WHOLE YEAR ANALYSIS OF TIM-PCM SOLAR THERMAL STORAGE WALL

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ABSTRACT

Building elements with ability to adaptation to changeable external conditions is preferable in passive solar systems. Phase change material (PCM) with almost isothermal change of phase combining with transparent insulation (TIM) can be successfully used as a highly efficient, external wall system, so-called "intelligent facade". This paper details the numerical modeling and simulation of TIM-PCM passive solar storage system with ESP-r. This partition consists of 25cm of ceramic composite modified by PCM, covered on the outside by 10cm of "honeycomb" TIM. The whole year analyses were conducted for a three-zone, highly glazed and naturally ventilated passive solar building. The behavior of TIM-PCM wall and its influence on internal wall temperature were estimated. The air, surface and resultant temperatures were compared with the "no-PCM" case and the diurnal latent heat storage effect was analyzed.

INTRODUCTION

The TIM-PCM facade system is commonly used in low-energy buildings. TIM components allowed collecting great number of solar energy whereas PCMs are able to store this energy in almost stable thermal conditions. In practice such kinds of wall are partially semitransparent and partially opaque. It caused some inconvenience in numerical modeling, especially in treatment the heat exchange in the gap between the TIM inside lining and absorber surface. The solution of that problem was reported in detail in Strachan & Johnstone (1994).

The work reported in this paper was concerned with the modeling of phase change materials combined with transparent insulation materials in the context of passive solar design. It is well known that the thermo-physical properties of the construction materials will have a strong influence on behavior of building elements in a storage system. Within a passive solar design, the heat capacity of the inner wall layer is dominant. Traditional heavyweight constructions can give rise to problems of excessive thermal mass and cost. Where traditional building materials are combined with a phase change materials compounds, isothermal phase change can be employed to provide close space temperature control at acceptable cost. Effectively, the additional latent heat of fusion is used to increase the thermal capacity of the construction.

Due to the factors mentioned above numerical analysis seems to be unnecessary in advanced building envelopes design. Generally two kinds of problems are encountered, one for transparent and second for the opaque part of the wall. The first one constitutes to a lack of satisfactory proportions between the solar heat gains and conduction heat losses. The second concerns the inadequate thermal mass for long term storage. On the basis of the problems already described it is reasonable to employ particular, additional strategies which improve solar systems efficiency. The strategies are usually those that aim at reducing heat losses and increasing storage abilities.

PCM-CERAMIC COMPOSITE

For the purposes of this work, PCM-ceramic composites made of clay with cellulose addition and fatty acids were considered. Base ceramic material was characterized by 30% of porosity, obtained by utilization of the wastes from paper industry. Fatty acids were introduced into the porous of the ceramic increasing its thermal capacity.

Some laboratory measurements of the ceramic compound with fatty acids were undertaken using Differential Scanning Calorimeter (Romanowska et al. 1998). The results showed that it is possible to obtain a heightened heat accumulation composite with almost isothermal change of phases. During the experiments three kinds of composites were selected for the purpose of that work. The PCMs considered here are self-nucleating and exhibit no overheating and overcooling effect. The heat of phase change obtained from laboratory measurements was about 25kJ/kg, which is an average value for PCM-composites and over twenty times higher as far as ordinary ceramics is concerned.

The designed melting temperatures were 20, 30 and 40°C.

MATHEMATICAL MODEL

Theoretical (Drake et al. 1987, Peippo et al. 1991) and experimental (Heim et al. 2001, Athienitis et al. 1997) analyses of the optimal transition temperature and latent heat capacity of PCM were conducted successfully. However, a building scale numerical simulation of phase-change phenomena is necessary to estimate the thermal behavior of storage elements e.g. walls, floors or roofs.

The heat transfer processes in the PCM structures are complex, especially when the chemical compound is in the transition stage. During the phase change process (melting or solidification), the PCM encapsulated in a porous building material can exist in three states: solid, liquid and 'mushy' (two-phase). Additionally, the thermal properties of a matrix of construction material are different from the constituent properties. To simplify the mathematical model, the following assumptions were made:

1. The PCM-gypsum composites are treated as a body of uniform equivalent physical and thermal properties—principally specific and latent heat, density and thermal conductivity.
2. The heat transfer process across the PCM-gypsum board is considered as one-dimensional.

The ESP-r control volume approach was adapted to describe the physical elements of the PCM model using ESP-r's zones and networks elements (Clarke 2001) and the effective heat capacity method to describe phase change phenomena (Heim 2002). Some initial applications of the method within ESP-r and initial results for gypsum composite are presented elsewhere: (Heim 2002, Heim & Clarke 2003). The exact description of the model is presented in (Heim 2003).

The control volume formulation is obtained by integrating associated partial differential equation of transient heat conduction over a small polyhedron control volume V, applying the mean value theorem and divergence theorem, with homogeneous material and uniform boundary at each surface (1):

$$\rho\left(\overline{T}\right) C_{eff}\left(\overline{T}\right) V\left(\overline{T}\right)\frac{\partial \overline{T}}{\partial t} = -\lambda_s(T)\frac{\partial T}{\partial n_s} + V\left(\overline{T}\right)\overline{g} \quad (1)$$

where $\overline{T}$ is the average temperature of V, ρ – density, λ – conductivity, C_{eff} – effective heat capacity, g the heat generation rate over the control volume and n_s the outward drawn normal unit vector.

According to the control volume and the effective heat capacity method, the effect of the phase transition is added to the energy balance equation via material property substitution. Effective capacity is a highly non-linear function of temperature within the phase change temperature range. It can be substituted, however, by a linear relationship. Such an approach has been proposed for the thermal simulation of single PCM components (Drake 1987, Jokisalo *et a.* 2000).

Within ESP-r, PCMs was modeled using the concept of *special materials* (Kelly 1998). Special materials were introduced to ESP-r as a means of modeling active building elements that have the ability to change their thermo-physical properties in response to some external excitation (e.g. electro-chromic glazing). The special material functions of ESP-r may be applied to a particular node within a multi-layer construction. Any node defined as a special material is then subjected to a time variation in its basis thermo-physical properties.

PROBLEM DEFINITION

TIM-PCM wall

For decades of investigations different forms of intelligent facades have been proposed and analyzed. With a view of effective gaining, long-term storage and easy distribution of solar energy TIM-PCM intelligent facade was proposed (Fig. 1). The collector-storage is divided into two, opaque and transparent parts. The outer part is 10cm of completely translucent TIM, which is a polycarbonate layer covered by glass from outside. The internal partition is built from 25cm of PCM-ceramic composite with cement plasters on both sides. The external side of the opaque layer is covered with the high absorptivity (α=0.90) finishing lining.

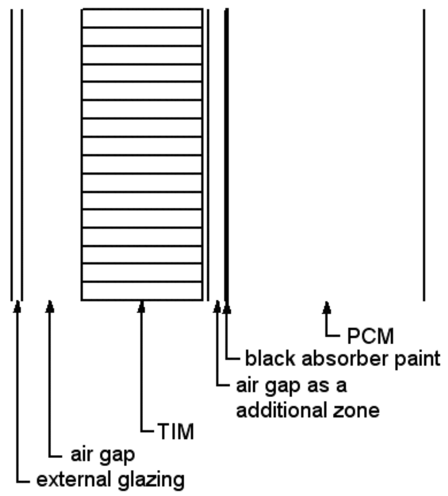

Figure 1. Cross-section through TIM-PCM wall

A hypothetical PCM-ceramic composite with a heat of fusion of 25kJ/kg (corresponding to a 30% of fatty acids mixture impregnated into the porous of ceramic) was taken into consideration. The melting temperatures T_m were set to 20°C, 30°C, 40°C and solidification T_s to 21°C, 31°C, 41°C. Thermophysical properties of TIM layers taken for calculations come from macro scale, laboratory measurements done within the framework of PASSYS program (Jensen 1993).

Four different arrangements were analyzed concerning the behavior of the storage walls under the changeable climatic conditions during a whole year. In every case the internal layer has a melting temperature equal to 20°C. All configurations are presented in Figure 2.

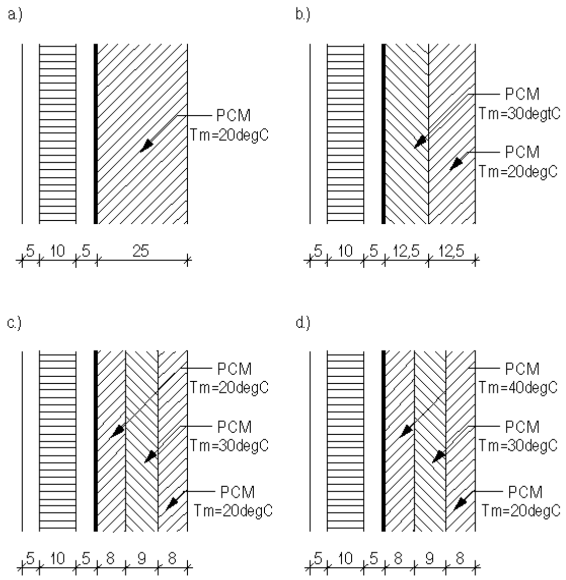

Figure 2. Configuration of multi-layered walls

Triple zone model

The triple zone, a naturally ventilated building with two direct gains rooms, insulated transparently, was modeled within ESP-r to conduct the numerical analysis. The perspective view presented in Figure 3 shows the scheme of ventilation network, windows and TIM-PCM walls, which was applied as a southern external partition for the east and the west passive rooms. Both zones, 4×5×2.5m each, are separated by a centrally placed, buffer zone. TIM-PCM wall was applied on the south elevation. The area of each intelligent facade equals 10m^2 and covers the whole south elevation. Therefore, the windows of both rooms had to be defined on the east and west side respectively. Thermophysical properties of partitions and magnitude of airflow were defined according to the European standards and existing rules. The heat transfer coefficient for all external, opaque partitions is set to 0.30W/m^{2}K, and for windows 1.3W/m^{2}K.

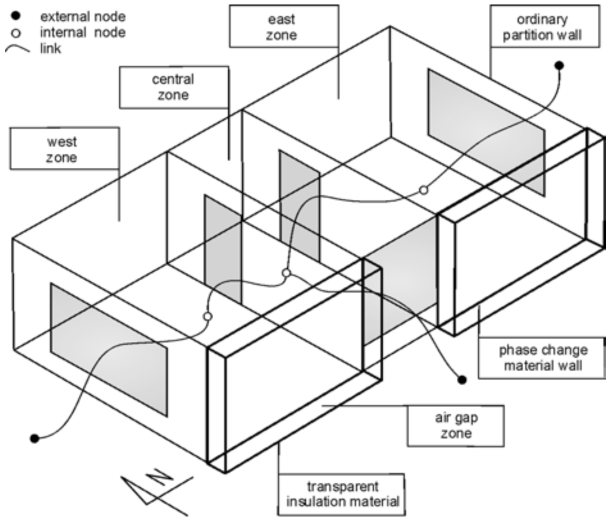

Figure 3. Schematic, prospective view of geometry and air flows in analyzed triple zone building

Operations and boundary conditions

The external boundary conditions were defined due to the Typical Meteorological Year for Warsaw – Poland (52ºN). For other, internal partitions, the boundary conditions for temperature were defined as an isothermal. The wind speed and direction determined infiltration flow through the gaps and openings. The magnitudes of components guaranteed the airflow to the order of 1ac/h. The equipment, light and occupant casual gains were neglected so as not to affect the results of the calculations. Continuous heating with the ideal control set on 20°C was defined for the whole heating season.

RESULTS

One of the most important thermal comfort parameters in the room is surface temperature. Traditional storage materials suffer from the overheating effects. Phase change materials should reduced this phenomena and decrease the comfort parameter inside the zones. The conducted analysis shows the effects of latent heat storage on thermal behavior of the internal lining.

A 15 minutes time step was used within both simulations. The values of the PCM node temperature in different parts of the wallboard were saved at each time step.

Firstly, the numerical simulation was conducted for a selected, one-day period to notice the effect of isothermal heat storage effect. The temperature distribution in the opaque part for an ordinary ceramic wall and PCM-ceramic composite are presented in Figure 4 and 5 respectively. Additional latent heat of phase change considerably reduces the surface temperature fluctuation between day and night.

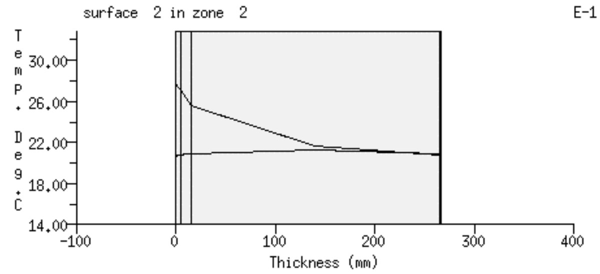

Figure 4. Temperature distribution through the ordinary ceramic wall

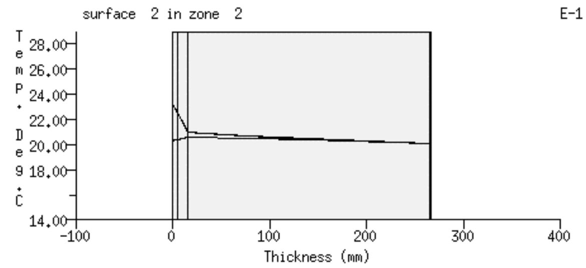

Figure 5. Temperature distribution through the PCM-composite wall

The quantity of latent storage is described very well by percentage distribution showed in Figures 6-10 for ordinary and PCMs materials respectively. The internal surface temperature is in the phase change temperature range during about 15% of the time, while for the ordinary materials it is less than 10%. It is evidence of a more stable temperature condition on the internal surface, which can be overcooled or overheated periodically. The surface temperature also affects the internal resultant temperature and fulfils thermal comfort parameters. The thermal behaviour of the wallboards also influences the room's resultant temperature. However the analysis of this data does not show significant differences in the zone's performance. This derives from a practical point of view, that some surfaces cannot be covered with a PCM-composite and therefore these surfaces heated rapidly and this had a significant impact on the room's resultant temperature.

To aid the analysis, the histories of internal surface temperature were presented in monthly time periods. Figures 11-22 show the differences between traditional ceramic and the four PCMs partitions. The absorber surface is highly exposed to direct solar radiation. The internal surface is charged by the energy absorbed on the outer surface and conducted to internal parts of the wall. The phase change process inside the wallboard allows a portion of solar energy to be stored as a latent heat. The process starts in each layer respectively, which is dependant upon the material's melting temperatures, however the inner side has T_m=20°C in every case. The greatest differences between ordinary ceramic and PCMs composites were reported in winter, where relatively small amounts of energy were absorbed during the day. The PCMs internal layer temperature was rather constant, while the ordinary material temperature varied more than 2 Kelvin during 24 hours.

In the summer the PCMs became overloaded as fast as the ordinary materials did. The PCM composites examined in that work provided no useful contributions during extreme summer conditions for the case studied here.

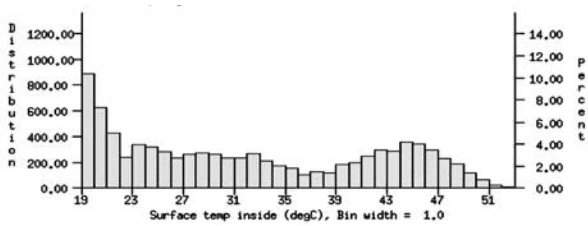

Figure 6. Ordinary ceramic

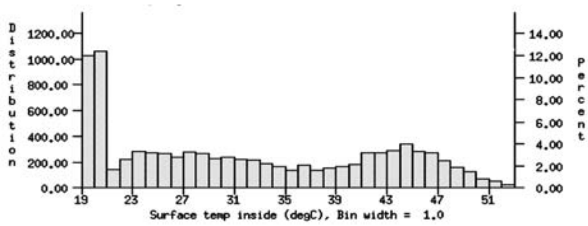

Figure 7. PCM T_m=20°C

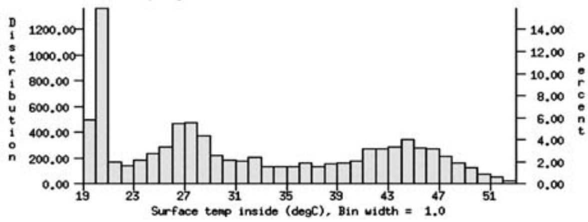

Figure 8. PCM T_m=30,20°C

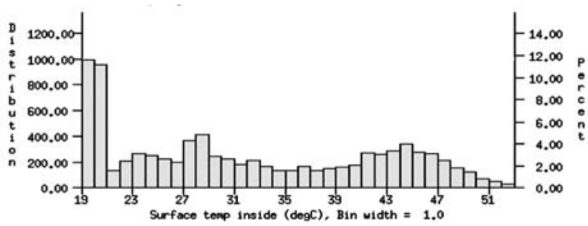

Figure 9. PCM T_m=20,30,20°C

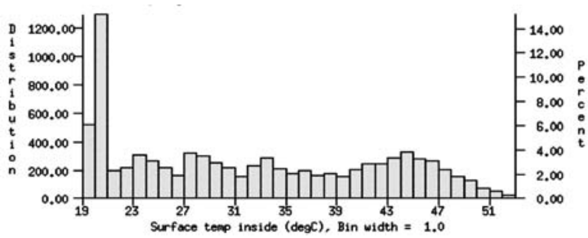

Figure 10. PCM T_m=40,30,20°C

CONCLUSION

This study is the first step in the integration of latent heat storage materials within building elements insulated by transparent materials for both, summer and winter application.

The results show the dynamic temperature variation on the opaque, massive part of the wall. The effect of latent heat storage allows a reduction these fluctuations during wintertime (December and January). However in the spring and autumn the influence of PCM on the thermal behavior of the wall is noticeable. On the other hand in summer time (June-August) there are no differences in temperature history for PCM-composites and ordinary ceramic.

The one-year analysis of internal surface temperature shows a significant fluctuation during the whole year (also for the storage wall with PCMs application). Using optimization techniques seems to be necessary during the design process of the storage multi-layered constructions.

The simulation was conducted with a continuous heating system of 20°C. However, loads on the equipment were reduced slightly. This effect should be more significant when the melting temperature would be greater than the heating set point ($T_m > T_i$). In our case the efficiency of analyzed wall systems is similar to a transparently isolated ordinary ceramic wall. However, PCMs highly improved thermal conditions on internal surfaces.

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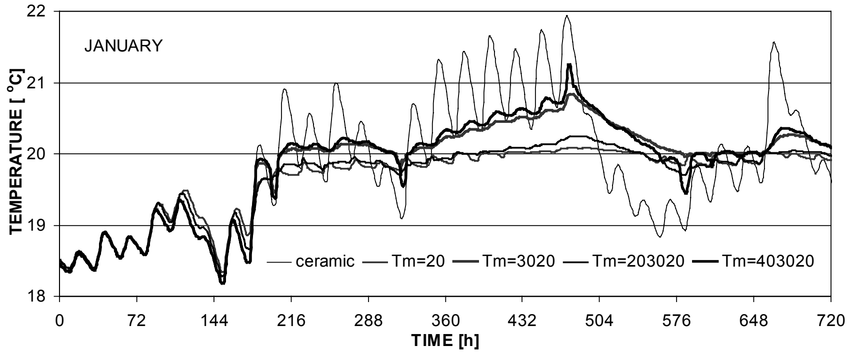

Figure 11. Internal surface temperature – January

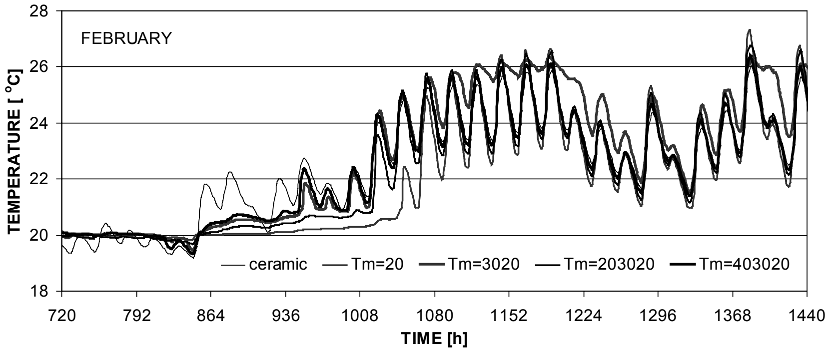

Figure 12. Internal surface temperature – February

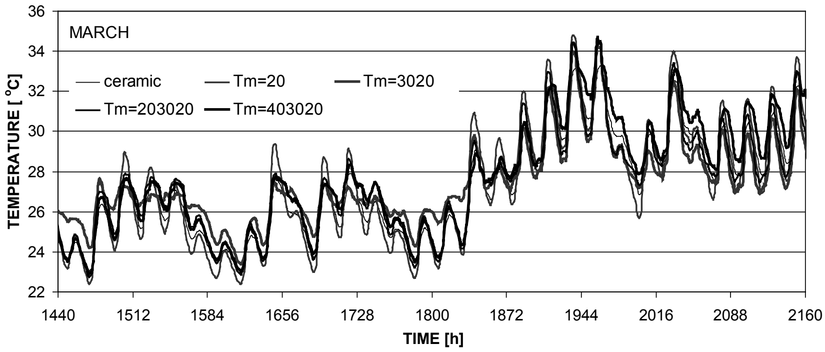

Figure 13. Internal surface temperature – March

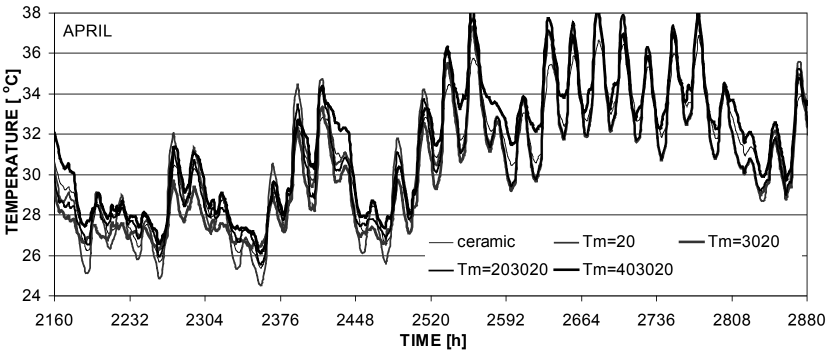

Figure 14. Internal surface temperature – April

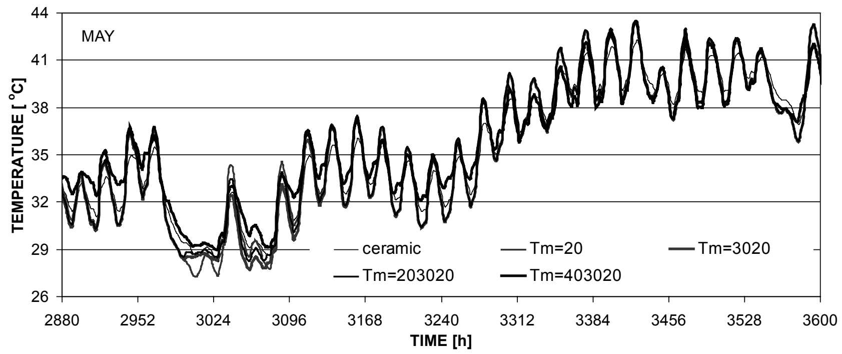

Figure 15. Internal surface temperature – May

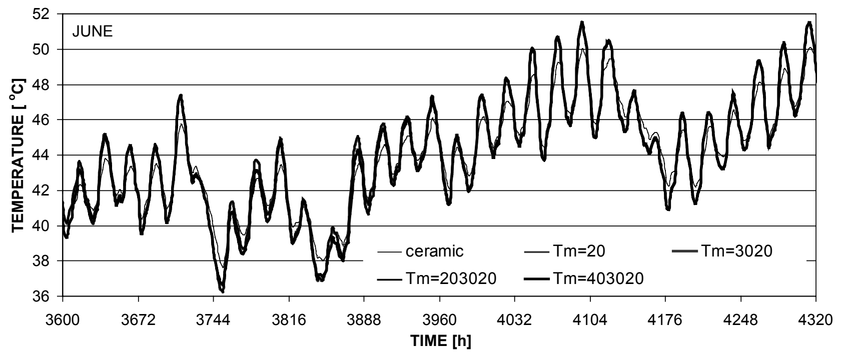

Figure 16. Internal surface temperature – June

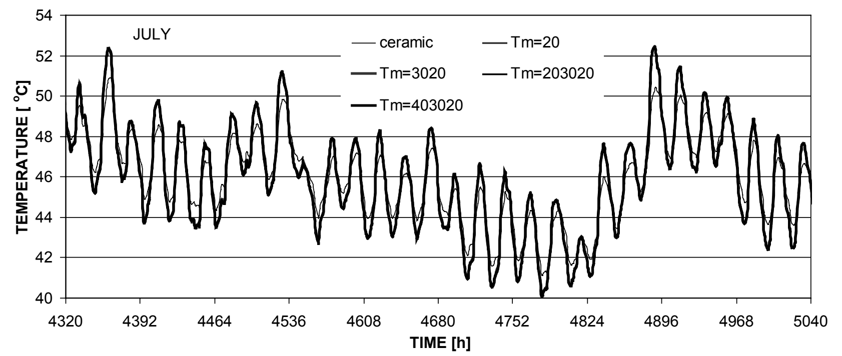

Figure 17. Internal surface temperature – July

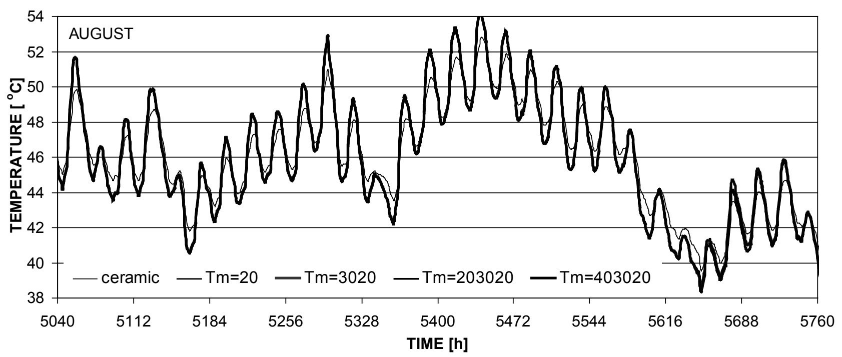

Figure 18. Internal surface temperature – August

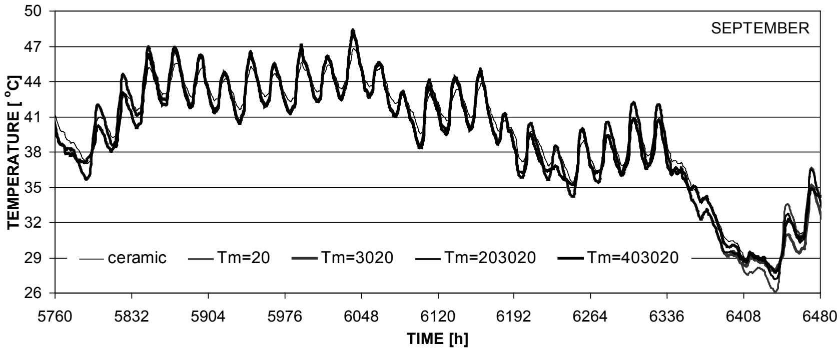

Figure 19. Internal surface temperature – September

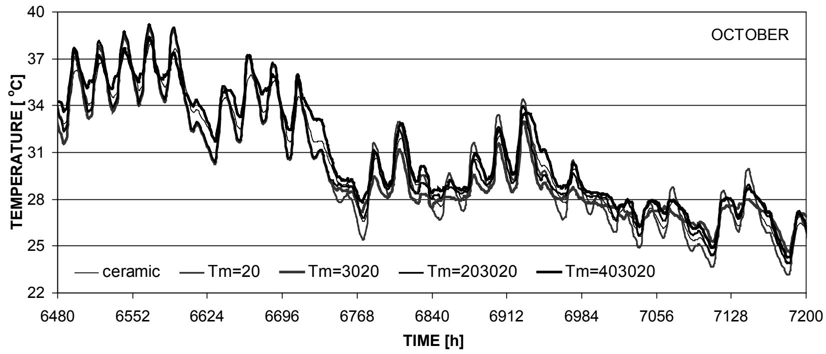

Figure 20. Internal surface temperature – October

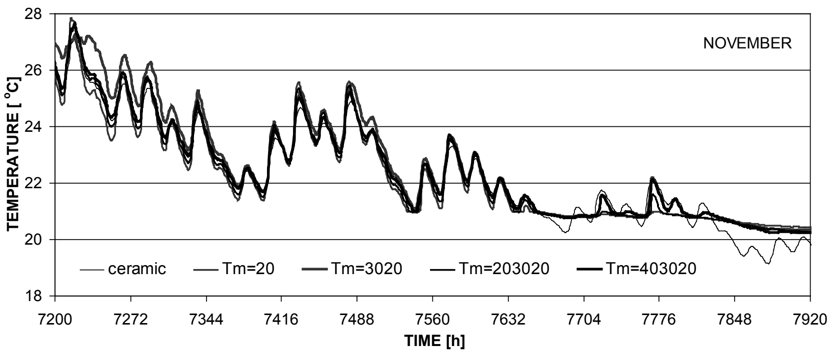

Figure 21. Internal surface temperature – November

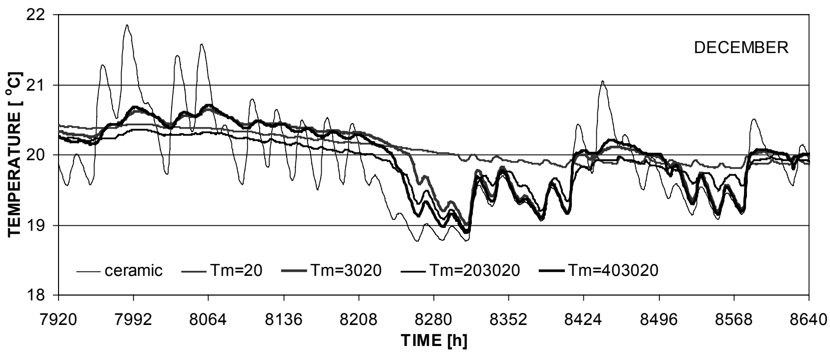

Figure 22. Internal surface temperature – December