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The feasibility of natural ventilation in plus energy houses in Germany

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Abstract

The Energy Performance of Buildings Directive of the European Commission has set a zero energy goal for all new buildings by the end of 2020. One of the relatively recent housing concepts is the plus energy house, which produces more energy than it consumes. Plus energy houses are generally ventilated by MVHR systems. However, many researchers have expressed concerns about the performance of such systems in terms of indoor air quality, thermal comfort and total carbon emissions. Thus, this study aims to investigate whether natural ventilation can be an integral feature of plus energy houses in central Europe. This was achieved by testing various CO_2-based demand control ventilation strategies for the climate of Stuttgart. The results showed that the proposed strategy resulted in an annual energy surplus of 1,299 kWh for home+, while maintaining acceptable indoor conditions throughout the day both in terms of indoor air quality and thermal comfort.

Keywords: Natural ventilation; Demand control ventilation; Plus energy houses

1 Introduction

More than one quarter of energy use in developed European countries is attributed to the residential sector (DECC, 2014). In response to that, the European Commission published the Energy Performance of Buildings Directive (EPBD) (Directive 2010/31/EU), which sets a zero energy goal for all new buildings by the end of 2020.

A relatively new concept that has gained popularity in several European countries is the plus energy house, which uses renewable energy sources in order to produce more energy than it consumes. These houses generally use mechanical ventilation systems with heat recovery (MVHR), as they provide better control over ventilation rates and minimise ventilation heat losses. However, many researchers have expressed concerns about the performance of MVHR systems in terms of indoor air quality, thermal comfort and total carbon emissions (Liddament, 2010) in new dwellings with high standards of airtightness, such as plus energy houses.

Recent research has shown that natural ventilation could be a satisfactory alternative to MVHR in airtight dwellings in mild climates (Sassi, 2013). However, a natural ventilation system has to be designed correctly, as potential failure in ventilating new airtight dwellings effectively could result in a range of adverse effects. Evans et al (1998) estimated that design, build and operating costs are in the ratio of 1:5:200. This means that poor standards of ventilation can have a significant negative impact on operating costs.

A determinant factor for the success of a natural ventilation system is the way it is controlled. One of the reasons for excessive energy consumption in buildings is the inability of the occupants to comprehend complicated controls. Automatic control of ventilation with manual override is a popular option in non-domestic buildings, with CO_2-based demand control ventilation (DCV) being suggested by CIBSE (CIBSE, 2009). While these systems are not widespread for residential applications, this is expected to change.

Showing the potential of natural ventilation in new dwellings in European countries is especially timely, as these countries are currently exploring ways to achieve their ambitious "zero-carbon" target for new dwellings. Thus, the aim of this study is to investigate whether natural ventilation can be an integral feature of plus energy houses in Central Europe.

2 Methodology

2.1 Choice of modelling software

The combination of dynamic thermal and air flow modelling has been identified as the most appropriate tool in order to test control strategies (Heisleberg, 2002). The simulation software that was used in this study is Virtual Environment by Integrated Environmental Solutions (IES-VE) (Version 2004.0.1). This commercially available software was chosen because of its comprehensive feature set, its extensive validation history and its regular use within academia and the building services industry.

2.2 Case study

Home+ is a small residential building located in Stuttgart, Germany. It was designed by an interdisciplinary team at the Stuttgart University of Applied Sciences (HFT Stuttgart) as an entry for the first edition of the Solar Decathlon Europe competition (Cremers et al, 2010). Home+ has a total usable floor area of 56 m², a floor to ceiling height of 2.5 m and can accommodate a two person household. It consists of four opaque modules separated by a glazed interspace which aims to provide daylight and ventilation to the interior that is enclosed by three of the modules. The fourth module serves as a loggia outside the main entrance. The entire external surface of the building is covered with photovoltaic elements. Figures 1 and 2 show an exterior view and the floor plan of home+, while figure 3 illustrates the model that was constructed in IES-VE.

Figure 1.
Exterior view of home+.

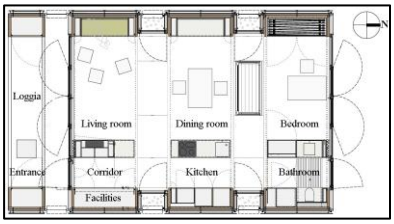


Figure 2.
Floor plan of home+.

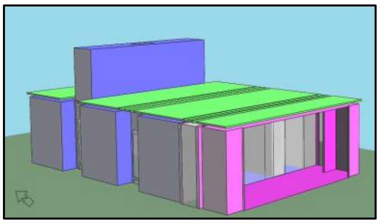


Figure 3.
IES-VE model of home+.

The envelope of home+ is highly insulated, while an air infiltration rate of 0.6 ach at 50 Pa was assumed. Thermal mass was added to the ceiling in the form of a 230 mm concrete block (k-value: 230 kJ/m^2K), while the rest of the timber construction is lightweight. There is a range of appliances and equipment in the house, resulting in variations of the internal gains. Details about heat gains and properties of the building envelope can be found in Cremers et al

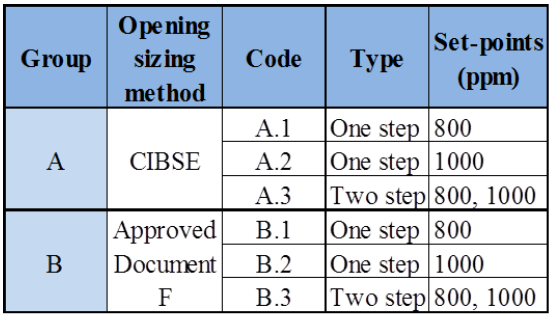
(2010). The heating system was set to operate throughout the day, as the house is occupied on a 24 hour basis. The heating period was set from the 1st of October to the 30th of April. A set-point temperature of $20^{o}C$ was used. Occupancy for the bedroom was assumed to be 23:00-07:00, in accordance with previous studies (Beizaee et al, 2013).

2.3 Control strategies and performance criteria

Two initial groups of control strategies were formed. Group A, which uses ventilation openings that were sized according to CIBSE suggestions, and Group B, which uses ventilation openings that were sized based on instructions of Approved Document F. According to the CIBSE sizing method (CIBSE, 2005b), the required free area is calculated based on the required airflow for the removal of heat emitted in a space. In contrast, Approved Document F (HM Government, 2010) states that background ventilators should be sized for the heating period, while additional needs for ventilation during summer should be covered by purge ventilation (which was not taken into consideration in this study). As ventilation requirements in winter and summer are different, two seasonal ventilation systems were designed: Cross ventilation through high level openings for winter, and stack ventilation with inlets at low level and an outlet on the top of the stack for summer. Moreover, night cooling through high level openings and the stack outlet is also used during summer, while all windows are shaded by internal blinds. The second method resulted in 30% and 92% smaller openings for summer and winter respectively. The choice of set-points was based on CIBSE Guide B (2005a), which states that a CO_2 level of 800 to 1000 ppm indicates that ventilation is adequate within a building. The initial control strategies are summarised in table 1.

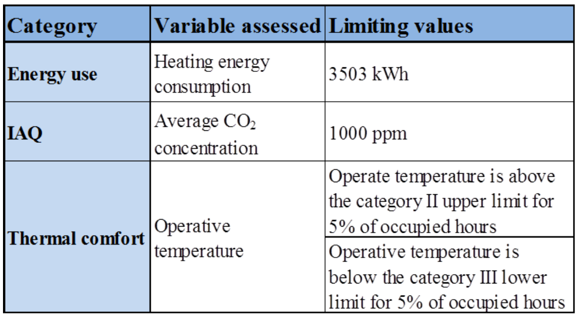
Based on the results of the initial simulations, a new control strategy was devised in order to improve the performance of home+. In regard to previous work by Khatami et al (2013), an additional group (group R.1) of control strategies was created in order to determine the optimum balance between the minimum free opening area and the maximum CO_2 set-point. The impact of increasing the controller resolution was also investigated by investigating a further group of control strategies (group R.2). Initially, an intermediate increment was added to the best control strategy of group R.1. Subsequently a range of CO_2 set-points and opening areas were tested in order to identify the best combination.

Table 1. Group A and Group B control strategies.



Group	Opening sizing method	Code	Type	Set-points (ppm)
A	CIBSE	A.1	One step	800
		A.2	One step	1000
		A.3	Two step	800, 1000
B	Approved Document F	B.1	One step	800
		B.2	One step	1000
		B.3	Two step	800, 1000

Table 2. Performance criteria.



Category	Variable assessed	Limiting values
Energy use	Heating energy consumption	3503 kWh
IAQ	Average CO_2 concentration	1000 ppm
Thermal comfort	Operative temperature	Operate temperature is above the category II upper limit for 5% of occupied hours
		Operative temperature is below the category III lower limit for 5% of occupied hours

A set of performance criteria was used to assess the effectiveness of each control strategy in terms of thermal comfort, indoor air quality (IAQ) and energy use. The criteria had to be met in both occupied zones of the house (bedroom: 23:00-07:00; living room: 07:00-23:00). Previous simulations of home+ showed that an annual heating energy consumption lower than 3,173 kWh would maintain the energy plus status of the dwelling for the climate of Stuttgart. Additionally, an average CO_2 concentration of 1000 ppm during occupancy was considered adequate for ensuring good IAQ. As for thermal comfort, the adaptive standard was used as it has gained acceptance within the research community for studies regarding natural ventilation. As the standard does not set strict criteria, this study used the same criteria as Beizaee et al (2013). All criteria are summarised in table 2.

3 Results and discussion

Table 3 includes the annual predictions of the simulations in both zones for all initial control strategies. Predictions about energy use refer to home+ as a whole.

Table 3. Annual results for all control strategies. Cells that are coloured red indicate that the control strategy did not meet the specific criterion described in the top of each column.

Strategies	**Energy**	**IAQ**		**Thermal comfort**			
	Heating Energy (kWh)	Annual average CO_2 concentration (ppm)		Percentage of hours above category II upper limit		Percentage of hours below category III lower limit	
	Whole house	Living room	Bedroom	Living room	Bedroom	Living room	Bedroom
A.1	3113	732	825	0.7%	0.0%	0.1%	0.2%
A.2	2504	877	954	1.2%	0.0%	0.1%	0.1%
A.3	2851	753	842	7.6%	0.0%	0.0%	0.0%
B.1	2789	795	884	13.3%	0.8%	0.0%	0.0%
B.2	2259	940	1024	16.1%	1.3%	0.0%	0.0%
B.3	2713	824	900	14.4%	1.0%	0.0%	0.0%

All one-step strategies succeed in meeting the criterion for heating energy consumption. Group A control strategies were less efficient, as their larger openings resulted in excessive heat loss during heating periods. However, the smaller openings of group B led to worse IAQ in both rooms (7-9% higher CO_2 concentration). B.2 fails to meet the relevant criterion, because of the combined effect of small openings and low CO_2 set-points. As expected, strategies with lower set-points (A.1 and B.1) result in lower CO_2 concentrations, because ventilators open more frequently, letting fresh air into the building. As for thermal comfort, it is apparent that overheating is the biggest risk, since 4 out of 6 strategies result in warm discomfort in the living room. The small windows of group B were proven insufficient, even with the use of night cooling and shading. The bedroom rarely suffered from any thermal discomfort during occupancy. This is explained by the lack of solar heat gains overnight and the operation of night cooling only when external temperature exceeded 12^{o}C.

Both two-step control strategies (A.3 and B.3) failed to meet the warm discomfort criterion in the living room, because the lower set-point maintains the windows half-closed, limiting their cooling potential. However, in winter they are useful because they result in lower energy consumption without significant penalties in IAQ. Therefore, refinement was attempted by adopting two-step control strategies in group R.2.

Figure 4 illustrates the seasonal difference in CO_2 concentration each strategy delivers in both rooms. CO_2 levels are low in summer in both rooms, mainly because of night cooling, while in winter CO_2 concentration is elevated, especially in the bedroom for higher set-points (A.2 and B.2). The fact that the bedroom has no ventilators might be a possible explanation, as the internal air flows that ventilate it have higher CO_2 concentrations than the ambient air.

In figure 5, the operative temperatures which lie within each BSEN15251 (2007) category were plotted in the manner suggested by the standard. Similarly to table 3, it is apparent that overheating in the living room is the main problem for strategies with small openings. Thus, small windows could be used during winter in order to avoid excessive heat loss, while larger openings seem to be necessary for maintaining acceptable temperatures in summer.

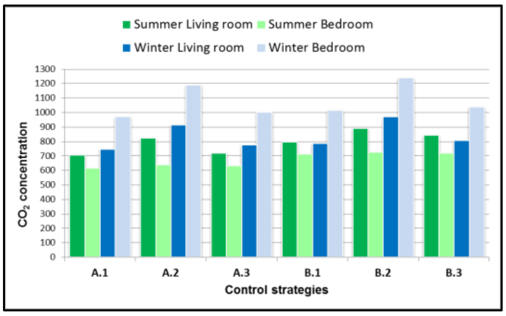


Figure 4.
Seasonal average CO_2 concentration in both zones.

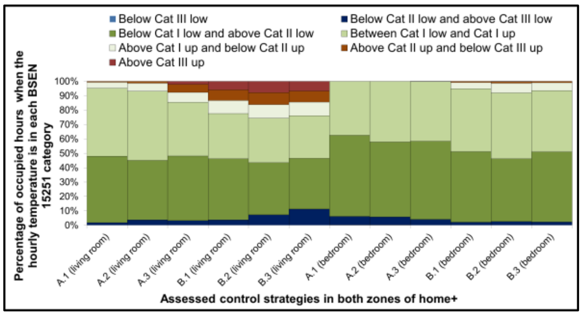


Figure 5.
Percentage of occupied hours when the living room air temperature is in each adaptive thermal comfort category.

Control strategies A.1 (min. hours of overheating) and B.2 (min. energy use) were chosen for ventilating home+ in summer and winter respectively. This combination resulted in a space heating energy consumption of 2,262 kWh, average annual CO_2 concentrations of 868 ppm and 981 ppm in the living room and bedroom respectively and almost no hours of thermal discomfort. B.2 for winter operation was further refined by successively reducing the opening area by 20%, 40% and 50% (Table 4) and by increasing the set-point by 50 ppm.

Table 4. Annual results for R.1 group control strategies. Cells that are coloured red indicate that the control strategy did not meet the specific criterion described in the top of each column.

Strategies	Whole house	Living room			Bedroom		
	Heating energy consumption (kWh)	Annual average CO_2 concentration (ppm)	Percentage of hours above category II upper limit	Percentage of hours below category III lower limit	Annual average CO_2 concentration (ppm)	Percentage of hours above category II upper limit	Percentage of hours below category III lower limit
R1.BC	2,262	868	3.0%	0.0%	981	0.0%	0.0%
R.1.20%.1000	2,234	873	3.5%	0.0%	989	0.0%	0.0%
R.1.40%.1000	2,220	877	4.4%	0.0%	995	0.0%	0.0%
R.1.50%.1000	2,212	882	5.1%	0.0%	1001	0.0%	0.0%
R.1.40%.1050	2,140	905	4.5%	0.0%	1026	0.0%	0.0%
R.1.50%.950	2,305	854	5.1%	0.0%	970	0.0%	0.0%

Table 4 shows that smaller free areas reduced energy consumption, but also deteriorated IAQ in both rooms. A 40% reduction of the base case opening areas reduced energy consumption by 42 kWh. Further refinement was not possible by increasing the set-point, as the bedroom CO_2 concentration failed to meet the IAQ criterion. Different combinations of free areas and set-points resulted in insufficient ventilation either for thermal comfort or IAQ.

Table 5. Annual results for R.2 group control strategies. Cells that are coloured red indicate that the control strategy did not meet the specific criterion described in the top of each column.

Strategies	Whole house	Living room			Bedroom		
	Heating energy consumption (kWh)	Annual average CO_2 concentration (ppm)	Percentage of hours above category II upper limit	Percentage of hours below category III lower limit	Annual average CO_2 concentration (ppm)	Percentage of hours above category II upper limit	Percentage of hours below category III lower limit
R.1.40%.1000	2,220	877	4.4%	0.0%	995	0.0%	0.0%
R.2.40%.800-1000	2,532	790	4.4%	0.0%	892	0.0%	0.0%
R.2.40%.800-1050	2531	791	4.4%	0.0%	896	0.0%	0.0%
R.2.40%.800-1100	2529	791	4.4%	0.0%	907	0.0%	0.0%
R.2.40%.900-1000	2342	834	4.4%	0.0%	949	0.0%	0.0%
R.2.40%.900-1100	2340	835	4.4%	0.0%	951	0.0%	0.0%
R.2.40%.1000-1100	2190	887	4.4%	0.0%	1014	0.0%	0.0%
R.2.40%.1000-1050	2192	887	4.4%	0.0%	1010	0.0%	0.0%
R.2.40%.950-1050	2262	860	4.4%	0.0%	980	0.0%	0.0%
R.2.40%.950-1050.0.4	2204	869	4.4%	0.0%	996	0.0%	0.0%

Further refinement was achieved by increasing the resolution of the controller in winter. A set-point of 800 ppm was set for the first increment, which was equal to 50% of the total effective area (Table 5). The table shows that this change did not affect the total hours of thermal discomfort. However, it had a significant impact on energy consumption as windows opened more frequently. A lower set-point of 950 ppm and a higher set-point of 1050 ppm achieved the optimum balance between energy consumption and CO_2 concentration. Additionally, a 20% reduction of the area of the first increment further reduced energy demand (2,204 kWh) without compromising IAQ.

4 Conclusions

Natural ventilation can be an integral feature of plus energy houses in central European climates, even with simplified control strategies. Night cooling and shading are considered to be crucial components for the success of natural ventilation in such dwellings. The proposed control strategy resulted in an annual energy surplus of 1,299 kWh for home+ in Stuttgart.

Adopting different control strategies in winter and summer can tackle the seasonal risks of poor ventilation. Correct sizing of the openings is essential as it has a significant effect on energy consumption. The CIBSE sizing method is most suitable for summer ventilation, while Approved Document F guidelines should be followed for background ventilation in winter.

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