Experimental and numerical analysis of overheating in test houses with PCM in Latvian climate conditions

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Abstract

Phase change materials' (PCM) efficiency is being studied experimentally and numerically. Five test houses have been built in Riga, Latvia and monitoring data (temperature, humidity, air velocity, etc.) have been collected every minute since winter 2012/13. After two seasons in two of the houses a different PCMs have been installed and during summer 2015 air conditioning is turned off but ventilation rate is 0.6 h^{-1}. The efficiency of PCMs is calculates form experimental data acquired before and after PCMs were installed. A numerical model in *WUFI Plus* is set up to evaluate the performance of PCMs numerically. Results acquired from experiment and numerical simulations are mutually compared.

1. Introduction

Although fact that phase change process can store large amount of heat is known and used for centuries, in building physics phase change materials are relatively new and in Latvian climate conditions haven't been tested. This is reasonable because of short summers and typical buildings that have small window to wall ratio and poor thermal insulation. This is not true however for newly built buildings where windows area takes on most of the wall or buildings with low thermal capacity and good thermal insulation. Previously studies on overheating and cooling in summer were done by Ozoliņš et.al. (2014, 2015).

To test the PCMs, they were installed in test buildings that are mainly used for monitoring of energy efficiency during the winter. The houses are built with the same inner dimensions 3 m each, see fig.1. Floor and ceiling constructions as well as doors and windows are made equal for all the buildings, but wall envelopes differ on materials used but the heat transmission coefficient that is range of 0.15 – 0.16 $[W/(m^2K)]$ for every building. Three of the test houses will be used in this study and described in more detail, for further information on test houses reader is referenced to (Dimdiņa et.al. 2013). The experimental setup is discussed in section 2 – experiment.

Fig. 1: Test buildings.

Due to experimental inequality between building structures – thermal capacity of materials used, initial humidity, etc., a numerical model is set up in *WUFI Plus* to calculate the building performance with and without phase change materials. The *WUFI Plus* used (version 2.5.4.0) does not allow shading form geometric data to be taken into account and therefore frame factor of windows is decreased. The procedure is described in section 3 – numerical model. In section 4 – results – experimental data are compared to numerical ones and the overheating differences are evaluated.

2. Experiment

2.1. Test buildings

The envelopes of test buildings in question are shown in fig. 2. For all the buildings floor and ceiling construction are made equal and consists of 0.2 m insulation layer with plywood layers on both sides. The wool for ceiling is better insulator and therefore U – values are 0.173 and 0.16 for floor and ceiling respectively.

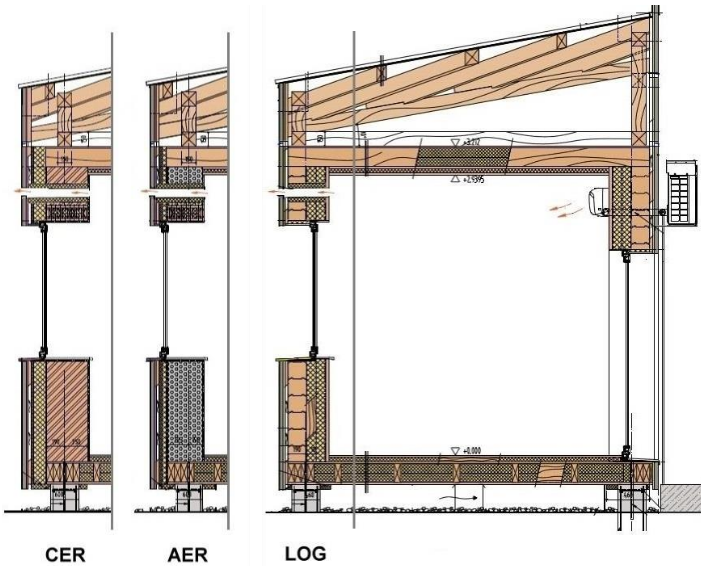

Fig. 2. Cross-section of test buildings' wall envelopes.

Each building has a ventilated façade outside that eliminates direct sun radiation and disallow rain to penetrate the construction. Each building also has an air – air type heat pump that is used for heating, cooling and mechanical ventilation. In this case only ventilation option is provided. The air exchange has been measured experimentally with a tracer gas unit (Gendelis et.al., 2013) and is set to 0.6 h^{-1}. The AER test building, see fig.2, is without phase change material and is made of 0.375 m aerated concrete and 0.05 m rock wool insulation. There are also plaster on both sides and total calculated thermal transmittance of wall is 0.153 *[W/(m^{2}K)]*. The measured value was found to be higher in the first years of exploitation because of high water content aerated blocks had initially. The humidity inside aerated concrete was 82.7% after more than 3 years – May 2015 – when building had been finished thus water is still evaporating, releasing latent heat and cooling the building.

The test building with abbreviation LOG, see fig.2, there are 0.2 m thick wooden logs on the outside, 0.04 m thick wood planks inside for the building to appear wooden throughout and a 0.2 m thick rock wool insulation layer between. This adds up to calculated thermal transmittance of wall being 0.15 *[W/(m^{2}K)]*. In this building a phase change material was installed on the walls, see fig.3 a for the material properties.

The test building CER is made of clay bricks with capillary microstructure and macroscopic air gaps for better thermal insulation. On the outer side there is rock wool insulation layer and thermal transmittance is 0.15 *[W/(m^{2}K)]*. PCMas shown is fig.3. are installed in test building. Thermal properties for both PCMs are given in Table 1.

Table 1: Thermal properties of phase change materials

Material	density, kg/m^3	latent heat, kJ	Thermal conductivity, W/(m*K)
CER	810	121	0.14...0.18*
LOG	860	200	0.2

*liquid and solid

Fig.3: PCMs installed in test buildings a) LOG and b) CER.

2.2. Data

There is one meteorological station located on the top of AER building that collects temperature, humidity, precipitation and other data. For this study only temperature, humidity and solar radiation are important. In each test building more than 20 sensors collect data on temperature, humidity, solar radiation etc. The indoor temperature is calculated as average from 5 sensors that are placed in the middle of horizontal plane in various heights (0.1, 0.6, 1.1, 1.7, 1.9 m above the floor). Data are collected every minute and once per day sent to server. For this study hourly average data are used. More on data and its collection can be found in the work of (Greitāns et.al., 2013) and (Beinarts et.al., 2014).

3. Numerical model

3.1. Equations and boundary conditions

To get numerical solution *WUFI Plus v.2.5.4.0* was used. The software solves 1D heat and moisture transport equations that are coupled together. The latent heat due to evaporation or condensation of water is taken into account in heat equation and temperature is taken into account when calculating humidity. The equations (1) and (2) are well known and are given here for convenience:

$$\rho \frac{dH}{dT} \frac{\partial T}{\partial t} = \nabla \cdot (\lambda \nabla T) + h_V \nabla \cdot (\delta_p \nabla(\varphi p_{sat})) \qquad \text{(eq.1)}$$

$$\frac{dw}{d\varphi} \frac{\partial \varphi}{\partial t} \nabla \left(D \nabla \varphi + \frac{\delta_p}{\rho} \nabla(\varphi p_{sat}) \right), \qquad \text{(eq.2)}$$

where H – enthalpy $\left[\frac{J}{kg}\right]$, λ – thermal conductivity $\left[\frac{W}{mK}\right]$, h_v – latent heat of evaporation $\left[\frac{J}{kg}\right]$, p_{sat} – saturation pressure $[Pa]$, δ_p – water vapor diffusion coefficient $\left[\frac{kg}{m \cdot s \cdot Pa}\right]$, w – water content [-], D – liquid water transport coefficient $\left[\frac{kg}{m \cdot s}\right]$.

The boundary conditions used is in a hidden form in the software, but it is clear that they are third kind, because boundary layer thermal resistance and temperature must be provided. The inner temperature and humidity is calculated from energy and mass conversation by using equations (3) and (4):

$$\rho C_p V \frac{\partial T}{\partial t} = \dot{Q}_{compoent} + \dot{Q}_{sources} + \dot{Q}_{ventilation} + \dot{Q}_{sinks} \qquad \text{(eq.3)}$$

$$V \frac{\partial c_i}{\partial t} = \dot{W}_{compoent} + \dot{W}_{sources} + \dot{W}_{ventilation} + \dot{W}_{sinks}, \qquad \text{(eq.4)}$$

where c_p – heat capacity $\left[\frac{J}{kg \cdot K}\right]$, $\dot{Q}$ – power $[W]$, c_i – moisture content $\left[\frac{kg}{m^3}\right]$,$\dot{W}$ – mass flow $\left[\frac{kg}{s}\right]$.

3.2. Heat sources and solar radiation

Solar radiation is the main source of heat that can produce overheating in the inner environment. It can be seen from experimental data as well as from numerical calculations that in Latvian climate conditions heat flux through construction is mostly outwards with exceptions when outside temperature rapidly increase. The version of software used does not support correction for the shading due to geometry of structure, however this is of great importance. As can be seen in fig.2, the window placement (distance from the outer wall) is different for each construction and all windows are pointed to the south where the solar radiation is most intense. In the case of LOG the window is placed approximately 0.4 m from the outer edge of facade. The window height is 1.5 m and therefore when the sun is at its highest point, approximately 32° from zenith, the solar gains through window is reduced by more than half. The assumption was made that throughout the summer sun is at the same position that is naturally not true, but is a good approximation, because the sun position change is small near the highest point during summer and change fast during around equinox in spring and autumn. To compensate the shading, underestimated frame factor of 0.43 was used.

The window in CER building is closer to the edge of the outer facade, but there is a tree nearby that does not have impact in winter due to leaves falling down, but has great impact in summer. This impact cannot be evaluated accurately by geometric means. The same frame factor of 0.43 was used for CER.

For the AER building there were no additional disturbances and shading due to depth also did not impact the solar gains and therefore the frame factor of 0.7 was chosen. This choice can be verified by experimental data because solar radiation sensors were placed, see fig.4, right behind the window. The solar gain in LOG building compared to AER is 22% less. Frame factors differ more than 22% but this is reasonable as the top part of window is shaded for longer period of time.

Fig.4. Location of solar sensors at the window, temperature and humidity sensors on vertical line and PCM on the walls and ceiling.

Additional heat sources are placed inside the buildings. Air – air heat pump as well as the data acquisition system consume electricity. Furthermore, additional experiments, air exchange, volatile organic compound concentrations, etc., are carried out in the test stands. Three different electric energy meters are installed to measure energy consumed. The power consumed inside the buildings is then added as internal source in the model.

4. Results

The effect of PCMs can't be compared directly due to various reasons:

- the melting temperatures of both PCMs used were different,
- the sensible heat that can be stored differ in each building,
- solar gains are different for each building

Therefore, it is only possible to look at the experimental data qualitatively. The numerical model however provides possibility to also do some quantitative research. Two cases for each of two buildings containing PCMs were computed – with PCM as in reality and without PCM – a hypothetical situation if PCMs weren't installed. The results for CER and LOG buildings are given in figs 5 and 6 respectively.

The fig.5a shows temperature fluctuations in test building in the range of phase transition. It can be seen that numerical and experimental correspond satisfactory, especially for the CER building. For the case when there is no PCM temperature fluctuations are much higher. The model assumes equal temperature in whole inside volume, however in reality it can be different and therefore the full potential of PCM is not used and in numerical model the temperature fluctuations are lower. Other cause of differences might be direct sun radiation to PCM that is not taken into account in model. Fig.5b shows the period when temperature inside is higher than phase transition temperature. In this case experiment and numerical results agree well with each other.

In LOG case it can be seen that numerical model overestimates the impact of PCM, this can be due to various reasons:

- the frame factor is estimated incorrectly,
- the manufacturer's data on PCM is incorrect and the real latent heat is smaller,
- the PCM geometry in model and real life is different

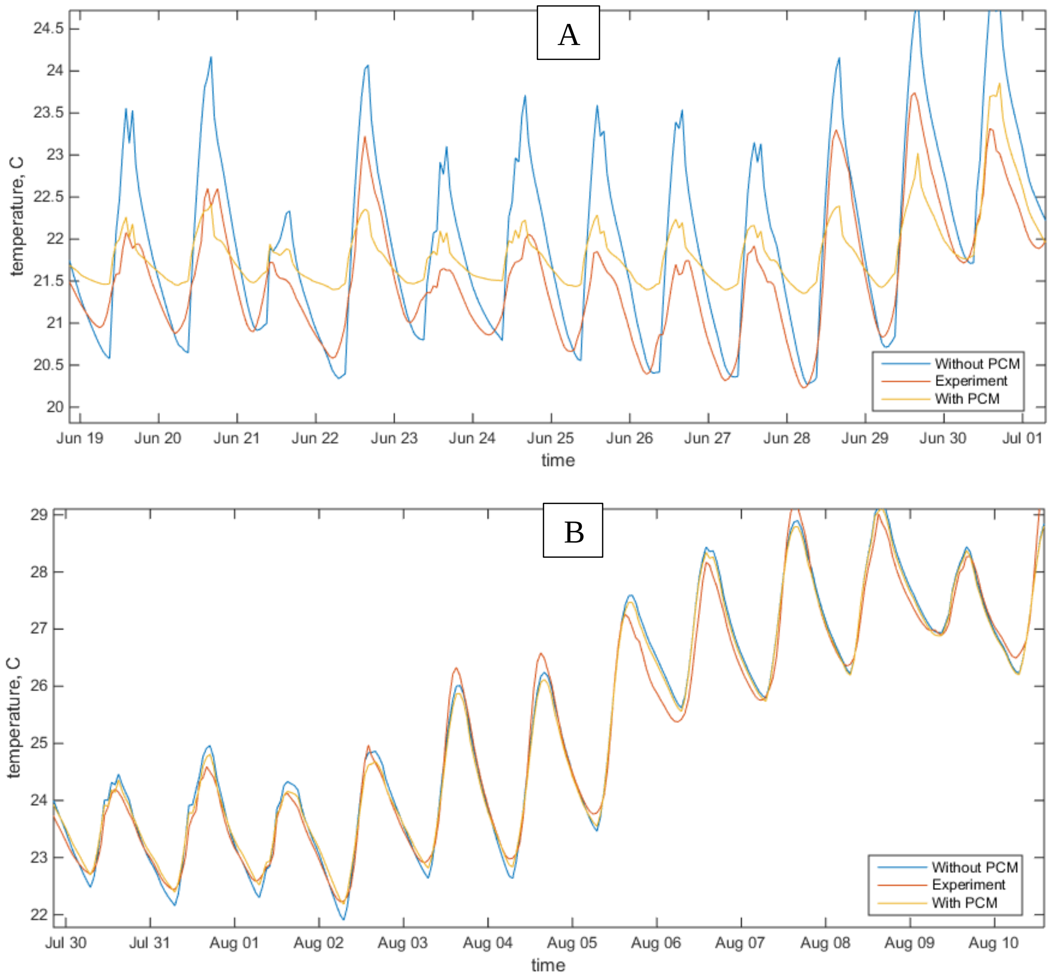

Fig.5: Experimental and numerical results for CER building

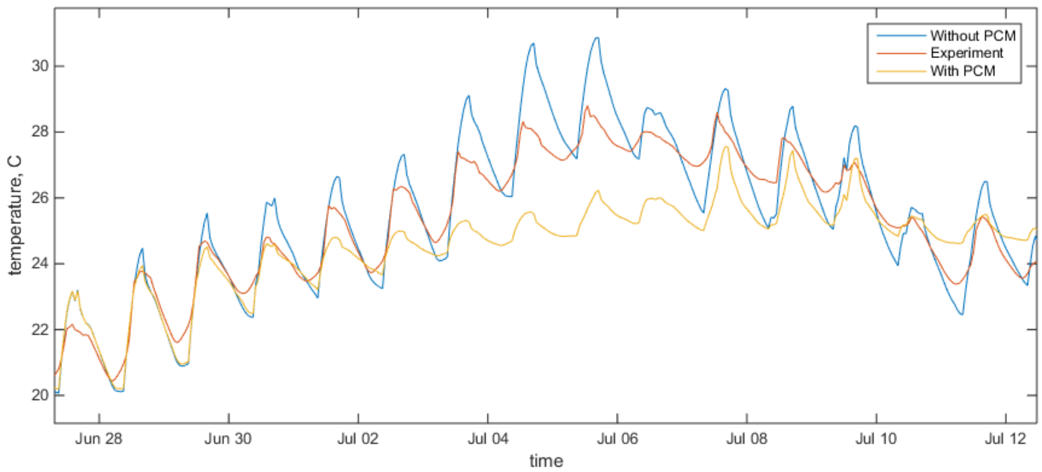

Fig.6: Experimental and numerical results for LOG building

The first two causes can be determined with additional experiments that are left for further studies. The third cause is an interesting one. In model the PCM is modelled as thin layer to cover all the wall, but in reality the material is in macroscopic capsules. By solving Stefan problem (Stefan, 1891), it can clearly be seen that thin layer of material will melt down and solidify faster. Another thing that fig.6 show is that PCMs are only a temporary solution when temperature is high for a few days. After some time PCM melts down and can't solidify enough during the night the difference can be seen if July 6th and July 7th are compared.

The AER building, although without PCM, show approximately the same temperature regime as the LOG building. The only reasonable explanation for this is the latent heat that is released from AER building by evaporation of water. The initial relative humidity of calculation period (15.05.2015 – 25.08.2015) inside the construction was 82.7% but at the end of period it was 72.3%. The initial distribution was assumed constant throughout construction. For numerical model initial conditions was set as experimental 82.7 and the final humidity value was 73.3% that is off by 1%. By using water storage function it was found that 89.2 kg of water have evaporated during the summer that is 56 kWh of cooling energy. Figure 7 shows that experimental values agree well with numerical ones except for amplitude. Numerical model predicts higher temperature amplitude inside then the real conditions are.

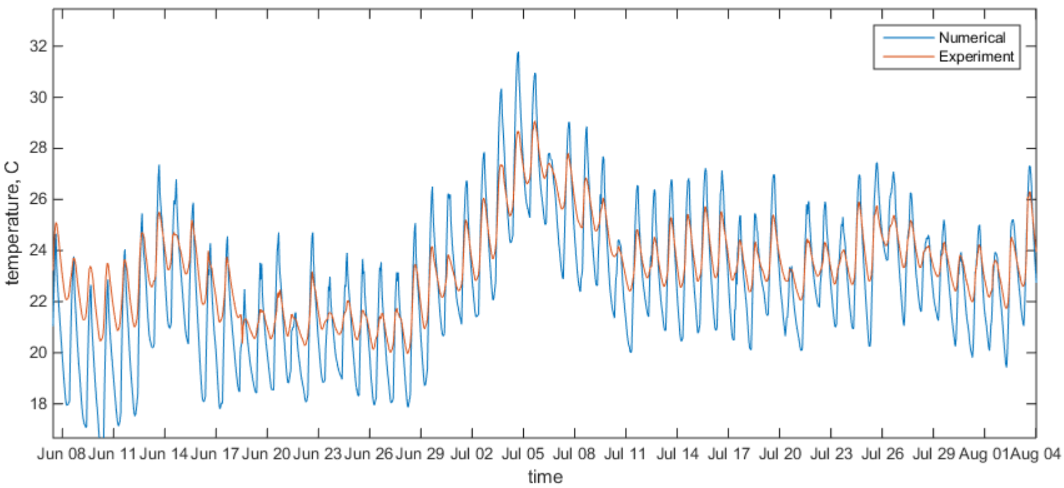

Fig.7. Experimental and numerical results for AER building

5. Discussion

In this paper results of monitoring and numerical modelling are compared. It is found that *WUFI Plus* software can sufficiently well predict impact of phase change materials. The software however has some limitations, the first being inability to calculate shading from geometry. This issue is fixed in version 3 of the software. Another probable issue is that materials are given as uniform layers and therefore a workaround might be necessary to correctly predict melting and solidification of PCM.

For buildings with good heat insulation in Latvian climate conditions solar gains through windows is the main heat source and therefore more care must be taken to calculate them correctly. This is one of the tasks for further studies.

It is clearly visible from calculated data that phase change materials can reduce overheating in Latvian climate conditions, however a great care must be taken to ensure that all the material melts and solidifies during daily cycle. Better arrangement of material would be fins that has large area to volume proportion.

6. Conclusions

The phase change materials are good for reduction of overheating, but are only good for periods of time when temperature is in the range of phase change and temperature is not high for a long period of time.

Study shows that building without PCM and larger solar gains can perform as well as buildings with PCM installed if the structure is losing humidity. The performance can be increased if air exchange is increased. The latent heat of liquid-gas transition is much higher than that of solid-fluid transition and therefore theoretically a new concept of wetting the walls during the summer can be developed. This approach would be active instead of passive but has higher efficiency.

7. Acknowledgements

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