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Evaluation of Indoor Climate in Low Energy Houses

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Abstract

The aim of the EU EPBD is to realize lower energy consumption in buildings, without neglecting the indoor climate, which can be specified as thermal comfort and indoor air quality. The research analysed 70 recently built dwellings in Flanders, Belgium, ranging from standard execution over low energy up to even energy positive houses. A monitoring campaign was set up to evaluate the indoor environment quality, both during winter and summer period.

Both in winter and summer, the temperature is mostly within comfort boundaries. However, in better insulated dwellings the mean temperature is generally somewhat higher and the deviation is smaller whereas on warm days the temperature can rise uncomfortably in both living room and bedroom. CO_2 and humidity measurements show good to reasonably good indoor air quality, independently from the type of ventilation system.

1. INTRODUCTION

For the last couple of years construction has evolved to better insulated buildings, which consume less energy. The motivation to this can be found in the awareness on global warming, exhaustibility of fossil fuels, increasing energy costs, etc.

In the EU, the obligations of the Kyoto-protocol regarding the reduction of energy use and CO_2 emissions of buildings resulted in the EU Energy Performance of Buildings Directive (EPBD 2002). This directive imposes requirements to the EU Member States concerning the energy performance of buildings. In 2010 the recast of this directive specified that by 2021 all new buildings have to be Nearly Zero Energy Buildings (Recast EPBD 2010).

In Flanders, Belgium, the EPBD was converted into the EPB-legislation in 2006 (EPB = Energy Performance and Indoor Climate). Requirements were not only imposed to the energy performance of new buildings, but also to the indoor climate, by means of minimum ventilation rates and control of summery overheating risk. Since then the requirements are tightened on a regular basis, in anticipation to the target for Nearly Zero Energy Buildings by 2021. Some individuals, however, do not wait for this target and choose to already perform better than the legal requirements. They combine several building techniques, like high insulation values, heat pumps, heat recovery, etc. to reduce the energy use of their dwelling. A recent report of the Flemish Government shows that since the introduction of the EPB legislation there is an increasing voluntary action for energy performance levels beyond legal requirements (Flemisch Energy Agency 2012).

The realization of these dwellings with a better energy performance label makes it possible to study their real energy and comfort performance. Since the EPB-legislation also pursues a good indoor climate, it is useful to evaluate the comfort in these dwellings, both thermal comfort as well as the indoor air quality. Different sources indicate that this might be a problem in these type of houses (Verbeeck, Carmans and Martens 2011; KULeuven 2009, 2011). For instance, Verbeeck, Carmans and Martens describes that the summer comfort in low energy houses is an important focus which already should be taken into account during the design of the dwelling to avoid overheating.

The results of this paper are part of a larger research project in which the robustness of the performance of low energy dwellings is studied. Through monitoring and simulations the sensitivity of low energy concepts is evaluated, with regard to their impact on both energy consumption and indoor comfort. The objectives of this research are to define guidelines to create high performance, comfortable and energy efficient dwellings.

In this paper the results on the indoor climate are described. Section 2 presents the dwellings as well as the methodology for the evaluation of the indoor climate, both thermal comfort and indoor air quality. Then section 3 and 4 present and discuss the main results of the monitoring campaign, for both winter and summer period. Finally, in section 5, conclusions are formulated together with some first guidelines for good indoor climate in (very) low energy buildings.

2. METHODOLOGY

2.1. Description of the dwellings

For this research, 70 dwellings were selected, distributed over the Flemish territory. This selection includes a wide variety in terms of energy performance, but also in terms of construction methods, building types, installation types, etc. Most of the houses were recently built, mainly just before or after the implementation of the EPB regulation in 2006. Three dwellings were thoroughly renovated, in a way they can be regarded as new buildings when investigating indoor climate or energy consumption.

With regard to typology, the selection consists of 45 detached, 24 semi detached and 2 attached houses. 44 dwellings are massive constructions with brick cavity walls and 27 are wood frame constructions. The 3 ventilation types, which are most frequently applied in Flanders, are represented: 14 dwellings have natural ventilation, 14 exhaust ventilation and 43 have balanced ventilation with heat recovery. With regard to the heating system, gas boilers, heat pumps, wood boilers and local electrical heaters are represented.

In Flanders, the energy performance of a dwelling is expressed in terms of the insulation level (K-level) and the energy performance level (E-level). The insulation level gives an indication of the thermal losses of the building envelope, taking into account the overall mean insulation value (U-value) in addition to the compactness of the building (ratio of heated volume and overall heat loss area) and the heat loss through 2D and 3D component junctions. Well insulated dwellings have a lower K-level. K45 represents a mean U-value of 0.45W/m²K for a compactness of 1m. Most passive houses have an insulation level between K10 and K20. The E-level is a measure for the primary energy consumption of a building, for standard climate and user behavior, as a ratio to the calculated reference primary energy consumption, depending on the compactness of the building. For dwellings, the energy consumption for heating, cooling, domestic hot water, pumps and fans is considered, reduced by the energy production of renewable energy sources. The lower the E-level, the better the energy performance. Negative E-levels can be considered for energy positive dwellings, which produce more primary energy by PV solar panels than they consume on a yearly basis for heating, cooling, domestic hot water and ventilation. Near-zero energy, the aim for new buildings by 2021, is represented by the level about E0. Figure 1 shows the distribution of the selected dwellings according to insulation level and energy performance level. Additional, the requirements since 2006 and the aim of near-zero energy (± E0) are indicated.

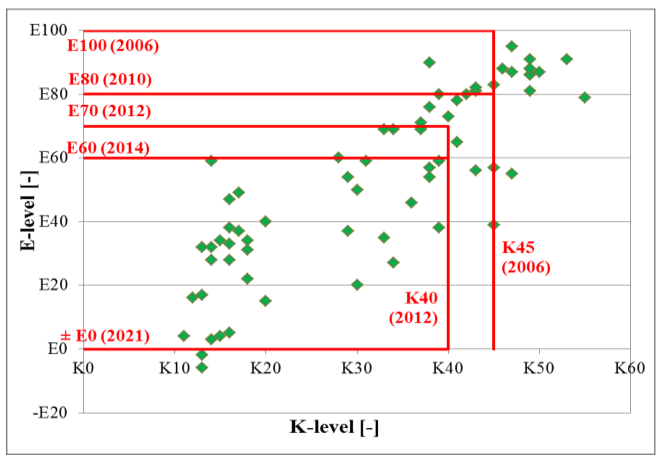

Figure 1. Distribution of the dwellings according to their insulation level (K) and energy performance level (E)

2.2. Monitoring campaign

In order to evaluate the quality of the indoor environment, a monitoring campaign was set up in each house during at least two weeks, in winter period between November 2011 and April 2012 and in summer period between June 2012 and September 2012. In the living room, master bedroom and bathroom, indoor air temperature and relative humidity were measured every 15 minutes with an ONSET HOBO U12 logger. CO_2 concentration was also measured every 15 minutes with a Telaire 7001, coupled with a HOBO U12 logger. In winter period, CO_2 concentration was monitored in most of the living rooms and in some master bedrooms, whereas in summer period these measurements were more focused on the situation in the master bedrooms and in some of the living rooms. As a reference for the outdoor climate for all dwellings, measurements of temperature, vapor pressure and solar radiation on one central location in Flanders were used.

2.3. Evaluation criteria for thermal comfort

Thermal comfort was evaluated by the mean indoor air temperature and the standard deviation in living room and master bedroom. In summer period also the maximum indoor temperature during occupation was verified.

Comfort boundaries are derived from ISO 7730 (ISO 2005). This standard describes limits for operative temperature. Since the considered dwellings are well insulated, air temperature and operative temperature will be very close. In this research, boundaries will therefore be set to indoor air temperature.

Weak point is that the ISO 7730 standard is developed for the thermal comfort in the work environment. However, different studies show that the experience of the occupants in their own house diverges from that in their work environment (Karjalainen 2008, Hong et al. 2008). Especially while sleeping, the principle of heat exchange is different than assumed in the PMV-model, resulting in lower comfort temperatures (Leung and Ge 2012, Peeters et al. 2008). However, none of these studies define adjusted boundaries for thermal comfort in dwellings.

Therefore, the comfort boundaries for indoor air temperature in winter period are set to 20°C - 24°C for living room and 18°C - 22°C for bedrooms. In summer period a comfort zone of 23°C - 26°C is set for both types of rooms.

2.4. Evaluation criteria for indoor air quality

A first method to evaluate the indoor air quality is by means of the CO_2 concentration. According to EN 13379, indoor air can be qualified in four levels (IDA1 to IDA4) based on the difference in CO_2 concentration of the indoor air ($c_{CO2,i}$) versus that of the outdoor air ($c_{CO2,e}$), see table 1 (CEN 2007). Outdoor air contains about 350 to 400 ppm CO_2 (Liddament 1996). Based on the value of the indoor CO_2 concentration in several dwellings outside occupation period, a general value of 350 ppm for the outdoor CO_2 concentration is used in the calculations. For a good indoor air quality, IDA1 or IDA2 level should be aimed for.

	$c_{CO2,i}$ - $c_{CO2,e}$ (ppm)	$c_{CO2,i}$ (ppm)	
IDA1	≤ 400	≤ 750	High IAQ
IDA2	400 – 600	≤ 950	Good IAQ
IDA3	600 – 1000	≤ 1350	Moderate IAQ
IDA4	≥ 1000	≥ 1350	Low IAQ

Table 1: Boundary conditions for the indoor air quality (IAQ) levels according to EN 13379.

Alternatively, the indoor air quality is assessed by means of the internal humidity, according to the internal climate classes (ICC) defined in EN 13788 (CEN 2001). Table 2 shows the boundary conditions for the different classes (ICC1 to ICC5) for the vapor pressure difference between indoor and outdoor ($p_i – p_e$) as a function of the monthly mean external temperature θ_{em}. Additionally the typical corresponding building types are shown. In order to avoid problems of interstitial condensation and mold, level ICC3 or lower should be aimed for.

	p_i - p_e (Pa)		
	θ_{em} < 0°C	0°C ≤ θ_{em} ≤ 20°C	Building types
ICC1	< 270	< 270 – 13.5 θ_{em}	Storage
ICC2	< 540	< 540 – 27.0 θ_{em}	Offices, shops
ICC3	< 810	< 810 – 40.5 θ_{em}	Buildings with low occupancy
ICC4	< 1080	< 1080 – 54.0 θ_{em}	Buildings with high occupancy
ICC5	≥ 1080	≥ 1080 – 54.0 θ_{em}	Special buildings, e.g. laundry, brewery, etc.

Table 2: Boundary conditions for the indoor climate classes according to EN 13788.

3. RESULTS

3.1. Winter period

3.1.1. Temperature

Figures 2-3 present the mean indoor air temperature and standard deviation in the living room and master bedroom, as a function of the insulation level (K-level). Distinction has been made between the different types of ventilation. The green zone represents the comfort zone.

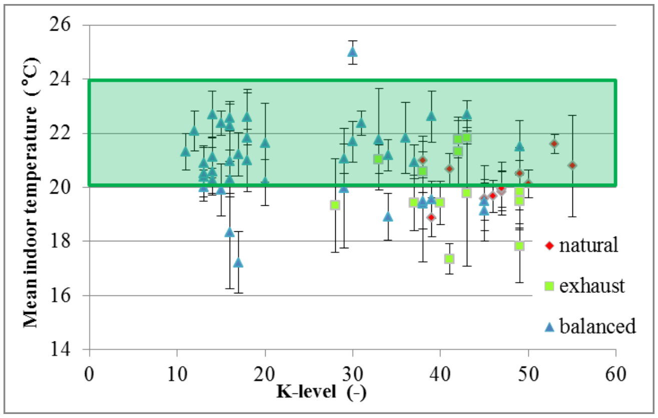

Figure 2. Mean indoor air temperature in winter period in all living rooms as a function of K-level and of the ventilation system

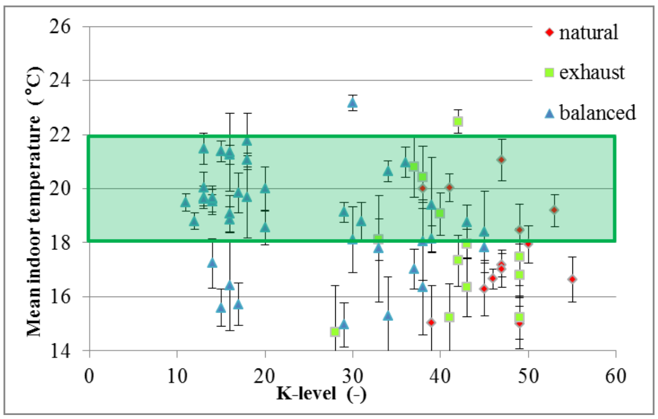

Figure 3. Mean indoor air temperature in winter period in all master bedrooms as a function of K- level and of the ventilation system

3.1.2. Indoor air quality

Figure 4 presents the individual results in 50 living rooms of the cumulative percentage of time the CO_2 concentration is within a certain IDA class or better. As the occupation period in the living rooms is variable and inconsequent, the whole monitoring period is taken into account. Distinction is made as a function of the ventilation system.

In figure 5, results of the indoor air quality in terms of vapor pressure differences between indoor and outdoor are given as a function of the ventilation system. Due to the limited monitoring period of 2 weeks, daily averaged vapor pressure differences are presented instead of monthly averaged. Each value for the vapor pressure difference of a dwelling is the volumetrically averaged value based on the measured vapor pressures in and the volumes of living room, master bedroom and bathroom.

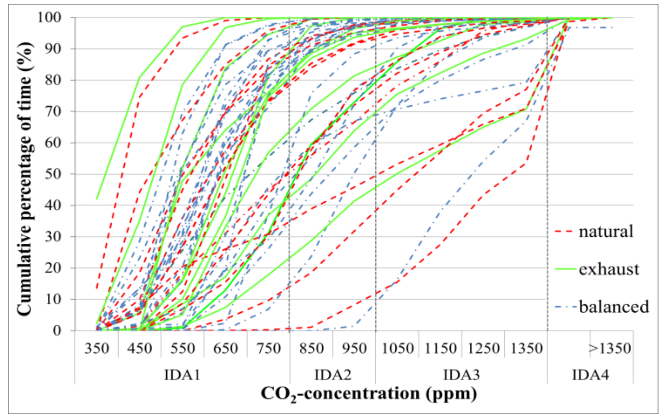

Figure 4. Cumulative percentage of time the CO_2 concentration in 50 living rooms is within an IDA class as a function of ventilation system

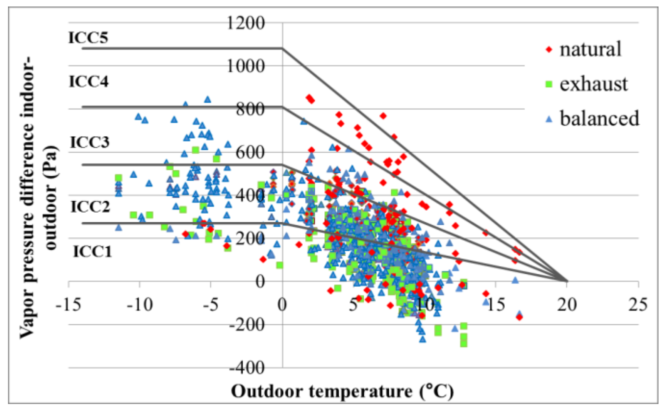

Figure 5. Daily averaged vapor pressure difference in all dwellings as a function of the daily averaged outdoor temperature and of the ventilation system in winter period

3.2. Summer period

3.2.1. Temperature

Figures 6-7 show the mean indoor air temperature and standard deviation in the living room and master bedroom as a function of K-level. The green zone represents the comfort zone.

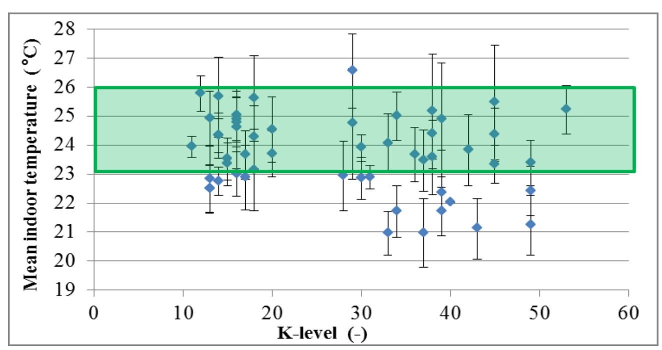

Figure 6. Mean indoor air temperature in summer period in all living rooms as a function of K-level

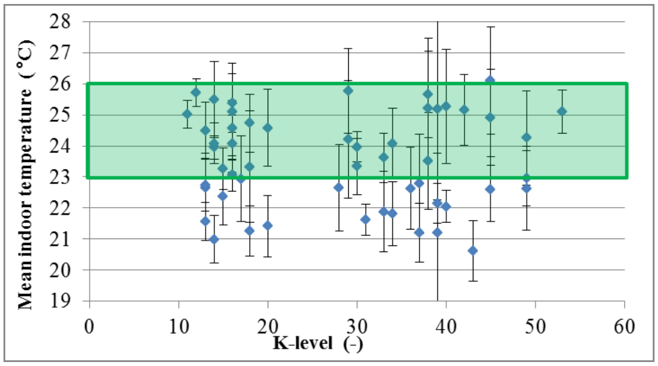

Figure 7. Mean indoor air temperature in summer period in all master bedrooms as a function of K-level

Figure 8, 9 and 10 give the maximum indoor air temperature in the living rooms during the (possible) occupation period between 3pm and 10pm, respectively in the master bedrooms, between 10pm and 7am. These are presented as a function of the mean outdoor air temperature during the whole measuring period in figure 8 and 9 and as a function of the mean daily amount of radiation during the whole measuring period in figure 10. Difference is made for massive constructions versus wood frame constructions. In two dwellings, active cooling was used during the measuring period. The maximum indoor air temperature in these dwellings is indicated by a green circle. In one bedroom the logger was installed close to a classic model television. During the use of this apparatus, high local temperatures were measured, which do not refer to the general room temperature. The maximum indoor air temperature in this bedroom is indicated by a red circle.

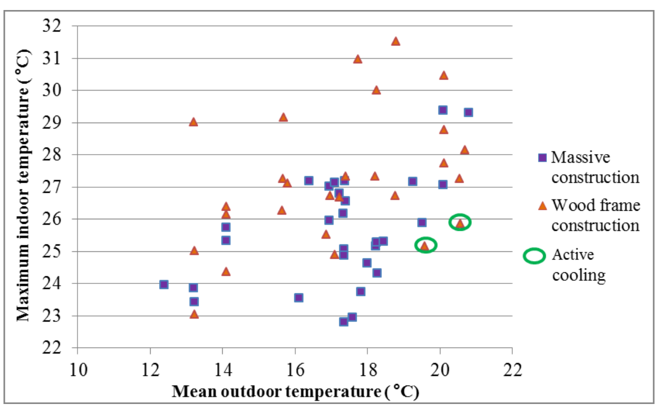

Figure 8. Maximum indoor air temperature in 56 living rooms during occupation time (between 3pm and 10pm) as a function of mean outdoor temperature of the whole monitoring period and the construction type

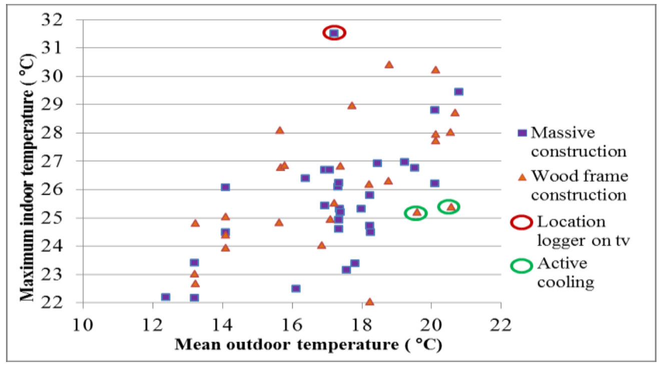

Figure 9. Maximum indoor air temperature in 55 bedrooms during occupation time (between 10pm and 7am) as a function of mean outdoor temperature of the whole monitoring period and the construction type

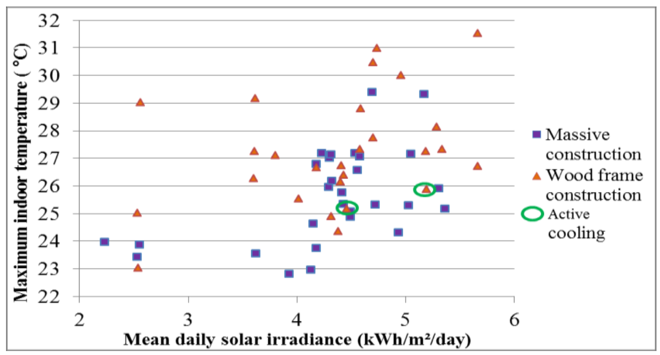

Figure 10. Maximum indoor air temperature in 56 living rooms during occupation time (between 3pm and 10pm) as a function of mean daily solar irradiance of the whole monitoring period and the construction type

3.2.2. Indoor air quality

Figure 11 presents the cumulative percentage of time the CO_2 concentration is within a certain IDA class or better in the master bedroom. To insure the results in the bedrooms give a correct indication of the CO_2 concentration during occupation period, only the measurements during the night, between 1am and 5am, are taken into account.

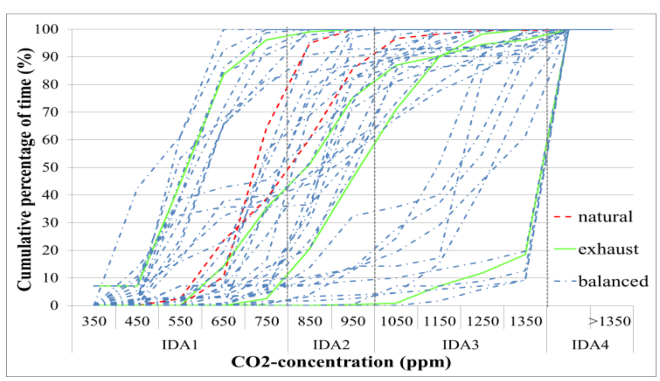

Figure 11. Cumulative percentage of time the CO2 concentration in 42 master bedrooms, during nighttime in summer period, is within an IDA class as a function of ventilation system

4. DISCUSSIONS

4.1. Temperature

As figures 2 and 3 show, in approximately 60% of all living rooms and bedrooms the mean temperature is in the comfort zone during winter period. In less than 40% it is below the comfort temperature and in some rare cases the temperature is above the comfort zone. Considering also the standard deviation, it can be concluded that most dwellings have a comfortable indoor air temperature during the entire measuring period. This is confirmed by the temperature trends of the individual dwellings where there is a small difference between the minimum and maximum temperatures.

For most dwellings where the mean indoor temperature in the living room is below the comfort zone, the standard deviation and individual trend show that during occupation periods of the room, the indoor temperature is within the comfort zone, but outside these periods there is a (small) reduction of the temperature. Especially in dwellings with natural and exhaust ventilation, where cold outdoor air directly enters the room, limited heating periods result in low mean temperatures. In some cases, a low set temperature is the residents' choice, resulting in a low mean temperature and small standard deviation.

In the bedrooms, the indoor temperatures are more often below the lower comfort boundary. The standard deviations show that also during occupation period the temperature does not reach the comfort zone. The trends of the individual measurements show that often the bedrooms are not heated and that realization of thermal comfort in these rooms is considered less important.

Figures 2 and 3 show that in better insulated dwellings, with low K-level, the indoor temperature is generally higher and the standard deviation is smaller. For dwellings with a K-level below 25, there are merely a few where the mean indoor temperature in the living room is below 20°C. For dwellings with a K-level above 25, however, it concerns half of the dwellings. This result is mostly due to the better insulation value of the houses, but is also influenced by the ventilation system. As shown in figures 2 and 3, these well insulated dwellings are all equipped with a balanced ventilation system with heat recovery. For the houses with higher K-level, it appears that the highest mean indoor temperature occur when a balanced ventilation system is present. However, the ventilation system is not the only determining parameter for the indoor temperature, as is shown by the fact that there are also dwellings equipped with a balanced ventilation system with heat recovery, where the mean temperature is below 20°C in the living rooms. In these cases the lower mean temperature is influenced by the residents' settings of the desired temperature and length of heating period during the day.

During the research also the influence of other parameters was checked, such as the construction type (massive versus wood frame construction), the percentage of glazing as window to floor ratio, the type of heat production and heat distribution, etc. However, these parameters did not have a significant impact on the mean temperature during heating season. It is important to notice that some of the well-insulated dwellings have a very limited heating capacity, for instance by means of a local, removable electrical heater. However, even this type of dwellings could easily realize thermal comfort in winter period.

The results for the thermal comfort in summer period are shown in figures 6 to 10. In this season the indoor conditions are far more dependent on the outdoor climate, namely outdoor air temperature and solar irradiance. Since the measurements had to be spread over the season due to logistical reasons, all dwellings had different outdoor conditions, which make a comparison among dwellings more difficult. In winter these differences are in most cases intercepted by the heating installation. In summer such compensation is not present, except for the two houses with active cooling.

Figures 6 and 7 show that the mean indoor air temperature is within the comfort zone for 64% of the living rooms and 58% of the bedrooms. For the other dwellings the mean temperature was below comfort zone. Only in one dwelling the mean temperature is above the upper boundary. The measurement in this dwelling took place during a hot, sunny period.

However, the according standard deviations indicate that temperatures can highly increase. This is confirmed by figures 8, 9 and 10 which present the maximum indoor air temperature during the occupation periods in both living room and master bedroom. The influence of the outdoor climate is included by showing the indoor temperature as a function of the mean outdoor air temperature or the mean daily solar irradiance during the measuring period. These figures show that in 55% of the living rooms and in 47% of the bedrooms the maximum indoor temperature rises above the upper comfort boundary of 26°C, even in periods when the outdoor climate is not extremely warm or sunny.

From figures 8, 9 and 10 it is clear that the temperature in wood frame construction dwellings rises higher than in massive constructions. In the latter the temperature remains within the comfort zone for a longer percentage of time. There was not a clear impact of the construction type on the mean temperature, but in wood frame constructions standard deviations were larger than in massive constructions.

With regard to the influence of percentage of glazing, orientation of living room and bedroom and type of ventilation system, no significant impact could be found, neither for the mean temperature nor for the maximum temperature.

4.2. Indoor air quality

As shown in figure 4 the CO_2 concentration in the living rooms during winter period is reasonably good. For most dwellings only a limited amount of time IDA3 or IDA4 is reached. Attention has to be drawn to the fact that these results concern averages on the entire measuring period, whether the living rooms were occupied or not. The conclusions may therefore be somewhat too positive, as mainly the indoor air quality during occupation is of interest. However, in 32 of the 50 monitored living rooms IDA2 or better is reached during more than 90% of the time, so it might be expected that also during occupation the indoor air quality is satisfying.

The results in the bedrooms are less positive: at least 40% of the time CO_2 concentration reached IDA3, regardless of the type of ventilation system and more than 20% of the time IDA4 was reached in dwellings with mechanical ventilation (exhaust or balanced). Dwellings with natural ventilation seem to perform better, but caution is needed with the limited amount of monitored bedrooms with this type of ventilation system.

As the results of figure 5 show, the internal humidity level is good. In most of the dwellings the vapor pressure differences between indoor and outdoor are below category ICC4 and most of the days even below category ICC3. Especially with mechanical ventilation indoor air quality, equivalence to buildings with low occupancy is realized. One dwelling influences the results for natural ventilation with a couple of days with high indoor humidity.

The measurements for CO_2 concentration in summer period show even better results in the living rooms. Especially with natural ventilation, IDA2 or better is reached. Here also caution is needed since there were only two living rooms monitored. Figure 11 shows that in 31 of the 42 monitored bedrooms the indoor air quality is high or good for more than 60% of the time (IDA2 or better). In these 31 dwellings, all types of ventilation system are represented. In the other 11 bedrooms, however, the indoor air quality is moderate or low for a large part of the time. These cases concern dwellings with a mechanical ventilation system (exhaust or balanced), but considering the limited amount of monitored dwellings with a natural or exhaust ventilation system, here also caution is needed.

During summer period the vapor pressure indoor is often lower than outdoor, due to humidity absorption by walls, furniture, etc. In some of the bedrooms it can be noticed that during the occupation period at night a high CO_2 concentration is accompanied by a high humidity. However, this high humidity is cleared out during the daytime, so no problems of mold and interstitial condensation are expected. In general, good results for indoor air quality in terms of internal humidity are reached in all dwellings, with all types of ventilation system.

Combining the information about the moderate to low indoor air quality in bedrooms and the high temperatures that can occur during the summer period, it can be concluded that in some dwellings with balanced ventilation, the occupants do not use the opportunity of opening windows during night. This extra ventilation could support or even replace the ventilation system and remove the surplus CO_2 and humidity. It could also bring in cooler outdoor air to reduce the temperature, since in Belgium outdoor temperature drops easily below 20°C on hot days and even below 15°C on cooler days in summer. Considering the temperature difference with the maximum indoor temperatures in the bedrooms during nighttime, as presented in figure 9, there is a great potential for natural night cooling.

5. CONCLUSION

In preparation of the requirement that, starting from 2021, all new buildings have to be Nearly Zero Energy Buildings, this research evaluated the in situ performance of a range of low energy dwellings. In this paper especially the performance on thermal comfort as on indoor air quality has been evaluated.

Results concerning the indoor air temperature during winter period show that the mean temperature lies within or close below the comfort boundaries and that the standard deviation is rather small. This effect is even stronger for well-insulated dwellings. Thermal comfort in winter can therefore definitely be realized in low energy houses. The comfort is even better because temperature reduction outside the heating periods is very limited. A balanced ventilation system with heat recovery supports this comfort, but in less insulated dwellings the effect is partially overruled by the residents' choices of set temperature and length of heating period.

In general the thermal comfort in summer is good. The mean indoor air temperatures are within the comfort boundaries. The maximum temperatures, however, can rise quite high, both in living rooms and bedrooms. Especially wood frame constructions are sensitive for this, although this type of dwellings also cools down faster. To facilitate this cooling down, it is important to make optimal use of opening windows, especially for night ventilation in bedrooms and regardless of the type of ventilation installed.

The indoor air quality is reasonably good in almost every dwelling, independently of the type of ventilation system. Only in a number of bedrooms the CO_2 concentration, and to a lesser extent the humidity, can rise to a moderate or low indoor air quality. In summer the opening of windows can also provide a solution for this.

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