Thermal Performance of a Passive House: Measurements and Simulation

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ABSTRACT

Energy efficiency in the built environment has become an important issue with global warming as one of the main drivers. An extreme example of lowering the energy consumption while still providing a good indoor environment for the occupants in residential construction are the so-called passive houses. Within the framework of the "Optimization of Extreme Low Energy and Pollution buildings" project, which studies low energy concepts for residential buildings from an economic, energy and environmental point of view, a recently constructed passive house in Belgium has been subjected to several measurements in order to verify and compare the achieved performance in situ with the predicted /calculated values.

INTRODUCTION

The term "Passive House" refers to a construction standard that can be met using a variety of technologies, designs and materials. It is basically a refinement of the low energy concept. "Passive Houses" are buildings which assure a comfortable indoor climate in summer and winter without the need of a conventional hydronic heating system (Schnieders, 2003).

To get the "passive" label, it is essential that:

- The end energy consumption for heating stays below 15 kWh/m.yr; (4755 Btu/ft/yr)
- The total end energy consumption for heating, domestic hot water, lighting and household appliances stays below 42 kWh/m.yr; (13314 Btu/ft/yr)

The energy savings are mainly realized by passive strategies. It is their optimization that makes a conventional hydronic heating system superfluous. In a first step the net energy demand is minimized through a careful design and construction of the building envelope. An extremely well performing thermal insulation reduces the transmission loss to a minimum. An air-tight design, combined with a mechanical ventilation system and a highly efficient heat recovery, using a heat pump or a heat exchanger, minimizes ventilation losses. Besides, by properly dimensioning and orienting the windows and by utilizing efficient exterior solar shading devices, solar heat gains may be maximized in winter and maximized in summer (php, 2006). Table 1 quantifies some of the performances imposed at the building and building component level. (Carsten, 2002).

Within the framework of the "Extremely Low Energy and Low Pollution in residential buildings" research project, which studies optimized low energy concepts for residential buildings from an economic, energy and environment perspective, a recently constructed passive house in Belgium was tested experimentally in order to verify and compare the achieved performance in situ with the theoretically predicted/ calculated values. (Hens, 2004), (Hasting, 2004), (Schnieders, 2003).

THE TESTED PASSIVE HOUSE

A passive house in Deinze (Belgium), was selected for testing and evaluation of the on-site performance (Figures 1 and 2). The house is designed as an extremely well insulated box with all functions organized within the space inside the

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Table 1. Passive House Requirements (Carsten, 2002)

Passive house design parameter	Requirements
End energy consumption for heating per year	<=15 kWh/(m^2yr) (4755 Btu/ft/yr)
End energy use per year for heating, domestic hot water and lighting plus appliances	<= 42 kWh/(m^2yr) (13314 Btu/ft/yr)
Primary energy use per year for heating, domestic hot water and lighting plus appliances	<= 120 kWh/ (m^2yr) (38040 Btu/ft/yr) with less than 55 kWh/(m^2yr) (17435 Btu/ft/yr) provided by the electricity provider.
U-value for wall, roof and floor-constructions	<0.15 W/m2K (0.026 Btu/h/ft/F)
U-value for the windows (demands low-e, gas filled triple glass with insulating spacers and thermally insulated frames)	<0.8 W/m2K (0.138 Btu/h/ft/F)
Air tightness	<0.6 /hour (infiltration at an air pressure difference of 50 Pa, air volume in the building as the reference)

Figure 1 *Exterior view of the building in Deinze.*

Figure 2 *Internal view of the building in Deinze.*

box. Neither load bearing indoor separation walls nor separating floors are present. Living room, kitchen, toilets, bedrooms, bathroom and services room in fact are constructed within the box.

The dwelling is a one-storey, detached single-family house with a duopitch roof. The façade walls consist of a plastered inside masonry leaf, a wood frame structure with insulation in between and finished at the outside with an MDF-board cladding. In the inside masonry leaf, reinforced concrete columns mark the windows. A detailed description of the wall, floor and roof constructions is given in Tables 2, 3, and 4. The connection between column and window is shown in Figure 3.

The calculated U-value of the wall amounts to 0.10 W/mK for a thickness of 70.5 cm. The windows consist of low-e, gas filled triple glass mounted in an improved window frame, giving a U-value of 0.8 W/(mK). In accordance with the passive house guidelines, the glazing areas are mostly oriented to the south (the sun-side in the northern hemisphere), whereas other facades have limited glass percentages, just to get an acceptable daylight level. The ratio of window areas to façade areas (transparency ratio-TR) in each direction is given in Table 5.

The temperature of the incoming ventilation air is first stabilized in an earth to air heat exchanger (length 40m., depth 2 m., diameter 180 mm) and passes then through the heat recovery unit of the balanced ventilation system. Domestic hot water and additional comfort air heating.is assured by a heat pump which uses the exhaust air as heat source (Figure 4). When there is no domestic hot water demand, all heat is used to preheat the incoming air which passed the heat recovery unit. Neither solar hot water panels nor PV panels are used in the house.

The house was built and made wind-and airtight in the summer of 2005. The measurements started during the finishing phase (autumn 2005). To see the impact of the outdoor temperature on heating consumption, a cold period in December was chosen. Since the house was not used by the owner during the measuring period no electricity was consumed neither for domestic hot water nor for lighting and household appliances.

Measurements

The passive house concept heavily relies on an extreme reduction of the transmission losses by means of very high

Table 2. Façade Walls (From Inside to Outside)

Material	Thermal Conductivity of the Material (λ Value), W/(m·K)	Thickness, mm
Plaster	0.52	15
Brick	0.24	190
Mineral wool/ wooden frame	0.15/0.037	60
Mineral wool/ wooden frame (I beam)	0.15/0.20/0.037	300
Fibre board (MDF)	0.050	22
Tiles+mounting wooden slats	0.025	118
U-value (W/m^2·K)	U=0.10	d= 705 mm

Table 3. Floor on Grade (From Inside to Outside)

Material	Thermal Conductivity of the Material (λ Value), W/(m·K)	Thickness, mm
Reinforced concrete	1.7	200
Insulation	0.028	240
Reinforced concrete	1.7	120
U-value (W/m^2·K)	U=0.11	d= 560 mm

Table 4. Pitched Roof (From Inside to Outside)

Material	Thermal Conductivity of the Material (λ Value), (W/m·K)	Thickness, (mm)
Plaster	0.52	5
Gypsum board	0.35	12.5
OSB board	0.12	12.5
Mineral wool/ wooden frame (I beam)	0.15/0.20/0.037	400
Fibre board (MDF)	0.050	22
Tiles+mounting wooden slats	0,018	118
U-value (W/m^2·K)	U=0.09	d= 570 mm

insulation thicknesses, while air leakage across the envelope may not exceed 0.6 ACH at an air pressure difference of 50 Pa. Therefore, a a blower-door measurement was done first, followed by a long-lasting co-heating test to get an idea of the thermal response of the building envelope. Additionally, to detect thermal defects, infrared scans were taken.

Airtightness (Blower Door Test). A blower door test is performed by certified energy auditors using a flexible front door system with a certified variable-speed fan. All windows

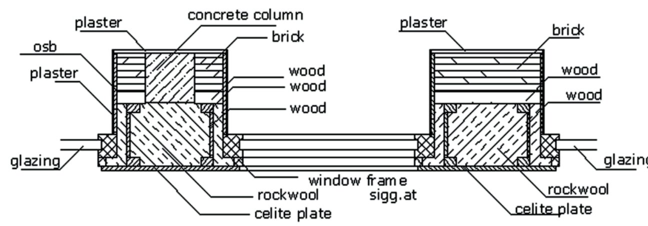

Figure 3 *Columns and window frame details.*

Table 5. Transparency Ratios (TRs) of the Facades

Facades	North	East	South	West
TR %	19	15	32	19

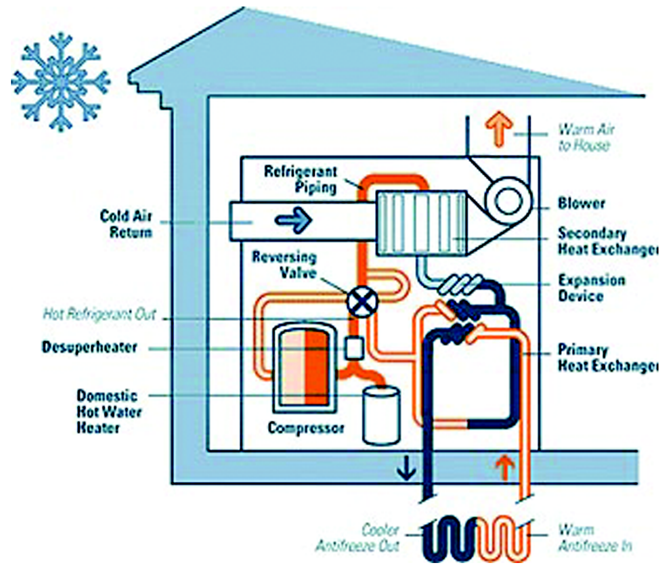

Figure 4 *Heat pump.*

and doors are closed, and the system with fan is installed in the front door. The fan sucks air out of the dwelling, lowering the air pressure inside. The higher outside air pressure then causes air flows through all cracks and openings. Once the fan is turned on, the energy auditor monitors stepwise the airflow through the fan, as well as the air pressure difference between the outside and the inside space. By measuring several sets of air pressure difference/air flow data, the infiltration characteristic of the dwelling can be determined and the air flow through the envelope at 50 Pa calculated. The main characteristics of the measurement are summarized in Table 6. The results given in Figure 5 indicated a n_{50}-level (air changes per hour at a pressure difference of 50 Pa between inside and outside) of 0.24 ACH. That should be interpreted as "extremely airtight". Consequently, infiltration losses and energy needed for heating up the infiltrating air are reduced to an absolute minimum. On the other hand, when the ventilation system breaks down, such an airtight envelope will not let any fresh air enter the building. In order to prevent the indoor air from polluting, or worse, the inhabitants from suffocating, natural ventilation should always be possible, e.g., by means of trickle vents.

Co-heating. The building envelope separates the indoor environment from outdoors. That way, a direct effect of the outdoor climate on the living conditions inside is prevented or modified. To give an example, according to its storage capacity and its insulation resistance, the building envelope scales the heat flow to and from the outside. A co-heating test allows evaluating that overall thermal performance, in the case for an envelope who combines an excellent thermal insulation, some thermal storage in the inside masonry leaf and non negligible solar heat gains,. In such co-heating test, an electrical heater with proportional control is used to keep the building at constant temperature during several weeks. During that period, outdoor conditions, the electrical energy consumed by the heater and inside temperatures are logged continuously and stored on hard disk. Temperatures inside were measured at two different levels in the dwelling. Six thermocouples were mounted at a height of 2m.10 at four different spots in the lower zone of the building whereas a 7th thermocouple was placed in the upper zone at 5m.05 height. The main characteristics of the measuring set-up are summarized in Table 7. The measuring points and the location of the electrical heating device are shown in Figure 6. During the measurements, all systems in the house were shut down. The test ran over a total of 24 days. As it was not in use, no effects of occupants should

Table 6. Blower Door Test Characteristics

Airflow at 50 Pascal	182 m^3/h (+/- 1.3%)
Leakage areas	65.1 cm^2 (+/- 7.3%) Canadian EqLA@10 Pa 32.9 cm^2 (+/- 11.6%) LBL ELA@4 Pa
Test Standard	EN 13829
Test mode	depressurization
Equipment	Model4 (230V) Minneapolis Blower Door
Inside temperature	20^0C
Outside temperature	7^0C
Inner volume	743 m^3
Outer volume	1153 m^3
Surface area	565m^2
Floor area	152m^2
Barometric Pressure	101325 Pa
Wind Class	3 gentle breeze
Building wind exposure	Highly exposed building
Type of heating	None
Type of air conditioning	None
Type of ventilation	Balanced ventilation with heat recovery

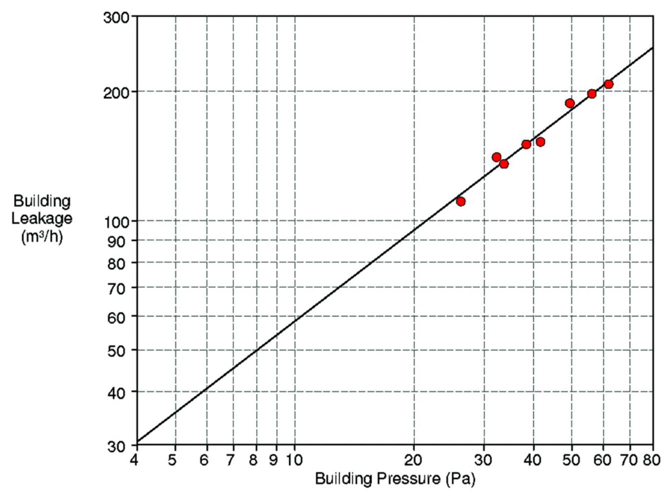

Figure 5 *Building leakage characteristic.*

Table 7. Measuring Setup

Electrical Heating	Heater with a power of 1330 W and 6 IR-lamps of 200 W, placed in 2 points on the main axis of the building. All regulated by a proportional controller, the energy consumption registered by a pulse counter
Electricity counter	100 pulses/kWh, Measures the energy consumption of the electrical heaters
Indoor Climate	temp +RH 10'
Regulator	Proportional temperature control,,, control temperature 0-50 ^{0}C with accuracy of 0,1 ^{0}C, set temperature 20/25 ^{0}C, band with 0,2 ^{0}C
Data logger	With 8 thermocouples channels, 8 voltage/current channels, 2 pulse counters channels. **Used:** 7 thermocouples channels, 1 voltage channel for the solar intensity sensor 2 pulse counters for the energy use counters
Thermocouples	Type T, copper-constantan, (-200 to 400 °C with accuracy of 0,2°C)
Outdoor Climate	temp +RH 10', solar intensity sensor measuring total horizontal radiation averaged every 10'

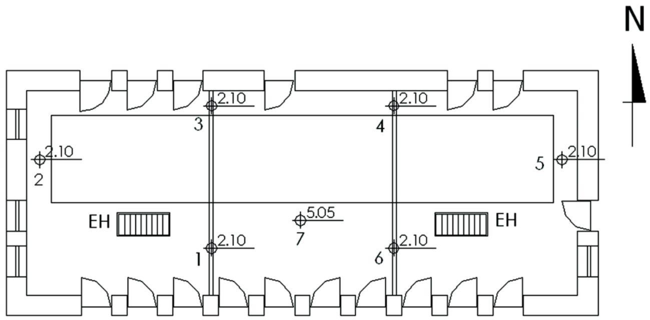

Figure 6 *Measurement points in the passive house.*

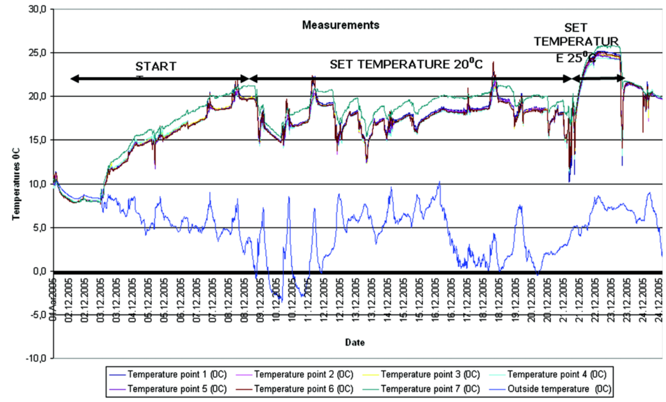

Figure 7 *Temperatures profile in the building: measurements.*

be detected on the measured temperatures. This, however, was not the case.

The measured temperature profile in the building is shown in Figure 7.

The measured results can be described in three periods.

1. Starting period with additional power, (1-6 December)
2. Period with a set temperature of 20°C for the indoor environment (6-21 December)
3. Period with a set temperature of 25^0C for the indoor environment (21-23 December)

The indoor climate got disturbed several times during the measurement period. The large inside temperature changes during the second period for example are due to unexpected activity in the dwelling. That activity was accompanied by intense door usage, causing considerable outside infiltration. From Figure 6, we learned that,

- The occasional daily peaks in temperature above the set temperature are caused by solar gains. At these moments the net energy demand of the building becomes so small that the solar gains are greater than the transmission losses, inducing an elevated temperature above the thermostat set point. During the second period, only two times (8-9 December and 18-19 December) the set temperature (20^0C) was logged in all measuring points whereas during the 3rd period, the set temperature (25^0C) was obtained in all measuring points(22-23 December).
- Apart from these short periods of stable conditions and apart from the unsettled periods, the six measuring points at 2.1 m gave readings below the set point temperature of 20°C whereas the temperature in the 7th point situated at 5m.05, met the set point value.
- Since no ventilation occurred in the building during the periods of non-activity, thermal stack was a dominant phenomenon.
- The building was treated as a single zone. However, measured average temperatures in the south oriented half of the box, which captured sunlight (points 1 and 6) were slightly higher (0,1-0,6^0C) than the measured average temperatures in the north oriented half of the box (point 3 and 4).
- Clearly the heat was not evenly distributed. The reason for that was stratification of the warm inside air due to stack effects. The upper zone (point 7) shows higher temperatures (0,4-1,8^0C) in comparison with the lower zone (points 1,2,3,4,5 and 6).
- If the test could have been repeated without any disturbance, temperature distribution in the building should have been more homogenous.

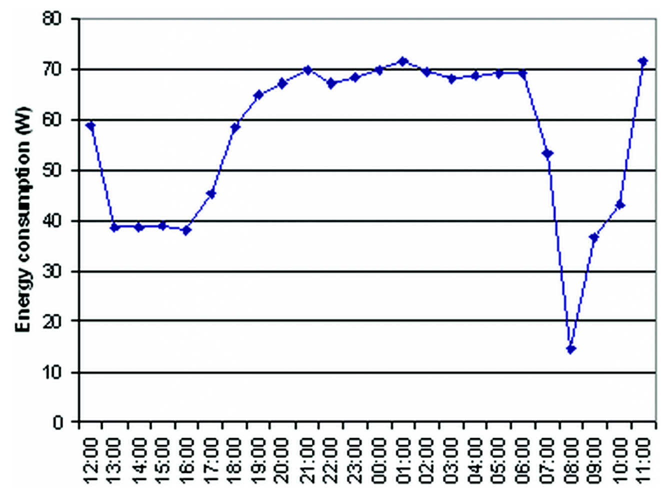

Figure 8 *Day profile of electricity consumption.*

To measure the total energy consumption in the passive house an electricity counter was used. For the electricity consumption, daily profile of a stable segment (8-9 December, with a set temperature 20°C) can be derived (Figure 8). From these data the energy consumption for heating is derived using the climatic data for Deinze. As a result the energy use for heating amounts to 26,9 kWh/m/yr is more than the passive house criterion of 15 kWh/m/yr. The amount of the energy consumption is a result of additional power caused by the disturbance of the measurements.

If the test was less disturbed, then, with the indoor air temperatures and several parameters of the outdoor climate measured, a least square analysis using the following Equations 1 and 2 could have produced a fair guess of the insulation quality of the building.

$$Q_{heat,\,use} = max[0, Q_T + Q_V - (Q_S + Q_I)]$$

$$Q_T = U_m A_T(\bar{\theta}_i - \bar{\theta}_e)\Delta t$$

with Q_T the transmission losses, [MJ/day], Q_V the ventilation losses [MJ/day], Q_S the solar gains [MJ/day], represented by total solar irradiation on the horizontal surface Q_I the internal gains, [MJ/day], $Q_{heating,\,use}$ required heat supply to maintain the indoor temperature at set point value (MJ/day), θ_i-θ_e the daily mean difference in external/internal temperature [°C], and A_T the heat loss surface [m^2].

As is shown in Equation 2 the average U-value can be derived from the estimated transmission losses. Further simplifications of the equations are justified: A Blower Door test showed that the air tightness of the building so high that the infiltration losses at real pressure differences (0-3 Pa) are negligible. Also the internal gains should have been zero, but, are not, because of the unexpected activity in the dwelling.

Using daily averaged values (excluding the days when the indoor climate was disturbed), a least square analysis produced the following correlation factors:

1. between energy consumption by the heater and external temperature, r = 0.615
2. adding solar radiation, r increases to 0.621
3. taking into account the inside temperatures, r = 0.71.

The average U value is derived from a least square linear relation between electricity consumption and inside temperature, outside temperature and solar radiation. For the calculation of U_m external dimensions were used. That way, all geometrical thermal bridges are included. This is a most common method. The average U value is calculated using the regression coefficient of the external temperature (0,109 W/mK).

Simulation

The simulations had as objective to compare the results of the co-heating test with the calculated thermal performance of the building, when subjected to the same outdoor conditions. The calculations were done using the steady-state three dimensional building simulation program Physibel-Trisco. The building was treated as a single zone with only the envelope as loss area. A quarter of the building, containing all elements with an important impact on the performance was simulated. The temperature beneath the floor slab is assumed to be equal to 10^0C, the annual mean external temperature in Belgium. The details of the façade walls and their connections with the foundation, the floor and the roof, which is simplified to a low slope roof, the windows and the columns, are shown in Figure 9. This corner is representative for the whole building. During successive simulation, the heat flow through the selected section was determined to calculate the average U value. Calculations were stepwise simplified, for example, by omitting the concrete columns between the windows. Both cases in fact gave the same mean U-value (0.12 W/m^2K).

The global thermal performance of the building turns out to be even better than expected according to the calculated level. When using the gross area the calculated U value exceeds the upper limit of the 90% reliability interval formulated for the measurement data. This indicates that the calculation method overestimates the heat loss through all two dimensional and three dimensional details. This conclusion seems reasonable since there is large difference between inner and outer dimensions of the passive house.

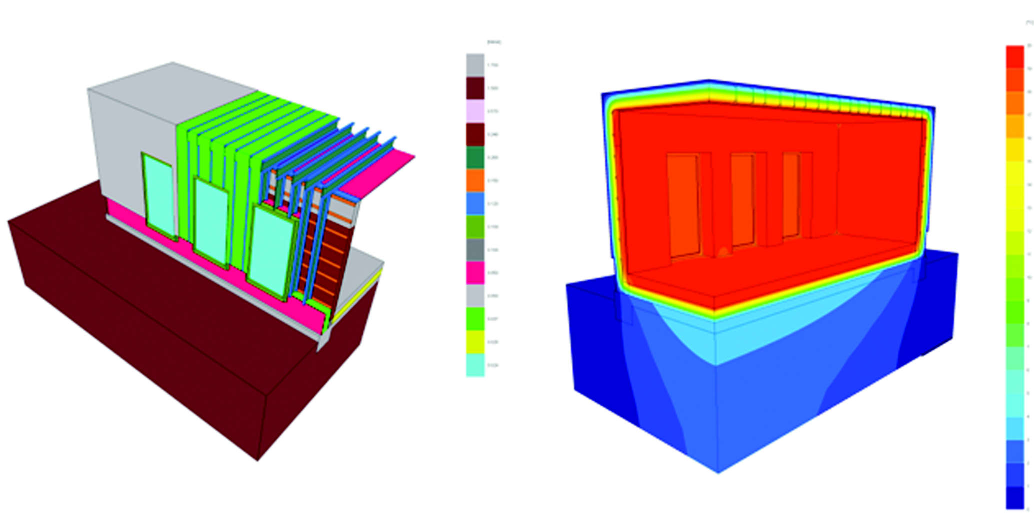

Figure 9 *The corner modelled with the different materials and thermal bridges on the model of the passive house.*

Thermographic Inspections (Infrared Camera). Infrared thermography allows evaluating thermal quality and air tightness of a building envelope. The technique has been used to detect thermal defects and air leakages in the envelope of the passive dwelling under scrutiny. An infrared camera sees the electromagnetic waves in the infra red range. As Figure 10 shows, temperature variations ranging from white for warm regions over red, green, yellow and blue to black for cooler areas were seen from outside. The openings have a temperature lower than the rest of the envelope. The areas of the building made with lighter materials show this change in temperature. They appear colder than the areas made of heavy materials like the walls. However the blue appearance of the highest window and the green color of the upper parts of the lower windows are the result of long wave reflection of the sky in the glass. So, a different color means different thermal behavior of the wall. The zones with a lighter color are colder than the dark zones (under the eave of the roof, wooden structure of the building). The picture learns that the west façade of the passive house hardly looses any heat.

Thermographic scans were also made with the blower door running. That way, air leakage through defects in the envelope is exaggerated as visible in of Figure 11. In that figure, some of the different thermal behavior between the two columns may also be due to the construction material used. The column t the left is made of concrete, the one at the right is brick masonry.

CONCLUSION

Energy consumption for heating is strongly reduced in the passive house tested, by taking several measures such as an extreme insulation, avoidance of thermal bridges, minimized losses due to infiltration and ventilation and quite an effective utilization of the passive solar gains in the living zone. Although each of these measures has a positive impact, the success of the passive package lies in the combination of all of

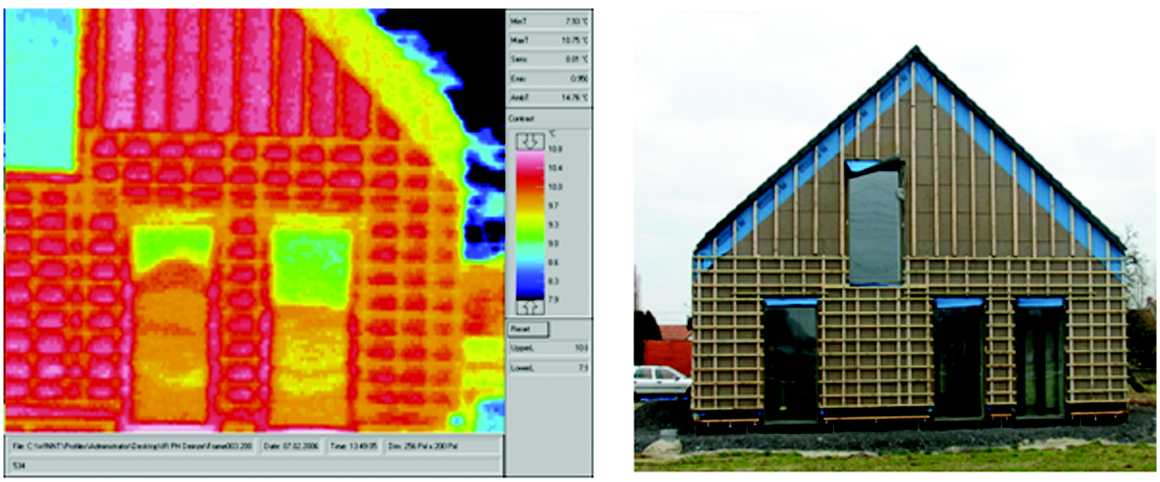

Figure 10 *Thermal and visual images of the west façade of the passive house Deinze.*

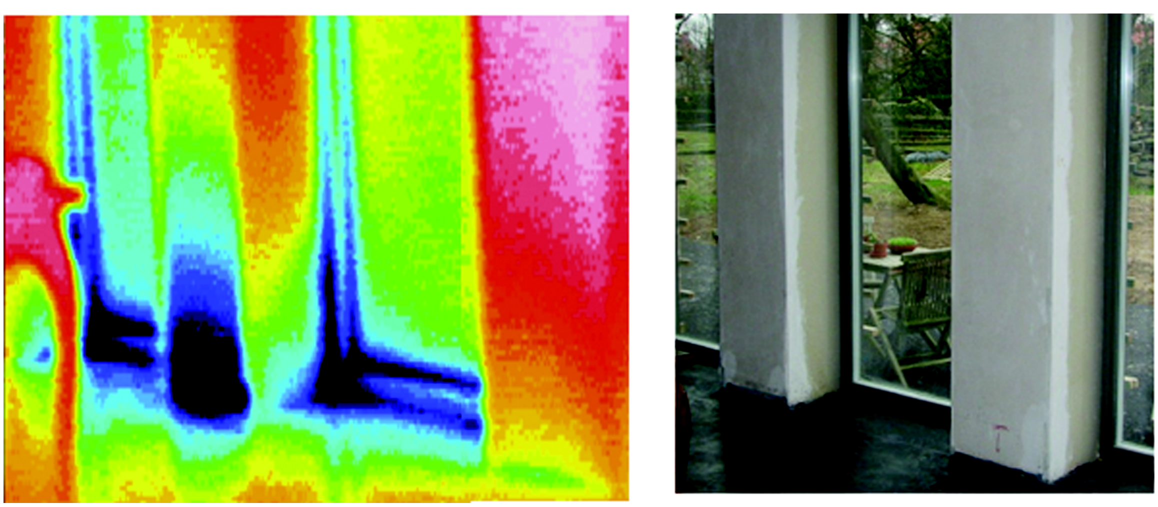

Figure 11 *Columns of the passive house Deinze.*

them and their translation in a performance based design brief. The passive house at Deinze fairly comply with the formulated target values most of the time.

Nevertheless, some improvements are still possible. The energy consumption is highly effected by the disturbance of the measurements. Thus, no effects of occupants should be detected on the measurement conditions. As regards thermal comfort, during wintertime the measured indoor temperatures in the living zone were rather low, although a set point of 20°C was maintained. The value was only met in the upper zone. One should also evaluate the performance in summer. Probably additional measures to avoid overheating such as solar shading and a regulation of the ventilation system for summer conditions, may eliminate the problems one could expect in the dwelling as it is now. And finally there is a need to evaluate the long-term performance of these passive buildings in order to quantify a mean final and primary energy consumption over the years (included energy consumption for domestic hot water and household appliances)

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