Numerical Investigation of a Novel Heat Pipe Radiant Floor Heating System with Integrated Phase Change Materials †

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Abstract: The subject of buildings energy efficiency has gained increased interest in modern society. Recently, researchers aiming to reduce the energy demand of buildings have studied the implementation of phase change materials (PCMs) in various building elements. At the same time, researchers studied the implementation of unconventional technologies such as heat pipes (HP) in the buildings’ heating system. This paper combines both of these technologies in order to take advantage of the thermal storage properties of PCMs and overcome their reduced conductivity with heat pipes. Through computational fluid dynamics (CFD) simulations, this paper studies and highlights that with the implementation of a PCM, a reduction of the daily energy demand is achieved through the increase in the discharge phase time.

Keywords: phase change material; floor heating; heat pipe; computational fluid dynamics

1. Introduction

Worldwide, energy consumption is increasing, and buildings require over 40% of the global energy demand. In terms of emissions, buildings produce over 30% of the global net greenhouse gas emissions as a result of the increase in the indoor residence time and subsequently the surge in the requirements for indoor thermal environments and the heavy increase in urbanization, deforestation, and global climate change [1].

The increase in the global energy demand is one of the key reasons for the degradation and unstable development of our planet. This increase in the worldwide energy demand is a result of the rise in population coupled with better accessibility to energy of developing countries. Currently, a big portion of the global energy production is represented by fossil fuels; this has a drastic impact on the environment due to the greenhouse gas emissions. Since energy demand and the gross domestic product (GDP) growth of a country are linked, a policy towards the reduction of the energy demand would have a negative impact towards the GDP, and since the growth of renewable energies is slower than the rise in energy demand, an increase in energy efficiency can have a significant impact [2–4].

On a European scale, in order to overcome the drawbacks and to reduce the impact energy has on the climate, the European Parliament adopted a legislation in 2012 with the aim to reduce CO₂ emissions by 20% by 2020 in comparison to the values recorded in 1990. Studies showed that this goal would not be met by the proposed deadline, and as a result, the target year was set to 2030,
but the required reductions values were imposed to 27% for the energy demand and 40% for the CO₂ emissions [5].

PCMs are special materials that are capable of storing increased quantities of thermal energy in comparison to other materials through the phase transition process. There are two main ways of storing thermal energy, in the form of sensible heat, when the temperature of the material increases, the material phase being unchanged during this process, and in the form of latent heat, when the material receives thermal energy, changing its phase in the process, the materials that store latent heat being called phase change materials. PCMs can be classified in three categories: solid–liquid PCMs, solid–gas PCMs and liquid–gas PCMs, but among these categories, solid–liquid PCMs are the most commonly used [6–8].

In order to address the global concerns regarding topics such as energy consumption, energy efficiency, and sustainable buildings, researchers interest towards PCM has increased drastically in the last decades, highlighted by the number of publications and research articles, Figure 1.

The interest in phase change materials in the scientific community is highlighted by the increased interest towards their applications in buildings and their integration in various building elements such as walls [9–13], windows [14,15], ceilings [16,17], floors [18–23].

Heat pipes are highly efficient heat exchangers, being able to rapidly transfer high quantities of thermal energy across a small temperature gradient. A key advantage of heat pipes is their capability to quickly transfer heat from one of their ends to the other one with a reduced heat loss in comparison to other materials; thus, heat pipes can be regarded as “superconductors” [24].

Heat pipe applications in buildings also include the possibility to integrate them in glazed facades to take advantage of the solar radiation [25] to recover the waste heat [26].

The objective of this research is the study of a HPHS with an original design and analyzing the advantages and disadvantages obtained through integrating a PCM into this system.

2. Research Methodology

To achieve the objective of the research paper, studies for an originally designed heat pipe floor heating system were performed using the ANSYS Fluent CFD software in order to simulate the correct operation of two floor heating systems, a floor heating system that uses heat pipes as heat exchangers, and the same heat pipe heating system with an integrated phase change material layer.

![Figure 1. Worldwide PCM research articles between 1996 and 2019.](image-url)
For the study, a floor heating system with heat pipes was designed; the heat pipes heat the floor from two opposing sides in order to ensure a uniform distribution of the temperature for the floor.

As a primary agent, water was chosen, being the most commonly used working fluid for floor heating systems. After using this system, two cases were analyzed, the system heating a regular concrete floor and the system heating a concrete floor with an integrated PCM layer; the PCM layer is represented between two layers of concrete, because due to the phase transition process, shape stabilization is a problem that needs to be resolved.

The research is based on multiple CFD simulations using the ANSYS STUDENT 2019 R3 package and addressed the heat transfer of both cases during the heating and cooling cycles in order to demonstrate the system feasibility. The 3D modelling was realized with the DesignModeler part of the package, as highlighted in the horizontal and vertical sections in Figures 2 and 3.

![Figure 2](image1.png)

Figure 2. A vertical section of the models highlighting the different layers of both models: (a) The HPHS (b) The PCMHPHS: 1. First concrete layer. 2. PCM layer. 3. Second concrete layer. 4. Rectangular heat pipes.

![Figure 3](image2.png)

Figure 3. A horizontal section through the heat pipes and distributor. 1. Hot water inlet. 2. Distributors. 3. Rectangular heat pipes.

The analyzed models' geometry and dimensions are as follows:

- first concrete layer 500 × 500 × 20/10 mm
- PCM layer 500 × 500 × 10 mm
- second concrete layer 500 × 500 × 30 mm
• rectangular heat pipes 10 × 10 mm, 510 mm in length
• two-circular distributors 22 mm in diameter, 500 mm in length.

In terms of mesh initialization, sizing, and quality, linear element order with a 5 mm element size was imposed, and for the mesh quality, a target skewness of 0.8 was set, as presented in Figure 4.

To have an accurate representation of CFD simulation for the models in the case of the PCM model apart from the energy equation, the solidification/melting model was used.

For the phase change material, a paraffin, RT 21 HC, produced by Rubitherm Technologies GmbH [27] was considered, because it presents impressive purity and specific composition, which translates to increased latent heat capacity with a small temperature range, the performance of the material remaining high for the phase change cycles as a result of the long lifetime of the material. The paraffin properties are shown in Table 1.

| Characteristics                  | Value     | Units   |
|----------------------------------|-----------|---------|
| Melting area                     | 20–23     | °C      |
| Solidification area              | 19–21     | °C      |
| Heat storage capacity            | 190       | [kJ/kg] |
| Specific heat capacity           | 2         | [kJ/kg·K] |
| Density solid (at 15 °C)         | 0.88      | [kg/L]  |
| Density liquid (at 25 °C)        | 0.77      | [kg/L]  |
| Heat conductivity                | 0.2       | [W/(m·K)] |
| Max. operation temperature       | 45        | °C      |

The reference temperature for the water inlet was considered to be 35°C, because it is a standard operating temperature for the working fluid in an underfloor heating system.

The initial temperature during the heating phase of the system was considered 10 °C.

In terms of the cooling phase, the temperature of 10 °C was imposed on the upper surface.

3. Results and Discussion

In order to analyze the thermal storage capacity of both systems, complete charging/discharging cycles were simulated.
The numerical simulation shows that in this case, the heating phase of the HPHS reached a convergence temperature after 30 min and 40 s. The heat pipes’ thermal properties are highlighted through the second section, presenting that the heat pipes start heating the concrete layer in less than 1 min (Figure 5). The cooling phase for the HPHS lasted 68 min (Figure 6).

![Figure 5. A section through the HPHS during the heating phase.](image1)

![Figure 6. A section through the HPHS during the cooling phase.](image2)
In the case where a PCM layer was integrated, from the liquid fraction during the heating phase the PCM melting can be viewed; the PCM started melting around after 500 s, and it is fully melted after 4800 s; from the point the PCM starts melting, it takes almost 72 min for the PCM to fully melt (Figure 7). The system is fully heated after 127 min (Figure 8).

Figure 7. A section through the PCMHPS during the heating phase, displaying the PCM liquid fraction over time.

Figure 8. A section through the PCMHPS during the heating phase.
During the cooling process, the PCM properties are evidenced through the liquid fraction; the PCM starts melting solidifying in under 10 min, but the solidification period is prolonged, reaching a fully solid state, 99.7%, after 135 min (Figure 9).

![Figure 9. A section through the PCMHIPS during the cooling phase, displaying the PCM liquid fraction over time.](image)

In case of the second heating system, with a layer of PCM, the discharge period is drastically prolonged in comparison to the system without the PCM; the system is fully cooled down after over 290 min, proving that PCMs can be used in buildings to increase the thermal energy storage (Figure 10).

From the figures, the thermal properties of the HPHS can be observed during the heating and cooling phase, and through adding a PCM layer, the thermal properties of the PCMHIPS change, the second system having a greatly increased discharge phase, but as a result, the heating phase is also increased. Due to an increase in both the heating and cooling time for the second system in comparison to the HPHS, a direct comparison of the heating and cooling time was not used; thus, an analysis on the number of cycles in a 24 h period was used, while recording the charging and discharging time.

Following the numerical simulations, the time for each case was recorded for the heating and cooling cycles (Figure 11) and used to make a comparison between the two systems.

Considering the heating and cooling time for both systems to make a comparison in terms of energy consumption, 24 h uninterrupted cycles were analyzed; thus, the HPHS would require 14.59 cycles over a 24 h period, and the PCMHIPS required 3.45 cycles.

Afterwards, knowing the number of cycles and the heating time, the number of daily hours the heating source would operate is 7.46 h/day for the heat pipe floor heating system and 7.30 h/day for the PCM integrated heat pipe floor heating system.

The results highlight that the HPHS can be a viable alternative to a classic heating system; furthermore, by integrating a PCM into the structure of the floor, a further reduction in the number of working hours for the heating source can be achieved.
In order to further verify these results, further research will be realized through studying the system in comparison to various classic floor heating systems on real scale models and an analysis on the efficiency of different types of PCMs in floor heating systems.

**Figure 10.** A section through the PCMHPHS during the cooling phase.

**Figure 11.** The results for the heating/cooling cycles.

### 4. Conclusions

The originally designed heat pipe floor heating system harnesses the properties of heat pipes in order to heat the floor in an efficient way and through integrating a PCM in this system a prolonged
discharge period can be achieved, highlighting that both technologies have great potential to reduce the energy consumption in buildings.

The proposed heat pipe floor heating system requires a number of 7.46 h/day for heating, while the PCM integrated system requires 7.30 h/day. Apart from the reduction in the required time for heating through integrating a PCM, a further reduction in costs can be achieved through programming and automation if the heating cycles are set during off-peak periods, taking advantage of the PCM thermal energy storage properties.

**Conflicts of Interest:** The authors declare no conflict of interest.

**Nomenclature**

| HP           | Heat Pipe       |
|--------------|-----------------|
| PCM          | Phase Change Material |
| HPHS         | Heat Pipe Heating System |
| PCMHPHS      | Phase Change Material integrated Heat Pipe Heating System |
| T            | Temperature, [°C] |

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