ZERO EMISSION BUILDING ENVELOPES - NUMERICAL SIMULATIONS OF A WELL-INSULATED BUILDING WITH PHASE CHANGE MATERIAL PANELS INTEGRATED IN THE FLOOR

Thomas Haavi[1,2,*], Mark A. Murphy[2], Frédéric Kuznik[3], Arild Gustavsen[1]
[1]Norwegian University of Science and Technology (NTNU), NO 7491 Trondheim, Norway.
[2]SINTEF Building and Infrastructure, NO 7465 Trondheim, Norway.
[3]Université de Lyon, CNRS, INSA de Lyon, CETHIL, UMR5008, F-69621, France.
[*]Corresponding author, Phone +47 98230442, Thomas.Haavi@sintef.no

ABSTRACT

In this paper, numerical building energy simulations were carried out with weather data for Karasjok, Stuttgart and Seville, to evaluate the energy saving potential of a floor with integrated PCM panels.

The reference case was a lightweight wood frame floor construction. The effect of adding different thicknesses of PCM, concrete and wood was investigated. The main conclusions are:

- There is a significant energy saving potential by adding thermal mass in the warmer climates in Stuttgart and Seville.
- PCM has generally the best energy saving potential, but the advantage of using PCM is decreasing when the thickness is increasing.

INTRODUCTION

Energy use in the building sector accounts for a significant part of the world's total energy use. It is therefore important to improve the energy efficiency of buildings. In this respect, concepts like passive houses, zero energy buildings and zero emission buildings are being introduced. However, such energy efficient buildings often have a cooling demand, especially during the summer season.

Phase change materials (PCMs) have introduced a new way of reducing the cooling and heating demand of buildings, due to the effective thermal energy storage and release capabilities of PCMs. The main property of phase change materials is the storage of heat energy in latent form, leading to greater heat storage capacity per unit volume than that of conventional materials (Baetens et al., 2010). When the temperature rises, the material changes from solid to liquid state. This phase change is an endothermic process that absorbs heat. When the temperature drops, the PCM returns to solid state and releases the absorbed heat.

Phase change materials is not a new concept, but the interest for PCM has increased during the last years, considering the increased number of publications (Baetens et al., 2010), (Kuznik et al., 2011). Several products have recently found their way to the market, using various types of PCMs. One of them is DuPont™ Energain®, which is PCM panels with a mixture of ethylene based polymer and paraffin wax laminated on both sides with an aluminium sheet (DuPont, 2007). These panels have been tested in a well-insulated wood frame wall construction in the NTNU/SINTEF laboratory (Cao, 2010), and is also the subject in these studies.

Studies of the energy saving potential of using PCM have been presented in several publications. Experiments with two test houses (1.83 m x 1.83 m x 1.22 m) in Kansas, USA (Zhang et al., 2005), showed that the cooling energy was reduced with up to 11 %, depending on the amount of PCM in the wood frame walls. Simulations of a room in Beijing, China with PCM in the walls and the floor (Chen et al., 2008), showed that the heating energy was reduced with up to 17 % during the winter season, depending on thickness, phase change temperature and phase change enthalpy. Simulations of a 120 m^2 well-insulated lightweight wood frame house, in the climates of Helsinki, Finland and Madison, USA (Peippo et al., 1991), showed that the heating plus cooling energy was reduced with up to 17 %, depending on the external climate and the internal temperature control strategy.

In this paper, numerical building energy simulations have been carried out, to evaluate the energy saving potential of a floor with integrated PCM panels. A well-insulated building, with a lightweight wood frame construction and different floor configurations has been simulated. To investigate the energy saving potential, the results have been compared with a reference case, where the floor is only a lightweight wood frame construction with insulation, i.e. a floor with low thermal mass. The reference case has been compared with floors with PCM, but also floors with concrete and wood, which are commonly used building materials that can act as thermal mass. The effect of changing the thickness of the PCM, concrete and wood has also been investigated, as well as the effect of changing the climate.

NOTE: The DuPont™ Energain® PCM panels is only 5.26 mm thick, but since this is a theoretical study, the material properties have been assumed to be applicable for different thicknesses.

DESCRIPTION OF THE BUILDING

The building is a single-family house with a lightweight wood frame construction. The internal length and width is 10 m x 8 m, and the heated floor area is 160 m^2, divided on two floors. The house fulfils the Norwegian energy regulations from 2010 (KRA, 2010), and the calculations have been carried out according to NS3031 (2007 and 2010).

The main input parameters, used in the energy simulations are summarized below.

NOTE: The thermal surface resistance is not included in the thermal transmittance shown below, i.e. the thermal surface resistance is added separately in the building simulations.

Dimensions (internal):

- Length x Width: 10 m x 8 m
- Height: 5 m (2 floors)
- Heated floor area: A_{BRA} = 160 m²
- Heated air volume: V = 384 m³

External walls:

- Internal area including windows and door: A_{wall} = 180 m²
- Internal area excluding windows and door: $A_{wall\ net}$ = 148 m²
- Thermal transmittance: U_{wall} = 0.18 W/(m²K)

Windows and door:

- Total area of windows and door: A_{wd} = 32 m² (A_{wd}/A_{BRA} = 20 %)
- Thermal transmittance of windows and door: U_{wd} < 1.2 W/(m²K)

Roof:

- Internal area: A_{roof} = 80 m²
- Thermal transmittance: U_{roof} = 0.13 W/(m²K)

Floor:

- Internal area: A_{floor} = 80 m²
- Thermal transmittance: U_{floor} = 0.15 W/(m²K)

Thermal bridges:

- Normalized thermal bridge value: ψ'' = 0.03 W/(m^2_{BRA}K)

Air tightness:

- Air changes at 50 Pa: n_{50} = 2.5 h^{-1}

Ventilation system:

- CAV ventilation
- Heat exchanger efficiency: γ_{he} = 80 %
- Ventilation rate: V_V = 192 m³/ h
- Specific Fan Power: SFP = 2.5 kW/(m³s)

Internal loads:

- Lighting during operational hours (16/7/52): P_l = 312 W (312 W heat gain)
- Technical equipment during operational hours (16/7/52): P_t = 480 W (288 W heat gain)
- Domestic hot water: P_{dhw} = 544 W (0 W heat gain)
- Heat gain due to people: 240 W

BUILDING ENERGY SIMULATIONS

General

The building energy simulations were carried out with the software TRNSYS version 17.00.0019. TRNSYS is an abbreviation for TRaNsient SYstem Simulation program and is developed at the University of Wisconsin-Madison (Klein et al., 2010).

The energy simulations were carried out with identical buildings, except from the floor constructions. The floor constructions had identical thermal transmittance, but different thermal mass. A total of 18 different floor constructions were simulated.

All the 18 buildings with different floor constructions were simulated with weather data for three different locations in Europe.

Modelling of building with PCM

The building was modelled in the TRNSYS "multizone building" Type 56 (Klein et al., 2010). To be able to simulate phase change material panels, which have properties that change with temperature, a Type 260 was used to model the floor. The Type 260 has been presented and validated in a publication by Kuznik et al. (2010).

The building envelope basis was a lightweight wood frame construction, insulated with glass wool, as illustrated in Figure 1.

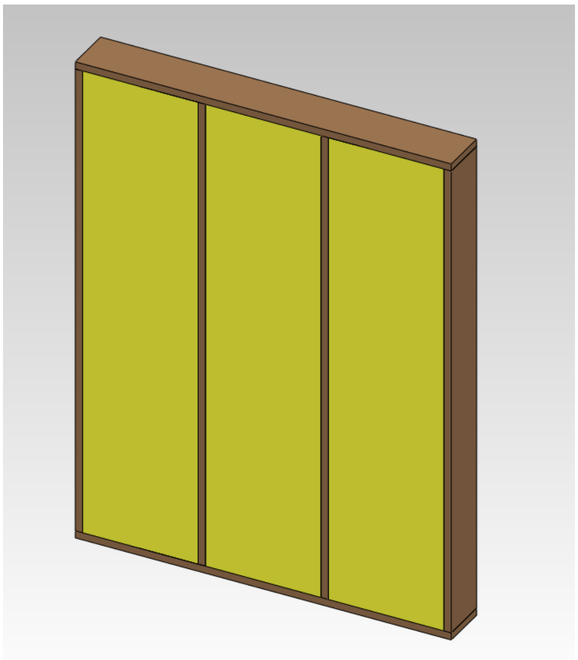

Figure 1 Wood frame with glass wool

The roof had the following layers from inside to outside:

- 13 mm interior gypsum layer
- 342 mm layer of wood frame insulated with glass wool
- 9 mm exterior gypsum layer

The walls had the following layers from inside to outside:

- 13 mm interior gypsum layer
- 245 mm layer of wood frame insulated with glass wool
- 9 mm exterior gypsum layer

The windows had the following specifications:

- Glass from the TRNSYS window library: Pilkington INFRASTOP Titan 6538 6/16/6 with window ID 12011
- Insulated spacer
- Area frame/window: 0.2
- Thermal transmittance of the frame: U_{frame} = 1.2 W/(m²K)

The door had the following specifications:

- Glass from the TRNSYS window library: Pilkington INFRASTOP Titan 6538 6/16/6 with window ID 12011
- Insulated spacer
- Area frame/window: 0.95
- Thermal transmittance of the frame: U_{frame} = 1.2 W/(m²K)

The floor was modelled with 18 different configurations. The reference case is a lightweight wood frame construction insulated with glass wool, which is 300 mm thick, i.e. there is no layer for thermal energy storage.

The remaining 17 configurations were modelled with one additional layer on the inside:

- 5 mm, 25 mm, 50 mm, 100 mm and 150 mm layer of concrete
- 5 mm, 25 mm, 50 mm, 100 mm and 150 mm layer of wood
- 5 mm, 10 mm, 15 mm, 25 mm, 50 mm, 100 mm and 150 mm layer of PCM

The thickness of the wood frame with glass wool was adjusted for each configuration, to get identical thermal transmittance (U_{floor} = 0.15 W/(m²K)), i.e. only the thermal energy storage and release capacity is changed.

The solar absorptance coefficient was 0.6 for all the internal and external surfaces except the external surface of the floor that was assumed to be zero.

The longwave emission coefficient was 0.9 for all the internal and external surfaces except the external surface of the floor that was assumed to be zero.

The convective heat transfer coefficient was 3.1 W/(m^{2}K) for all internal surfaces and 17.8 W/(m^{2}K) for all external surfaces.

Material properties

The material properties used in the simulations are summarised in Table 1, Figure 2 and Figure 3. The properties for the concrete, wood, gypsum boards and the glass wool were taken from NS-EN ISO 10456 (2007), except the thermal conductivity of the glass wool which was taken from the product data sheet (Glava, 2010). The properties of the wood frame with glass wool (see Table 1), is estimated on basis of the share of wood and glass wool in the construction. It should be noted that the actual share of wood versus glass wool varies in the construction, but as a simplification, the properties are assumed constant.

The thermal conductivity and the density of the PCM panels were taken from the product data sheet (DuPont, 2007). The specific heat capacity of the PCM panels was taken from the CSTB test report (Sallee, 2008). The CSTB test report present curves for specific heat capacity as function of temperature at different heating and cooling rates, and the curve for the slowest available heating rate was used as basis for the simulations (0.05 °C/min). It should be noted that the curve in the simulations (see Figure 3) is a simplification of the curve in the CSTB report, since only a limited number of temperature – heat capacity points can be specified in the simulations.

Table 1
Material properties in simulations

	THERMAL CONDUC-TIVITY	DENSITY	SPECIFIC HEAT CAPACITY
PCM	See Figure 2	856 kg/m^3	See Figure 3
Concrete	1.15 W/mK	1800 kg/m^3	1000 J/kgK
Wood	0.13 W/mK	500 kg/m^3	1600 J/kgK
Gypsum	0.21 W/mK	700 kg/m^3	1000 J/kgK
Glass wool	0.037 W/mK	16 kg/m^3	1030 J/kgK
Wood frame with glass wool	0.045 W/mK	59 kg/m^3	1080 J/kgK

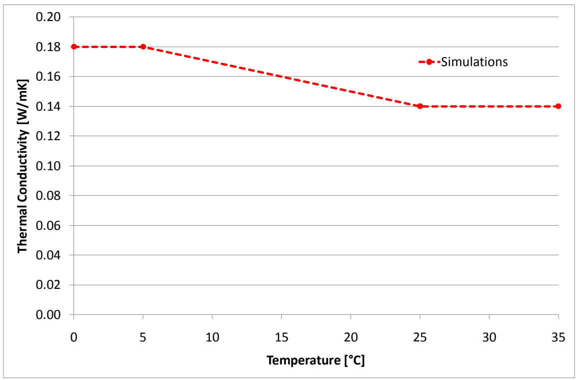

Figure 2 Thermal conductivity of PCM

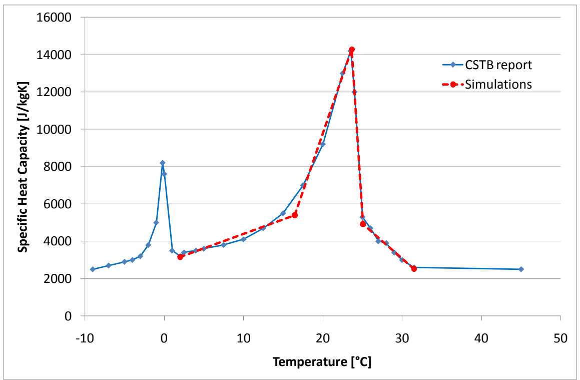

Figure 3 Specific heat capacity of PCM

Boundary conditions

The internal temperature in the building was set to minimum 21 °C during the day (7 – 23), and minimum 19 °C during the night (23 – 7), i.e. heating was provided if the temperature got below the set point.

The maximum internal temperature was set to 26 °C, i.e. cooling was provided if the temperature got above the set point.

The external climate applied to the building, was weather data in Meteonorm data files that was taken from the TRNSYS weather database (Klein et al., 2010).

All the buildings, i.e. with the 18 different floor constructions, were simulated with weather data for three different climates:

- Northern European – Karasjok in Norway
- Central European – Stuttgart in Germany
- Southern European – Seville in Spain

The maximum, minimum and average outdoor temperatures for Karasjok, Stuttgart and Seville are shown in Table 2 and the corresponding temperature profiles for the whole year is shown in Figure 4. The background for choosing these places was to compare a cold (Karasjok), intermediate (Stuttgart) and warm (Seville) climate.

Table 2
Outdoor temperature

	MAXIMUM	MINIMUM	AVERAGE
Karasjok	27.0 °C	-38.0 °C	-2.5 °C
Stuttgart	31.7 °C	-13.2 °C	9.0 °C
Seville	41.0 °C	0.5 °C	18.2 °C

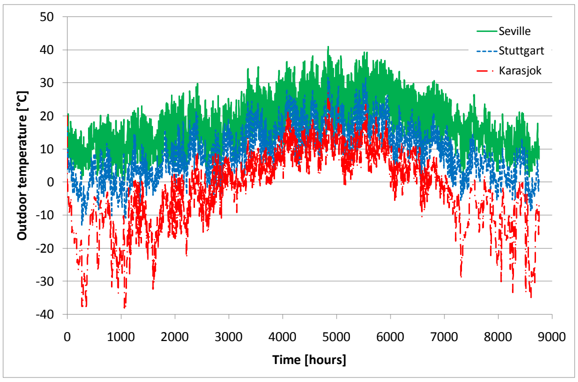

Figure 4 Outdoor temperature

The building was oriented with the long sides towards north/south, and the short sides towards east/west. The north facing facade had 8 m^2 of windows, and a 2 m^2 door. The south facing facade had 10 m^2 of windows, and the east/west facing facades had 6 m^2 of windows each.

The roof was flat, and the floor was exposed to open-air.

RESULTS

The results are summarised in Table 3 and Figure 5 to Figure 11. Table 3 shows the average annual indoor temperature when there is no additional thermal mass (glass wool), and when there is 25 mm PCM in the floor (PCM). The corresponding outdoor temperature is also shown. The indoor temperature and the corresponding heating and cooling demand in Seville, are shown in Figure 5 for the first three days of February and in Figure 6 for the first three days of August. Positive values of the energy demand are heating, and negative values are cooling.

Figure 7 shows the energy demand for the reference case, i.e. the building with only a wood frame construction in the floor, which has low thermal energy storage capacity. The total energy demand is shown for the three different climates, together with the energy demand for heating and cooling.

Figure 8 shows the total reduction in energy demand compared with the reference case, i.e. the total reduction due to reduced heating demand and reduced cooling demand. The results are plotted as function of the thickness of PCM, concrete and wood, i.e. the thickness of the layer for thermal energy storage.

Figure 9 to Figure 11 shows the total reduction in energy demand and the share of reduced heating demand and reduced cooling demand.

The total energy demand consists of heating and cooling demand, but also the energy demand for domestic hot water, fans, lights and technical equipment. The annual energy demand for this equipment was calculated on basis of the requirements in the Norwegian energy regulations (KRA 2010) and the Norwegian standard (NS 3031, 2007 and 2010):

- Domestic hot water: 4765 kWh
- Fans: 1168 kWh
- Lights: 1822 kWh
- Technical equipment: 2803 kWh

The total annual energy demand for this equipment is 10558 kWh, and this number is the same for all the building energy simulations.

Table 3
Average temperature

	INDOOR GLASS WOOL	INDOOR PCM	OUTDOOR
Karasjok	20.7 °C	20.5 °C	-2.5 °C
Stuttgart	22.1 °C	22.1 °C	9.0 °C
Seville	24.1 °C	24.3 °C	18.2 °C

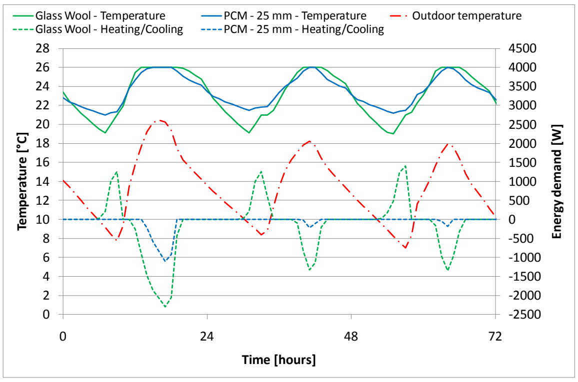

Figure 5 Temperature and heating (+)/cooling (-) for the first three days of February in Seville

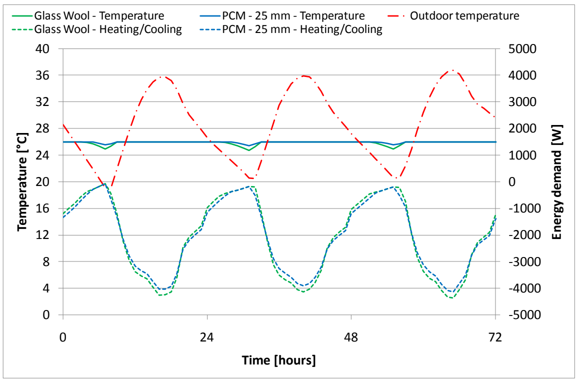

Figure 6 Temperature and heating (+)/cooling (-) for the first three days of August in Seville

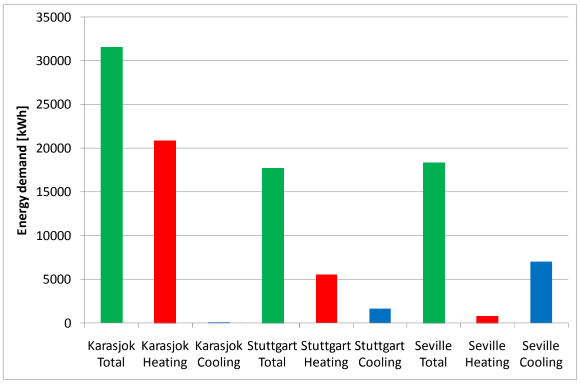

Figure 7 Energy demand for reference case (floor with 300 mm glass wool)

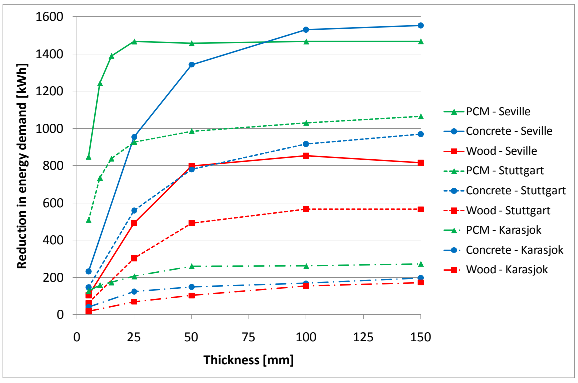

Figure 8 Reduction in energy demand (heating and cooling) compared with reference case

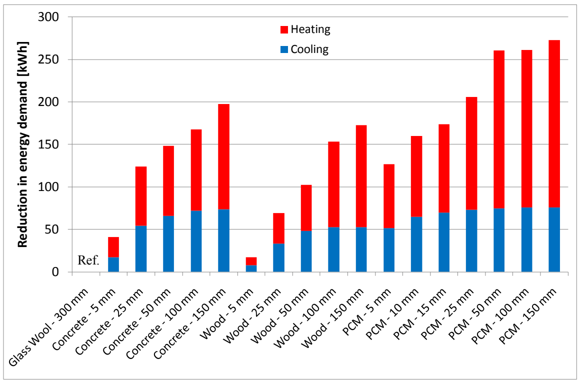

Figure 9 Reduction in energy demand for Karasjok

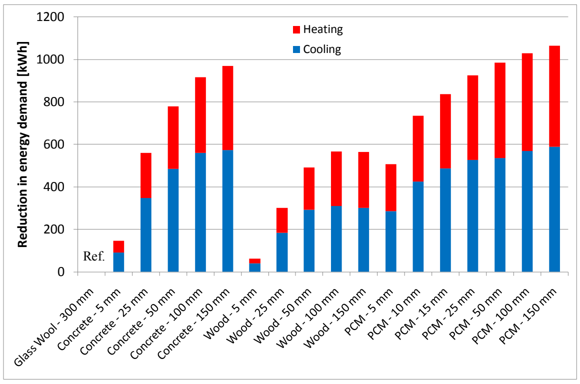

Figure 10 Reduction in energy demand for Stuttgart

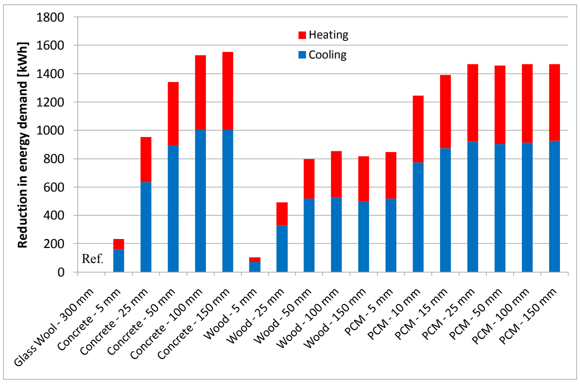

Figure 11 Reduction in energy demand for Seville

DISCUSSION

The average temperatures in Table 3 shows that the indoor temperature in Stuttgart is about 1.5 °C higher than in Karasjok and the indoor temperature in Seville is about 2 °C higher than in Stuttgart. It can also be seen that the average indoor temperature is almost the same with and without PCM in the floor.

The indoor temperature fluctuations in Figure 5 show the effect of the thermal mass. With the added thermal mass, which in this case is a 25 mm layer of PCM, the maximum peaks are lower, and the minimum peaks are higher than without thermal mass. This is because thermal energy is stored when the indoor temperature is increasing, and released when the indoor temperature is decreasing. It can be seen that this removes the heating demand, and reduces the cooling demand during these three days.

The situation is different during the very hot days in August, which is shown in Figure 6. The indoor temperature is almost all the time at 26 °C, which is the set point for cooling. Due to the small fluctuations in indoor temperature, the reduction in cooling demand is small during these hot days. This shows that the combination of outdoor climate and the control strategy for the indoor temperature is of great importance for the annual energy saving potential.

The results in Figure 7 show that the total energy demand in Karasjok is significantly higher than in Stuttgart and Seville. This is due to the high heating demand. The cooling demand in Karasjok is very low.

Stuttgart and Seville has a total energy demand that is quite similar, but in Stuttgart the heating demand is significantly higher than the cooling demand, and in Seville the situation is opposite.

In Figure 8 to Figure 11, it can be seen that the energy saving potential is significantly higher in warm climate than cold. In Seville, the energy saving is up to about 1500 kWh per year depending on material and thickness. In Stuttgart, the savings are 28 % - 42 % lower than the savings in Seville, depending on material and thickness. In Karasjok, the savings are 79 % - 89 % lower than the savings in Seville.

The energy saving potential in the cold climate in Karasjok is small, and most of the savings are due to reduced heating demand. The reduction in the heating plus cooling demand for Karasjok is only up to about 1 %.

The energy saving potential in Stuttgart and Seville is significantly higher than in Karasjok. The larger share of the savings is due to reduced cooling demand, but the reduction in heating demand is also significant. The reduction in the heating plus cooling demand for Stuttgart is up to 8 % for wood, 14 % for concrete and 15 % for PCM. The reduction in the heating plus cooling demand for Seville is up to 11 % for wood, 20 % for concrete and 19 % for PCM.

The results show that the energy saving potential is generally highest for PCM, lower for concrete and lowest for wood. The energy savings generally increases with the thickness of the thermal storage layer, but the effect of increasing the thickness of PCM and wood diminish quite rapidly due to the relatively low thermal conductivity. Concrete has a relatively high thermal conductivity, which increases the penetration depth and thereby the effect of increasing the thickness.

The thermal energy storage and release capacity is dependant on the combination of specific heat capacity, density and thermal conductivity. This can be illustrated by the results for PCM and concrete with the climate for Seville. A PCM layer of 5 mm reduces the heating plus cooling demand with 11 %, a 25 mm layer gives a 19 % reduction, and a 150 mm layer also gives a 19 % reduction. A concrete layer of 5 mm reduces the heating plus cooling demand with 3 %, a 25 mm layer gives a 12 % reduction, and a 150 mm layer gives a 20 % reduction. The thermal energy storage and release capacity of PCM is significantly better than for concrete at low thickness, because the specific heat capacity is much higher, but the storage and release capacity for concrete is better at large thickness due to the significantly higher thermal conductivity.

Since there is a large number of parameters affecting the results, it is difficult to compare these results with previous studies. However, the simulations of a 120 m^2 well-insulated lightweight wood frame house with PCM (Peippo et al., 1991) are somewhat comparable. With the climate of Madison, USA (average temperature of 8 °C), and a similar control strategy for the indoor temperature (minimum 18 °C and maximum 26 °C), the energy saving potential for heating plus cooling was 17 % reduction. This is in the same area as the results in these studies (up to 15 % reduction with PCM in Stuttgart, and 19 % in Seville).

NOTE: The heating due to internal loads is not accounted for in the heating demand that forms the basis for the percentual reductions that is given in the sections above. The internal loads are accounted for in the energy demand for the equipment that is part of the total energy demand.

CONCLUSIONS

A total of 54 building energy simulations have been carried out. The buildings in the simulations were identical, except from the floor constructions. The floor constructions had identical thermal transmittance, but different thermal mass, i.e. different energy storage and release capacity. A total of 18 different floor constructions were simulated with weather data for three different locations in Europe; Karasjok, Stuttgart and Seville.

The reference case was a lightweight wood frame floor construction without any additional layers. An additional layer, with different thicknesses of PCM, concrete and wood was compared with the reference case. The main conclusions are:

- There is little potential to save energy by adding thermal mass in the floor in the cold climate in Karasjok.
- There is a significant energy saving potential by adding thermal mass in the warmer climates in Stuttgart and Seville.
- The reduction in the heating plus cooling demand for Stuttgart is up to 8 % for wood, 14 % for concrete and 15 % for PCM.
- The reduction in the heating plus cooling demand for Seville is up to 11 % for wood, 20 % for concrete and 19 % for PCM.
- PCM has generally the best energy saving potential, but the advantage of using PCM is decreasing when the thickness is increasing.
- Concrete has the best energy saving potential at high thicknesses when the climate is very warm as in Seville.

The same building has been compared for different climates in this study, to minimize the number of variables affecting the results. However, the building is adapted for the cold climate in Norway and the Norwegian energy regulations, and not the hot climate further south. It is therefore recommended to study the effect of changing different parameters, such as the ventilation and the insulation of the building. It is also recommended to study the cost-benefit of e.g. adding thermal mass and/or insulation in the building.

ACKNOWLEDGEMENTS

This work has been supported by the Research Council of Norway, AF Gruppen, Glava, Hunton Fiber as, Icopal, Isola, Jackon, Maxit, Moelven ByggModul, Rambøll, Skanska, Statsbygg and Takprodusentenes forskningsgruppe through the SINTEF/NTNU research project ”Robust Envelope Construction Details for Buildings of the 21st Century” (ROBUST). Université de Lyon, by Frédéric Kuznik, is acknowledged for supplying the TRNSYS Type 260.

REFERENCES

Baetens, R., Jelle, B. P., Gustavsen, A. 2010. Phase Change Materials for Building Applications: A State-of-the-art Review, Energy and Buildings 42, 1361-1368.

Cao, S. 2010. State of the Art – Thermal Energy Storage Solutions for High Performance Buildings, Master Thesis, Norwegian University of Science and Technology/University of Jyväskylä/SINTEF Building and Intrastructure, Norway/Finland.

Chen, C., Guo, H., Liu, Y., Yue, H., Wang, C. 2008. A New Kind of Phase Change Material (PCM) for Energy-storing Wallboard. Energy and Buildings 40, 882-890.

DuPont. 2007. DuPont™ Energain® Energy-Saving Thermal Mass Systems, Data Sheet – Measured Properties, DuPont de Nemours, Luxembourg.

Glava. 2010. FDV-documentation (in Norwegian), Glava Plate A 37, Norway.

Klein, S. A., et al. 2010. TRNSYS 17 - A TRaNsient SYstem Simulation Program, User Manual, Solar Energy Laboratory, University of Wisconsin-Madison, Madison, USA.

Kuznik, F., Virgone, J., Johannes, K. 2010. Development and Validation of a new TRNSYS Type for the Simulation of External Building Walls Containing PCM, Energy and Buildings 42, 1004-1009.

Kuznik, F., David, D., Johannes, K., Roux, J-J. 2011. A Review on Phase Change Materials Integrated in Building Walls. Renewable and Sustainable Energy Reviews 15, 379-391.

Ministry of local government and regional development (KRD). 2010. FOR 2010-03-26 no. 489: Regulations on Technical Requirements for Construction (in Norwegian). Norway.

NS 3031:2007. 2007. Calculation of Energy Performance of Buildings - Method and Data, Norway.

NS 3031:2007/A1:2010. 2010. Amendment A1 - Calculation of Energy Performance of Buildings - Method and Data, Norway.

NS-EN ISO 10456:2007. 2007. Building Materials and Products - Hygrothermal Properties – Tabulated Design Values and Procedures for Determining Declared and Design Thermal Values, Norway.

Peippo, K., Kauranen, P., Lund, P. D. 1991. A Multicomponent PCM Wall Optimized for Passive Solar Heating. Energy and Buildings 17, 259-270.

Sallee, H. 2008. Thermal Characterization, Before and After Ageing of DuPont™ Energain® Panels, CSTB, N/Réf. CPM/09-035/HS/MLE/, Saint Martin d'Hères, France.

Zhang, M., Medina, M. A., King, J. B. 2005. Development of a Thermally Enhanced Frame Wall with Phase-change Materials for On-peak Air Conditioning Demand Reduction and Energy Savings in Residential Buildings. International Journal of Energy Research 29, 795-809.