Heat flux measurements for phase change material characterization in buildings to improve thermal simulations

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Phase Change Materials (PCM) are finding their way into buildings as high performance storage materials for improving energy efficiency. For construction planning, in terms of investment cost vs. cost savings by energy reduction, models are required. The theoretical models are often not accurate enough matching the real use case. This study shows, how such models can be improved by characterizing existing PCM window installations made by GlassX in a new building using heat flux sensors from greenTEG's gSKIN® U-Value Kit. Moreover, it is evident that heat flux measurements give a better general understanding of how to use the PCM installation. For example, the results recommend that it is crucial to shadow the PCM window in summer to get the full effect of cooling. Furthermore, it was shown, that the model could be improved drastically through calibration. For an outlook it can be concluded, that the model even could further be optimized by adapting the heat transfer coefficient. Also there is high potential in using heat flux sensors for measuring the state of the PCM material, which will become important for controlling the material actively (by ventilation or air-condition) to optimize the insights gained from weather forecasts.

1 Introduction

The goal of this study is to gain insights from the latest PCM technology installed in occupied buildings. These insights will be gathered with the help of gSKIN® Heat Flux Sensors. The examined object is an office building with PCM windows integrated into the façade (see Figure 1 and Figure 2) and is the Headquarter of a Swiss restaurant chain. The measurement was conducted in a collaboration between GlassX (producer of PCM windows) and greenTEG (manufacturer of gSKIN® Heat Flux Sensors) between 3rd September 2015 and 2nd October 2015.

During the experiment the following questions have been addressed:

- How does a PCM window behave inside a building to regulate indoor climate and reduce energy demand?
- Do weather conditions influence the performance of the PCM?
- Are there additional factors that influence the performance of both PCM facade parts and heat flux sensors?
- How does the measurement with the gSKIN® Heat Flux Sensor validate performance of the PCM?
- How can the measurements with the gSKIN® Heat Flux Sensor be used to calibrate PCM building simulations?

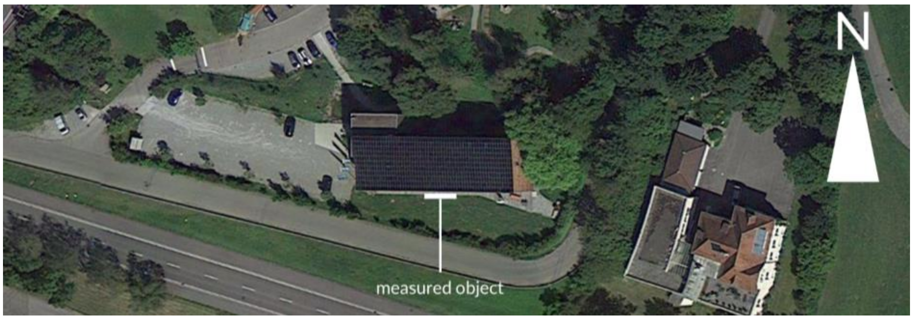

Figure 1: Geographical location of the measured object[a]

[a] Google. (n.d.). [Google Maps coordinations: 47.448145, 8.700022]. Retrieved November 11, 2016, from goo.gl/3IUP9a

Figure 2: Marché International AG, Kemptthal[b]

2 Heat Flux and Temperature Measurements

2.1 Setup

The measurement of the heat flux and temperature was conducted at the south side of the building. Four gSKIN® U-Value Kits were installed at the PCM window and the regular window (2 at each, one at the bottom, one at the top) located next to each other (see Figure 3). Each of the measurement setups included:

- 1 x gSKIN® XO sensor
- 2 x temperature sensors
- 1 x Data logger

For each setup a heat flux sensor was mounted on the inside of the window using regular adhesive tape. One of the two temperature sensors was mounted in close proximity to the heat flux sensor. The second temperature sensor was mounted on the outside in roughly the same position as the heat flux sensor. In addition, each of the heat flux sensors was covered with aluminum foil in order to minimize the influence of the sun radiation on the measurement results (see Figure 4). The whole setup was connected to the data logger, which recorded simultaneously the outside temperature (T_2), inside temperature (T_1) and the heat flux (HF) at a sampling rate of 1 sample per 10 minutes.

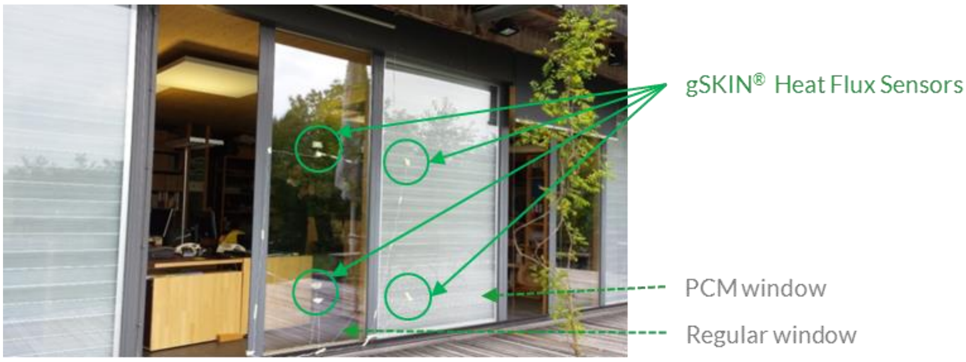

Figure 3: Outside view of measurement set-up

The measurement was conducted during a 4-weeks period. Throughout the measurement a special attention was paid on the influence of the:

- Sun radiation
- Heating and air-conditioning system
- Presence of office workers
- Ventilation of the room

[b] Marché® Restaurants (2016). [HQ Kemptthal]. Retrieved November 11, 2016, from goo.gl/LB3KJs

In order to present the results of the measurement, a read out software by greenTEG was used. The results of the heat flux measurement as well as those of the temperature were compared with the data from the nearby weather station in order to take the influence of the radiation into account to prove the credibility of the measurement.

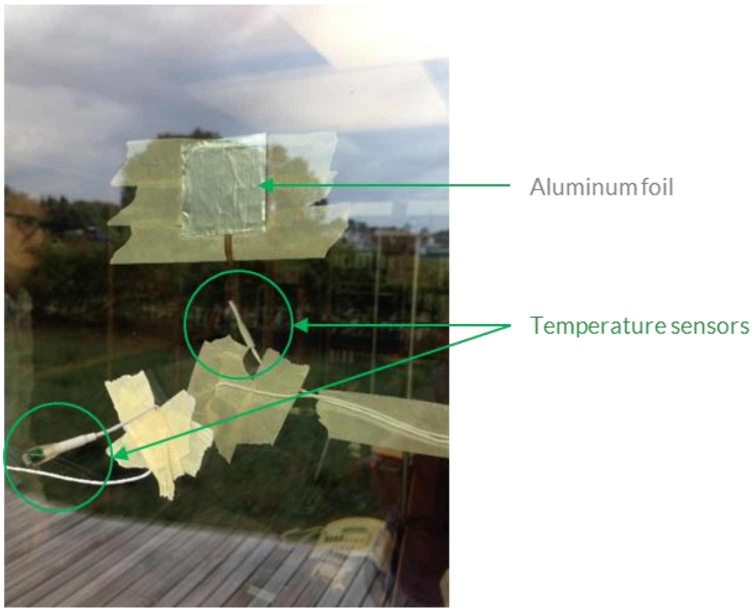

Figure 4: Aluminum foil protection against the sun radiation

2.2 Results

With the U-Value Kit from greenTEG, the diffusive energy absorption and release in relation to the temperature of the room can be measured. This is demonstrated in Figure 5.

Figure 5a shows heat fluxes measured at the inner side of the PCM (red) and regular window (black). The corresponding room (green) and outside (orange) temperature measurements can be seen in Figure 5b. During the night, the heat flux from the regular window into the room is negative, while the heat flux from the PCM window into the room is positive. During the day, both heat fluxes change the direction (see 2nd day). During the night temperature differences between inside and outside of up to 20°C are reached, while during sunny days, the outside temperature measured at the south facade of the building rises up to 25°C.

The measurement can be interpreted as illustrated in the schematic drawing in Figure 6: During the night the regular window releases the heat into the outside (energy is lost), while the PCM releases its stored energy (which was absorbed the day before) into the room (energy is gained). During the day the regular window allows heat to flow into the room, while PCM absorbs most of this energy influx and furthermore cools down the room by absorbing the energy from the air through convection. Strong negative heat flux measured at the regular window during the day is due to sun absorbance of the heat flux sensor and its release to the room. This illustrates the energy absorption by the room because of the solar radiation.

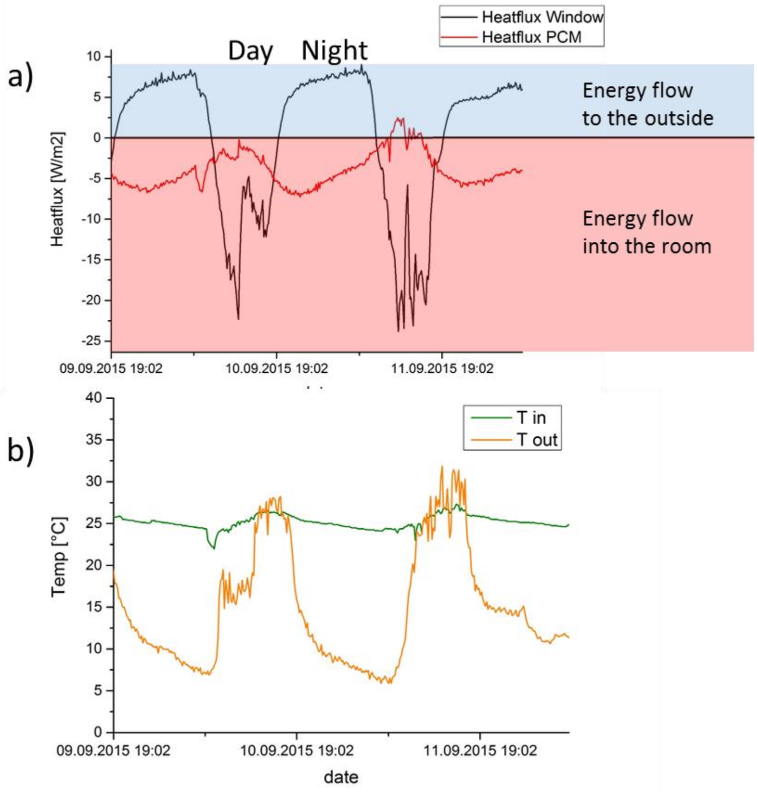

Figure 5: a) Heat flux measured during two sunny days on a regular window (black) and a PCM Window in relation with b) the measured room (green) and outside (orange) temperature measurements

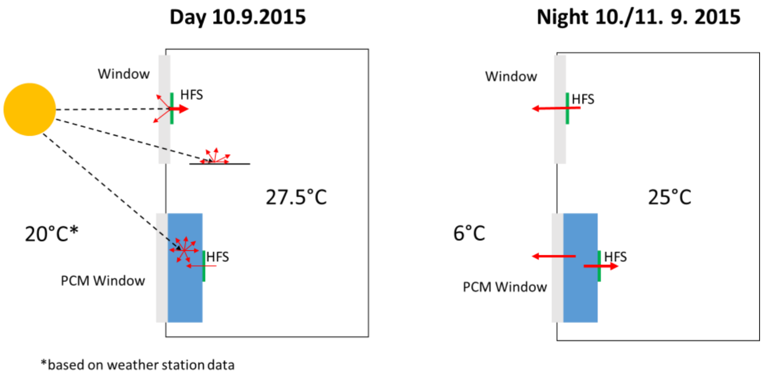

Figure 6: Schematic drawing explaining the heat generation and fluxes during day and night in the PCM window and the regular window

Figure 7 compares the measurement between the upper part of the PCM window (shadowed by a balcony) and the lower part of the window. It clearly demonstrates, that when the sunlight is blocked, PCM takes up less energy during the day, which results in less energy release into the room during the night (and day).

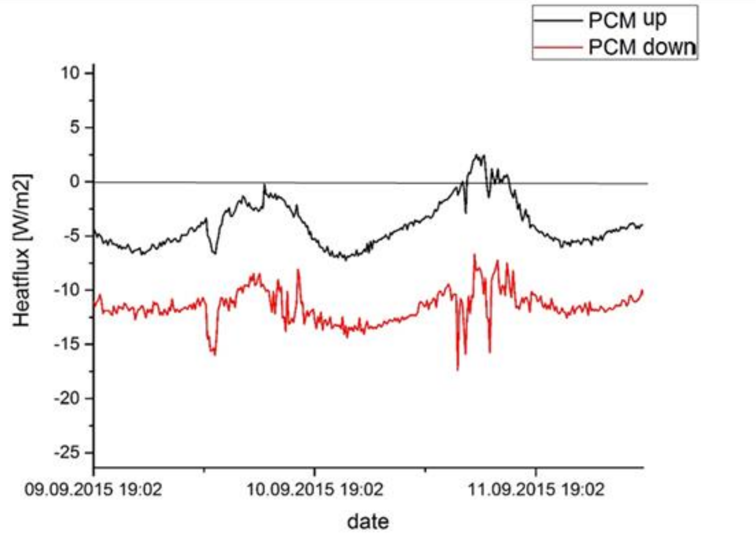

Figure 7: Heat Flux measurements by two heat flux sensors at the top part of the window (red) and at the bottom part of the window (black)

The conclusion from this measurement is, that during winter time and consecutive days with low amount of sun, shadowing should be omitted, while during the summer days, the PCM window should be completely shadowed so it can damp high room temperature by absorbing energy from the room (this would not be possible, if it was at some point completely loaded by the sunlight).

For several consecutive days without sun, PCM cannot absorb energy and thus the heat release into the room during night is drastically decreasing as shown in Figure 8. The PCM might be in a fully unloaded stage, when it starts to act as a regular window by absorbing heat from the room (this is the case for the upper part after the 22^{nd} and for the lower part at the 23^{rd} of September).

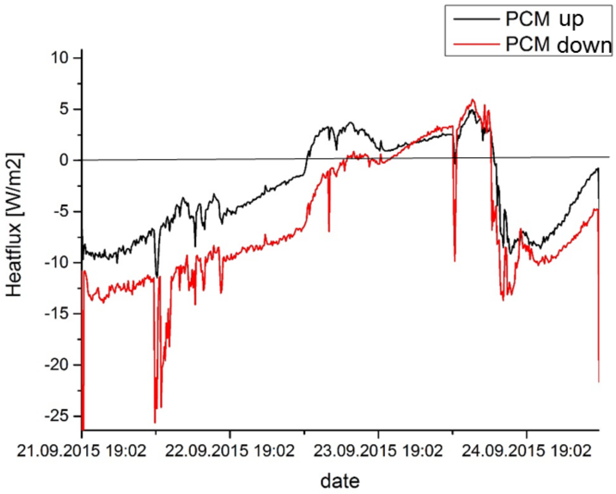

Figure 8: Heat Flux through PCM window (top and bottom) when there is no sun for several consecutive day

2.3 Conclusion

Heat Flux Sensors from greenTEG are powerful tools for investigating the **energy issues** in buildings. As shown in the study, the measurements allow for:

- **Thermal characterization** of windows and walls
- **Sun radiation detection** (during the day)
- Detection of the **energy loading stage** of the PCM
- Detection of **energy release or absorption** of PCM material depending on the weather conditions

This helps improving:

- The construction of the building in order to reduce the **energy consumption**
- Thermal **simulations** of buildings and PCM
- The **thermal regulation systems** (for optimal shadowing, ventilation, and air-conditioning)

3 Use of measurements for building simulations

With the use of building simulation software it is possible to quantify the effects of PCM energy storage windows on building energy demand and thermal comfort. While such calculations are valuable tools to compare different design options, it is difficult to accurately calculate the values for a real building. One reason for this problem is the large number of variables and resulting complexity of building models (dimensions, building envelope, design and operation of HVAC, shading operation, etc.). Additionally, it is challenging to accurately predict the behavior of building users, which often deviates from "ideal" models.

To increase the reliability and credibility of building simulation tools, it would therefore be highly valuable to have a simple tool for calibrating models against real buildings. On the one hand, this would allow determining the performance of the models used in the design process as soon as the building has been built. On the other hand, it would provide a very elegant way to create simple, accurate models of existing buildings for the planning of retrofits.

The simple setup and handling of the gSKIN® Heat Flux Sensors and temperature sensors provides an optimal solution for the collection of measured data for such a calibration exercise. Based on the measurement campaign described in the previous chapters, modeling and calibration was undertaken. The approach and results are presented in the following pages.

3.1 Setup

A simplified building model was established based on the available data on the building used for the study (see Figure 1 and Figure 2), such as dimensions, envelope, HVAC setup and occupation. Special consideration was given to the behavior of building occupants as reported during interactions during the measurement campaign (such as opening of windows at the start of the working day). The building simulation tool used was the IDA Indoor Climate and Energy (IDA ICE)[c], for which GlassX has developed a simulation module characterizing the PCM energy saving windows.

Weather data was acquired from a nearby weather station (Zurich Kloten) for the time period of the measurements. This is necessary, because the local measurements do not contain information about solar irradiation. The weather station is located a few kilometers from the building. A comparison of the outdoor temperatures in the weather data file and the local measurements was therefore undertaken and has shown a close fit. It is therefore assumed that the weather data provided by the Kloten weather station is sufficiently accurate for using it in the building simulation.

3.2 Results

3.2.1 Indoor temperatures

A first comparison between measured data and simulation was conducted based on indoor temperatures. The results are shown in Figure 9. The profile of the simulated indoor temperatures is mostly influenced by the assumed behavioral schedules of the human occupants (such as breaks, window openings, etc.). While the temperature ranges are matched, it is clearly visible from the plot that the simulation does not capture the temperature dynamics within the building. Any output determining indoor thermal comfort or HVAC energy demand will therefore deviate from the real building performance.

Also visible is the difference between the indoor temperature measurements taken behind the window and the PCM glazing. The shielding of solar irradiation and the heat radiation from the PCM are responsible for these differences. Neither of the two temperature readings can therefore be used as a precise representation of indoor temperature, but together they provide a range sufficiently close to calibrate the model.

[c] EQUA (2016). [IDA ICE]. Retrieved November 11, 2016, from www.equa.se/en/ida-ice

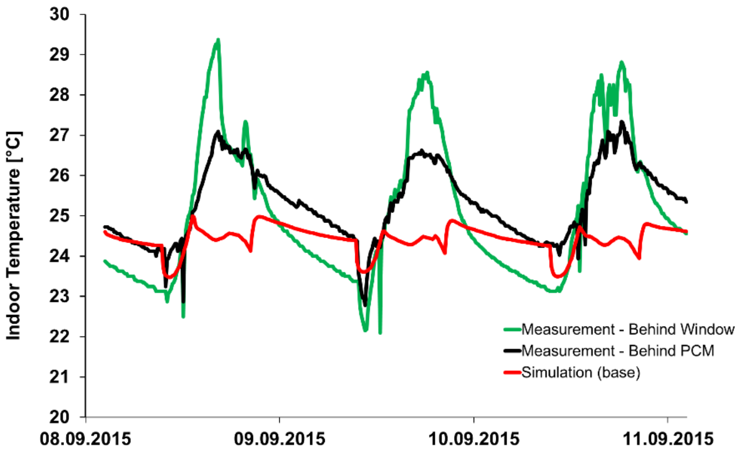

Figure 9: Comparison of simulated and measured indoor temperatures

In a next step, the building simulation model was calibrated based on the measurements. Indoor temperature was used as a calibration variable, since it is the most important input to user thermal comfort. The key levers for calibration are ventilation and heating/air condition set points and control, shading characteristics and control and user behavior. The results of the calibration are visible in Figure 10.

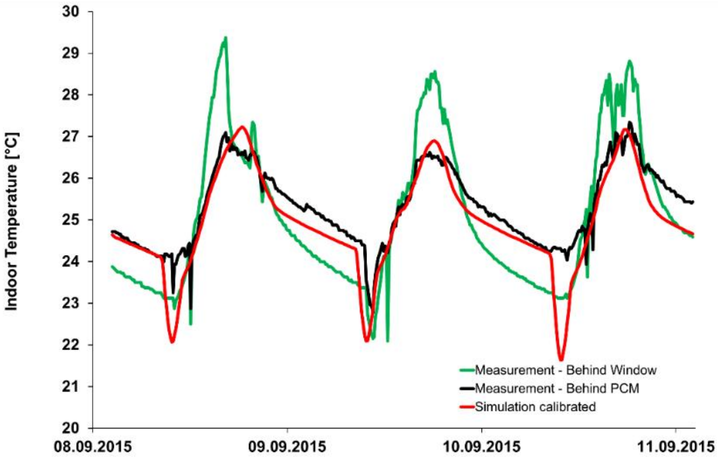

Figure 10: Comparison of simulated and measured indoor temperatures for the calibrated model

In comparison with the base model, the calibrated model is able to capture the dynamics of the actual building. While there is some uncertainty about the actual peak temperatures, the model provides a close enough fit to allow for an accurate determination of the thermal comfort during most times and a solid foundation for the calculation of HVAC energy and power demands.

To check for the effects of over fitting, the calibrated model was tested on additional time periods not used in the calibration process. The results are visible in Figure 11. While the same differences exist when it comes to the window opening schedule, the overall fit of the model is good enough also during the additional time period. Its usefulness for quantification of effects and support of design decisions is therefore given.

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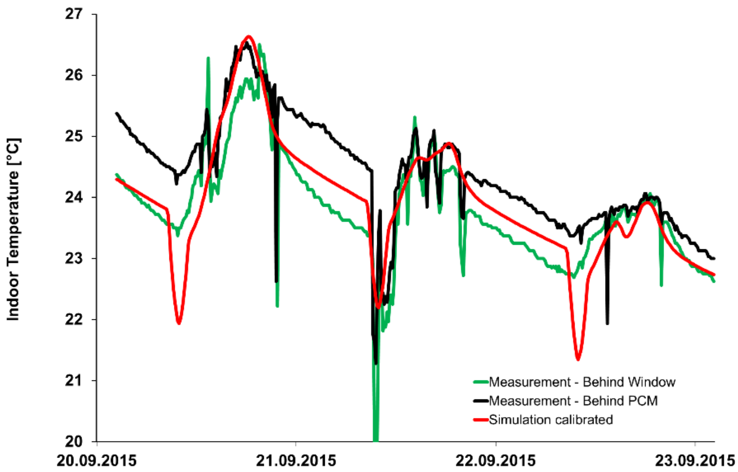

Figure 11: Comparison of simulated and measured indoor temperatures for the calibrated model (additional time period)

3.2.2 Heat flux

After the calibration step based on indoor temperatures, the measured heat flux was used to further analyze the performance of the PCM glazing in the building simulation tool. The results of the comparison are shown in Figure 12.

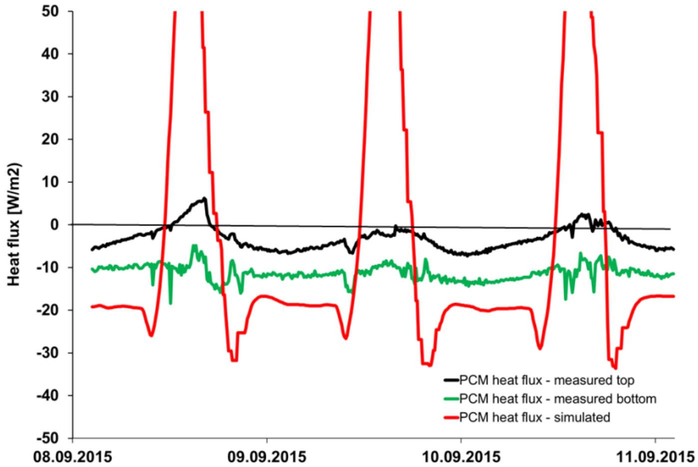

Figure 12: Comparison of simulated heat flux based on the indoor temperature optimized model and the heat flux measured at the upper and lower part of the PCM window

The curves seem to diverge greatly, however this is mainly due to a difference in the definition of heat flux between measurement and simulation. The simulation takes a composite view, which provides the net of inflows and outflows through both sides of the PCM glazing. The strong solar irradiation during the day is therefore visible as peaks. The measurement is dedicated to the heat flux through the boundary between the PCM and the internal room. The peaks during times of solar irradiation are therefore counterbalanced by the simultaneous changes to the indoor temperatures, which is also influenced by these periods of solar energy influx.

The night time temperatures are more comparable, yet they still show some offset from the measured heat flows. This reflects both errors due to the simplifications in the PCM simulation (such as a one dimensional temperature distribution, rather than special as captured by the measurements). Additionally, it might indicate the need to better align the heat transfer coefficients and material parameters used in the simulation.

3.3 Conclusions

Based on the measurements taken with the gSKIN® Heat Flux and temperature sensors it was possible to **calibrate a simplified building model** and **capture the temperature dynamics of the building**. The key aim of improving building models and offering a simplified characterization method for the retrofitting of buildings was therefore achieved, greatly supporting the building simulation efforts of GlassX.

A comparison of the detailed heat flux measurements has shown deviations, which will be addressed in future developments of the PCM simulation component.

It is envisioned that similar measurement campaigns will be undertaken in the future as part of both client support work and software development.

4 Overall conclusions

The results of the measurements have the following conclusions:

- The gSKIN® Heat Flux Sensor allows for **accurate measurement of heat flux** in different types of materials including **PCM** and regular glass
- Such measurements greatly help to **understand and evaluate the effects** of including novel products such as PCM windows in buildings
- Results from the measurements can be used as a very efficient method to **calibrate building simulation models**. This reduces the effort and improves the accuracy of calculations aimed at quantifying the effects of including PCM in a specific building
- While conducting the heat flux measurement it is important to **take human factors, heating times and influence of the sun radiation into account**