IOP Conference Series: Earth and Environmental Science

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To cite this article: Lubomír Klimeš *et al* 2019 *IOP Conf. Ser.: Earth Environ. Sci.* **238** 012016

# An optimization study into thermally activated wall system with latent heat thermal energy storage

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**Abstract.** Thermally activated building structures with latent heat thermal energy storage (LHTES) are relatively new elements of building thermal energy systems. The system considered in the present study involved lightweight wall panels with a plaster containing a microencapsulated phase change material (PCM). The polyethylene tubes of small diameter for heat transfer fluid were embedded in the plaster. The wall panel system could be used for both heating and cooling. The PCM provided short-term thermal energy storage in case of intermittent supply of heat and cold (e.g. in case of a PV powered heat pump). A 1D computer model of the wall system was developed and implemented as a TRNSYS type. Consequently, an optimization model based on the 1D model of the system was developed. The optimization model employed a metaheuristic particle swarm optimization method. The aim of the optimization was to determine the position of the tubes for HTF, relative to the surface of the panel, that would provide fast thermal response and, at the same time, high amount of stored heat. The optimization was performed for heating operation.

## 1. Introduction

Thermally activated building systems (TABS), which boast with a large surface area for heat transfer with the indoor environment, are a very suitable option for low-temperature heating and high-temperature cooling in buildings [1]. Low-temperature heating and high-temperature cooling make it possible to use renewable energy sources, such as solar thermal [2]. The TABS can also contribute to better performance (COP) of heat pumps when these are used as heat and cold sources. A combination of thermally activated building structures with thermal energy storage (TES) allows for balancing of demand and supply of heat and cold, and thus it contributes to higher energy flexibility of buildings [3]. However, the increased thermal capacity of the TABS with TES can negatively influence their thermal response. When a thermally activated building structure is at the room temperature, and heating or cooling is needed, it takes some time before the structure heats up or cools down and delivers heat or cold to the indoor space. This problem is addressed in the present paper for a thermally activated wall panel with a microencapsulated phase change material (PCM).

## 2. Thermally activated wall panels

The considered thermally activated wall panel was of a rather simple design (Figure 1). It consisted of a baseboard with a thermal insulation layer on one side of the baseboard and a layer of plaster containing a microencapsulated PCM on the other side. Plastic tubes for liquid heat transfer fluid (HTF) were embedded in the plaster. The tubes were connected to the supply pipe at the top of the panel and to the return pipe at the bottom of the panel (Figure 1b). The inner diameter of the tubes was 2.5 mm and the outer diameter was 3.5 mm. The pitch of the tubes was 15 mm. The plaster layer was 20 mm thick. The aim of the optimization study was to determine the position of the tubes for HTF, relative to the surface of the panel, that would provide fast thermal response and, at the same time, high amount of stored heat. The minimum considered distance of the tubes from the room facing surface of the panel was 4 mm (from the surface to the center of the tube) and the maximum distance was 16 mm (Figure 1a).

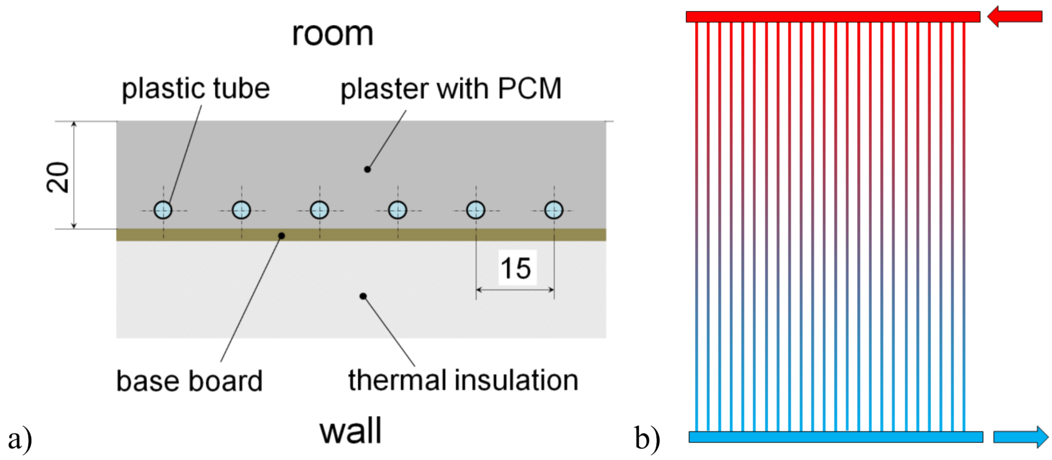


**Figure 1.** a) Section of the panel, b) Arrangement of the tubes in the panel.

## 3. Model of wall panel and optimization approach

The numerical model of the wall panel was written in C++ and implemented as a TRNSYS Type. The model combines a 1D model for heat conduction with the internal heat source for heat transfer in the plaster and the energy balance model for the heat transfer fluid. The modeling approach is described in detail in [4]. Since the panel contains many plastic tubes, only a periodic segment containing one tube and the corresponding part of the panel were modeled. For simplicity, the surface of the wall panel oriented to the wall was considered adiabatic. The room environment in this study is represented only by means of the room temperature, and thus the room itself is not modeled in the physical sense. A validation and comparison of the model with a 3D model created in the off-the-shelf commercial tool COMSOL Multiphysics can also be found in [4]. The results of both models were in very good agreement for the design of the wall panel shown in Figure 1.

As for the optimization approach, the metaheuristic optimization was utilized motivated by previous optimization results of the authors [5]. One of main benefits of metaheuristics is that they allow for the use of the numerical model as a black box. This means that the optimization model only needs to run the numerical model of the panel with certain parameters and no further details are required for the optimization part. Such approach also enables a simple coupling of a TRNSYS model with the optimization solver. In the paper, a particle swarm optimization (PSO) algorithm named PSwarm and implemented by Vaz and Vicente [6] was utilized. The PSO algorithm, similarly as other metaheuristics, is inspired by a behavior of species in the nature. A set of initial randomly generated solutions is called a population and the algorithm adopts nature-inspired selection, mutation, and reproduction operations to create new generations of the population [7]. New generations are created with the expectation that their individuals have progressively better and better properties (i.e. the value of the objective function for an optimization problem) converging to an optimal solution.

## 4. Modeled scenarios

Only heating operation of the wall panel is addressed in the present paper. The study was conducted for the thermophysical properties of the plaster shown in Table 1 containing all necessary properties for simulation of the considered heat transfer problem. Water was considered as the heat transfer fluid in the study. The volumetric flow rate of water through one tube was 1 ml/s. The inlet water temperature $T_{\mathrm{water,in}}$ was 35 °C, the room air temperature $T_{\mathrm{room}}$ was 20 °C and the constant value of the combined heat transfer coefficient of 8 W/m$^2$K was considered at the surface of the panel facing the room. The initial temperature of the wall panel (plaster) was considered the same as the room air temperature (20 °C).

**Table 1.** Properties of the plaster with PCM.

| Parameter | Value |
|---|---|
| Density | 677 kg/m$^3$ |
| Thermal conductivity | 0.176 W/m·K |
| Heat capacity | 1550 J/kg·K |
| Amount of latent heat | 90 kJ/kg |
| Temperature range of phase change | 4 K |

As already mentioned, there were two objectives in the conducted optimization, fast thermal response and high amount of stored heat. Such optimization problem thus pertains to the multi-objective optimization. Thermal response of the wall panel was evaluated in terms of the amount of heat delivered to the room in the first 60 minutes after heating was switched on. The time needed to reach the steady state conditions could be another way of evaluating the thermal response. However, since the surface temperature in the steady state operation depends on the position of the tubes (the distance of the tube from the surface of the panel) such comparison would be problematic. The purpose of thermally activated building structures is to deliver thermal energy to the room, and thus the comparison of amounts of heat is rather straightforward. Another objective of the optimization was to maximize the amount of heat stored in the wall panel. The stored heat would be released to the room when the supply of heat from the heat source would not be available. The room temperature was the reference level for the amount of stored heat (the wall panel at room temperature contained no usable heat). The selection of the objective function reflects what potential users expect from the system: it should have a capability to deliver heat to the room (heat source) as well as it should serve as a heat accumulator (heat redundant in a certain time period could be stored and released later when needed).

## 5. Results and discussion

Table 2 shows computational results for heating operation. First, the PSO model was launched in order to determine the optimal distance of the tubes from the surface of the wall panel (plaster with PCM). The results presented in Table 2 were acquired for the PCM having the phase change between 26 °C and 30 °C with the peak (mean value) at 28 °C. The goal was to maximize both the heat flow to the room (denoted as Qroom) and the amount of heat stored in the panel (denoted as QPCM). The objective function was formulated as

$$\text{maximize } \{w_{\text{room}} \cdot Q_{\text{room}} + w_{\text{PCM}} \cdot Q_{\text{PCM}}\} \tag{1}$$

where $w_{\text{room}}$ and $w_{\text{PCM}}$ were weights for the adjustment of the effective ratio between the heat flow to the room and to the plaster, respectively. The weights may be set specifically for a particular application. For simplicity, the results presented below were computed for $w_{\text{room}} = w_{\text{PCM}} = 1$. The PSO model found that the optimal distance of the tubes from the surface is 7.64 mm as shown in Table 2.

**Table 2.** Simulation and optimization results for the distance of the tubes from the surface of the plaster with the mean phase change temperature of 28 °C.

| Distance of the tubes from the surface [mm] | $Q_{\text{room}} + Q_{\text{PCM}}$ (value of the objective function) [kJ] | $Q_{\text{room}}$ [kJ] | $Q_{\text{PCM}}$ [kJ] |
|---|---|---|---|
| 4 | 35.049 | 7.041 | 28.009 |
| 6 | 36.391 | 5.813 | 30.578 |
| **7.64** | **36.499** | **5.253** | **31.246** |
| 8 | 36.236 | 5.137 | 31.100 |
| 10 | 35.629 | 4.622 | 31.008 |
| 12 | 35.746 | 4.210 | 32.536 |
| 14 | 33.828 | 3.833 | 29.995 |
| 16 | 30.489 | 3.504 | 26.986 |

Once the optimal distance of the tubes from the surface was determined by the PSO model, the computer model of the wall panel was evaluated for selected distances of the tubes with the attempt to verify the optimal distance determined by the PSO model. Table 2 shows results for seven positions of the tubes with the distance to the surface of 4 mm, 6 mm, 8 mm, 10 mm, 12 mm, 14 mm, and 16 mm. As can be seen from Table 2, the value of the objective function for the optimal distance of 7.64 mm is indeed the highest value and corresponds to the trend of values as well.

Figure 2 shows the effectiveness for the heating (heat charging) operation of the wall panel defined as

$$\varepsilon = \frac{T_{\text{water,in}} - T_{\text{water,out}}}{T_{\text{water,in}} - T_{\text{room}}} \tag{2}$$

where Twater,out is the outlet water temperature from the tubes computed with the use of the model of the wall panel, the inlet water temperature $T_{\text{water,in}} = 35\,°\text{C}$ and the room temperature $T_{\text{room}} = 20\,°\text{C}$. Figure 2 presents several curves as dependencies of the effectiveness on time during the heating operation for various distances of the tubes from the surface facing the room. As can be seen in Figure 2, the effectiveness for the optimal distance of the tubes attains the highest values in comparison to curves for other distances of the tubes. This behavior confirms that the optimal distance of the tubes 7.64 mm is indeed (at least for the case shown in Figure 2) optimal.

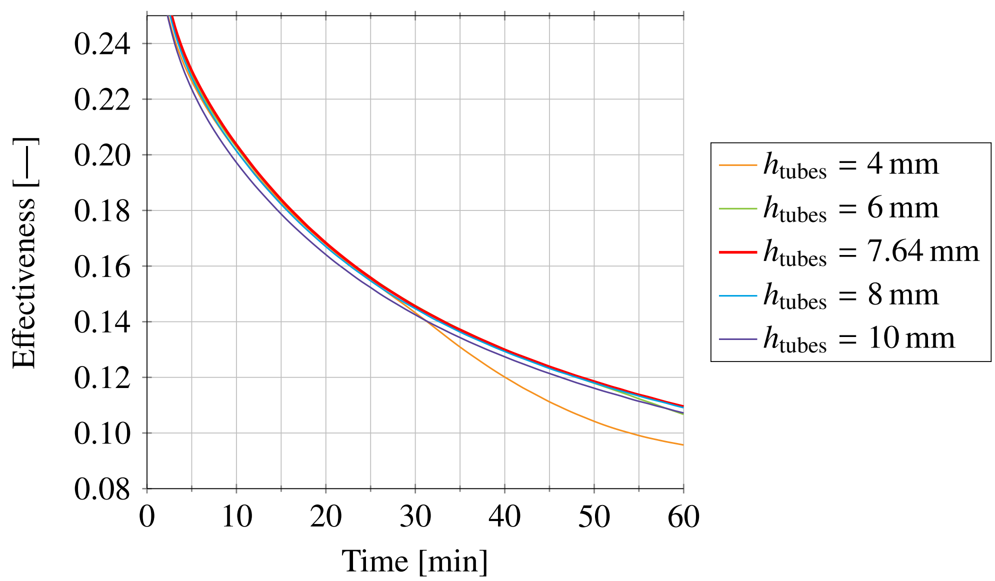


**Figure 2.** Effectiveness of wall panel in heating operation for various distances of the tubes from the surface of the plaster.

Table 3 presents optimization results (optimal distances of the tubes from the surface of the plaster facing the room) for the plasters with PCMs having various mean phase change temperatures. As can be seen in Table 3, the PSO model found that the highest value of the objective function is attained for the mean phase change temperature of 21.96 °C and for the distance of the tubes of 9.21 mm. This result indicate that the best solution is to use the lowest phase change mean temperature providing the entire phase change temperature range (in this case 4 K) is above the room temperature of 20 °C, which was also the initial temperature of the wall panel.

**Table 3.** Optimization results for the distance of the tubes from the surface facing the room for various phase change temperature ranges.

| Mean phase change temperature [°C] | Optimal distance of the tubes from the surface [mm] | $Q_{room} + Q_{PCM}$ (value of the objective function) [kJ] | $Q_{room}$ [kJ] | $Q_{PCM}$ [kJ] |
|---|---|---|---|---|
| 20 | 4.47 | 33.698 | 7.231 | 26.468 |
| **21.96** | **9.21** | **46.852** | **2.605** | **44.247** |
| 22 | 9.20 | 46.850 | 2.602 | 44.248 |
| 24 | 9.22 | 45.134 | 2.813 | 42.322 |
| 26 | 8.69 | 41.238 | 3.874 | 37.365 |
| 28 | 7.64 | 36.499 | 5.253 | 31.246 |
| 30 | 8.15 | 30.936 | 6.128 | 24.808 |
| 32 | 4.47 | 24.763 | 8.260 | 16.503 |
| 34 | 4.00 | 19.627 | 9.040 | 10.587 |

## 6. Conclusion

A computer model of thermally activated wall panels with a microencapsulated phase change material was coupled with an optimization solver in order to perform an optimization study. The model of the wall panels was developed and implemented as a user type for TRNSYS. As for the optimization model, a metaheuristic particle swarm optimization (PSO) solver was adopted and coupled with the model of the wall panels. The positions of the tubes in the plaster with PCM and of the mean phase change temperature of PCM were investigated as design parameters. The performed analysis showed that the system employing the PSO solver is capable to efficiently perform the design optimization of the considered system.

## Acknowledgments

This work was supported by the project Sustainable Process Integration Laboratory SPIL, No. CZ.02.1.01/0.0/0.0/15_003/0000456, funded by European Research Development Fund, Czech Republic Operational Programme Research, Development and Education, Priority 1: Strengthening capacity for quality research, by the Czech Science Foundation under project No. 18-19617S Hysteresis of the temperature-enthalpy curve during partial phase change of latent heat storage materials and by the project LTC18053 of the MEYS of the Czech Republic Advanced methods of nature-inspired optimisation and HPC implementation for the real-life applications.

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