FIELD EXPERIMENTS ON THE USE OF PHASE CHANGING MATERIALS, INSULATION MATERIALS AND PASSIVE SOLAR RADIATION IN THE BUILT ENVIRONMENT

A.G. ENTROP Eng.[1]
H.J.H. BROUWERS Prof. Dr. Eng.[1]
A.H.M.E. REINDERS Dr.[2]

[1] Department of Construction Management and Engineering, University of Twente, Enschede, Overijssel, The Netherlands, a.g.entrop@utwente.nl, h.j.h.brouwers@utwente.nl
[2] Department of Design, Production & Management, University of Twente, Enschede, Overijssel, The Netherlands, a.h.m.e.reinders@utwente.nl

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Summary

This paper describes the development of an experimental research facility to assess the effectiveness of Phase Change Materials (PCM), that can be used for passive solar heating. Four test boxes are constructed representing the conventional and future Dutch building practices regarding insulation and glazing. In the future scenario materials to cover walls and floors in the test boxes will be partly filled with PCMs. In this paper the theoretical framework of thermal behaviour of PCMs in buildings, the realisation of the experimental set up and the design of the monitoring system will be explained.

1. Introduction

During the last decade many energy saving concepts have been developed to enable sustainable building design. In Western Europe, with its moderate climate, passive solar energy forms the most promising measure for reducing the consumption of fossil fuels for heating of houses. Traditionally the (Dutch) building designs were not optimized for using solar energy. With the introduction of the Energy Performance Coefficient in December 1995 as part of the formal Building Code (Staatsblad, 1995) the use of passive solar energy became indirectly more appreciated. This paper results from the research project on “exergy in the built environment” at the University of Twente. Within this research project the adoption of conventional energy saving measures and future low cost measures, such as passive solar energy, in building processes are important issues.

On first sight The Netherlands does not seem suitable for passive solar heating, because the average outside temperature of 9.5 °C is relatively low and the incoming solar radiation on a windowpane of, depending on its orientation, is just 1,313 to 2,881 MJ/(m^2·y) (364.7 to 800.3 kWh/(m^2·y)). However, the passive use of solar radiation offers many opportunities in low exergetic heating applications. In common Dutch houses solar irradiance enters the room by large windows oriented to the south, therefore less heating and electric power will be used. Solar irradiance will mostly be transmitted and a small part will be absorbed or reflected by the glazing. Behind the glazing the air in the room will absorb a small part of the energy, before irradiance will be absorbed by the floor covering and constructions beneath it. On the north side of the buildings it is common to install smaller windows than on the south side, since the energy losses by outside transmission are larger than the input of irradiance. Not much is known though about the heat absorption capacity of the interior of buildings and the speed of release of captured solar heat for interior heating during cold evenings or nights.

The specific energy performance of glazing and windows has been regarded by Nielsen et al. (2001). He perceived the issue as a combination of thermal transmittance and total solar energy transmittance. However, it might be more accurate to consider the actual energy performance of glazing and windows within the building design in relation to the absorption factors and heat capacity of the materials used in the interior of the building.

Three major factors to be considered are:

1. The absorptivity of the internal constructions of a building, for example materials used, thickness or mass of internal construction parts, installation of extra internal heat absorption walls, color of the interior, and introduction of Phase Change Materials (PCM, e.g. Peippo et al., 1991, Nepper et al., 2000, Nagano et al., 2006, Shilei et al., 2007);

2. The absorptivity of the external constructions of a building in which the distance of the insulation to the outer surface of the exterior wall and the mass in this section can be regarded (e.g. Yumrutaş et al., 2007);
3. The internal transport system for heat which is normally used to convey heat to the rooms, but in some cases it can be used to stabilize the temperature through the whole object by conveying heat from the one room to the other.

Being substances that are able to store latent heat PCMs might improve the first factor: the absorptivity of the internal constructions. Thermal energy transfers in PCMs take place during melting and solidification (Sharma et al., 2008). Inorganic (e.g. salts) and organic (e.g. paraffins and fatty acids) substances can be suitable to be a PCM (Zalba et al., 2003). Because little is known about the application of PCM and their potential to save exergy[1] within building designs, this paper describes the development and execution of an experimental research project on the use of PCM in concrete floors and gypsum plasterboards. They will accumulate solar energy to obtain a constant indoor temperature during day-night cycles.

The use of a latent heat storage system, which PCMs provide, is an effective way of storing thermal energy (Sharma et al, 2008). Research on the use of PCM in energy-storing wallboard of Chen et al. (2008) shows that energy savings for heating a room are starting at 10% or 17%, and higher percentages are conceivable. In this paper an experimental setup is presented that can be used to gain more insights in the effectiveness and efficiency of these measures. The results of this research can help to improve the energy performance of both new and existing buildings.

In the second section of this paper the background on the use of solar radiance in Dutch dwellings will be given. After that the development of the test boxes will be explained in which the dimensions and used materials will be considered. In the fourth section the test site will be addressed in close relation with the monitoring system that is explained in the fifth section. Finally, the conclusions, recommendations and prognosis on future research will be elaborated on.

2. Basic assumptions in researching solar radiance in Dutch dwellings

The goals of the proposed experiment are to gain insights and data on how solar radiation can be absorbed, buffered and distributed effectively and efficiently within the building shell and how this thermal energy affects the indoor temperature. Before developing an experimental setup to achieve this goal, the following specific considerations need to be stated regarding the thermodynamic aspects of Dutch houses:

- The living room is regarded as the most important room within residential real estate from an energetic point of view. In this room the radiators are controlled by one thermostat that often regulates the working of the heating system for the whole house. The experiment will focus on simulating this space. The inside temperature is in Dutch standards fixed to 18 °C for the heating season. The necessity to cool the building exists, according to Dutch standardization references, when the indoor temperature rises above 24 °C (NNI, 2005);
- The residential building stock in the Netherlands, consisting out of 7 million houses, offers enormous possibilities to save energy. The characteristic row house will be used as point for departure for simulation. This means that in theory there will be no heat transmission to the neighbours. The Dutch agency for sustainability and innovation, SenterNovem, has specified six different residential real estate reference objects to use for energy analysis, of which one constitutes the considered row house (SenterNovem, 2006);
- The ceiling of the ground floor is normally not insulated and consists most of the time solely out of a concrete hollow-core slab with a height of 200 mm. In dwellings where the floors are carried by wooden beams, plasterboard is sometimes used to finish off the ceiling.
- In existing houses the ground floor, roof and walls are often insulated. Starting from 1992 it is compulsory to install insulation in the building shell with $R \geq 2.5$ ($m^2 \cdot K$)/W, but many older houses have been refurbished by installing floor insulation with the same heat resistance. Nowadays insulation with $R = 3.5$ to 4.0 ($m^2 \cdot K$)/W is often applied in the floor and roof of new houses.

The feasibility of the proposed experimental research can be demonstrated by using standardized Dutch figures on solar radiation (NNI, 2004) and the specifications of a standardized reference dwelling for new row houses (SenterNovem, 2006). The energy balances at the glass surface on the south side, north side and roof are shown in Figure 1. On a yearly base more than 33,000 MJ (= 9,167 kWh) of solar radiation could enter through the windows of the referred standard house. The thermal resistance of windows is however quite low ($U = 1.8$ W/($m^2 \cdot K$)) compared to the insulated walls of new buildings. Therefore, more than 11,000 MJ will leave the building, when the temperature inside is set to be 18 °C and average outside temperatures

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[1] The concept of exergy is used, because it can better express the effect of low temperature heat and the qualitative difference between solar irradiance and fossil fuels than energy.

are taken of 2.5 to 17 °C (depending on the month). Nevertheless, even in The Netherlands the gains (33,000 MJ – 11,000 MJ = 22,000 MJ) are not negligible and can especially during spring and autumn in houses offer great opportunities to reduce the natural gas consumption. Natural gas is the most commonly used fossil fuel to heat houses in the Netherlands. Figure 1 also shows that during winter solar radiation through glazing will not surpass its heat transmittance and that during the summertime a large surplus is available demanding additional measures. With these considerations in mind the setup for the experiment is further developed. The living room of a standard Dutch row house will be modelled in the form of a test box.

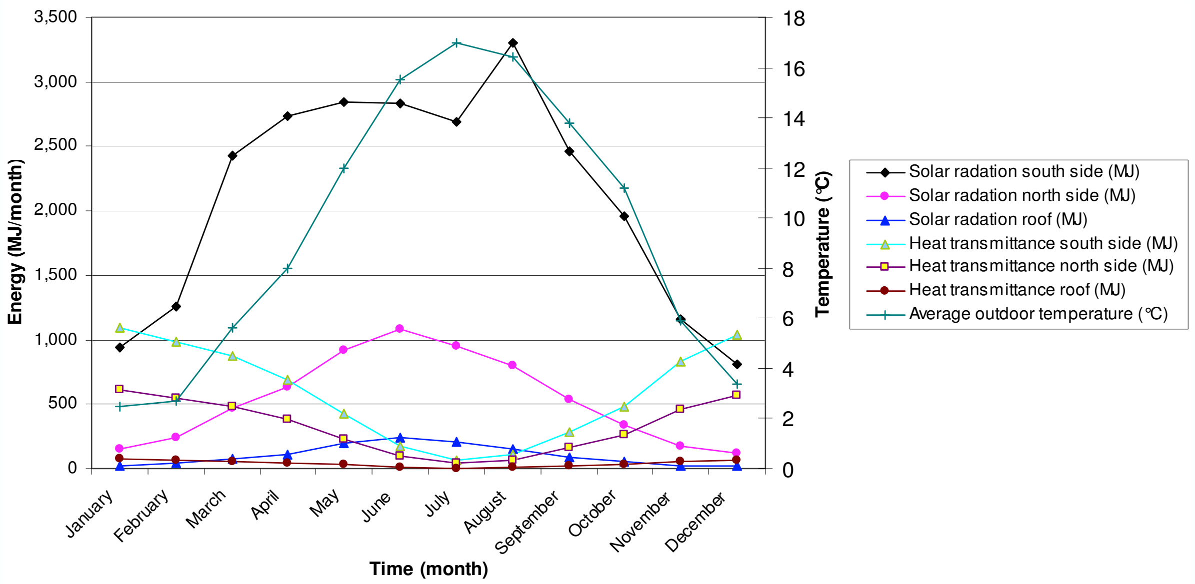

Figure 1 Accumulated monthly solar radiation and heat transmittance through glazing into a standard Dutch row house (computations are based on NNI, 2004 and SenterNovem, 2006)

3. Development of the test boxes

In the field of building physics only little research has been published about experiments with test boxes. The use of test boxes for an experimental study of PCM has for example already been described by Kissock et al. (1998). The dimensions of such a box are essential to represent real buildings. In the calculations on the heat capacity of buildings by Nishikawa and Shukuya (1999), the volume of the researched system seemed to be too small. Desta et al. (2005) used in their research on heat phenomena a whole chamber. In this case it was fully constructed out of plexi glass to have a clear view on the ventilation flows. In this paragraph, first the size of the test boxes will be discussed. Secondly, the materials that are involved in constructing the test boxes are addressed.

3.1 Size of test boxes

Because the experimental research has to represent phenomena in real sized houses, the sizing of the test boxes has to be considered. However representative down-scaling of both volumes and surfaces is limited by differences in their scaling factors which are based on resp. cubed and squared relations. The area of surfaces, walls, windows and floors in our test box in relation to the volume of the test box can not represent real(size) houses or living rooms. This will result in a floor surface that is relatively large in relation to the volume of the test box compared to a real size dwelling. This means that the capacity to store heat of a real size living room should be larger than the capacity of the test box. Because of the manageability of the setup, the size of the test field, costs and time restraints, it is obvious that real size testing was not possible and therefore scaling is necessary. The references for the dimensions of the scaled boxes are the living room of the standardized row house of SenterNovem (2006) and the test boxes used by Kissock et al. (1998).

The ground floor of the row house has a surface of 8.92 m by 5.10 m (l × w). The living room takes 26.1 m^2 of the ground floor. The adjacent window in the southern façade of the reference house is 4 m long and 2.4 m high. The internal height of the first floor is 2.6 m. The sizes of the test boxes of Kissock et al. (1998) are 1.22 m x 1.22 m x 0.61 m (l × w × h). To approximate these sizes the test box could be built on a scale of 1 to 5. In that case the size of the test box should be 1.024 m x 1.020 m x 0.520 m (l × w × h). A plastic container with sizes that approaches these dimensions is used as a base for the test boxes (see Figure 2). These dimensions will result in an air volume that is 115 times smaller and a floor surface that is thirty times smaller than the original living room. The impact of this down scaling is expected to be relatively small, because the mass of air and heat capacity per kilogram are low compared to the mass and heat capacity of the floor.

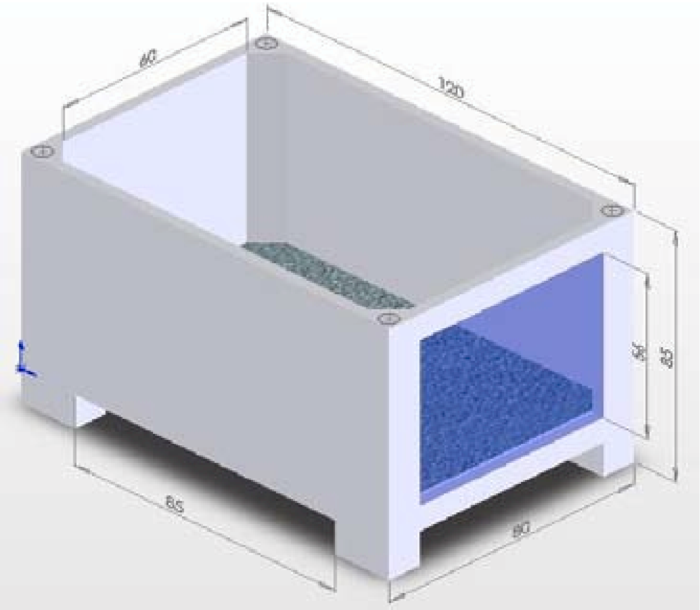

Figure 2 The basis for the test box will be a plastic container (dimensions in cm).

3.2 Materials for the test boxes

The experiment will focus on thermal exergy flows resulting from exposure to solar radiation. The boxes will have at one side a window to let solar energy in. All other sides will be strongly insulated to mimic adiabatic conditions. In this paragraph the materials to construct the test boxes will be specified.

3.2.1 Glazing

The front side of the test box will consist out of 0.36 m^2 glass. Nowadays in Dutch building practice high performance glazing is used with a U-value of approximately 1.2 $W/(m^2 \cdot K)$ and a g-value of 0.60. Window frames of wood or plastic have a higher U-value than the glass; approximately 2.4 $W/(m^2 \cdot K)$. For windows an overall U-value of 1.8 $W/(m^2 \cdot K)$ results (NNI 2004, SenterNovem 2006). The conductivity of the glazing in the test boxes will be 1.1 $W/m^2 \cdot K$ and 0.5 $W/m^2 \cdot K$ to reflect on the standard Dutch situation and best practice situation. Based on the size of the windows computations on the overall U-values led to 1.3 $W/m^2 \cdot K$ and 0.6 $W/m^2 \cdot K$ respectively, their glazing have g-values of 0.47 and 0.60 respectively.

3.2.2 Insulation materials

Five sides of the box will consist of a hard insulation material. In this experimental setup fibreglass insulation or mineral wool are not desirable materials, because the homogeneity of the material and a fixed thickness can not be guaranteed after their installation. Furthermore, the heat resistance of these soft materials can unintentionally be lowered by the absorption of rainwater. Therefore a hard and heavy insulation material being cellular glass will be used with a thermal resistance of 3.81 $(m^2 \cdot K)/W$.

In Europe there is a debate on the effectiveness of light insulation products compared to heavy forms of insulation. Our research will contribute to this debate by using also a light form of a homogenous insulation. This product consists of fourteen thin layers of reflective and insulating materials. The producer claims that this product has a R-value of 5.6 $(m^2 \cdot K)/W$, when on both sides a cavity is applied of at least 20 mm deep. The exterior of both types of boxes will be finished by using plywood of 15 mm. They will be painted white, because of its high reflection and low absorptivity.

3.2.3 Phase Change Materials

Sharma et al. (2008) distinguishes three main groups of PCM: organic, inorganic, and eutectic. Within the group of organic PCM there are two different types: paraffin and non-paraffin compounds. In our research a mixture of paraffins in powder form encapsulated in polymethyl methacrylate microcapsules will be used, that has a melting point of 23°C (BASF, 2005). This micro encapsulated PCM has already been used in gypsum board that is also able to store heat, and that will be used to cover the interior of the test box with exception of the floor and the window frame.

The same micro-encapsulated PCM (Micronal DS 5008 X) will be used to increase the heat capacity of the concrete floor (see Table 1). The amount of PCM in the concrete mixture will firstly be determined by computations on the amount of heat entering and leaving the box. The first target to be set is to avoid temperatures below 0°C. More favourable is a higher target to maintain an indoor temperature of at least

15℃ and 25 ℃ at maximum. Based on local irradiation and temperature data of 2007, the specifications in Table 1, and the dimensions and materials of the box, the concrete floor needs to store at least 3.2 MJ and the PCMs in the concrete floor and gypsum walls needs to store at least 1.4 MJ. This means a floor with a height of 60 mm containing 5 % of encapsulated PCM and 2.7 m^2 of gypsum board having a latent heat of approximately 330 kJ/m² (Knauf, 2006) will be installed.

Table 1 Specifications of the materials involved in the experiment that are able to store heat

	Latent heat capacity (at room temperature)	Specific heat capacity	Bulk density
Concrete	0 KJ/kg	3.3 KJ/(kg·K)	2,400 kg/m^3
PCM	110 KJ/kg	Negligible	250-350 kg/m^3
Gypsum board	0 KJ/m^2	0.85 KJ/(kg·K)	700 kg/m^3
Gypsum board	330 KJ/m^2	1.20 KJ/(kg·K)	770 kg/m^3

Compressive tension tests will demonstrate the impact of this 5 % Micronal on the strength of concrete. It is possible that during the hardening of concrete the Micronal already avoids temperature peaks due to cement hydration heat. This could offer great advantages, when large amounts of concrete are needed. A case (see Fig. 3) was developed to store four concrete cubic moulds during hardening. To approach adiabatic conditions during temperature monitoring this case is closed and well insulated.

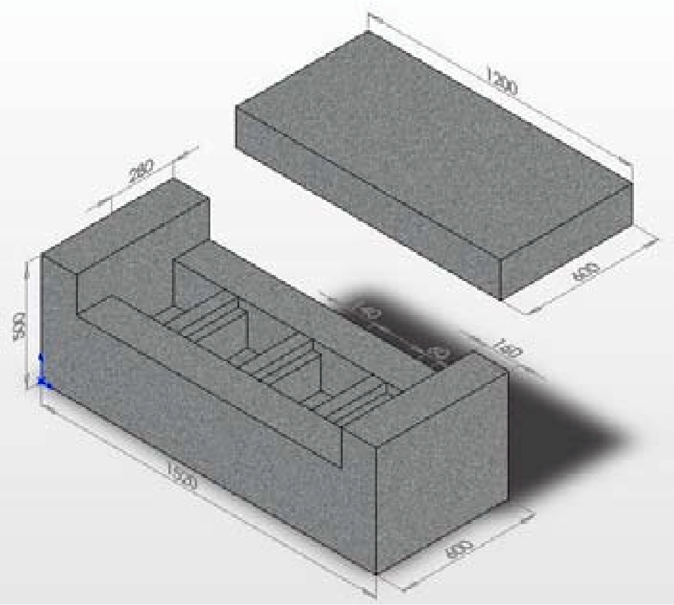

Figure 3 Case to monitor the temperatures of four molds of concrete during hardening (dimensions in mm).

4. Test site

Based on the different materials that need to be tested, four different test boxes will be constructed with the characteristics that are summarized in Table 2. These boxes will be placed outdoors on a test site for a whole year. This enables monitoring of the behaviour of the box and the materials during all seasons. The test site (see Fig. 4) will be located at the Campus of the University of Twente (Enschede, The Netherlands). To give an impression of the solar irradiance at this university Figure 5 shows the daily irradiance on a clear sunny day on different facades of a building. To make sure that there are no obstacles, which can cause shading, the boxes will be placed 2.5 metres above ground level in an open area. A weather station (WS) will be installed behind the boxes to measure the weather conditions.

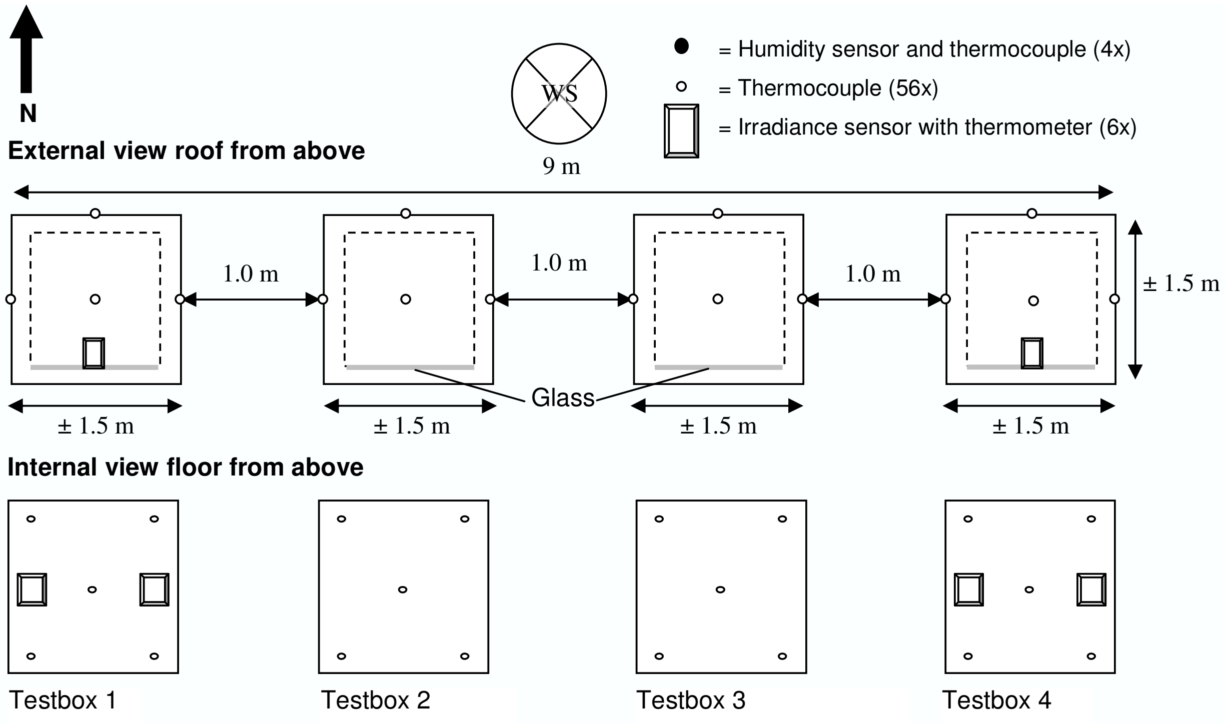

Figure 4 Layout of the test site with an external (roof) and internal (floor) view of the four boxes with their sensors.

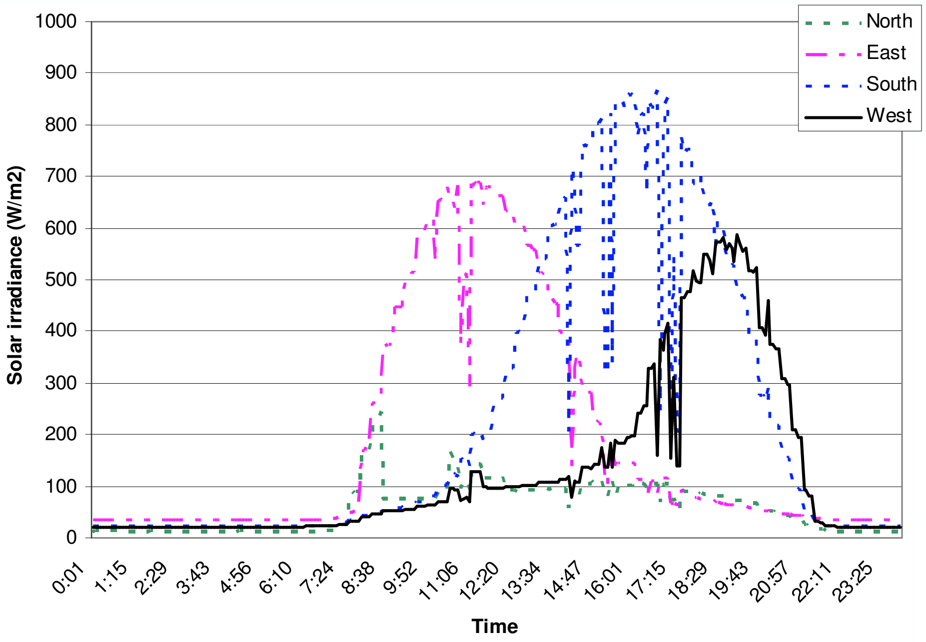

Figure 5 Solar irradiance on a sunny clear day at the four facades of one of the buildings of the University of Twente. Total irradiances are: North 1.41 kWh/m^2, East 4.39 kWh/m^2, South 5.57 kWh/m^2, and West 3.09 kWh/m^2 (measurements collected on April 26th, 2007).

Table 2 Building physical constitution of the test boxes in the experimental setup

	Testbox 1	Testbox 2	Testbox 3	Testbox 4
Insulation material (thermal resistance)	Cellular glass 3.8 $(m^2 \cdot K)/W$	Cellular glass 3.8 $(m^2 \cdot K)/W$	Light 5.6 $(m^2 \cdot K)/W$	Light 5.6 $(m^2 \cdot K)/W$
Phase Changing Materials in concrete floor (weight percentage)	Present ± 5%	Absent 0%	Present ± 5%	Absent 0%
Thermal resistance glazing (thermal transmittance)	High 1.1 $W/(m^2 \cdot K)$	Low 0.5 $W/(m^2 \cdot K)$	High 1.1 $W/(m^2 \cdot K)$	Low 0.5 $W/(m^2 \cdot K)$

5. Monitoring system

The boxes will be continuously monitored with a sampling interval of 5 minutes. On top of the floor the surface temperature will be measured at five different points. The surface temperature at the underside of the floor will also be measured. Two thermocouples will be located in the middle of both sides, in the middle of the roof and in the middle of the backside. In the middle of the box the humidity degree and temperature are measured. The temperatures at the internal and external sides of the glazing will also be measured. In total twenty thermocouples will be used per box (see Figure 4). Data acquisition will take place by using two USB TC-08 of Pico, two USB 6218 (offering 32 channels each) and two USB 6215 (offering 16 channels each) of National Instruments. Two personal computers will be used to store this data.

All thermocouples will be made out of 400 metres Teflon insulated TX wire. The amount of solar irradiance is measured by six silicon irradiance sensors type Si-01 TC-T of Mencke & Tegtmeyer placed horizontally on top of and within the test boxes. These irradiance sensors each have a sensor to measure their temperature. The humidity of the air inside the boxes will be measured by four A05 Basic Capacitive Humidity Modules with sensor type P14 SMD of LinPicco. The weather conditions are measured by a WS. The weather station is a Vantage Pro 2 of Davis Instruments with thermometer (℃), humidity meter (%), anemometer (m/s and 0° - 360°), and solar sensor (W/m^2).

6. Conclusions and future research

In this paper the use of solar irradiance for saving fossil fuels consumption for residential heating is investigated. Advanced glazing and PCM can offer the necessary storage capacity for heat obtained from solar irradiance.

At this moment strength tests are conducted to determine the appropriate mixture of Micronal with concrete so that construction's strength is not significantly decreased. In the forthcoming months the developed boxes will be put to the test in the open air and data can be collected. The results will give more insights in how buildings can be heated by making use of a passive solar technique. The experiment comprehends different elements, which in former research were considered in stand alone conditions. The interaction between irradiance & window frames, heat & concrete floors and conductivity & insulation are now all brought together in one situation.

In this experiment downscaled models of a living room are used, but future research with real(size) houses could confirm if downscaling is an acceptable method to do this type of experimental research in building physics. In other fields of scientific research this is already common practice.

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