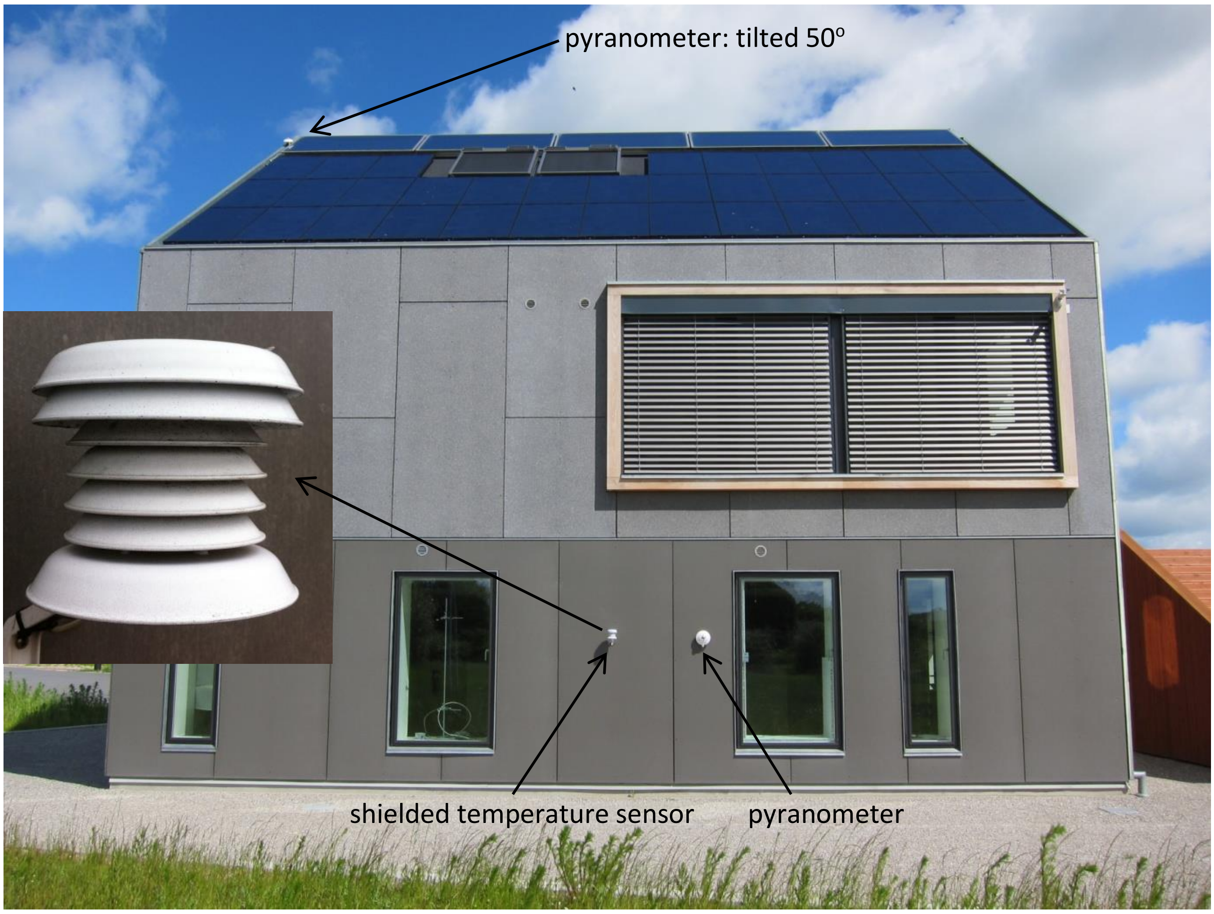

Figure 4.7. The pyranometer and shielded ambient temperature sensor at the south façade of EFHlab.

5 Indoor environmental quality

In the experiments, the natural ventilation was controlled based on the comfort criteria in (EN15251, 2007).

EN15251 gives comfort classes for different parameters, which influence the well-being of human beings. Only three of these parameters were included in the performed experiments: operative temperature, relative humidity and CO_2 concentration.

For these parameters, EN15251 gives the following comfort classes:

- class I: High level of expectation and is recommended for spaces occupied by very sensitive and fragile persons with special requirements like handicapped, sick, very young children and elderly persons
- class II: Normal level of expectation and it should be used for new buildings and renovations
- class III: An acceptable, moderate level of expectation and it may be used for existing buildings
- class IV: Values outside the criteria for the above categories. This category should only be accepted for a limited part of the year

5.1 Operative temperature

The operative temperature is a combination of the air temperature and the temperature of the surrounding surfaces. The housing of the temperature sensors in EFHlab resembles something in between the air temperature and the operative temperature, but as the air speed in the rooms is mostly low, the measured room temperatures are supposed to be close to the operative temperature. Table 5.1 shows only the thermal comfort classes for the summer situation for persons with light summer clothes (0.5 clo) and mainly sedentary activities (1.2 met). The temperature levels are shown together with the PPD (Predicted Percentage of Dissatisfied).

Comfort class	Operative temperature range Summer, [°C]	PPD [%]
I	23.5-25.5	<6
II	23.0-26.0	<10
III	22.0-27.0	<15
IV	<22.0-27.0<	>15

Table 5.1. Example criteria for operative temperature and PPD for typical spaces with sedentary activity in mechanical ventilated or air-conditioned buildings (EN15251, 2007).

Table 5.1 shows the criteria for buildings, which are mechanically ventilated or air-conditioned. The criteria for the thermal environment in naturally ventilated buildings without mechanical cooling may be specified differently from those with mechanical cooling during the warm season due to the different expectations of the building occupants and their adaptation to warmer conditions. The levels of adaptation and expectation are strongly related to the outdoor climatic conditions.

The recommended criteria for the indoor temperature are given in figure 5.1 based on a weekly running mean outside temperature.

The operative temperatures (room temperatures) presented in figure 5.1 are valid for:

- office buildings and other buildings of a similar type used mainly for human occupancy with primarily sedentary activities
- dwellings, where there is easy access to operable windows and where occupants may freely adapt their clothing to the indoor and/or outdoor thermal conditions.

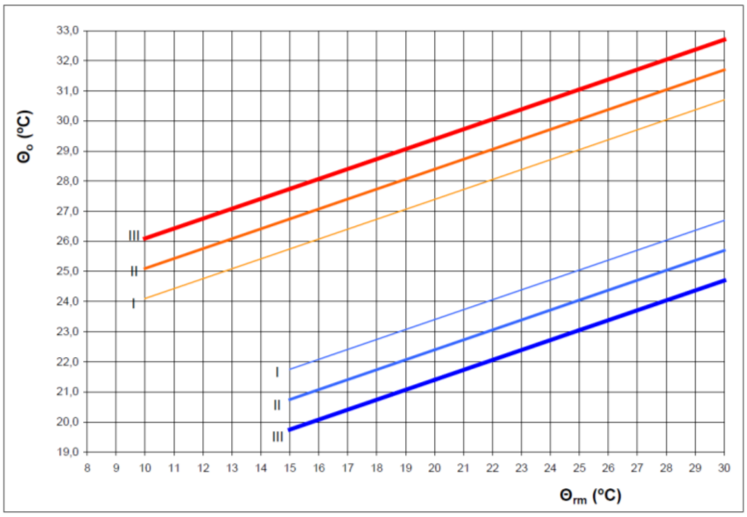

Figure 5.1. Design values for the indoor operative temperature for buildings without mechanical cooling systems as a function of the exponentially weighted running mean of the outdoor temperature (EN15251, 2007).

Θ_O = Operative temperature °C.

Θ_{rm} = Outdoor running mean temperature °C.

Θ_{rm} = (Θed-1 + 0,8 Θed-2 + 0,6 Θed-3 + 0,5 Θed-4 + 0,4 Θed-5 + 0,3 Θed-6 + 0,2 Θed-7)/3.8

Where

Θed-1 = the daily mean external temperature for the previous day

Θed-2 = the daily mean external temperature for the day before etc.

5.2 Relative humidity

EN15251 gives the criteria for the relative humidity in rooms. The criteria are shown in table 5.2.

Comfort class	Relative humidity [%]
I	30-50
II	25-60
III	20-70
IV	<20-70<

Table 5.2. Recommended design criteria for the humidity in occupied spaces.

5.3 CO_2 concentration

The air in a building is contaminated by the activity of the people and the materials in it. The contaminants are bioeffluents from people, humidity, particles, fibres, VOC, etc. Therefore, a certain flow rate of outdoor air dependent on the use of the building is necessary in order to maintain a good quality of the air. As several of the contaminants are difficult to measure, CO_2 and humidity are often used as indicators for the pollution generated by people - and for setting the criteria for the quality of the air. In connection with CO_2, EN15251 suggests the classes given in table 5.3.

Comfort class	CO_2 above outdoor [ppm]
I	0-350
II	350-500
III	500-800
IV	800<

Table 5.3. Example of recommended CO_2 concentration above outdoor concentration, which in this case is considered to be around 400 ppm (EN15251, 2007).

The Danish Labour Inspection has a threshold for the CO_2 concentration of 1,000 ppm (i.e. mid class III). If this threshold is exceeded, the ventilation conditions should be examined and possibly improved.

The Wisconsin Department of Health Services states that the exposure to CO_2 can produce a variety of health effects. These may include headaches, dizziness, restlessness, a tingling, pins or needles feeling, difficulty breathing, sweating, tiredness, increased heart rate, elevated blood pressure, coma, asphyxia, and convulsions.

The levels of CO_2 in the air and the potential health problems are:

CO_2 concentration [ppm]	Possible problems
250 - 350	background (normal) outdoor air level
350- 1,000	typical level found in occupied spaces with good air exchange
1,000 – 2,000	associated with complaints of drowsiness and poor air
2,000 – 5,000	associated with headaches, sleepiness, and stagnant, stale, stuffy air. Poor concentration, loss of attention, increased heart rate and slight nausea may also be present
>5,000	indicates unusual air conditions where high levels of other gases could also be present. Toxicity or oxygen deprivation could occur. This is the permissible exposure limit for daily workplace exposures
>40,000	this level is immediately harmful due to oxygen deprivation

Table 5.4. Health problems related to CO_2 concentration (Wisconsin Department of Health Services, 2013).

High CO_2 concentrations in homes are mainly obtained in bedrooms as seen in the introduction and later in the measurements in EFHlab and private homes. A high CO_2 concentration may influence the sleep quality. There is, however, not much scientific proof of this. A new study at the Technological University of Denmark (TUD) indicates that a high CO_2 concentration leads to a reduction of the sleep quality (Strøm-Teisen, 2014a). The study was carried out in 16 identical dormitory rooms at TUD, where the test persons normally lived. The test person were exposed to one week with CO_2 controlled mechanical ventilation and one week with natural ventilation with closed windows. The mean CO_2 concentration in the rooms were 835 ppm (comfort class II) during bedtime with mechanical ventilation and 2,395 ppm during natural ventilation. The room temperatures were very close to each other during the two experiments. The relative humidity was 40 % during mechanical ventilation and 54 % during natural ventilation. The test persons filled in a questionnaire each morning and slept with an actigraph unit measuring their movements. The test persons reported that they were more rested and less sleepy the following day during the experiment with mechanical ventilation. This was supported by the readings from the actigraphs units and a performance test, to which the test persons were exposed to.

An earlier study undertaken in the same dormitory shows the same tendency (Strøm-Teisen, 2014b). This study included 14 test persons. They were exposed to one week with open windows (air gap of 100 mm) and one week with closed windows. During the period with open windows, the mean CO_2 concentration was 660 ppm, whereas the concentration was 2,585 ppm during the period with closed windows. The study showed that the test persons fell asleep easier, i.e. slept longer, they were less sleepy during the day and better at concentrating when the windows were open during the night. The better sleep was also supported by the measurements of the actigraph units.

It is well-known that a poor sleep quality results in less effectivity at work and poorer learning for children. In the worst-case, it may also lead to depression and anxiety (Strøm-Teisen, 2014a). Therefoe, there is every reason for reducing the CO_2 concentration in bedrooms, - also because a high CO_2 concentration indicates a poor air change rate which may result in a high contraction of other contaminants.

5.4 Control of the natural ventilation in EFHlab

The operation of the roof windows, the windows in the aisle and the fresh air valves was, as stated in section 3.1, controlled based on combinations of the temperatures on the first floor or in the parents' bedroom and the CO_2 concentration in the parents' bedroom as the highest CO_2 concentrations were observed in this room.

The natural ventilation was controlled based on the following classes:

- temperature: class I: Opening of windows/fresh air valves at a temperature above 25.5°C. Closing of windows/fresh air valves at a temperature below 23.5°C.
- CO_2: Class II: Opening of windows/fresh air valves at a CO_2 level above 900 ppm. Closing of windows/fresh air valves at a CO_2 level below 750 ppm.

At combined temperature and CO_2 control, where CO_2 had priority the windows/fresh air valves were closed, if the temperature got below 20°C. This latter control was only activated during experiments 3 and 10.

6 Measurements

The measurements from the 11 experiments are all shown in Appendix B. There are 18-22 graphs available for each experiment. The content of the graphs is:

Bx.1.	the air temperature in the:	- the parents' room (room 6) – mean value[8] - the children's room (room 3) – mean value[8] - the master bathroom (large bathroom) (room 1) - second bathroom (small bathroom) (room 4) - aisle west (room 10) – mean value[8] - aisle middle (room 10) – mean value[8] - kitchen (room 7) - living room (room 8) and the ambient temperature
Bx.2.	the relative humidity in the:	- the parents' room (room 6) – mean value[8] - the children's room (room 3) – mean value[8] - the master bathroom (large bathroom) (room 1) - second bathroom (small bathroom) (room 4) - aisle west (room 10) – mean value[8] - aisle middle (room 10) – mean value[8] - kitchen (room 7) - living room (room 8) and the ambient relative humidity
Bx.3.	the CO_2 (Vaisala) in the: (for experiments 2-10)	- the parents' room (room 6) - the children's room (room 3) - room 2 (north facing) - room 5 (south facing) - kitchen (room 7) - living room (room 8) - indication of open/closed windows/fresh air valves
Bx.4.	the CO_2 (IC-Meter) in the:	- the parents' room (room 6) - the children's room (room 3)
Bx.5.	the air temperature at three levels 0.3, 1.2 and 2.2 m in:	- the parents' room (room 6)
Bx.6.	the air temperature at three levels 0.3, 1.2 and 2.2 m in:	- the children's room (room 3)
Bx.7.	the air temperature at three levels 0.3, 1.2 and 2.2 m in:	- aisle west (room 10)
Bx.8.	the air temperature at three levels 0.3, 1.2 and 2.2 m in:	- aisle middle (room 10)
Bx.9.	the relative humidity at three levels 0.3, 1.2 and 2.2 m in:	- the parents' room (room 6)
Bx.10.	the relative humidity at three levels 0.3, 1.2 and 2.2 m in:	- the children's room (room 3)
Bx.11.	the relative humidity at three levels 0.3, 1.2 and 2.2 m in:	- aisle west (room 10)

[8] the shown value is the mean value of the temperatures/rh measured at three heights shown in figures 3.1 and 4.3

Bx.12.	the relative humidity at three levels 0.3, 1.2 and 2.2 m in:	- aisle middle (room 10)
Bx.13.	solar radiation:	- global - diffuse
Bx.14.	solar radiation:	- in plane with the PV-panels: 50°, south facing - on the western façade - on the southern façade - on the eastern façade
Bx.15.	wind:	- wind velocity - wind direction (0° and 360°: north, 90°: east, 180°: south and 270°: west)
Bx.16.	ambient temperature:	- at the Vaisala weather station – 10 m height - at the north side of the building
Bx.17.	ambient temperature:	- at the south side of the building - at the west side of the building - at the east side of the building - at the north side of the building

Experiment 2-4:

Bx.18.	opening of roof and aisle windows - and fresh air valves in experiment 4	- temperature in the living room - windows open = 12, windows closed: 10

Experiment 5 and 10:

Bx.18.	opening of roof windows	- windows open = 12, windows closed = 10
Bx.19.	opening of aisle windows and fresh air valves	- windows open = 12, windows closed = 10 - valves open = 12, valves closed = 10
Bx.20.	opening of aisle windows	- windows open = 12, windows closed = 10
Bx.21.	opening of fresh air valves	- valves open = 12, valves closed = 10

Experiment 6-8:

Bx.18.	opening of aisle windows and fresh air valves	- temperature in the parents' room - windows/valves open = 12 windows/valves closed = 10

Experiment 9:

Bx.18.	opening of aisle windows	- temperature in the parents' room - windows open = 12, windows closed = 10

Experiment 10:

Bx.22.	rain	- mm rain per hour

The above measurements are available as four-minutely data, expect for the readings from the IC-meters, which are available as five-minutely data. The indication of open/closed windows/fresh air valves is at varying time steps. A log of events during the measuring is available in Danish.

The data is available free of charge as Excel files. However, further explanation of the measurements than the one included in this report requires a fee.

There are a few "gaps" in the measurements. However, these are not due to failure in the measuring system, but due to the fact that the gas cylinders containing CO_2 ran empty during parts of some of the experiments and in between the experiments. The "missing" days are excluded in table 3.3 and the result of the missing CO_2 injection is e.g. seen in figure B10.3.

6.1 Results of the measurements in EnergyFlexLab

The measurements listed in Appendix B contain an enormous amount of information that makes it very difficult to perform an exhaustive description of all possible findings. Thus, only the main findings will be described in the report. The description of the measurements and results is divided into subsections: weather conditions, relative humidity, room temperatures and CO_2 concentration.

In these subsections, there is referrences to the graphs in Appendix B with the notation Bx.y. Only close-ups of some of the graphs and summarizing graphs will be shown in the following subsections.

6.1.1 Weather conditions

Figures Bx.13-14 show that there were shifting cloud cover during the measuring period. Figure 6.1 shows the mean daily irradiation on vertical south (which is mainly responsible for any overheating problems) for the 11 experimental periods. For comparison: on a day in the middle of the measuring period with clear sky conditions (day 214, figure B6.14), the daily irradiation on vertical south was 4.5 kWh/m², while on a similar day near the end of the measuring period (day 249, figure B10.14) this number was 5.3 kWh/m².

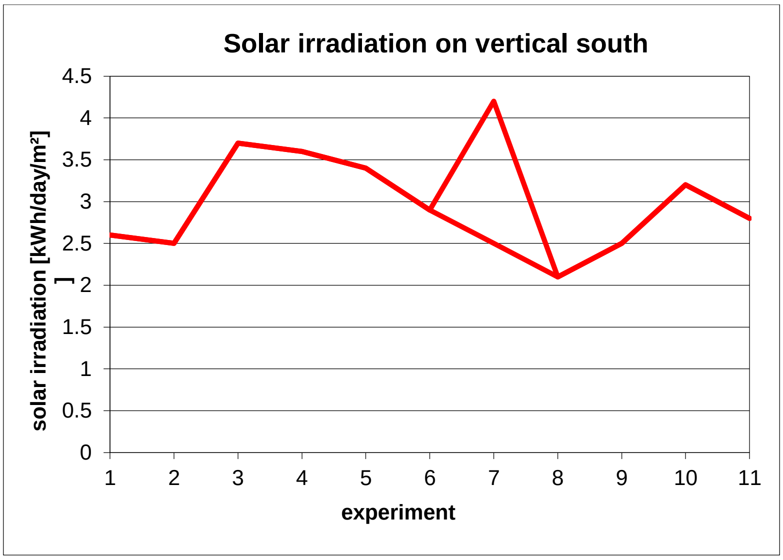

Figure 6.1. Mean daily irradiation on vertical south for the 11 experiments. There are two values for experiment 7 as this experiment was split into two periods separated by nearly a week.

The max/min ambient temperatures from figures Bx.16 are shown in figure 6.2. The measuring period started chilly, went very hot for Danish conditions and ended rather cold during the nights. The difference in the level of the ambient temperature over the measuring period has of course a major impact on the overheating risk and the possibilities of cooling down the house with ambient air.

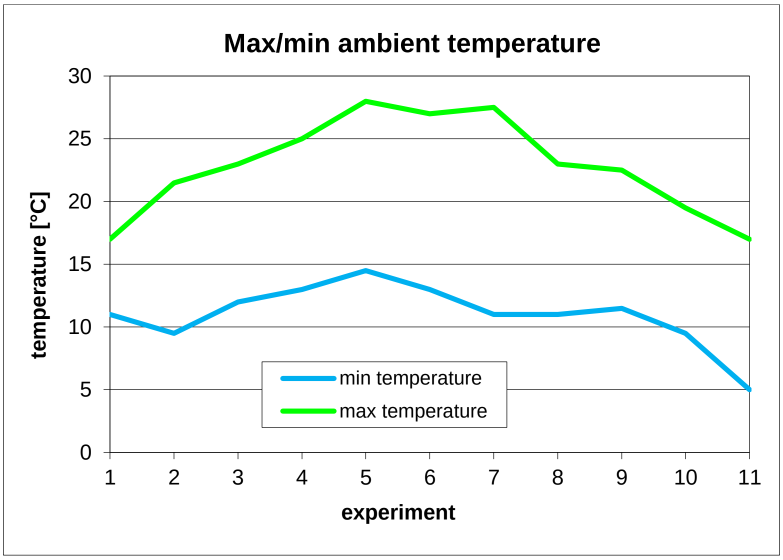

Figure 6.2. The max and min ambient temperatures for the 11 experiments.

Figure 6.3 shows that the ambient relative humidity varied between up to 90 % during the night and down to 28 % during the day. There was only little rainfall during the measuring period.

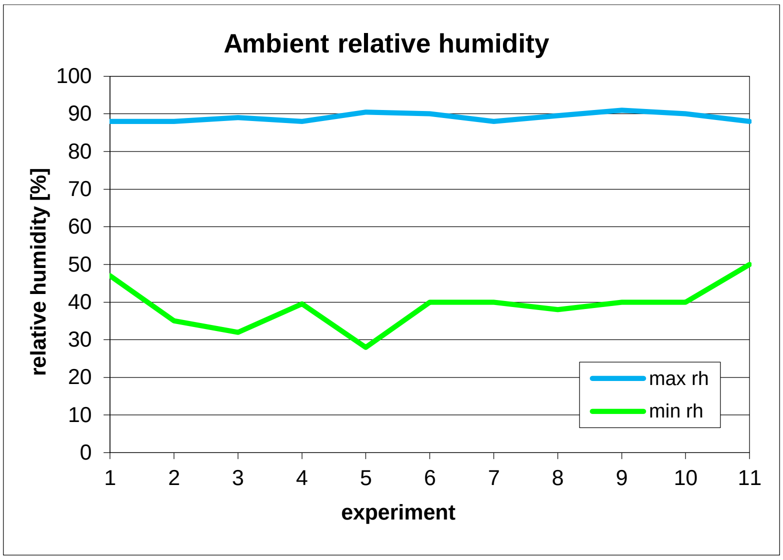

Figure 6.3. The max and min relative humidity for the 11 experiments.

Figures Bx.15 shows that the wind conditions were very fluctuating during the measuring period: from nearly zero wind speed up to 10 m/s and from all directions.

6.1.2 Relative humidity

The relative humidity in the house should mainly be within class II (see table 5.2): 25-60 % rh and it should only exceed class II for shorter periods, but still be within class III: 20-70 % rh. This is the case for all rooms in EFHlab (see figures Bx.2) except for the master bathroom and during experiment 10 in some of the rooms during day 258. However, as explained in the following section the relative humidity after day 246 should be disregarded.

6.1.2.1 Master bathroom

Twice a day, the relative humidity is higher than 90 % due to the bathing in the morning and in the evening – see table 3.1. However, this changes on day 246 (end of experiment 9) and onwards. After day 246, the heights of the peak of the relative humidity in the master bathroom start to fluctuate, because the domestic hot water production of the heating system was used for another project. Therefore, the relative humidity should only be investigated up until day 246.

Figures Bx.2 show that although there is a large relative humidity in the master bathroom just after bathing, the relative humidity is quickly decreased to 70 % and lower. Before the next bath, the relative humidity is almost at the same level as the relative humidity in the rest of the rooms in the house.

In figure B3.2 which includes measurements for day 190 (figure 6.4), it is e.g. seen that the relative humidity stays at almost 100 % for one hour after bathing after which it drops to 70 % within again one hour.

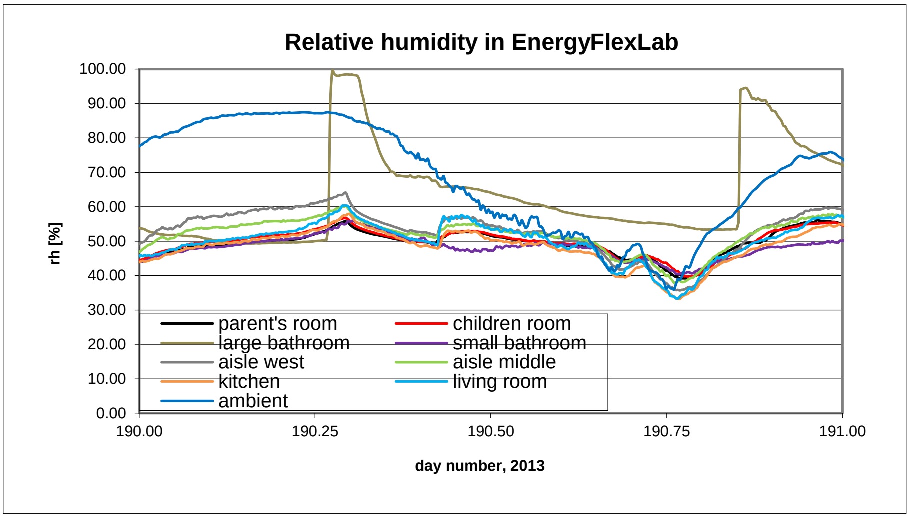

Figure 6.4. Relative humidity in the house during day 190 (July 9th, 2013). Close-up of figure B3.2.

When comparing figure B3.2 (natural ventilation) with figure B1.2 (mechanical ventilation), it is seen that in figure B1.2 the relative humidity in the master bathroom reaches a maximum of 95 %. Immediately after, the relative humidity starts to decrease and after 24 minutes it reaches 70 % on e.g. day 176 in the morning, and 50 % after another 40 minutes (figure 6.5). Thus, the drying out of the master bathroom is quicker with mechanical ventilation than with natural ventilation. The reason for this is that the exhaust from the bathroom during natural ventilation is through a 150 mm Ø duct leading to above the roof while the air inlet to the bathroom is through the 35 mm gab under the door. If a window had been open, the air exchange might have been higher. However, as the bathroom is dried out before the next bath and the house is a low energy house with limited cold bridges the lower air change rate during natural ventilation does not constitute a problem. Nevertheless, care should be taken in other houses.

The relative humidity in the master bathroom does not seem to affect the relative humidity in the rest of the house, which was expected as the moist air is sucked out of the bathroom to the ambient, while the supply air to the bathroom comes from the aisle through the 35 mm gap under the door.

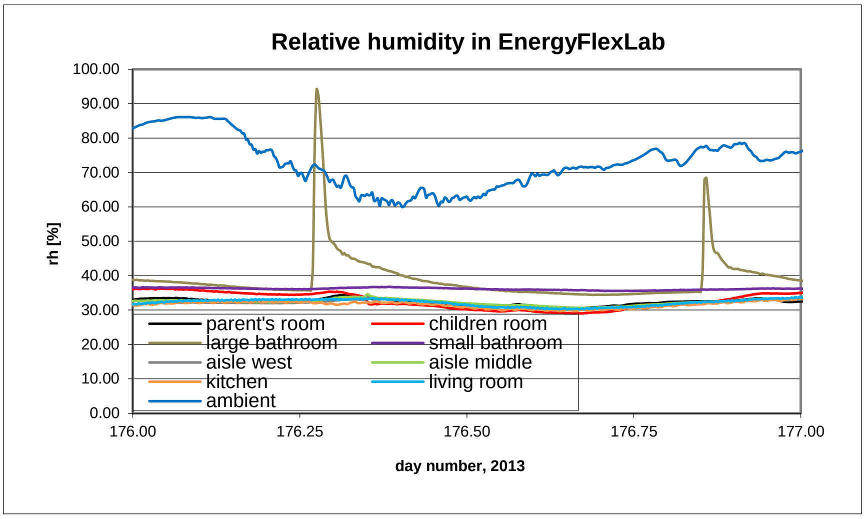

Figure 6.5. Relative humidity in the house during day 176 (June 25th, 2013).

6.1.2.2 General observations

When comparing figures B1.2 and B11.2 with B2.2-B10.2, it is seen that in general the relative humidity in the house was less affected by the ambient relative humidity when the house was mechanical ventilated as opposed to when it was natural ventilated. This is due to a missing bypass in the mechanical ventilation system – see section 6.1.3.4. The fresh air was always heated by the exhaust air, which reduced the relative humidity of the air blown into the rooms and led to more stable relative humidity conditions in the house. With a bypass, the relative humidity conditions with mechanical ventilation would be similar to those with natural ventilation.

The levels of the relative humidity in the different rooms are very close – especially during mechanical ventilation. This means that the humidity from the persons here has only little influence on the relative humidity in the occupied rooms. One exception is the relative humidity in the children's room as seen for days 205-206 on figures B5.2 and days 246-247 on figure B9.2, where the doors to the bedrooms were closed. Here, the relative humidity in the children's room is significantly higher than in the rest of the house. However, this is not the case during days 211-213 (figure B6.2), where the doors also were closed. The measurements provide no explanation for this. However, a reason could be that there were problems with the humidifier in the children's room – the humidifier was reported broken on day 206. The humidifier may have increased the emittance of moisture during the days leading up to the break down. Days 225-228 on figures B7.2-8.2 show a different pattern for the relative humidity in the children's room – i.e. lower relative humidity than in the rest of the house. This seems to be caused by the higher air temperature in the children's room during this period – see figures B7.1-8.1.

6.1.2.3 Conclusions on relative humidity

There have not been problems with the level of the relative humidity in the house in connection with the described experiments.

During mechanical ventilation, the relative humidity level was more stable than during natural ventilation due to the missing bypass in the mechanical ventilation system. However, the relative humidity mainly stayed within EN15252 class II.

Except for the master bathroom, the levels of the relative humidity in the different rooms of the house were quite similar indicating that the persons in the described experiments had only little effect on the relative humidity in the rooms, which they occupied.

The master bathroom was dried out faster during mechanical ventilation than during natural ventilation. An open window during natural ventilation may have increased the drying out rate.

In principle, the above conclusions are only valid for the described experiments. Opening of windows, drying of clothes inside the house, cooking, etc. may have changed the level of the relative humidity during the experiments significantly. Therefore, care should be taken when applying the conclusions of this report to other houses.

6.1.3 Room temperatures

Figure 6.6 shows the max/min temperatures for both the ambient and the rooms in the house (for the one story building the temperatures on the first floor are excluded) for the 11 experiments based on figures BX.1. In figures BX.1 the temperatures shown for the bedrooms and the aisle are the mean values of the three temperature sensors shown in figure 4.3 and in figures BX.5-8. Tables 6.1-2 show during which period there has been problems with overheating or too low room temperatures according to comfort class I-III (table 5.1).

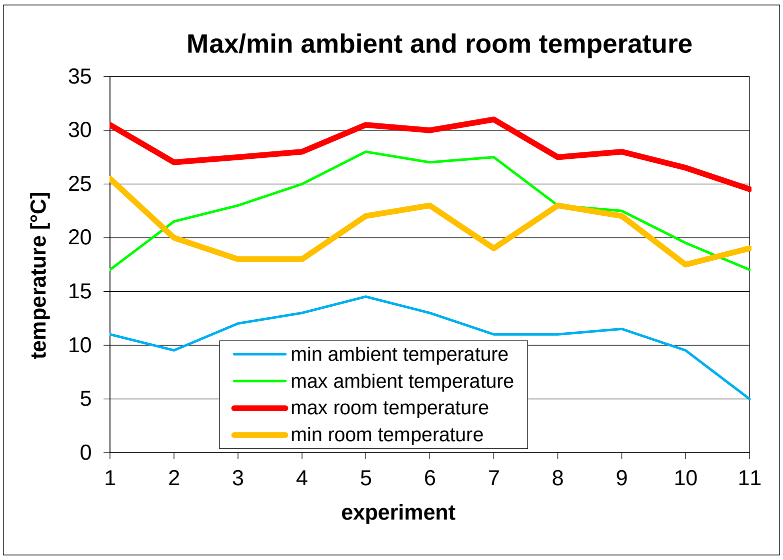

Figure 6.6. The max/min temperatures for the ambient and the rooms of the house for the 11 experiments.

Comfort class	Experiments with overheating										
	1	2	3	4	5	6	7	8	9	10	11
I	X	X	X	X	X	X	X	X	X	X	
II	X	X	X	X	X	X	X	X	X	X	
III	X	X	X	X	X	X	X	X	X		

Table 6.1. Experiments where overheating occurred, dependent on comfort classes according to table 5.1.

Comfort class	Experiments with too low temperatures										
	1	2	3	4	5	6	7	8	9	10	11
I		X	X	X	X	X	X	X	X	X	X
II		X	X	X	X		X		X	X	X
III		X	X	X			X			X	X

Table 6.2. Experiments where too low room temperatures occurred, dependent on comfort classes according to table 5.1.

Tables 6.1-2 shows that none of the experiments were without comfort problems – either overheating problems or too low temperatures. There are several explanations for this, which will be described in the following.

6.1.3.1 Overheating during natural ventilation

The overheating problems during experiment 1 with mechanical ventilation will be dealt with later in section 6.1.3.4.

The overheating problems during experiment 5-7 were of course not avoidable without mechanical cooling as the max ambient temperature exceeded all three comfort classes in table 5.1. However, if instead of using table 5.1, figure 5.1 is applied, this gives figure 6.7. Instead of using the exponentially weighted running mean of the ambient temperature, the mean ambient temperature from the previous experiment has been used. For comparison, the max room temperatures in figure 6.8 are shown together with the comfort classes from table 5.1.

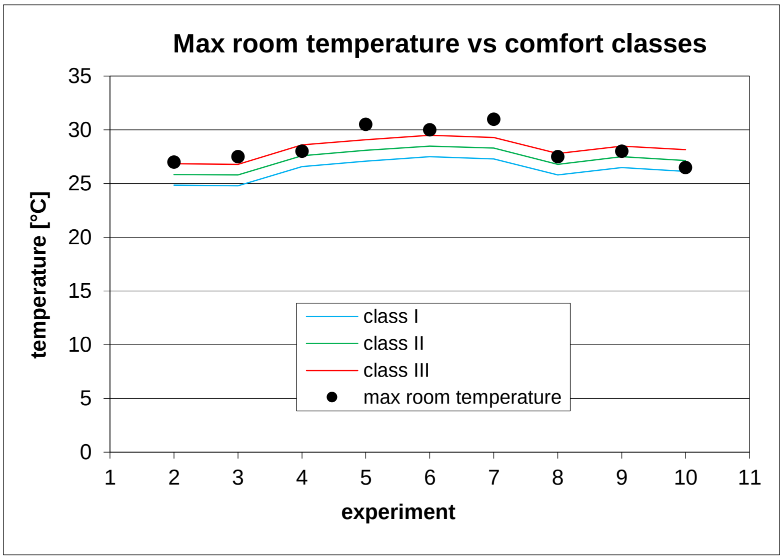

Figure 6.7. Max room temperature and the comfort classes based on figure 5.1 where the weighted temperature for ease is the mean ambient temperature from the previous experiment.

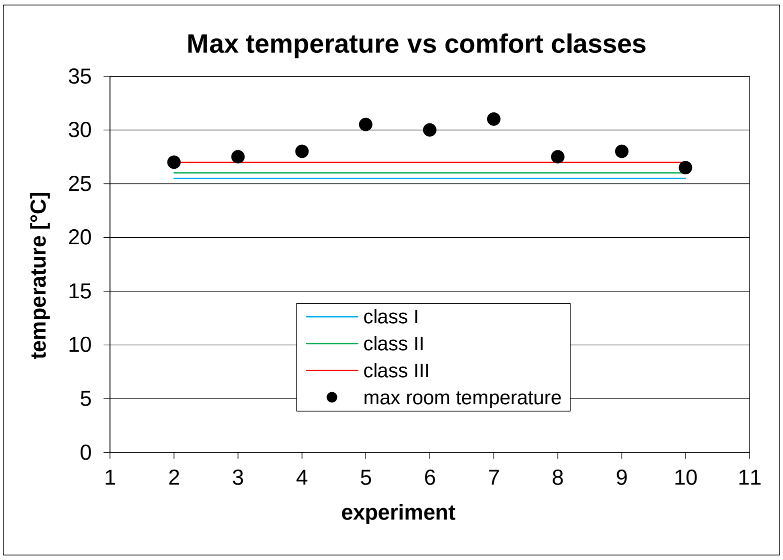

Figure 6.8. Max room temperature and the comfort classes from table 5.1.

When applying the comfort classes in figure 5.1, most of the max temperatures are within or close to comfort class III.

However, the overheating problems are not created by the natural ventilation strategy. Figure 6.6 shows a strong correlation between the max room temperature and the ambient temperature. Furthermore, the max room temperature can of course not be expected to be within the comfort classes in table 5.1, when the ambient temperature exceeds the max temperature of all the comfort classes in experiment 5-7. Figure 6.9 shows the difference between the max room temperature and the max ambient temperature. It is seen that during the hot period, it is possible to maintain the max room temperature at max 4 K above the max ambient temperature.

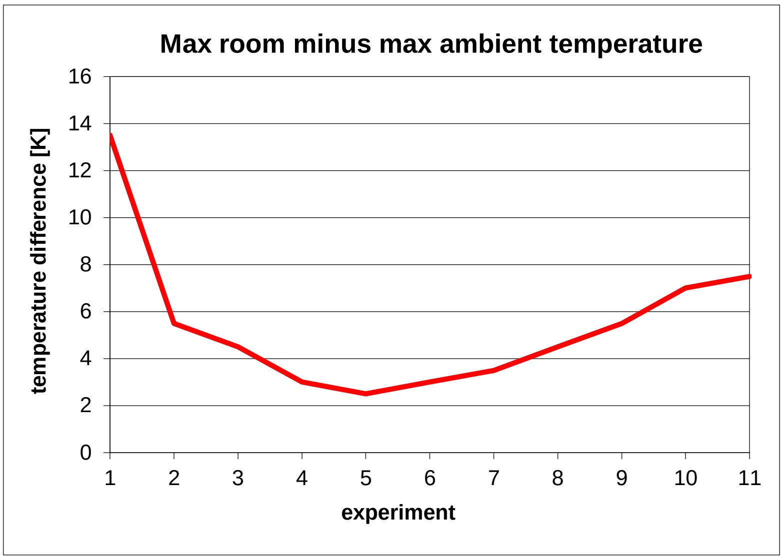

Figure 6.9. Max room temperature minus max ambient temperature for the 11 experiments.

In figure 6.10, the max room temperature is plotted against the max ambient temperature. As seen, there is a very nice correlation between these two temperatures for the nine experiments with natural ventilation. Figures 6.6 and 6.9 show a very different pattern for experiment 5 and 10 although an identical ventilation strategy has been applied. However, as seen in figure 6.11 they perform identically, - i.e. they are both lying on the regression line.

As all experiments lie closely around the regression line, it seems that there is no difference in the performance of the five natural ventilation strategies nor whether it is a one-storey or a two-storey building when it comes to the prevention of overheating.

In the above discussion, it has been neglected to mention that the doors to the bedrooms during the experiments have been closed, open or ajar. In figure 6.12, the max room temperature has been shown dependent on whether these doors have been open or closed. The figure shows close to insignificant differences. The reason why the max room temperature is lower with closed doors than with open doors in experiment 3 and 9 is that the control strategy here forces the windows in the aisle to stay open longer than with open bedrooms doors due to a higher CO_2 concentration in the parents' bedroom. During experiment 7, the weather condition were very different between the parts of the experiment with open and closed doors, respectively, as seen in figure B7.1. There were almost a week between the two parts where the weather conditions changed greatly.

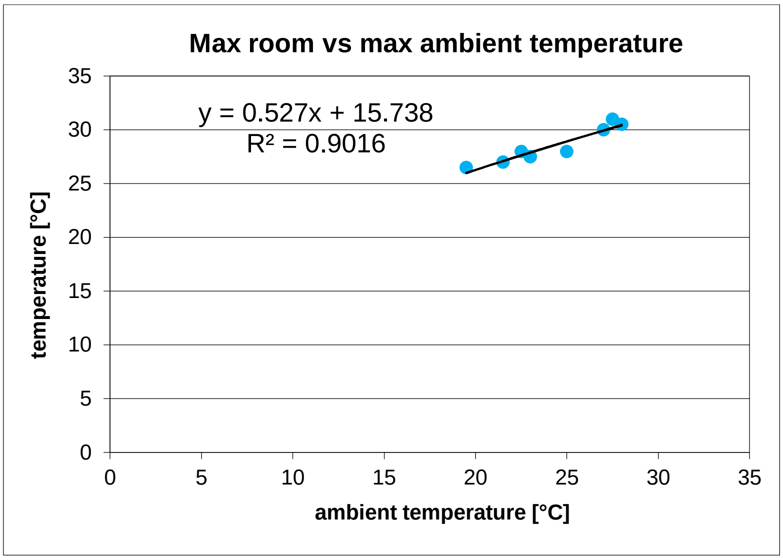

Figure 6.10. Max room temperature vs max ambient temperature for the 11 experiments.

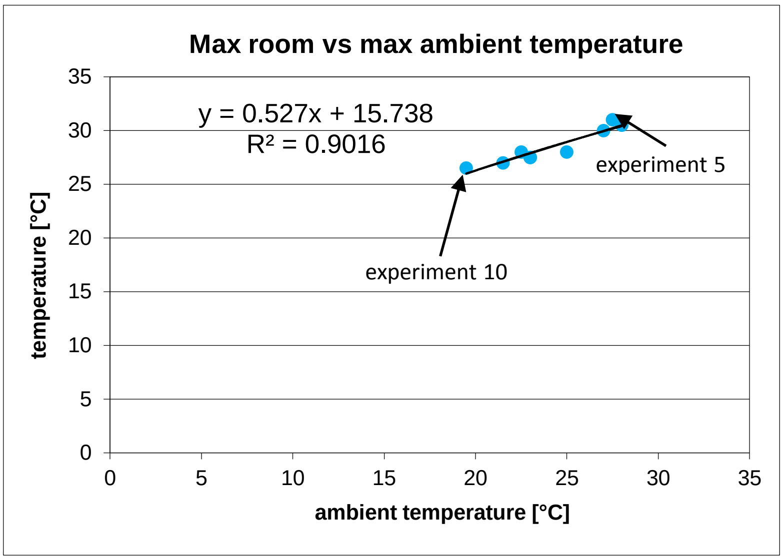

Figure 6.11. Max room temperature vs max ambient temperature for the 11 experiments - with experiment 5 and 10 pointed out.

6.1.3.1.1 Special peak of the room temperature in the aisle

Figure B4.7 shows a peak in the room temperature in the western part of the aisle on day 199 – see also figure 6.13, which is not present in the measurements from the middle of the aisle (figure B4.8). The reason was that the middle sensor in the western part of the aisle was hit by the sun. Following this incidence, these sensors were shielded from the sun, but peaks are still observed in experiments 6 and 7 (figures B6.7 and B7.7). However, in these latter incidences, it is only the sensor at 1.2 m height, which is affected, while it was mainly the bottom sensor in figure 6.13.

As these temperature readings are not included in the following analysis, no attempt has been made to find out the reason for the peaks during experiment 6 and 7.

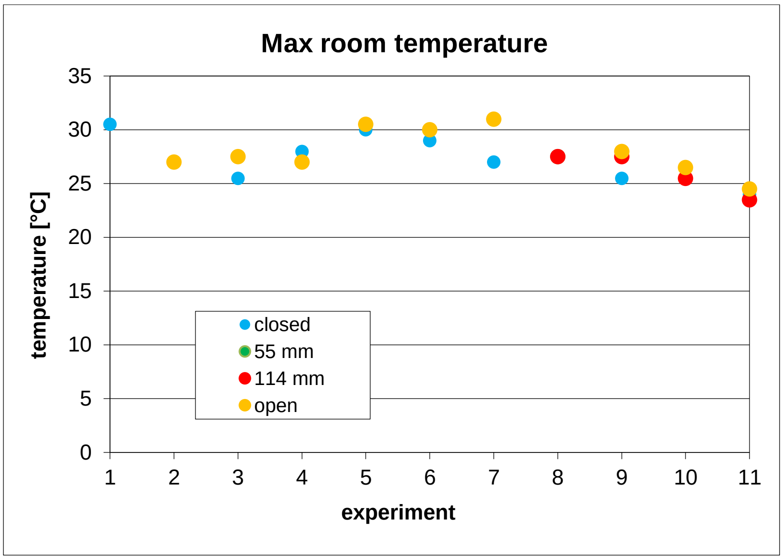

Figure 6.12. Max room temperatures for the 11 experiments dependent on whether the doors to the bedrooms have been closed, ajar or fully open. A 55 mm opening was only tried out in experiment 8. However, this is not seen here as the max room temperature at 55 mm ajar was identical to and, therefore, behind the max room temperature of the 114 mm opening.

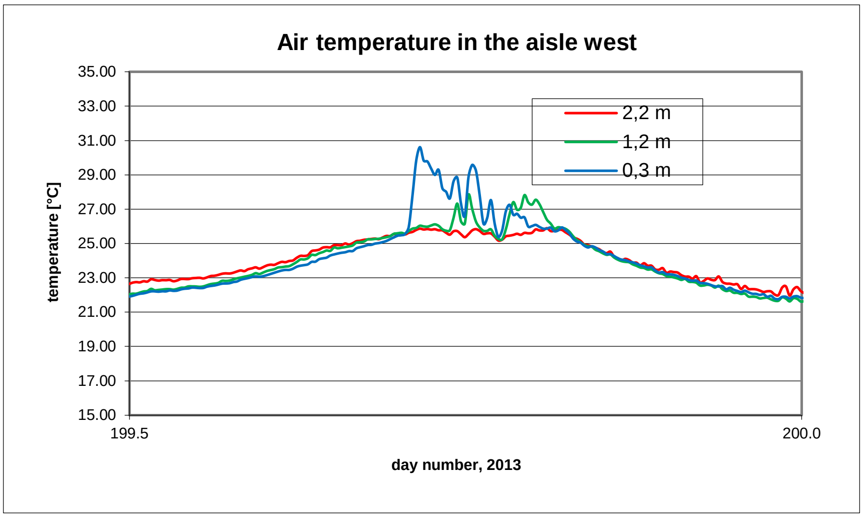

Figure 6.13. Close up of figure B4.7 showing the air temperatures in the western part of the aisle during the second half of day 199.

6.1.3.2 Too low temperatures during natural ventilation

Table 6.2 shows that none of the natural ventilations strategies are within comfort class I with respect to low room temperatures. Only two are within class II while four is within class III. The reason for this is that when trying to reduce the overheating cold ambient air is let into the house. When the ambient air is below the values of the comfort classes some rooms may be cooled too much, while others are still overheated. This is especially the case for the experiments with the two-storey house. Low room temperatures were, however, also experienced during experiment 7 (one-storey building), but here the reason was that the windows in the southern facing bedrooms were left open in theft protection mode during the entire experiment.

The lowest temperatures were obtain in the experiments with the two-storey building and with the control strategies including reduction of the CO_2 level in the parents' bedroom –

experiments 3, 4 and 10, however, not experiment 5 where the control strategy was identical to experiment 10.

During experiments 3 and 4, the roof windows and the windows in the aisle (in experiment 4 also the fresh air valves in the bedrooms) were opened if the temperature on the first floor got above 25.5°C or the CO_2 level in the parents' bedroom got above 900 ppm.

During experiment 5, the roof windows and the windows in the aisle were opened if the temperature on the first floor got above 25.5°C or the roof window and the fresh air valves in the bedrooms were opened if the CO_2 level in the parents' bedroom got above 900 ppm. The CO_2 control had first priority.

This meant that the windows in the aisle were less open during experiment 5 than during experiments 3 and 4, when the doors to the bedrooms were closed. The high CO_2 concentration demanded for CO_2 control in experiment 5 and thereby closed windows in the aisle, which led to lower air change rates due to the small opening area of the fresh air valves. This is true for the first days of experiment 5 – se figures B5.19-21. During days 204-208, the aisle windows were only open during the day at high ambient air temperatures.

However, from noon on day 207 and for the rest of experiment 5 (with open doors to the bedrooms) the aisle windows were always open, except for a few very short periods. However, at the same time the night-time ambient temperature increased to around 20°C leading to less problems with undercooling of rooms. On day 210, the night ambient temperature dropped to 16°C and the min temperature of the house starts to drop. However, EnergyFlexHouse has a high time constant – around 50 hours – so it takes some time to cool down the building.

The fact that the level of the ambient temperature makes the difference between experiments 3 and 4 and the last days of experiment 5 is supported by experiment 10 with the same control strategy as in experiment 5. Although mainly CO_2 control (see figures B10.19-21) min room temperatures below the comfort classes were observed most of the days. This is caused by the rather low ambient temperatures, which are let in during the night even if the house is not overheated.

The sudden drop in air temperature on day 241 in the bedrooms and the aisle (figures B9.5-8) was due to an experiment with airing – see table 3.3. The doors of the aisle and the technical room connected to the aisle, the windows in the south facing bedrooms and the bedroom doors were all open for one hour. The temperatures dropped very quickly to a min temperature of 15.5°C in the middle of the aisle due to an ambient temperature of 15°C as seen in figure 6.14 (a one day close up of figure B9.1). Due to the thermal mass of the EnergyFlexHouse the temperatures in the bedrooms were almost restored an hour after stopping the airing while it took longer for the aisle as the aisle windows remained open, as seen in figure B9.3.

6.1.3.2.1 Combined temperature and CO_2 control

The above reveals the conflict between temperature and CO_2 control: it may often not be possible to obtain the desired comfort class for both. Figures B2.1 and B2.3 show that the CO_2 level of the bedrooms during the nights exceeds comfort class III when only using temperature control, also with open doors to the bedrooms. Moreover, the level is clearly above the concentrations obtained when CO_2 is included in the control. One the other hand, CO_2 control may lead to too low temperatures in the house.

This latter problem was anticipated from the start of experiment 3. Therefore, the windows was set to close when the temperature of the living room dropped below 20°C (here without a hysteresis). Figure B3.14 shows the temperature of the living room together with the control signal for opening/closing of the window. Figure 6.15 shows a close up of the two first days where the temperature in the living room dropped below

20°C. Figure 6.15 shows that the control gets very fluctuating due to the missing hysteresis. Figure B3.5-6 show that the temperatures in the bedrooms stay above 21°C even when the doors to the bed rooms are open. However, the stratification of the room temperatures increases up to 2 K with the temperature just above the floor dropping to 21.5°C. Figures B3.7-8 show that the temperature in the aisle is very influenced by the incoming ambient air. Here, the temperature dropped one night to 17.5°C just above the floor, and it was still down to 18°C in the morning when the family woke up. Without CO_2 control (experiment 2 – B2.7-8), the temperature remains generally higher but drops for a short while to 18°C.

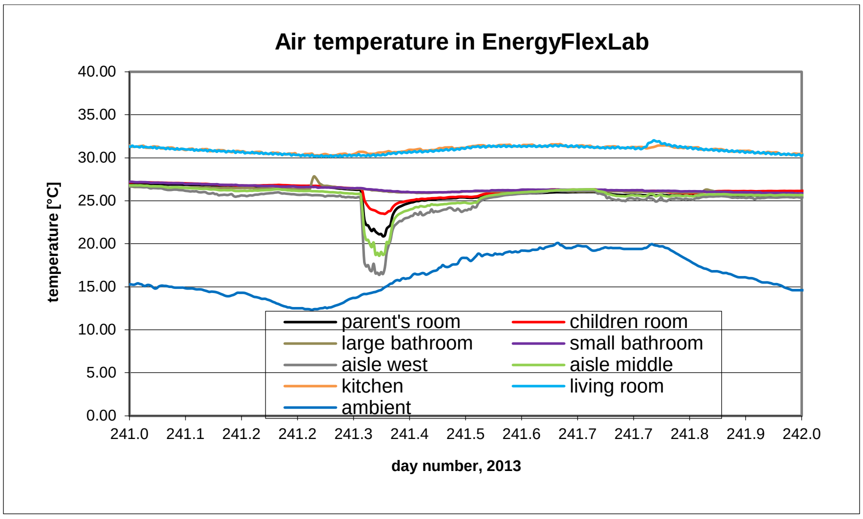

Figure 6.14. The temperatures in the house during day 241. Airing was conducted between 8:20 and 9:20.

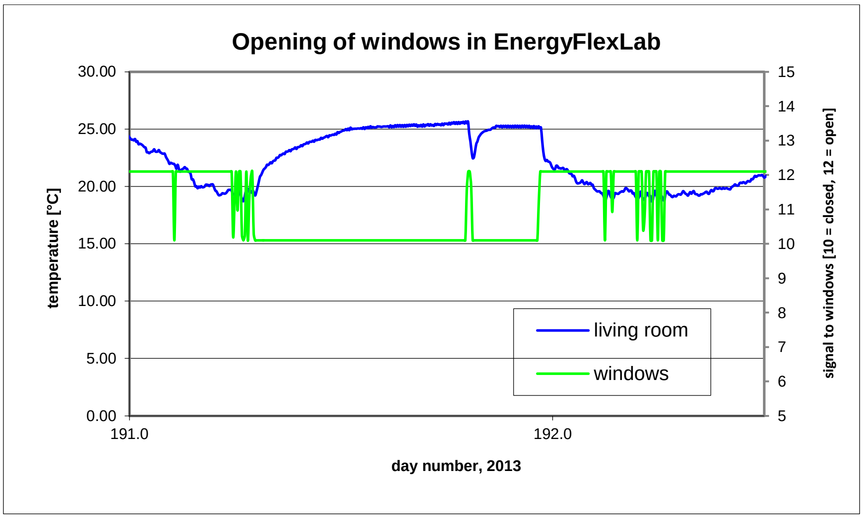

Figure 6.15. The air temperature in the living room and the control signal for the windows during experiment 3.

The temperature in the aisle fluctuates generally very much during natural ventilation, - especially when compared to mechanical ventilation (figures B.1.7-8 and B11.7-8) which could be expected as the fresh air mainly is lead in through windows in each end of the aisle. The temperatures in the bedrooms fluctuate far less, but they often drop outside the comfort bands. This is, however, not necessarily a problem as it is known to be healthy to sleep in rooms, which are colder than preferred when being awake. Furthermore, the aisle is not used for occupation during the night. But, the floor is cold when going to the bathroom during the night.

The low temperatures in the aisle are mainly a problem in connection with the combination of control based on the CO_2 level in an occupied bedroom and closed bedroom doors. Therefore, in this control case the bedroom doors should be left open or at least ajar during the night. This reduces the CO_2 concentration as seen in section 6.1.4.

6.1.3.3 Temperatures in rooms due to occupation

The temperature on the first floor is mainly governed by solar radiation, the ambient temperature and the control strategy. The volume is large so that the presence of persons hardly influences the temperature.

The presence of persons has little influence on the temperature level and the stratification in the bedrooms when the building is mechanically ventilated – figures B1.5-6 and B11.5-6. The influence is less than 1 K. The presence of persons influences more the temperature level and the stratification during natural ventilation. Figures B9.5-6 show an influence of above 1 K. However, the influence is small during the conducted experiments and will, therefore, not be considered further in the report.

6.1.3.4 Mechanical ventilation – experiment 1 and 11

Mechanical ventilation turned out to be worst when it comes to reducing overheating – experiment 1. The reason for this is for the here described experiments that the heat recovery unit of the compact ventilation system did not have a bypass. A bypass is used during warm periods when it is beneficial to let in colder ambient air directly to the house without heat recovery in order to cool down the building. Figure 6.16 shows what happens when the heat recovery unit does not have a bypass or the bypass is not used. Instead of blowing in ambient air (blue curve in figure 6.16) with a temperature of 10-15 K below the room temperature (orange curve in figure 6.16), the temperature of the inlet air (red curve in figure 6.16) is only 2-3 K below the room temperature. The reason for the high inlet temperature is seen in figure 6.17. Most of the time, the efficiency of the heat recovery unit is above 80 % (the drop in efficiency during the end of the experiment may be due to a decrease in the air-flow rate of the exhaust air. However, this has not been investigated here as it was beyond the scope of the project). A recovery efficiency of above 80 % is excellent during the winter, but constitutes a problem during the summer if no bypass is included in the ventilation system.

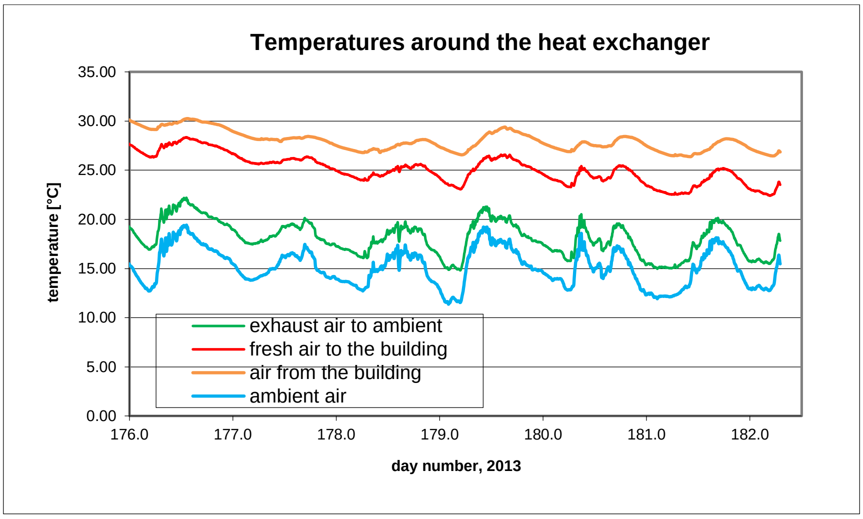

Figure 6.16. Temperatures to and from the heat recovery unit in the mechanical ventilation system during experiment 1.

Although the cooling capacity of the inlet air was only 2-3 K, the temperature of the building was slowly decreasing (orange curve in figure 6.16). This is because the overheating risk was smaller during mechanical ventilation (lower ambient temperatures) than during the natural ventilation strategies in experiment 3-5: the ambient temperature was lower during experiment 1 – compare figure B1.1 with figures B3.1-B5.1, and the solar radiation was also lower – compare figure B1.13-14 with figures B3.13-14-B5.13-14.

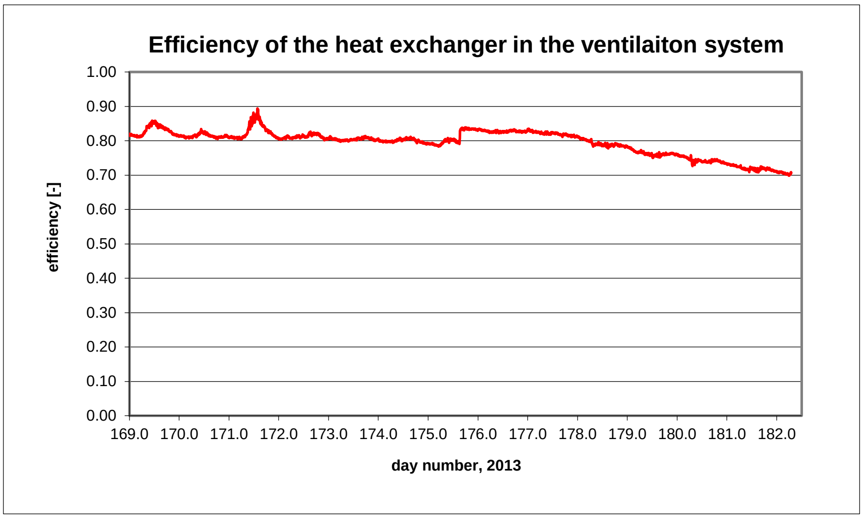

Figure 6.17. Efficiency of the heat recovery unit in the mechanical ventilation system during experiment 1.

Based on the above, it may be concluded that mechanical ventilation with heat recovery should be equipped with a bypass for summer operation or should be combined with natural ventilation so that mechanical ventilation is only applied during the heating season, while natural ventilation is utilized during the rest of the year. Furthermore, this will save electricity to the fans. Another way of dealing with the missing bypass is to stop the inlet fan so that the ventilation system functions as exhaust ventilation during the off-heating season. This will save half the electricity to the fans and the inlet temperature to the house will be the ambient temperature. However, as the ventilation system is no longer balanced, there is a need for fresh air intakes in all rooms - as for natural ventilation. Moreover, the ventilation system was running at its max meaning that the air change rate of the house is fixed, which is unlike natural ventilation where it is possible to create very high air change rates leading to a higher cooling capacity with ambient air. Therefore, even without a bypass it will be more difficult to prevent overheating with the mechanical ventilation system when compared to natural ventilation.

No experiment was conducted without heat recovery. However, the efficiency of the heat recovery unit dropped for unknown reasons to 60 % during experiment 11. During the first three days of this experiment, the ambient temperature during the night was somewhat lower than during experiment 1. This brings the room temperature down to around 20°C. However, during the last three days of the experiment, with similar weather conditions as during experiment 1 the room temperatures start to increase. The reason for this is seen in figures B1.14 and B.11.14. The max solar radiation on the south façade was up to 650 W/m² during experiment 1 while it was up to just below 900 W/m² during experiment 11.

Table 6.2 and figure 6.6 show that too low temperatures occurred in the building during experiment 11. The reason for this is shown in figure 6.18. Due to a low night-time ambient temperature and the rather low efficiency of the heat exchanger, the temperature of the fresh air to the house is one night below 15°C, but stays otherwise in the range of 16-21°C with is often too low in order to maintain the rooms at a comfortable temperature level. Heating would have been needed in order to obtain comfortable room temperatures. However, mid-September is too soon to start heating in a low energy house in Denmark.

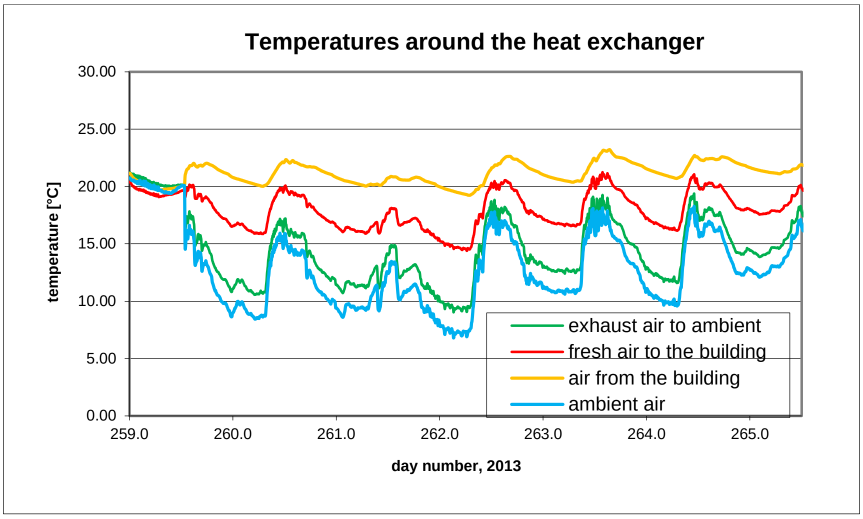

Figure 6.18. Temperatures to and from the heat recovery unit in the mechanical ventilation system during experiment 11.

When applying the dilution equation, the effective air change rates within the parents' room and the children's room have been calculated using the increase and decrease of the CO_2 concentration of these rooms from figure B1.3. The result is shown in table 6.3. Based on the air-flows from table 2.3 and the fact that the volume of the parents' room and children's room is 27.1 and 28.8 m^3, respectively, the air change should be 1.49 h^{-1} in the parents' room and 1.04 h^{-1} in the children's room. The values in table 6.3 are not that far away from this, except for the parents' room during CO_2 emission. The reason for this difference has, however, not been investigated here, but could be explained with a high uncertainty when using the dilution equation during CO_2 emission.

Day no.	Parents' room		Children's room	
	CO_2 emission effective h^{-1}	CO_2 decay effective h^{-1}	CO_2 emission effective h^{-1}	CO_2 decay effective h^{-1}
179	1.09	1.4	0.92	0.9
180	1.11	1.4	0.92	0.9
181	1.05	1.4	1.02	0.9
182	1.08	1.4	1.02	0.9

Table 6.3. Effective air change rates in the parents' room and the children's room during experiment 1.

6.1.3.5 Conclusions on room temperatures

The studies show that the different control strategies for natural ventilation performs almost equally well when it comes to preventing overheating in the conducted experiments. This is the case in for EFHlab, both as a one-storey and a two- storey building.

Although several of the experiments were conducted under very warm weather conditions, it was possible to maintain the max temperature in the house as low as up to 4 K above the ambient temperature during these periods. Even though the max ambient temperature was at or above the comfort level in all three classes of EN 15251 for mechanically ventilated buildings, the max temperature in the house was within or just above comfort class III when applying the comfort classes from EN 15251 for naturally ventilated buildings.

In the study the mechanical ventilation system was less able to prevent overheating in the house than natural ventilation, because there was no bypass for the recovery unit and because the fixed "low" volume flow rate (lower than possible to achieve with natural ventilation). However, no experiments were conducted without heat recovery in the balanced mechanical ventilation system.

The experiments showed that it is often difficult to obtain comfortable temperatures all over the house and at the same time keep the CO_2 concentration in the bedrooms low during the nights. Only temperature control will lead to high CO_2 concentrations in the house, also with open bedroom doors. On the other hand, the CO_2 control often resulted in too low temperatures, especially in the aisle. Open bedroom doors decrease these difficulties as the CO_2 concentration is kept lower in the bedrooms, which lead to the roof windows being open for shorter periods during CO_2 control. It also leads to more CO_2 being ventilated out during temperature control.

The conclusions from the here conducted experiments are for EFHlab for the given weather conditions. The experience obtained from other houses under different weather conditions may differ considerably. However, the here obtained conclusions may be used as inspiration when designing the control of natural ventilation. Nevertheless, care should be taken with respect to the actual conditions.

6.1.4 CO_2 concentration

When analyzing figures B1.3-B11.3, it is seen that high CO_2 concentrations mainly occur in the parents' bedroom and the children's bedroom during the night. The CO_2 concentration in the two other bedrooms and on the first floor stays mainly within comfort class II or III expect for experiment 2 and the experiment with a one-storey building. However, this is dealt with under the analysis of the respective experiments.

Therefore, the following analysis will mainly deal with the CO_2 concentration in the parents' bedroom and the children's bedroom.

6.1.4.1 Mechanical ventilation

Figures B1.3 and B11.3 show that the concentration level is repeatable at identical conditions. On day 178 (figure B1.3), the CO_2 emission was adjusted to the correct level. In figure B11.3 there were two days with closed bedroom doors, two days with open doors and two days with the doors 114 mm ajar. The two days of identical door position show almost identical CO_2 levels. Based on this, it can be concluded that the experiments with regard to CO_2 concentration are repeatable (= the artificial persons (barrels) are emitting a constant flow rate of CO_2) meaning that differences in the CO_2 level during natural ventilation are due to the control strategy and not to fluctuations in the emission of CO_2.

Figures B1.3 and B11.3 show that the position of the bedroom doors has an effect on the CO_2 level in the two occupied bedrooms. With closed doors, the CO_2 level is outside comfort class III (1200 ppm) in the parents' room during the night while the comfort class is just fulfilled in the children's room. When opening the bedroom doors ajar (114 mm), the CO_2 concentration lowers from 1600/1100 to 1200/900 ppm (figure B11.3) for the parents' bedroom and the children's bedroom, respectively – i.e. the parents' bedroom gets just within comfort class III while the children's bedroom gets just within comfort class II. Totally open doors bring the CO_2 concentration down to a mean of 900 ppm in the parents' bedroom and 800 ppm in the children's bedroom – i.e. both rooms now within comfort class II as was the aim. This will be further investigated in section 6.1.4.3. The opening of the bedroom doors only has little effect on the CO_2 concentration on the first floor (figure B11.3), but it increases the CO_2 concentration in the two unoccupied bedrooms (however within comfort class II), which had a CO_2 concentration close to ambient with closed bedroom doors.

6.1.4.2 Natural ventilation

In the following the CO_2 concentration during the experiments with natural ventilation will be analyzed – figures B2.3-4 until B10.3-4. Here, it is important to compare the measured CO_2 concentration with the state of the control of natural ventilation – i.e. the black line at the bottom of figures B.2.3-B.10.3 (and more clearly in figures B2.18-10.21). A value of 12 means that natural ventilation is allowed (windows and fresh air valves were open) while a value of 10 means that natural ventilation is prevented.

6.1.4.2.1 Experiment 2 with only temperature control – two-storey building

Figure B2.3 shows a different pattern with open bedroom doors than the other experiments with natural ventilation. This is because only temperature control and not CO_2 control was applied in experiment 2. It is seen that the windows in experiment 2 were closed during the night, except for day 186 where the windows did close in the middle of the night.

IC-Meters were not installed during experiment 2 so the max CO_2 concentration during day 183 and day 184 has not been measured. However, for day 192 during experiment 3 the output from the dilution equation was compared with the measurements from the IC-Meters. The air change rate found during the decay of CO_2 was used to calculate the max CO_2 concentration in the parents' bedroom and the children's bedroom. It was determined that the dilution equation predicted a max concentration that was 10-20 % lower than measured with the IC-Meters. Based on this, it was judged that the dilution equation could be used on experiment 2 to estimate the max concentration in the parents' bedroom and the children's bedroom for day 183 and 184. The result was:

	day 183	day 184
Parents' bedroom	4,800 ppm	6,200 ppm
Children's bedroom	2,700 ppm	2,700 ppm

The dilution equation shows consistency for the children's bedroom, but a larger deviation for the parents' bedroom.

During the nights in experiment 2 the windows were mostly closed. Day 183-184 show very large differences between the two occupied bedrooms and the rest of the house although the CO_2 concentration by the end of the night gets outside comfort class II on the first floor. With open bedroom doors, the CO_2 concentration during day 185-188 is very similar for all rooms. Thus, the experiment with open doors shows a decrease in the CO_2 concentration of the occupied rooms, when the rest of the house acts as a buffer and shows, therefore, the infiltration (air change rate) of the house as a whole.

The dilution equation calculated an air change rate of the two occupied bedrooms of 0,32 h^{-1} (parents' room) and 0,28 h^{-1} with closed bedroom doors, - i.e. below the recommended value of at least 0,5 h^{-1} and well below the air change rate during mechanical ventilation of 1.4 (parents' room) and 0.9 h^{-1} (children's room) found in table 6.3. Thus, this situation is not satisfactory. With open doors, the air change rate for the two occupied bedrooms was between 2.4 and 3.2 h^{-1} at open roof and aisle windows and thus better than during mechanical ventilation.

Due to the open bedroom doors, the concentration of CO_2 shows identical pattern in the entire house as seen in figure 6.19 where the CO_2 concentration of the bedrooms is 250-350 ppm higher during the night than the other rooms. When the CO_2 emission stops in the bedroom the CO_2 concentration in the bedrooms quickly decreases and shortly after it also decreases in the other two bedrooms. The CO_2 concentration on the first floor continues to increase as CO_2 emission had started here. When the windows open (dashed line), the CO_2 concentration quickly decreases with the same speed in all rooms. When using the dilution equation, the air change rate was calculated to 3.2 h^{-1}. The dilution equation didn't give stable results for day 186 and day 187, but for day 188 the air change rate was calculated to be 2.4 h^{-1}. It is judge that the difference in air change rate between day 185 and day 188 is mainly due to calculation uncertainty as the ambient temperature (figure B2.1) and wind conditions (figure B2.15) were very similar. However, the above shows that it is possible to obtain higher air change rates using natural ventilation than with the mechanical ventilation system, - at least in the here described experiments.

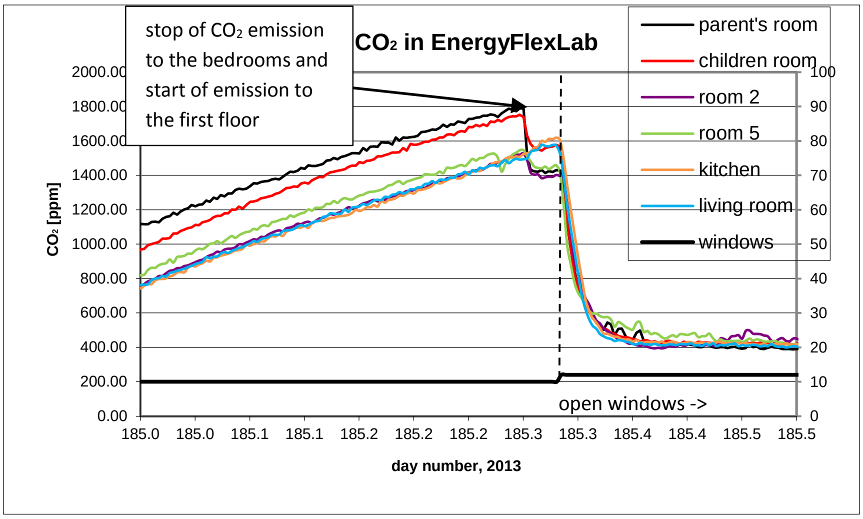

Figure 6.19. Close up of figure B2.3 showing the first 12 hour of day 185.

The CO_2 concentration was only close to comfort class II during the night on the first part of day 186. The rest of the days, the CO_2 concentration exceeded comfort class III during the night.

Based on the above findings it was decided to include control based on CO_2.

6.1.4.2.2 Experiment 3 with combined temperature and CO_2 control – two-storey building

During experiment 3 the windows in the roof and in the aisle were controlled both in terms of the temperature on the first floor and the CO_2 concentration in the parents' room. When comparing figure B3.3 with figure B2.3, it is seen that when including the CO_2 concentration in the control with open bedroom doors the CO_2 concentration was between 800 and 1000 ppm compared to the up to 1600 ppm without CO_2 control. It is also seen that the windows are now open during the night while closed during experiment 2. The CO_2 concentration with CO_2 control and closed bedroom doors is up to 5000 and 2800 ppm for the parents' room and the children's room, respectively, which is quite similar to the calculated values for experiment 2 of 4800/6200 and 2700 ppm, respectively.

A peak in the CO_2 concentration for all rooms are seen in the evening of days 189, 191 and 193. This is due to the windows being closed during the evening and only opened when the CO_2 concentration reaches the set point in the parents' bedroom. The CO_2 concentration lay with open bedroom doors, though, mainly within comfort class II and it only exceeds this for a very short period.

The CO_2 concentration with open bedroom doors is similar to mechanical ventilation with open bedroom doors as seen when comparing figure B3.3 with figure B11.3 (days 262-263)

During experiment 2, the CO_2 concentration of the other rooms was close to the concentration of the occupied bedrooms, when the bedroom doors were open. The other rooms were influenced when the bedroom doors were closed, but to a lower degree than when the bedroom doors were open. The latter illustrates the small air change rate with closed doors. Figure B3.3 shows a different pattern; here the CO_2 concentration in the other rooms is barely influenced by the CO_2 concentration in the occupied bedrooms with open doors. The CO_2 from the occupied bedrooms to the other rooms was ventilated away through the open windows. This is, however, not the case after the occupants have left the building at 8:00 am in the morning of day 191 and day 193, - see figure 6.20. The reason for this is that the windows were closed. The fact that the CO_2 concentration is almost stable during the two shown periods in figure 6.19 (the red ovals) illustrates that the house is very well sealed when all windows are closed. This is seen even more clearly in figure B4.3 for experiment 4 (days 197, 198 and 200).

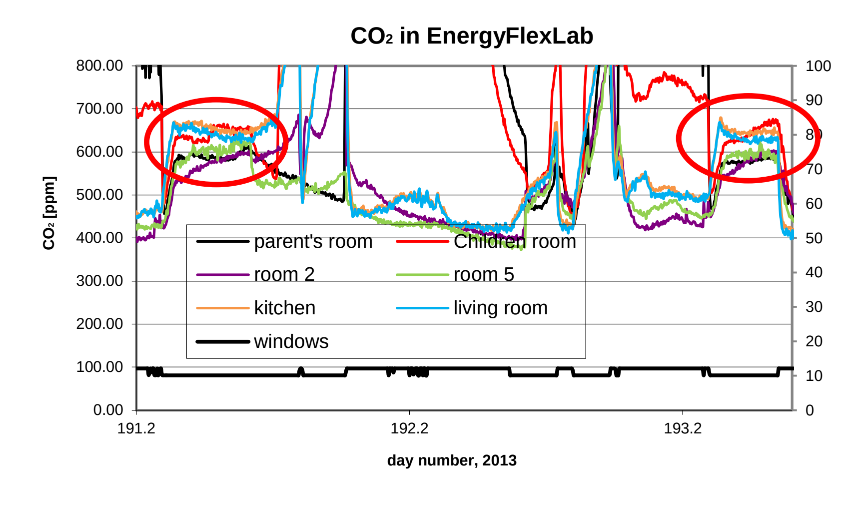

Figure 6.20. Close up of figure B3.3 showing two periods (red ovals) without natural ventilation during experiment 3.

The dilution equation only gave reasonable results for days 191, 192 and 194. With closed bedroom doors (day 192) the air change rate in the two bedrooms was calculated to 0.45 h^{-1} (parents' room) and 0.35 h^{-1}, i.e. considerably higher than the 0.32 and 0.28 h^{-1} found for experiment 2. However, the two experiments cannot be compared directly for the periods with closed bedroom doors as seen when comparing figure B2.3 with B3.3. The roof windows and aisle windows were both open and closed during the CO_2 decay on days 183 and 184 in figure B.2.3 while always open during day 192 in figure B3.3.

With open doors to the bedrooms, days 191 and 194 show an air change rate of between 9 and 10 h^{-1} for both occupied rooms, which is considerably higher than the one found for experiment 2. One reason for this is that, while the CO_2 level in experiment 2 was rather similar in all rooms (days 185-188 in figure B2.3), the CO_2 concentration in the non-occupied rooms in experiment 3 was often close to the ambient. The reason for this is that the roof windows and the aisle windows in experiment 3 were open all night, while these were mainly closed during experiment 2. Therefore, while the air change rate of 2.4-3.3 h^{-1} may be assumed to be the air change rate of the two occupied bedrooms and the whole house, the air change rate of between 9 and 10 h^{-1} is only for the two bed-rooms and not for the whole house.

6.1.4.2.3 Experiment 4 with same control as experiment 3 but with fresh air valves – two-storey building

The control during experiment 4 was identical to the control applied during experiment 3. The only difference was that the fresh air valves in the bedrooms now were operated in combination with the windows in the roof and in the aisle.

When comparing figure B.4.4 with figure B3.4, it is seen that the CO_2 concentration for days 197-198 with closed bedroom doors in B4.4 was identical to the CO_2 concentration in figure B3.4. The CO_2 concentration decreases slowly from day 199 until day 203. The reduction between these days is 750 ppm. The wind conditions were quite similar during the two experiments (figures B3.15 and B4.15) even though the house was warmer during experiment 4 than during experiment 3 (figures B3.1 and B4.1), especially during the last part of the experiment. This may explain the lower CO_2 concentration level by the end of experiment 4 as a higher temperature in the house creates a higher driving force for the natural ventilation and thereby a higher air flow rate. Another explanation is found when using the dilution equation. The air change rate during days 199 and 201-203 was calculated to between 0.3 (only day 203 for the children's room) and 0.45-0.55. Based on this, it seems that the fresh air valves have a small positive influence on the CO_2 concentration with closed bedroom doors for the conducted experiments.

The air change rate of the bedrooms with open bedroom doors was calculated to between 7 and 11 – i.e. equal to experiment 3. Thus, open bedroom doors it seem that the fresh air valves have no influence, at least not with the control strategy applied during experiment 3 and 4.

On the morning of day 200, the bedroom doors were opened at the same time as the barrels in the bedrooms were switched off and the barrels on the first floor were switched on in order to simulate that the family was waking up and opening the bedroom doors. Figure 6.21 shows a close up of days 199-201 in figure B4.4. It is seen that the decay of the CO_2 concentration is much more sudden on the morning of day 200 compared to days 199 and 201. The CO_2 concentration drops from 4700 to 1000 ppm in approx. 15 minutes. The dilution equation suggests an air change rate of 9-11 h^{-1} for the two occupied bedrooms (highest for the children's room), which not surprisingly is equal to the calculated air change rates for the two rooms with always open bedroom doors.

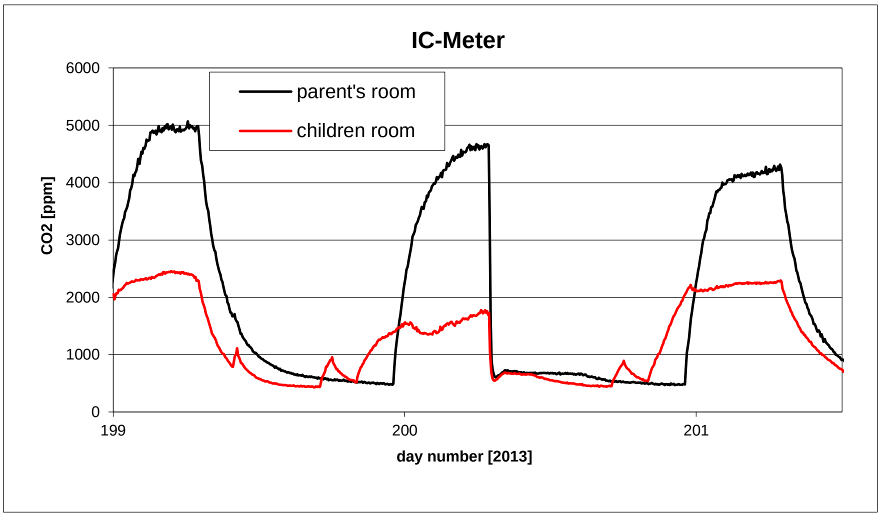

Figure 6.21. Close up of figure B4.4 showing the bedroom doors being opened in the morning of day 200 during experiment 4.

6.1.4.2.4 Experiment 5 and 10 with separate temperature and CO_2 control (priority to CO_2 control) – two-storey building

Figures B5.19-21 shows that during the first three days (days 205-207), the roof windows/fresh air valves (CO_2 control) were open during the night due to the priority of CO_2 control – figure B5.21, while the roof windows/aisle windows (temperature control) were open during the day - figure B5.20. During the rest of the period, only temperature control (roof windows/aisle windows) was active. The CO_2 control (only roof windows/fresh air valves) leads to a similar CO_2 concentration in the parents' bedroom during day 205 (figure B5.4) with closed bedroom doors as in experiment 3 and 4 (figures B3.4 and B4.4). However, the CO_2 concentration in the children's room was lower: 1800 ppm compared to 2300-2800 ppm in experiment 3 and 4. The dilution equation, however, suggests an air change rate of 0.33 and 0.35 h^{-1} for the parents' room and the children's room, respectively, which is similar to experiment 3 but lower than the air change rate in experiment 4.

During days 206 and 207 the windows in the two south facing bedrooms were opened in theft-protected mode – i.e. a small gap of 10 mm. This decreased the CO_2 in the parents' room on day 206, still with closed bedroom doors from 4300 ppm to up to 1500 ppm, while the CO_2 in the children's room was more or less unchanged, as the window here couldn't be opened. The open window makes the CO_2 concentration comparable with mechanical ventilation, also with closed bedroom doors (figure B1.3). The calculated air change rate for the parents' bedroom during day 206 is also comparable with mechanical ventilation: 1.2 h^{-1}, while the air change rate of the children's room of course remained low: 0.29 h^{-1}. As expected opening of a window has a positive effect on the air change rate during natural ventilation with closed bedroom doors.

However, this is not seen during day 207 still with open windows, but now also with open bedroom doors. Here, the CO_2 concentration in the parents' room drops only to around 1000 ppm compared to the around 800 ppm achieved during days 208-210 (figure B5.4). The reason for this is seen in figures B5.19-21: during the night of day 207, the natural ventilation was CO_2 controlled while it was temperature controlled during the following days. The higher CO_2 concentration is, therefore, due to the smaller area of the fresh air valves and theft-protected open windows compared to the area of the windows in the aisle. The dilution equation suggests an air change rate of 5 and 6 h^{-1} (parents' room lowest) during day 207, but 8-9 h^{-1} during the following days. The latter is comparable with experiment 3 and 4, also with open bedroom doors, but not open windows. However, even if the air change rate is lower during CO_2 control (day 207), it is almost sufficient to keep the CO_2 concentration within comfort class III and close to comfort class II.

Although the bedroom doors were open, the CO_2 concentration in the children's room on day 207 was slightly higher than during the following days. The reason is the higher CO_2 concentration in the parents, room, which lead to a higher concentration in the whole house (figure B5.3) combined with a lower air change rate as explained above.

The test setup in experiment 10 was identical to experiment 5: the same control strategy and a two-story building. During days 248-256 the bedroom doors were open (the CO_2 cylinder ran empty on day 249 and it was not replaced until day 252), while the bedroom doors were ajar with a 114 mm gap during days 257-259 – figures B10.3-4. Due to the lower ambient temperature (compare figure B10.1 with B5.1), the natural ventilation were mainly CO_2 controlled – see figures B10.19-21. This means that the roof window and fresh air valves didn't open before a while after the barrel had started to emit CO_2 in the parents' bedroom. This leads to a high CO_2 concentration at the start of the bedtime (except for day 248 where temperature control was in operation at bedtime) – 1100-1600 ppm after which the concentration fell to 900-1000 ppm for the parents' bedroom and 700-900 ppm for the children's bedroom. No significant difference is observed for the CO_2 concentration by the end of the night with the doors fully open or 114 mm ajar, but the CO_2 concentration reaches a higher level in the bedrooms before the roof window and the fresh air valves open in the evening with the bedroom doors 114 mm ajar compared to fully open.

6.1.4.2.5 Experiment 6-8 with combined temperature and CO_2 control – one-story building

During experiment 6-8, the first floor was sealed off from the ground floor in order to create the situation of a one-storey house. Only the ground floor is of interest in the following, so measured values on the first floor should be disregarded in the following even though the time schedule in table 3.1 was still in force – also for the first floor. The control of the natural ventilation (aisle windows and fresh air valves) was a combination of temperature and CO_2 without priority for neither of them. The set points were the temperature and the CO_2 concentration in the parents' room as this was the most stressed room. Again, the aim of the control was comfort class I for the room temperature and comfort class II for the CO_2.

In experiment 6 (figures B6.3-4), the bedroom doors were either open or closed.

In experiment 7 (figures B7.3-4) the bedroom doors were either open or closed but the windows in the south facing bedrooms were open in theft-protected mode.

In experiment 8 (figures B8.3-4), the bedroom doors were either fully open, 114 mm ajar or 55 mm ajar. During the last day of the experiment, the windows in the south facing bedrooms were open in theft-protected mode.

When comparing figures B6.3-B8.3 with B3.3-B5.3 it is seen that with open bedroom doors or the bedroom doors ajar a higher CO_2 concentration is often obtained in the non-occupied rooms during the night than in experiment 3-5. The reason for this is that the ventilation in experiments 6-8 was more dependent on the wind condition than in experiments 3-5 where the driving force mainly were the buoyancy. The wind condition during experiment 6-8 where mainly low wind speed from a southern direction. Day 215 (figure B6.3) shows similar CO_2 concentration as during experiment 3-5. During day 215 the wind came from the east with a wind speed of between 3 and 6 m/s (figure B6.15) meaning that air was blown through the aisle from east to west. A southern wind direction will not lead to this effect. This is also seen when comparing days 218 and 219: lower CO_2 concentration during day 218 with easterly wind at a higher wind speed than during day 219 where the wind direction was from the south and at low speed during the main part of the night (figure B7.15). These conditions also let to a lower CO_2 concentration in the unoccupied bedrooms during day 218 (and day 215). The CO_2 level in the children's room is very high during day 219. It is believed that the southern wind resulted in CO_2 going from the parents' bedroom directly to the children's bedroom.

The above is supported by the results of calculations with the dilution equation. During day 215 the air change rate of the parents' room and the children's room was 3.5 and 3 h^{-1}, respectively, while during days 214, 216 and 217 it was between 0.7 and 1.1 h^{-1} for the two rooms. An air change rate of 0.7 – 3.5 h^{-1} is far less than obtained during experiment 3-5 where air change rates between 5 and 11 h^{-1} were calculated.

A lower CO_2 concentration in both occupied and unoccupied bedrooms at an eastern wind direction is also seen when comparing day 230 with days 229 and 231-232. During days 229 and 231, the wind was mainly from the south. However, during the night of day 232, the wind was mainly from the west and the wind speed was low. For this reason, day 232 shows a lower CO_2 concentration in all the rooms than days 229 and 231, but slightly higher than day 230. The wind speed increases during the night of day 230 which led to a continuous decrease of the CO_2 concentration in the parents' room.

Figure B8.3 shows that there is not much difference in the CO_2 concentration with the bedroom doors 55 mm and 114 mm ajar.

In tables 6.4-5 the range of the CO_2 concentration in experiments 3-5 is compared with experiments 6+8 and experiment 7 depending on the position of the bedroom doors and if the windows in the south facing bedrooms were open in theft-protected mode.

Table 6.4 shows that the CO_2 concentration in the parents' bedroom was 20-30 % higher during experiment 6 and 8 compared to experiment 3-5. Table 6.5 shows a more scattered picture for the children's room with an increase of between 0 and 50 %. The higher CO_2 concentration leads to the not surprising conclusion that it is easier to obtain higher air change rates in two-storey buildings than in one-storey buildings, as less buoyancy is present in the latter.

However, better ventilation can be obtained with external windows open ajar as seen in table 6.4 for experiment 7. With open bedroom doors there is not much difference with or without open windows (experiment 7 compared to experiments 6 and 8). However, with closed bedroom doors the effect is very clear: around 50 % lower CO_2 concentration compared to experiment 6 and 8, and around 40 % lower concentration compared to experiment 3-5. This is supported by the dilution equation which calculated air change rates during experiment 7 in the occupied bedrooms between 1.5-5 h^{-1} with open bedroom doors and 0.6-1.3 h^{-1} with closed bedroom doors. These values were 1-3.5 h^{-1} for experiment 6 with open bedroom doors and 0.4-0.6 h^{-1} with closed bedroom doors (for experiment 8, the dilution equation gave mainly odd results in that the obtained decay curve did not fit the measured decay).

The CO_2 concentration is strangely also reduced in the children's room when the windows in the south facing bedrooms are open even when the bedroom doors are closed – table 6.5. This must be due to a generally lower CO_2 concentration in the house.

Experiment	Position of the bedroom doors ppm			
	open	114 mm	55 mm	closed
3-5	700-1200	1000-1200		4300-5000
6 and 8	1200-1500	1200-1600	1600	5200-6000
7 (open south windows)	1200-1400			2300-3200

Table 6.4. CO_2 concentration in the parents' bedroom with either one or two storeys depending on the position of the bedroom doors and the windows in the south facing bedrooms.

Experiment	Position of the bedroom doors ppm			
	open	114 mm	55 mm	closed
3-5	600-800	800-1000		2000-2800
6 and 8	800-1200	1000	800-1100	2000-3000
7 (open south windows)	700-1000			1300-1400

Table 6.5. CO_2 concentration in the children's bedroom with either one or two storeys depending on the position of the bedroom doors and the windows in the south facing bedrooms.

6.1.4.2.6 Experiment 9 with combined temperature and CO_2 control with only the aisle windows – one-story building

Experiment 9 was identical to experiment 6-8 except for the fact that the fresh air valves in the bedrooms were sealed. This lead of course to a higher CO_2 concentration during periods with closed bedroom doors: 6500-7700 ppm (days 246-247 in figure B9.4) in the parents' bedroom compared to 5200-6000 ppm during experiments 6 and 8. For the children's room, the CO_2 concentration during experiment 9 was 3200-3400 ppm compared to 2000-3000 ppm during experiments 6 and 8. Thus, the fresh air valves have a noticeable effect on the CO_2 concentration in the bedrooms with closed door, but they are not sufficient to obtain a good air change rate.

The above is supported by calculations with the dilution equation as seen in tables 6.6-7.

Although calculations show a lower air change rate with open bedroom doors during experiment 9 (days 239-241 in figures B9.3-4) than during experiments 6 and 8 (tables 6.6-7), the CO_2 concentration (tables 6.7-8) is similar in the parents' room and slightly higher in the children's room. The same tendency is seen with the bedroom doors 114 mm ajar (days 234-238 in figures B9.3-4).

A special test was conducted during days 242-245. Here the bedroom doors to the two unoccupied bedrooms were closed while the doors to the occupied bedrooms were open. As seen in figure B9.3, this has only little effect on the CO_2 concentration in the parents' bedroom and the children's bedroom – if there is any effect it is a decrease in concentration even though an increase would have been expected. However, the decrease is so low that it is of no significance, and it may be a result of fluctuating wind conditions as seen in figure B9.15. The CO_2 concentration in the unoccupied bedrooms was much reduced. A possible conclusion of the test may be that the buffer effect of the rooms without CO_2 emission has only a small effect on the CO_2 concentration in the occupied rooms.

Experiment	Position of bedroom doors h^{-1}	
	Open	Closed
6 and 8	0.7-3.5	0.5-0.6
9	0.7-1.0	0.2-0.3

Table 6.6. Air change rate in the parents' bedroom depending on the position of the bedroom doors.

Experiment	Position of bedroom doors h^{-1}	
	Open	Closed
6 and 8	0.9-3.0	0.4-0.5
9	0.7-1.1	0.2-0.3

Table 6.7. Air change rate in the children's bedroom depending on the position of the bedroom doors.

Experiment	Position of bedroom doors ppm		
	Open	114 mm ajar	Closed
6 and 8	1200-1500	1200-1600	5200-6000
9	1000-1450	1400-1450	6500-7700

Table 6.7. CO_2 concentration in the parents' bedroom depending on the position of the bedroom doors.

Experiment	Position of bedroom doors ppm		
	Open	114 mm ajar	Closed
6 and 8	800-1200	1000	2000-3000
9	900-1450	1200-1250	3100-3200

Table 6.8. CO_2 concentration in the children's bedroom depending on the position of the bedroom doors.

A final experiment with open bedroom doors was conducted in the morning of day 241: the two doors in the aisle and the south facing bedroom windows were fully opened for one hour between 8:20 and 9:20 am. The effect on the temperatures has already been discussed in section 6.1.3.2.1 and shown in figure 6.14. Figure 6.22 shows a close up of figure B9.3 including the day with airing (day 241) and the two previous days. Figure 6.22 shows that the decay of the CO_2 on day 241 is faster than the two previous days: a CO_2 concentration of 400 is reached at 9:30 on day 241 while this concentration level is reached at 10:30 on day 239 and 12:00 on day 240. However, figure 6.23 shows that this was not because of the airing.

The period between the dashed lines in figure 6.23 is the period when the airing occurred. No sudden drop is seen when the airing started. In comparison, a small increase in the CO_2 level is seen, which is not seen for the two previous days. Except for the small increase in the CO_2 concentration, the decay seems to continue as if no airing had happen. Figure 6.24 shows that the wind condition was rather stable before, during and after the airing. Figure 6.14 shows a very sudden drop in the temperature level inside the house. However, this is not seen in the CO_2 concentration.

Figure 6.25 shows one reason for the faster decay during day 241 compared to days 239-240. The wind speed increases around 7:00 am on day 241 - when the CO_2 emission stops. This is also seen for day 239, but for day 239 there was an easterly wind direction during the decay, while it came from the southwest during day 241. The wind direction during day 240 was also from the southwest, but the wind speed was very low this day. This may explain the differences seen in the decay of the CO_2 concentration for these three days. It may also explain the difference in CO_2 concentration during the nights. A correlation between the CO_2 concentration, the wind speed and the wind direction has, however, not been established in the project.

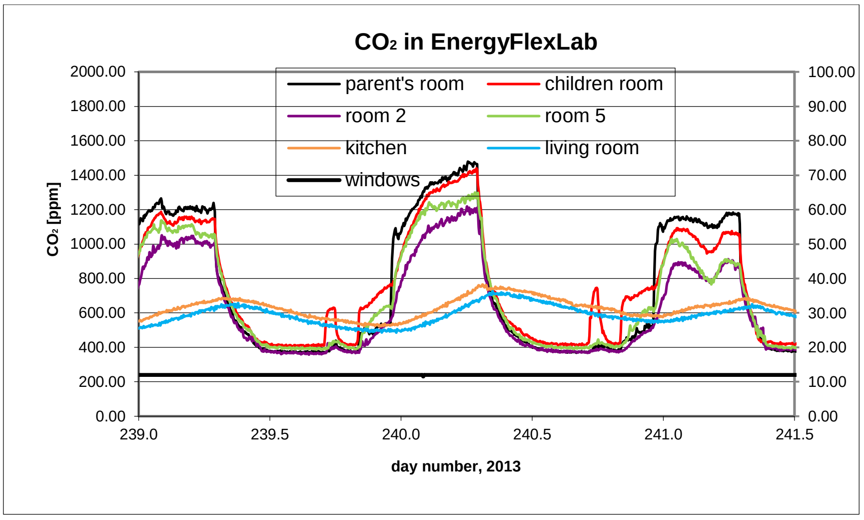

Figure 6.22. Close up of figure B9.3 showing the day with airing (day 241) and the two previous days.

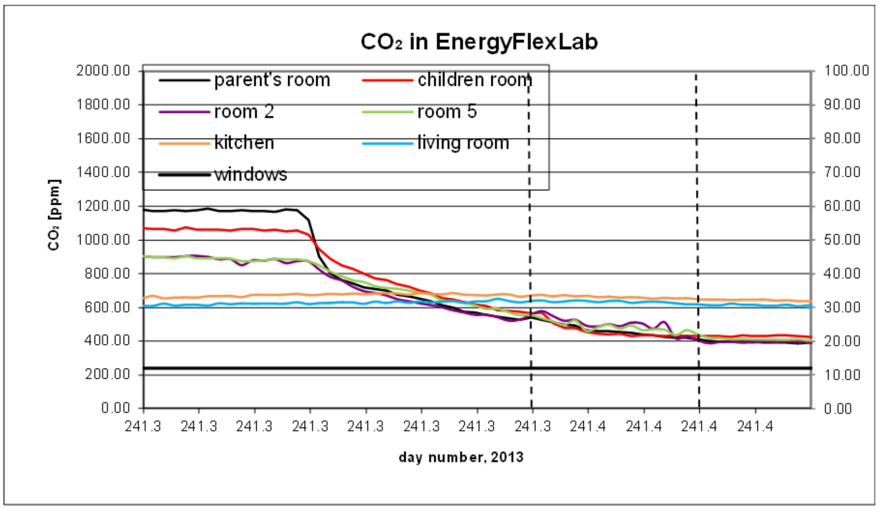

Figure 6.23. Close up of figure B9.3 - day 241 from 6:00 to 10:00 am. The time between the two dashed lines is the period when airing occurred.

Figure 6.22 shows a dip in the CO_2 concentration for all rooms at 4:00 am on day 241. An explanation could be the sudden increase in wind velocity, which occurred at the same time – see the arrow in figure 6.25.

The above shows that the air change rate for the one-storey house is very much influenced by the actual wind condition as the driving force is mainly wind and less buoyancy due to the low height of the building compared to the two-story house.

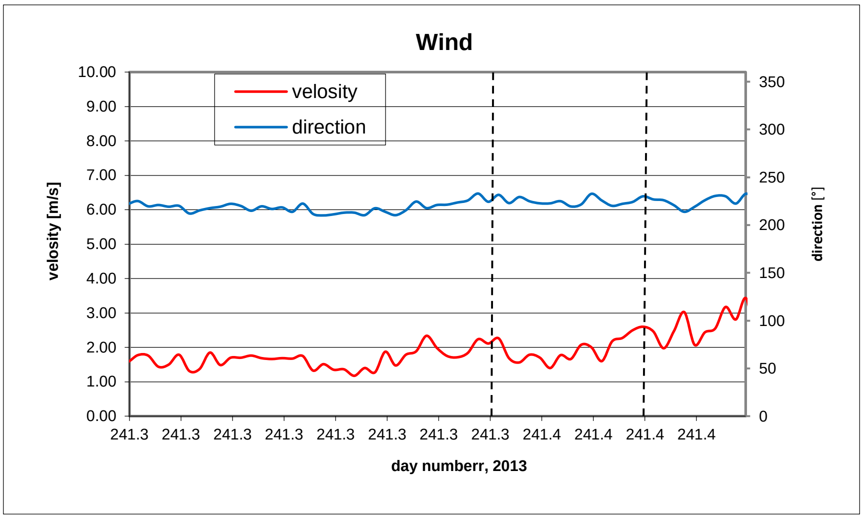

Figure 6.24. Close up of figure B9.15 showing the day with airing (day 241) during the period 6:00-10:00.

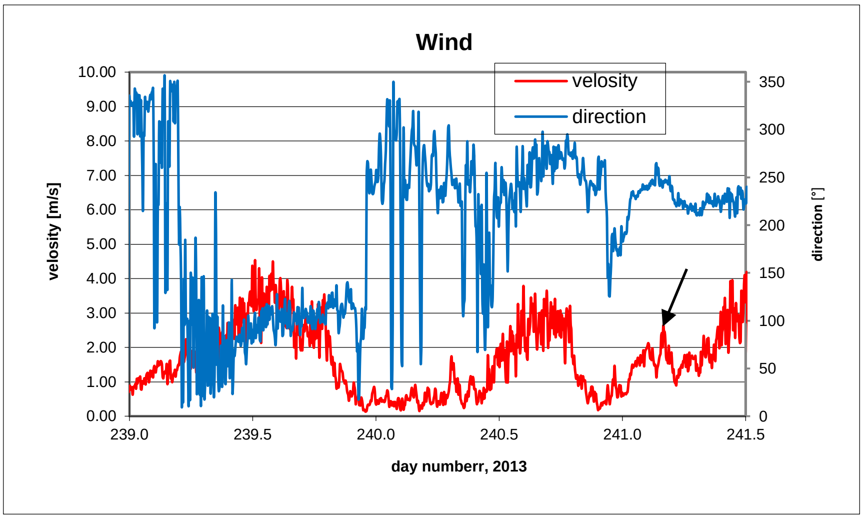

Figure 6.25. Close up of figure B9.15 showing the day with airing (day 241) and the two previous days.

6.1.4.3 Effect of open bedroom doors

As mentioned in the above sections, the opening of the bedroom doors has a large effect on the CO_2 concentration in the occupied bedrooms. This will be investigated further in this section. Tables 6.9-10 show the visually determined mean values for the following configurations:

- experiment 11: mechanical ventilation
- experiment 3-5: natural ventilation in a two-storey building with temperature and CO_2 control – with and without fresh air valves

- experiment 6+8: natural ventilation in a one-storey building with temperature and CO_2 control and fresh air valves
- experiment 9: natural ventilation in a one-storey building with temperature and CO_2 control and without fresh air valves

The CO_2 concentration is given for the parents' room and the children's bedroom depending on the opening degree of the bedroom doors: closed, 55 mm ajar, 114 mm ajar or fully open (500 mm). The values highlighted with yellow are estimated values as only one experiment with the bedroom doors 55 mm ajar was conducted for experiment 8. The highlighted values have been visually estimated based on the values found for the parents' bedroom during experiment 8 with the bedroom doors 55 mm ajar – see figures 6.26-27.

opening degree [mm]	Experiment ppm			
	11	3-5	6+8	9
0	1750	4650	4600	7100
55	1500	1600	1600	2000
114	1300	1100	1400	1425
500[1]	1150	950	1350	1225

Table 6.9. CO_2 concentration in the parents' bedroom depending on the position of the bedroom doors. [1] 500 means here fully open.

opening degree [mm]	Experiment ppm			
	11	3-5	6+8	9
0	1100	2400	2500	3150
55	1000	1100	900	1400
114	925	900	1000	1225
500[1]	825	700	900	1175

Table 6.10. CO_2 concentration in the children's bedroom depending on the position of the bedroom doors. [1] 500 means here fully open.

The values in tables 6.9-10 and figures 6.26-27 are rather uncertain. However, figures 6.26-27 show an interesting tendency. Closing the bedroom doors during the night is not a good idea for all cases: both for mechanical and natural ventilation and as well as for one-storey and two-storey naturally ventilated houses. On the other hand, there is really no difference, whether the bedroom doors are fully open or 114 mm ajar. It also seems that there is only little difference, whether the bedroom doors are 55 or 114 mm ajar.

Therefore, a more general conclusion is that bedroom doors should not be closed during the night, but a small opening of 50-100 mm is sufficient to reduce the CO_2 concentration considerably.

With the bedroom doors more than 100 mm ajar, there is only a small difference in the CO_2 concentration except for the children's room in the one-storey house without fresh air valves. In natural ventilated houses, it is important to have fresh air valves or other openings (e.g. a window ajar) in the bedrooms, when the bedroom doors are closed. With open bedroom doors, openings other places in the bedrooms are less important for keeping the CO_2 concentration down in the bedrooms.

If closed bedroom doors are preferred, it is better to live in a mechanically ventilated house than in a naturally ventilated house. Except if one likes to sleep with the window open all year round. However, this increases the heating demand of the house.

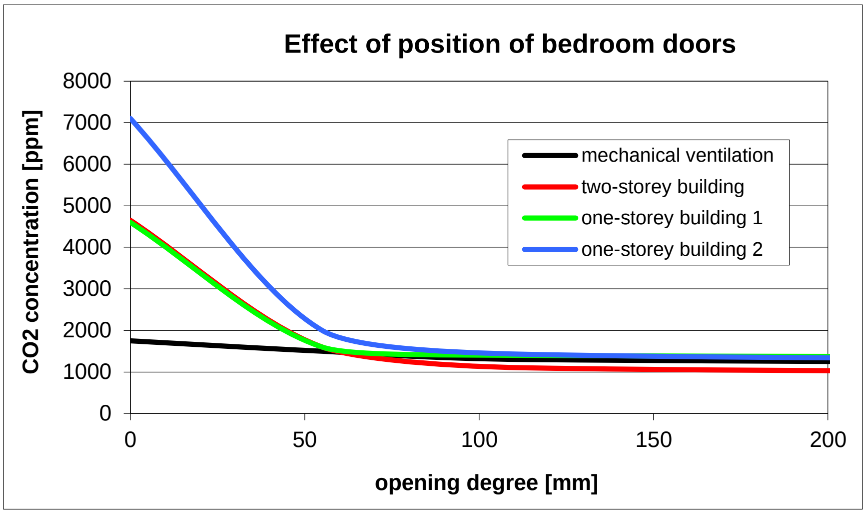

Figure 6.26. The effect of the position of the bedroom doors on the CO_2 concentration in the parents' bedroom in mechanically or naturally ventilated houses, one-storey or two-story naturally ventilated houses and one-storey houses with open fresh air valves in the bedrooms (one-storey building 1) or without fresh air valves in the bedrooms (one-storey building 2).

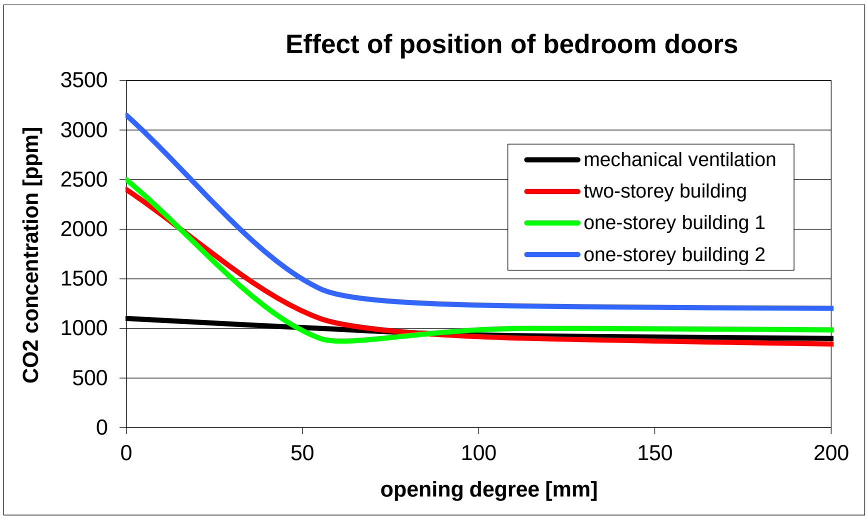

Figure 6.27. The effect of the position of the bedroom doors on the CO_2 concentration in the children's bedroom in mechanically or naturally ventilated houses, one-storey or two-storey naturally ventilated houses and one-storey houses with open fresh air valves in the bedrooms (one-storey building 1) or without fresh air valves in the bedrooms (one-storey building 2).

6.1.4.4 Conclusions on CO_2 concentration

The above studies show not surprisingly that the rooms mostly exposed to CO_2 were the occupied bedrooms. The CO_2 concentration may also be high in e.g. smaller living rooms exposed to many people. However, people tend to spend more time in the bedroom than in any other room of the house. The studies also show a higher CO_2 level than the level causing problems with the sleep quality in the studies carried out at the Technological University of Denmark – section 5.3.

Figures 6.26-27 summarize most of the findings regarding the bedrooms from the studies. However, it should be remembered that the roof windows and the aisle windows have been operated in order to reduce the CO_2 concentration:

- mechanical ventilation dimensioned according to today's standard results in higher CO_2 concentration with closed bedroom doors than the three comfort classes in EN 15251 in the two-person bedroom and just inside comfort class III in the bedroom occupied by one person

- open bedroom doors reduced the CO_2 concentration significantly for all ventilation strategies, including mechanical ventilation - down to comfort class III

- bedroom doors should, therefore, not be closed

- there was not much difference between having the bedroom doors fully open or having them 50-100 mm ajar

- the fresh air valves in the bedrooms had only little influence on the CO_2 concentration in the two-story building

- the fresh air valves in the bedrooms had a positive effect on the CO_2 concentration in the one-storey building when the bedroom doors were closed, but an insignificant effect when the bedroom doors were open or ajar

- the CO_2 concentration was lower in two-storey buildings than in one-storey buildings both with open and closed bedroom doors

- opening a window ajar had a positive influence on natural ventilation with closed bedroom doors, while it had only little effect with open bedroom doors

- the air change rate was more dependent on the wind conditions in a one-storey building than in a two-story building.

Based on the above it may be concluded for the EnergyFlexHouse and for the examined-control strategies that:

- bedroom doors should be left open or ajar during the night

- it is possible to obtain reasonable CO_2 concentrations with both balanced mechanical ventilation and natural ventilation. However, more care should be taken when designing natural ventilation

- the air change rate was higher and less influenced by the wind conditions in the two-story house than in the one-store house due to the higher buoyance effect in the former

For the experiments conducted in EFHlab, the conclusions are for the given control strategies and weather conditions. The experience from other houses with different control strategies may differ considerably. However, the here obtained conclusions may be used as inspiration when designing the control of natural ventilation. Nevertheless, care should be taken with respect to the actual conditions.

7 Measurements in real homes

Results from measurements taken in occupied homes are described in this chapter. The purpose of the measurements was twofold:

- to investigate if the indoor climate and especially the CO_2 concentrations found in EnergyFlexHouseLab are comparable with the indoor climate in occupied homes and if overheating occurs in existing none low-energy homes
- to test how well-suited IC-Metres are for measuring in occupied homes.

For the latter, the purpose was especially to investigate how easy it is for unexperienced persons to connect the IC-Metres to the WIFI in the homes.

Measurements have been carried out in six homes, - five of them being naturally ventilated while the last home has exhaust ventilation from the bathroom. It was attempted to include a few more homes in the investigation, but the connection of the IC-Metres to the WIFI failed in these homes.

7.1 Weather conditions during the first half year of 2014

The weather conditions were not measured at the location of the private homes. However, in order to give an impression of the likely weather conditions the weather conditions measured at EFHlab during February-August 2014 are shown in Appendix D. Four of the homes are situated within a distance of 20 km from EFHlab, one (Home 2) within a distance of 30 km, and the last (Home 6) is situated within 40 km from EFHlab.

7.2 Description of the homes and findings

The aim was to carry out measurements in the occupied bedrooms and in the living room. This was possible in five of the six homes. In addition an IC-Meter was shortly placed in a bathroom in Home 1 in order to compare with the measured humidity level in the master bathroom of EFHlab.

The measuring campaign started in February 2014 and lasted until August 2014 in order to obtain measurements for both the heating season and the off-heating season. However, the measurements in February were only obtained for Home 1 and 2. The measuring was stopped before August in several homes – for Home 5 e.g. due to vacating.

The obtained measurements are shown in Appendix C. Please notice that the scale on the y-axis on the graphs showing the CO_2 concentration varies from graph to graph.

7.2.1 Home 1

Home 1 is a terraced house with three floors: basement 52 m², ground floor 52 m² and first floor 40 m² - all areas are gross area. The home was occupied by three adults.

The home was built in 1952, but it has been energy renovated with e.g. new triple layered low energy windows and external doors on the ground floor and the first floor. The new windows and doors have well-functioning sealing strips.

The IC-Metres were located in the one-person and two-person bedrooms on the first floor, in the living room at the ground floor and in the bathroom in the basement.

The person in the one-person bedroom likes to sleep with the bedroom door and window closed. The persons in the two-person bedroom sleep with the bedroom door ajar and with closed window during the winter, while sleeping with the window ajar during off-heating season.

7.2.1.1 Relative humidity

The relative humidity stayed between 25 and 77 % in all rooms, except for the bathroom. The 77 % was a single peak. Otherwise, the relative humidity stayed below 70 %

and mainly below 60 %, which is similar to the conditions measured in EFHlab and mainly within comfort class II.

The bathroom in the basement is only used by one person for showerings (the two other occupants use the bathroom on the first floor). However, the bathroom in the basement is also used for drying laundry 3-4 times a week.

The relative humidity didn't get above 90 % and the humidity level quickly dropped after the shower as in EFHlab. This is due to a small exhaust fan in the bathroom, which is switched on after showering and when drying laundry.

7.2.1.2 Room temperatures

The room temperature suddenly dropped very much and the relative humidity increased suddenly in the rooms during February (figures C1.2-3), but these was quickly back up and down again, respectively. The calibration of the IC-Metres was tested at these occasions by placing the sensors outside for a short while to test if the measured CO_2 concentration went down to the background level of around 400 ppm and to test how fast the temperature and relative humidity measurements reacted on sudden changes - see section 7.3.

During the heating season, the room temperatures stayed between 18 and 27°C. The temperatures were highest in the one-person bedroom, as the person here likes a warm room, and lowest in the two-person bedroom due to long periods of airing (with closed bedroom door) during the day. The daily fluctuation in the room temperatures was otherwise due to night setback.

From mid-May, the room temperatures started to follow the development of the mean daily ambient temperature on a long-term basis and the daily variation on a one-day term.

Figures C1.11, C1.14, C1.17 and C1.20 show that overheating did occur in the home, - above 30°C during July (figure C1.17). It also occurred in the two-person bedroom, although the window was left ajar all day. All the windows in the two bedrooms and the living room have are facing south. The measured room temperatures are quite similar to the findings in EFHlab. The weather conditions during July were very similar to the weather conditions during experiment 5-7 in EFHlab - compare figures B5.13-B7.13 with D6.1 and B5.16-B7.16 with D6.2.

7.2.1.3 CO_2 concentration

The CO_2 concentration in the one-person bedroom was mainly between 2500 and 3500 ppm during the night due to the closed bedroom door and window. This is in the same order of magnitude as the concentration level found for the children's room with closed bedroom door in EFHlab.

The CO_2 concentration in the two-person bedroom stayed mainly between 1500 and 2500 ppm during the heating season – February–mid-May. Lower concentrations during this period were due to only one person sleeping in the bedroom, and the high concentrations, e.g. 5000 ppm on day 65 (figure C1.4), is believed to have been caused by the bedroom door accidentally being nearly completely closed. The CO_2 concentration was higher than measured in the parents' room in EFHlab with the bedroom door ajar. The reason for this is believed to be that the aisle in EFHlab was better ventilated than in Home 1. This indicates that automatically controlled ventilation openings in the aisle may enhance the natural ventilation.

During the off-heating season (from day 142) with the window ajar, the CO_2 concentration in the two-person bedroom was mostly reduced to between 1000 and 1500 ppm. This is comparable with the measurements in EFHlab.

The CO_2 concentration in the living room stays mainly below 1500 ppm. Higher concentrations were due to more than three people occupying the room, e.g. the nearly 4000 ppm measured on day 61 (figure 1.4) was due to a birthday party with around 12 people. The much lower CO_2 concentration in EFHlab is due to the very large volume of the combined living room and kitchen.

7.2.2 Home 2

Home 2 is a one-storey terraced house with a gross floor area of 60 m². The house consists of a living room/kitchen, two bedrooms, a bathroom and an aisle. The windows in the living room and the parents' room are facing west, while the window in the the children's bedroom are facing east. The house was occupied by two adults, two children (age 5 and 8) and a large dog.

The building was built in 1974. The windows are large with two layers of traditional glazing. Especially the terrace door is somewhat leaky. There is exhaust ventilation from the bathroom.

The IC-Metres were located in the two bedrooms and in the living room.

The windows in the bedrooms were closed during the heating season and open during the off-heating season.

7.2.2.1 Relative humidity

The relative humidity stayed between 17 and 71 % in all rooms. The 71 % was a peak. Otherwise, the relative humidity stayed below 60 %, which is lower than the relative humidity measured in EFHlab.

7.2.2.2 Room temperatures

During the heating season, the temperatures in the rooms were between 22 and 27°C, except during airing where the temperature dropped down to 17°C at the lowest in the parents' bedroom. During three days in April the temperature went above 30°C in the parents' room in the afternoon and above 27°C in the living room (figure C2.8). This was because of the large windows facing west and clear sky conditions during these days (figure D3.2) with a max ambient temperature close to 20°C (figure D3.1).

In May, the temperature in the parents' room went up to 35°C (figure C2.11), maybe due to a closed bedroom door, while the temperature stayed below 28°C in July. The same applied to the eastern facing children's room, - maybe due to cross ventilation of the apartment. During July, the temperature in the living room went up to 32°C when ambient temperatures up to 28°C were observed. Thus, there are overheating problems in the house. During the off-heating season, the temperatures of the rooms followed the development of the mean daily ambient temperature on a long-term basis and the daily variation on a one-day term.

7.2.2.3 CO_2 concentration

The CO_2 concentrations were high during the first days of measurements (figure C2.1) – above 3000 ppm in the bedrooms. Normally the occupants slept with closed bedroom doors. However, the occupants started to sleep with open bedroom doors after seeing the measurements. Thus, the CO_2 concentration fell to up to 2200 ppm in the parents' room and up to around 1700 ppm in the children's bedroom and the living room. The CO_2 concentration stayed mainly here for the rest of the heating season, except for some nights with above 3000 ppm in the parents' bedroom, which is believed to be due to the old custom of closing the bedroom door. From April (figure C2.7), the CO_2 concentrations were between 1000 and 2000 ppm during occupation (except for the end of May/start of June where the CO_2 concentration again went up to between 2000-3000 ppm). The CO_2 concentration were similar in the three rooms – again possibly due to cross ventilation.

The CO_2 concentration in the children's room with open bedroom doors were quite similar to the findings during experiment 6-9 in EFHlab, but somewhat higher in the parents' room than in EFHlab. However, the CO_2 concentration was lower (halved) with closed bedroom doors compared to the experiments in EFHlab. It is assessed that the latter is caused by the exhaust ventilation of the bathroom. The two bedrooms have each a door directly to the bathroom, while the living room/kitchen hasn't.

7.2.3 Home 3

Home 3 is an apartment with a gross floor area of 76 m². The apartment is situated on the first floor of a multifamily building. The apartment consists of a living room, a bedroom, a small room, a kitchen, a bathroom and an aisle. The windows in the living room and the bedroom are facing southeast. The apartment was occupied by two adults.

The building was built in 1906. The windows have two layers of traditional glazing. The apartment is somewhat leaky. The window in the bathroom is left ajar all night long.

The IC-Metres were located in the bedroom and in the living room.

The window in the bedroom was closed during the heating season, while open during the off heating season. The bedroom door was always open.

7.2.3.1 Relative humidity

The relative humidity stayed between 18 and 64 %. However, it was mainly below 50-60 % in both rooms. This is lower than the relative humidity measured in EFHlab.

7.2.3.2 Room temperatures

During the heating season the temperature in the bedroom was between 22 and 25°C, except during airing where the temperature dropped up to 7 K in the bedroom. The temperature in the living room was generally around 1 K higher than the temperature in the bedroom.

In mid-April, the room temperatures started (figure C3.5) to follow the development of the mean daily ambient temperature on a long-term basis and the daily variation on a one-day term. The highest temperature of 30°C was observed during the second half of July (figure C3.14) where the ambient air temperature (figure D6.1) reached 28°C during daytime.

7.2.3.3 CO_2 concentration

The CO_2 concentration of the two rooms is very similar due to the open bedroom door and the small size of the apartment. The CO_2 concentration stays mainly below 2000 ppm, which is slightly higher than the concentration level measured in EFHlab with the bedroom doors ajar. This is because the ventilation of the apartment was mainly infiltration via cracks and the open bathroom window during the night.

The CO_2 concentration was very low during the last half of July. This is supposed to be due to the warm weather, which led to the windows being more open.

7.2.4 Home 4

Home 4 is a detached one-storey single-family house with full basement and a gross floor area of 119 m² excl. basement. The house consists of a living room, three bedrooms, a kitchen, two bathroom and an aisle. The living room has large windows, which are facing approx. south and west. The occupied bedroom has a window facing approx. east. The house was occupied by two adults.

The house was built 1947, while the living room is an extension to the house from 1968. The windows have two layers of energy glazing and they are 10-15 years old. All the windows, except the ones in the living room, have built-in fresh air valves.

The IC-Metres were placed in the occupied bedroom and the living room.

The window in the bedroom was closed during the heating season and open during the off-heating season. The bedroom door was always open.

7.2.4.1 Relative humidity

The relative humidity stayed between 25 and 70 % in both rooms. Except for shorter periods, the relative humidity was below 60 %, which is lower than the relative humidity measured in EFHlab.

7.2.4.2 Room temperatures

The temperature of the occupied bedroom was very stable around 20°C during the heating season (figures C4.2 and C4.5), except during unoccupied periods (figure C4.5 when the CO_2 concentration dropped to around 400 ppm). The temperature in the living room was very fluctuating during the heating season. This is caused by the floor heating system and a wood stove. The forward temperature to the floor heating system was maintained low so that the floor heating system only could heat the living room to 17-19°C, depending on the ambient temperature. The stove was used to boost the room temperature when the living room was occupied, which often led to temperatures above 25°C.

During the off-heating season the temperature in the bedroom followed the development of the mean daily ambient temperature. So did the temperature in the living room, but on top of that it had larger daily fluctuations. The latter is believed to be caused by the large windows in the living room, which let in much solar radiation and also make the room temperature more exposed to the daily fluctuations of the ambient temperature.

Overheating occurred, especially during July and most profoundly in the living room. As the temperature here peaked around 18:00, it is believe that the large windows facing west were the cause of the overheating.

7.2.4.3 CO_2 concentration

The two high peaks of 2700 and 3500 ppm in the CO_2 concentration level in the bedroom during March (figure C4.1) were caused by the occupant testing how high the concentration would rise with closed bedroom door. The CO_2 concentration during these two nights is much lower than obtained with closed bedroom doors in EFFlab (experiment 6-9). The reason for the lower CO_2 concentration in home 4 is believed to be a much higher infiltration flow rate than in EFHlab.

With open bedroom door, which is the normal case, the peak in the CO_2 concentration stayed below 2000 ppm and normally up to 1800 ppm. This is the same CO_2 concentration level as obtained in the parents' bedroom in EFHlab with balanced mechanical ventilation and closed bedroom door. However, it is around 50 % higher than the concentration level obtained in the parents' bedroom in EFHlab during experiment 6-9 with open bedroom door. However, just as often the CO_2 concentration in the bedroom was as low as the CO_2 concentration in EFHlab with open doors. The two levels in CO_2 concentration could be caused by the wind conditions, but no correlation has been established. Moreover, it is not obvious when comparing the CO_2 concentration with the wind conditions in Appendix D.

7.2.5 Home 5

Home 5 is an apartment with a gross floor area of 61 m². The apartment is situated on the second (and top) floor of a multifamily building. The apartment consists of a living room, a bedroom, a kitchen, a bathroom and an aisle. The window in the living room faces south while the window in the bedroom is facing north. The apartment was occupied by two adults.

The building was built in 1931. The windows were replaced with two layered energy glazed windows in 2008.

The IC-Metres were placed in the bedroom and the living room.

The window and the fresh air valve in the bedroom were closed during the heating season and open during the off-heating season.

Only measurements from March-June are available due to vacating in June.

7.2.5.1 Relative humidity

The relative humidity stayed between 25 and 62 % in both rooms, which is lower than the relative humidity measured in EFHlab.

7.2.5.2 Room temperatures

During the heating season the temperature in the bedroom was between 22 and 24°C except during airing where the temperature dropped 1-3 K. A lower temperature is also observed during the winter vacation days 69-84 (figure C5.2). The temperature in the living room was generally around 3 K lower than the temperature in the bedroom.

From the end of April (figure C5.5), the room temperatures dropped to around 20°C in both rooms. In mid-May, the room temperatures starts to depend on the development of the mean daily ambient temperature on a long-term basis and the daily variation on a one-day term. The highest temperature during May-June is 25°C. Thus, no real overheating is seen, which most probably is because there are no measurements from July where overheating occurred in the four former homes. When comparing May-June with the measurements from the previous four homes, one gets the indication of overheating in this apartment as well.

7.2.5.3 CO_2 concentration

The CO_2 concentration started high on the first day of February (figure C5.1) – 3700 ppm (about half of what was measured in EFHlab). This was due to a closed bedroom door. However, when the occupants discovered the high CO_2 concentration, they started to sleep with the bedroom door ajar.

The CO_2 concentrations of the two rooms are very similar due to the open bedroom door and the small size of the apartment. The CO_2 concentration stayed mainly below 2500 ppm during the heating season. The higher peaks can mostly be explained by visitors. The 2500 ppm is higher than the concentration level measured in EFHlab with the bedroom door ajar. This is because the ventilation of the apartment was mainly infiltration via cracks and an open hatch in the kitchen.

The start of the opening of the window and the fresh air valve in the bedroom is not known. However, a good guess would be day 141 (figure C5.7), where the CO_2 concentration started to be lower (1000-1500 ppm), but also more fluctuating. This indicates that opening of the window and fresh air valve (it is supposed that the opening of the window is the main reason) has a big and reducing influence on the CO_2 level. The fluctuations indicate that the ventilation becomes more wind dependent. The peaks in CO_2 concentration during the summer (figure C5.10) are in the same order of magnitude as the level measured during experiments 6-9 with EFHlab as a one-storey house. Though, it seems to be more influenced by the wind. This is possible due to the more exposed location on the second floor.

7.2.6 Home 6

Home 6 is a detached one-storey single family house with full basement and a gross floor area of 126 m² excl. basement. The house consists of a living room, three bedrooms, a kitchen, two bathrooms (+ one bathroom in the basement) and an aisle. The parents' bedroom and the living room have windows facing west-southwest. The house was occupied by two adults and two teenagers.

The house was built in 1986. The windows are original with three layers of glazing.

One IC-Meter was placed in the parents' bedroom as it was not possible to connect to the WIFI from other rooms. There are only measurements from March-April. It is not know why the measurements stopped on April 19, maybe due to the loss of connection to the WIFI.

The window in the parents' bedroom was closed during the heating season and open during the off-heating season. The door to the parents' bedroom was mainly ajar.

7.2.6.1 Relative humidity

The relative humidity stayed between 35 and 66 % in both rooms. This is similar to the conditions measured in EFHlab.

7.2.6.2 Room temperatures

The temperature of the occupied bedroom was very stable around 20°C during the heating season (figures C6.2 and C6.5), except during one unoccupied period (figure C6.4 - when the CO_2 concentration dropped to around 400 ppm).

7.2.6.3 CO_2 concentration

During the first ten days of measuring, the CO_2 concentration was between 1500 and 2500 ppm and after that the CO_2 concentration was between 1500 and 2000 ppm. The peaks of 2500 ppm are supposed to be due to a closed bedroom door during these given nights. The CO_2 concentration between 1500 and 2000 ppm is a bit higher than the level measured in EFHlab in the parents' bedroom with the bedroom ajar.

7.3 Experience with IC-Metres

Based on the installation of IC-Metres in Home 1 a detailed guideline on how to connect IC-Metres to WIFI was developed. The IC-Metres and the guideline were given to the occupants of the homes in order for themselves to install the IC-Metres. In a few cases, the installation went alright while others struggled with the installation. In this process, it is very important to know how to reset the IC-Meter when a connection trial fails.

Not all the intended homes could be equipped with IC-meters, and in Home 6 it was only possible to connect one IC-Metre. The problem is likely due to a too weak WIFI signal. However, this has not been investigated.

There are some falling outs of measurements in Appendix C – e.g. figures C1.7-9 and figures C4.1-3. These were not due to instability of the IC-Metres, but due do disconnection of the metres. When properly connected to the WIFI the IC-Meters seems very stable. However, the experience from Home 6 suggests that the data stream from the IC-metres should be checked at regular intervals.

No validation of the measurements from the IC-Metres have been performed. However, the auto calibration of the CO_2 measurements and how fast the sensors react to sudden changes were briefly investigated in Home 1 – figures C1.1-3:

- on day 34 the measured CO_2 concentration only went down to 510 ppm for the sensor in the two-person bedroom
- on day 36 the sensor in the two-person bedroom went down to 470 ppm while the sensor in the bath room went down to 360 ppm
- on day 54 the sensor in the living room went down to 270 ppm. This low CO_2 concentration is also seen on day 45-46 for this sensor

The measured CO_2 concentration should have been approx. 400 ppm. However, the lowest measured CO_2 concentration stabilizes around 400 ppm, as seen in e.g. C1.7. This is also the case for the IC-Metres in the other homes, as seen in the graphs for the CO_2 concentration. Thus, the IC-Meter seems to need some time to adjust to the correct min. CO_2 concentration.

The values of the temperature and rh sensors have not been validated, but they seem reasonable. The trials on days 34, 36 and 54 show that the large drop/increase in temperature/rh occurs within half an hour. However, the temperature/rh is back to room conditions within half an hour. Thus, the sensors are responding sufficiently fast in order to detect normally sudden changes in rooms.

Data can be downloaded via the homepage of IC-Meter, but only for 30 days back in time. For this reason, a prototype of a program that downloads values from a random numbers of IC-Metres with an arbitrary start and length of measuring period has been developed. The program will be further developed in future research programs utilizing IC-Metres for the measuring of the indoor climate in buildings.

7.4 Conclusion

The relative humidity measured in the bedrooms and living rooms is similar to or lower than the relative humidity measured in EFHlab. The relative humidity measured in a bathroom is also comparable to the measurements in EFHlab, - i.e. a very short peaks up to 90 % and then a fast drop down to a relative humidity level similar to that of the rest of the house.

The room temperatures during the summer are comparable to the temperatures measured in EFHlab. Max room temperatures between 27 and 35°C were measured proving that overheating also is a problem in existing houses non low-energy houses..

With closed doors and windows in the bedrooms, the CO_2 concentration was much lower than the level measured in EFHlab. This is because EFHlab is much more air tight than the existing homes. One exception was the one-person bedroom in Home 1, where the CO_2 concentration was similar to that of EFHlab. The reason for this is that Home 1 has new airtight windows, and that the bedroom door has no gap between the door and the doorstep.

With open bedroom doors or the doors ajar, the CO_2 concentration was mainly somewhat higher than the concentration measured in EFHlab, which is because the CO_2 concentrations in the homes were not lowered by fresh air intake in the aisle as in EFHlab.

Open windows and bedroom doors or these ajar gave similar CO_2 concentrations as in EFHlab.

Based on the above it may be concluded, that the measured conditions in EFHlab were realistic.

IC-Metres seem applicable for measuring the indoor climate in private homes, but they are difficult to install by inexperienced persons.

8 Conclusion

Overheating and high CO_2 concentrations in bedrooms have been reported in low energy houses. Measurements in the present project show that these problems are also present in existing older homes. However, there is still a need for solving these problems in new low-energy houses.

The present report focuses on natural ventilation during the summer to overcome the above problems during the off-heating season. Experiments with different strategies for controlling natural ventilation have been examined and compared to mechanically balanced ventilation using the full-scale test facility EnergyFlexHouse at Danish Technological Institute.

As the effect of natural ventilation is very much dependent on the behaviour of the occupants, it is difficult to test many control strategies during a short period of time in real occupied houses. Therefore, it was chosen to use artificial persons in the form of barrels emitting controllable heat, humidity and CO_2. The tests showed that these "people" are very reliable and they lead to repeatable results. Thus, many different control strategies could be tested for both a one-storey and a two-storey house. Measurements in real homes showed that the findings in EnergyFlexLab are realistic.

The conclusions from the here conducted experiments are from EnergyFlexLab for the given control strategies and weather conditions. The experience gained from other houses under different control strategies may differ considerably. However, the here obtained conclusions may be used as inspiration when designing the control of natural ventilation. Nevertheless, care should be taken with respect to the actual conditions.

The measurements were conducted during the period June 25-September 22, 2013. This measuring period contained a period with quite warm weather conditions compared to Danish standards, - an ambient temperature of up to 28°C

There have been no problems with the level of relative humidity in the house during the tests. The relative humidity mainly stayed within EN15252 class II. Except for the master bathroom, the relative humidity of the different rooms in the house was quite similar indicating that the persons in the here described experiments only had little effect on the relative humidity in the rooms which they occupied. The master bathroom dried out quite fast after showering both with mechanical and natural ventilation.

The studies show that the different control strategies for natural ventilation perform almost equally well when it comes to preventing overheating in the conducted experiments. This goes for EFHlab both as a one-storey and a two-storey house.

Although several of the experiments were conducted under very warm weather conditions, it was possible to maintain the max temperature in the house as low as up to 4 K above the ambient temperature during these periods. Moreover, even though the max ambient temperature was at or (often much) above the comfort level in all three classes of EN 15251 for mechanically ventilated buildings (table 5.1), the max temperature in the house was within or just above comfort class III when applying the comfort classes from EN 15251 for naturally ventilated buildings (figure 5.1).

The mechanical ventilation system in the studies could not prevent over-heating in the house, because there was no bypass for the recovery unit (fresh air was always heated by the exhaust air). Even with a bypass the mechanically ventilation system will be less effective due to the fixed "low" volume flow rate (lower than the volume flow rate possible to achieve with natural ventilation).

The experiments showed that it often might be difficult to obtain comfortable temperatures all over the house and at the same time keep the CO_2 concentration in the bedrooms low during the nights. Only temperature control will lead to high CO_2 concentrations in the house also with open bedroom doors. On the other hand, CO_2 control often resulted in too low temperatures, especially in the aisle. Open bedroom doors decreases these difficulties as the CO_2 concentration is kept lower in the bedrooms. This leads to the roof windows being open for shorter periods during CO_2 control and that more CO_2 is ventilated out during temperature control.

To no surprise the studies show that the rooms mostly exposed to CO_2 were the occupied bedrooms. The CO_2 concentration may also be high in e.g. smaller living rooms exposed to many people. However, people tend to spend more time in the bedroom than in any other room in the house. Furthermore, the studies show a higher CO_2 level than the level that caused problems with the sleep quality in studies carried out at the Technological University of Denmark.

The below findings are based on the fact that the opening of the roof and aisle windows kept the CO_2 concentration down in the aisle of the house during natural ventilation:

- mechanical ventilation dimensioned according to today's standard results in higher CO_2 concentrations with closed bedroom doors than the three comfort classes in EN 15251 in the two-person bedroom and just inside comfort class III in the one-person bedroom

- open bedroom doors reduce the CO_2 concentration significantly for all ventilation strategies including mechanical ventilation - down to comfort class II-III – for a one-person and two-person bedroom, respectively. Therefore, bedroom doors should not be closed when occupied. There is, however, not much difference between the bedroom doors being fully open or being 50-100 mm ajar

- the fresh air valves in the bedrooms had only little influence on the CO_2 concentration in the two-story building. The fresh air valves in the bedrooms had a positive effect on the CO_2 concentration in the one-storey building when the bedroom doors were closed, and an insignificant effect when the bedroom doors were open or ajar

- the CO_2 concentration was lower in two-storey buildings than in one-storey buildings, both with closed and open bedroom doors

- opening a window ajar had a positive influence on natural ventilation with closed bedroom doors, while only little effect with open bedroom doors

- the air change rate was more dependent on the wind conditions in a one-storey buildings than in a two-story building

Based on the above, it may be concluded for the EnergyFlexHouse and for the examined control strategies concerning CO_2 that:

- bedroom doors should be left open or ajar during the night

- it is possible both with balanced mechanical ventilation and natural ventilation to obtain reasonable CO_2 concentrations. However, more care should be taken when designing natural ventilation

- it is easier to obtain high air change rates that are less influenced by the wind conditions in a two-story house than in a one-storey house due to the higher buoyance effect in the former

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