EXPERIMENTAL RESEARCH ON THE USE OF PHASE CHANGE MATERIALS TO COME TO PASSIVE SOLAR ENERGY CONCEPTS

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Abstract

An efficient and effective use of solar radiation is one way to come to sustainable development in the built environment. Because of an average temperature of 9.5 °C and an annual incoming solar radiation of 1,313 to 2,881 MJ/m^2, The Netherlands seem on first sight not to be suitable for solar heating. Nevertheless, the passive use of solar radiation can offer many inexpensive opportunities in low exergetic heating applications. In this regards relatively little is known about the application of Phase Changing Materials (PCM) and their potential to save exergy in the built environment within building designs.

This paper describes the development, execution and results of an experimental research project on the use of PCM in concrete floors for the accumulation of solar energy, in order to obtain a constant indoor temperature during day-night cycles. The results of this research can help to improve the energy performance of both new and existing buildings.

To execute the experiment four different test boxes, representing scaled living rooms, were constructed. Their windows are oriented to the South to make optimum use of solar radiation. Two boxes have concrete floors with microencapsulated PCM's, while the other two are without PCM's. Two boxes are insulated with thick heavy insulation material and two have thin light insulation material. During the experiment the outdoor weather conditions and the temperature of the concrete floors are being measured in order to gain more insights in the practical use of PCM within the Dutch moderate climate. The first results show that concrete floors containing PCM can have a steadier temperature gradient than floors without PCM. The PCM makes it possible to come to lower maximum temperatures and higher minimum temperatures of the concrete floor, and hence, of the indoor air.

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 is placed within the context of the research project "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 do 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); NNI, 2004). 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, reducing the need for thermal and electric energy. 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 (containing double or high efficiency glazing) than on the

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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, Neeper 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, PCM might improve the first factor: the absorptivity of the internal constructions. Thermal energy transfers in PCM 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[3] 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 PCM 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 in The Netherlands. In this research four different test boxes are being used, resembling scaled living rooms. The findings of this research can help to improve the energy performance of both new and existing buildings.

In the second section of this paper the development of test boxes will be explained by considering their dimensions and the used materials. In the third section the test site will be addressed in close relation with the monitoring system that is explained in the fourth section. In the fifth section some preliminary results will be presented. Finally, the conclusions, recommendations and prognosis on future research will be elaborated on.

2. 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 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 their case it was fully constructed out of acrylic glass to have a clear view on the ventilation flows. In this paragraph, first the size of the test boxes (see Figure 1) will be discussed. Secondly, the materials that are involved in constructing the test boxes are addressed.

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[3] 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.

Figure 1 Two boxes for the experiment, one with PCM and one without PCM in the concrete floor

2.1 Size of test boxes

The experimental research has to represent phenomena in real sized houses; therefore the sizing of the test boxes has to be carefully 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 cannot 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 this standard Dutch 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. 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.

2.2 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 used materials (shown in Table 1) to construct the test boxes will be specified.

Table 1 Building physical constitution of the test boxes in the experimental setup

	Testbox A	Testbox B	Testbox C	Testbox D
Insulation material (thermal resistance)	Cellular glass 3.8 (m^2·K)/W	Cellular glass 3.8 (m^2·K)/W	Light multilayered 5.6 (m^2·K)/W	Light multilayered 5.6 (m^2·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·K)	Low 0.5 W/(m^2·K)	High 1.1 W/(m^2·K)	Low 0.5 W/(m^2·K)

2.2.1 Glazing

The front side of the test box consists 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·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·K). For windows an overall U-value of 1.8 W/(m^2·K) results (NNI 2004, SenterNovem 2006). The conductivity of the glazing in the test boxes will be 1.1 W/m^2·K and 0.5 W/m^2·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·K and 0.6 W/m^2·K, respectively, their glazing have g-values of 0.47 and 0.60 respectively.

2.2.2 Insulation materials

Five sides of the boxes are insulated. In this experimental setup fibreglass insulation or mineral wool were not desirable materials, because a steady heat resistance throughout the material 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 with a thermal resistance of 3.81 (m^2·K)/W, is used in two boxes.

Furthermore, there is a debate in Europe on the effectiveness of light insulation products compared to heavy forms of insulation. Our research will contribute to this debate by using, in two other boxes, 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 an R-value of 5.6 (m^2·K)/W, when on both sides a cavity is applied of at least 20 mm deep. The exterior of both types of boxes is finished by using plywood of 15 mm. The boxes are painted white, because of its high reflection and low absorptivity, so that there adiabatic conditions are approximated as closely as possible.

2.2.3 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. In future experiments this gypsum board will be used to cover the interior of the test box with exception of the floor and the window frame to increase the total heat capacity.

The same micro-encapsulated PCM (Micronal DS 5008 X) is now being used to increase the heat capacity of the concrete floor in two test boxes. The amount of PCM in the concrete mixture was 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°C and 25 °C at maximum. Based on local irradiation and temperature data of 2007, the specifications in Table 1 and 2, 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 at least 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 2 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

3. Test site

Based on the different materials that need to be tested, four different test boxes were constructed with the characteristics that are summarized in Table 1. These boxes are placed outdoors on a test site to conduct data for a whole year. This enables monitoring of the behaviour of the box and the materials during all seasons. The test site (see Figure 2) is located at the Campus of the University of Twente (Enschede, The Netherlands). To give an impression of the solar irradiance at this university, Figure 3 shows the irradiance and outdoor temperatures at the location. To make sure that there are no obstacles, which can cause shading, the boxes were placed 2.5 metres above ground level in a rather open area. A weather station (WS) has been installed behind the boxes to measure the weather conditions.

Figure 2 The boxes at their test site on the campus of the University of Twente

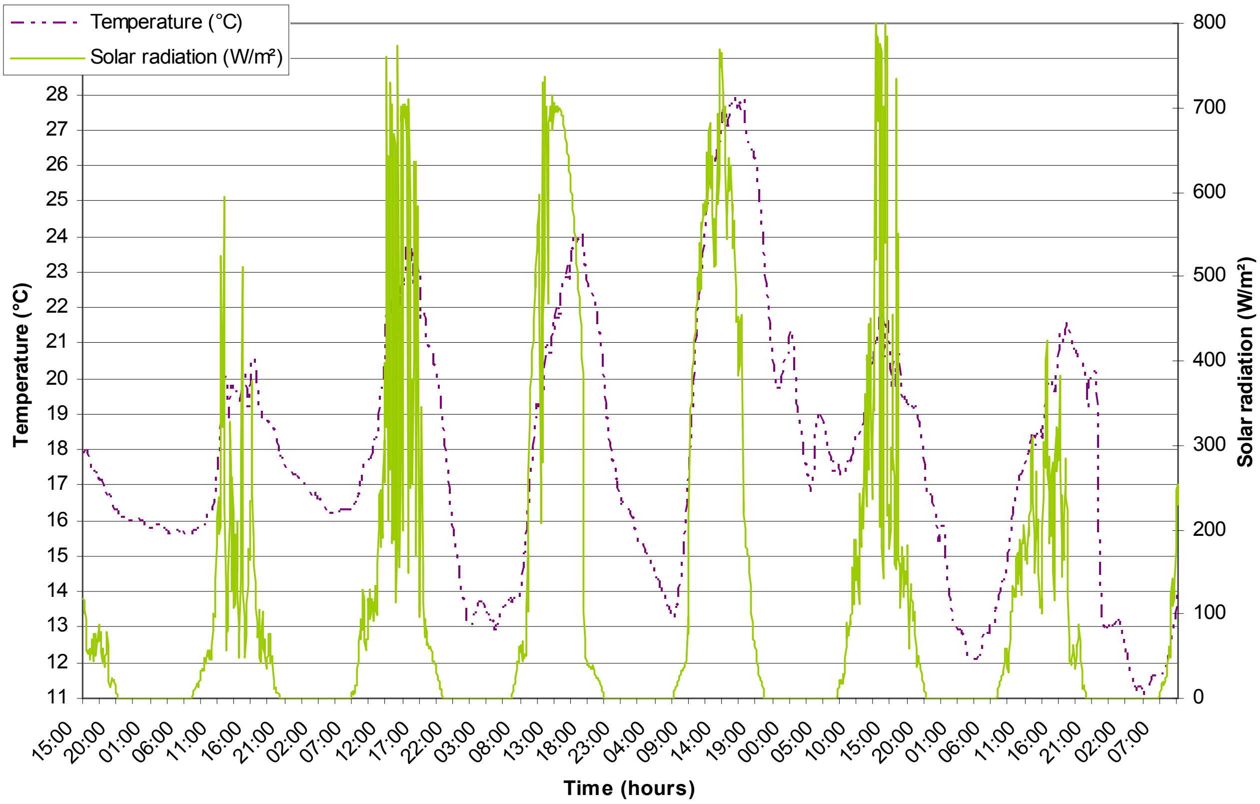

Figure 3 Data of solar irradiance and ambient temperature given by the weather station from 8-27-2008 15:00 till 9-3-2008 09:45.

4. Monitoring system

The boxes will be continuously monitored with a sampling interval of five minutes. On top of the concrete 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 thirteen thermocouples will be used per box. 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. 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 weather station, being a Vantage Pro 2 of Davis Instruments with thermometer (°C), humidity meter (%), anemometer (m/s and 0° - 360°), and solar sensor (W/m^2). Table 3 addresses the accuracy of the sensors.

Table 3 Applied sensors in the monitoring system

	Sensor	Unit	Accuracy
Temperature	Thermocouples type T	°C	± 0.5 °C
	Vantage Pro 2 of Davis Instruments	°C	± 0.5 °C
Irradiance	Si-01 Tc-T of Mencke & Tegtmeyer	W/m^2	± 5%
	Vantage Pro 2 of Davis Instruments	W/m^2	± 5%
Humidity	P14 SMD of LinPicco	% RH	< 3% RH
	Vantage Pro 2 of Davis Instruments	% RH	5% RH
Rain rate	Vantage Pro 2 of Davis Instruments	Mm	±1 mm/h
Wind speed	Vantage Pro 2 of Davis Instruments	m/s	± 5%

5. Preliminary results

During the writing of this paper the installation of sensors and thermocouples still continues and therefore the lids of the boxes have not been insulated yet, nor was the gypsum plasterboard containing PCM installed. Although the boxes are not completely insulated yet, there have been created two comparable situations, namely box A-B and C-D in which one of the concrete floors contains PCM and one does not contain PCM (see Table 1). Furthermore, the weather station and twelve thermocouples have already been collecting data. The thermocouples are equally distributed among the four floors and are located in the core of the concrete in the front, middle, and back of the box. In Box A and C these thermocouples are surrounded by concrete containing PCM. The generated data offers some first insights in the effectiveness of PCM in concrete floors.

Figure 4 shows the average temperatures of the floors per box from 8-27 15:00 till 9-3 9:45. This time period corresponds with the data shown in Figure 3. Box A and C, each containing approximately 5.1 kg of PCM, have lower peak temperatures than box B and D, which do not contain any PCM. The total mass of each concrete floor is approximately 104 kg, corresponding to a floor height of approximately 60 mm.

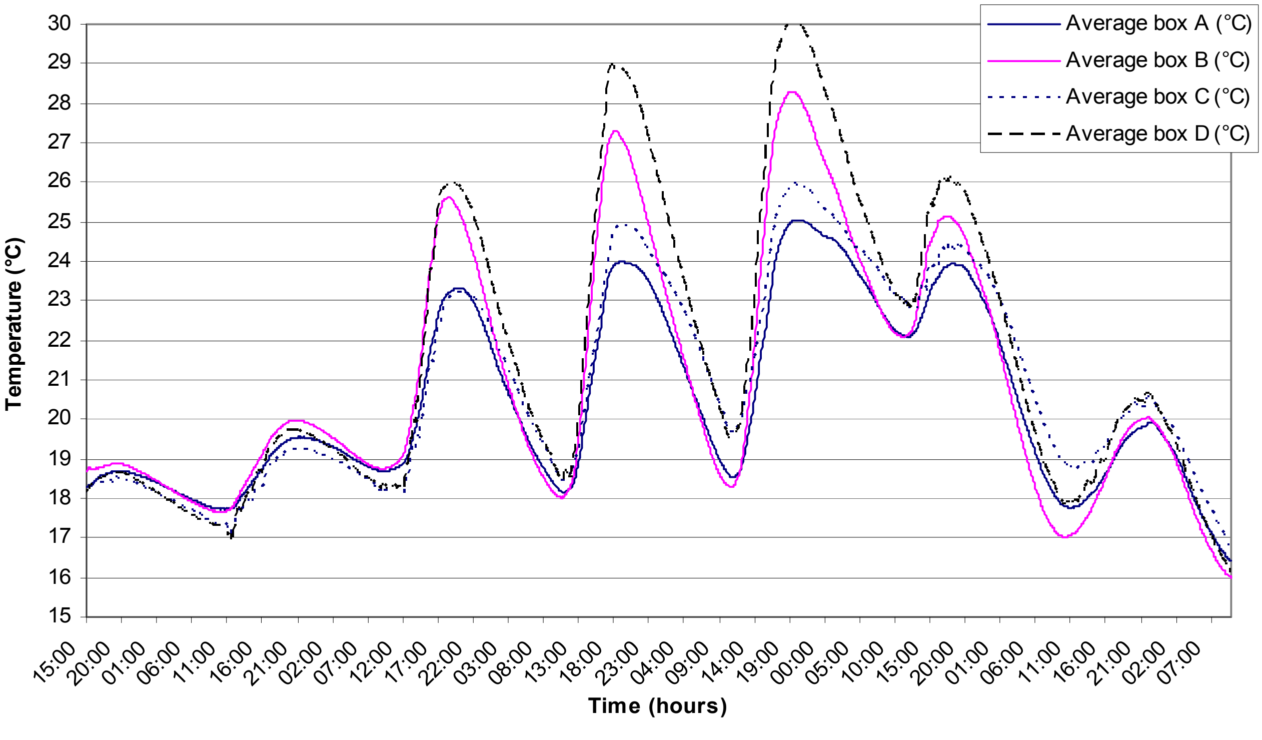

Figure 4 Temperature measurements in four concrete floors of the test boxes from 8-27-2008 15:00 till 9-3-2008 09:45.

Starting from 15:25 of 29th of August the floors in the boxes containing insulation made of cellular glass (A and B) seem to have lower average temperatures than the boxes containing thin multi layered insulation. At that moment the PCM were able to use their latent heat capacity, because at that moment the temperature of the floor was around 23°C. The maximum temperatures per day exceeded 23°C on the 29th, 30th, 31st of August and the 1st of September. Before this time the temperature gradients of the four floors showed just small differences, because no latent heat was stored. In the morning of the 2nd of September the floors containing PCM have clearly a higher temperature than the floors without PCM. The stored energy was used to maintain a higher floor temperature.

A more detailed analysis per time period (see Appendix A) shows that in all cycles the maximum temperature of the floors with PCM is lower than the floors without PCM. The minimum temperature of the floors per time period is in almost all cases higher than the floors without PCM. When the standard deviations per time period per box are compared, then the floors with PCM show a steadier temperature gradient than the floors without PCM.

6. Conclusions and future research

In this paper the use of solar irradiance for saving fossil fuels consumption for residential heating is investigated. In theory, PCM can offer storage capacity for heat obtained from solar irradiance. An experimental setup has been developed to do research on the efficiency and effectiveness of concrete floors containing PCM in the Dutch climate. Although the setup has not completely been finished yet, the preliminary results are promising regarding the effectiveness of concrete floors containing PCM. These floors have higher minimum temperatures and lower maximum temperatures and show a more steady construction temperature in general.

To be able to conclude if this measure is efficient and effective in the Dutch built environment, the setup will be further developed, providing an enclosed environment that should be heated by the PCM during night time. Based on the preliminary results it is expected that when the latent heat capacity is not used or charged, the temperatures could drop below the desired minimum values.

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Appendix A. Statistical analyses on generated data

Table A Statistical analyses per time period on generated data (values in ^{O}C)

Time period	Box	Average temperature	Minimum temperature	Maximum temperature	Standard deviation
8-27 15:00 till 8-28 09:00	Box A	18.34	17.75	18.70	0.29
	Box B	18.43	17.68	18.89	0.40
	Box C	18.09	17.40	18.53	0.34
	Box D	18.11	17.31	18.65	0.43
8-28 09:01 till 8-29 09:00	Box A	18.87	17.72	19.55	0.60
	Box B	19.10	17.65	19.98	0.74
	Box C	18.52	17.01	19.25	0.65
	Box D	18.74	16.97	19.74	0.82
8-29 09:01 till 8-30 09:00	Box A	20.86	18.49	23.33	1.70
	Box B	21.67	18.24	25.61	2.49
	Box C	20.89	18.03	23.24	1.75
	Box D	22.05	18.23	25.98	2.69
8-30 09:01 till 8-31 09:00	Box A	21.41	18.15	23.99	2.02
	Box B	22.56	18.01	27.31	3.14
	Box C	22.24	18.42	24.91	2.13
	Box D	24.00	18.46	28.99	3.47
8-31 09:01 till 9-1 09:00	Box A	22.89	18.54	25.04	2.21
	Box B	24.32	18.29	28.30	3.20
	Box C	23.73	19.67	25.96	2.06
	Box D	25.80	19.52	30.08	3.41
9-1 09:01 till 9-2 09:00	Box A	21.91	17.99	23.95	1.78
	Box B	22.03	17.13	25.12	2.48
	Box C	22.74	19.14	24.47	1.51
	Box D	23.06	18.15	26.12	2.37
9-2 09:01 till 9-3 09:00	Box A	18.53	16.55	19.93	0.95
	Box B	18.31	16.11	20.05	1.22
	Box C	19.21	16.95	20.55	0.92
	Box D	18.84	16.34	20.65	1.22