Modeling of the discharging process of a heat storage tank filled with PCM to cover the heat demand of a building

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Abstract

The paper contains a brief description of calculations made for model tanks filled with PCM (Phase Change Material) that are used to cover the heat demand. The used model of the tanks takes into account the heat losses from the tanks' surfaces and the heat flux transferred between the PCM and water. The process of heat transfer in the PCM only uses the thermal conductivity phenomenon, which is appropriate for materials with high kinematic viscosity. The results of the change in thermal power of the storage tanks, outlet water temperature, PCM temperature and the amount of changing phase were considered significant. The article shows that the heat flux transferred between the PCM and the water depends primarily on the thermal resistance between the internal wall of the nodule and the moving front of the phase change from which energy is released. The mass flow rate of the water through the storage tanks has a lower impact on the speed of heat release. The article also shows the effect of PCM phase change and the flux of released heat on the temperature of the water flowing out of the tanks.

Keywords: thermal storage, phase change materials, heat balance

1. Introduction

The issue of heat accumulation for the purpose of heating a building is not new. Many years of research means that current heating installations successfully use water tanks for heat accumulation. However, the possibilities of such accumulation in water are limited. Therefore, more and more research is being devoted to the use of PCMs for this purpose.

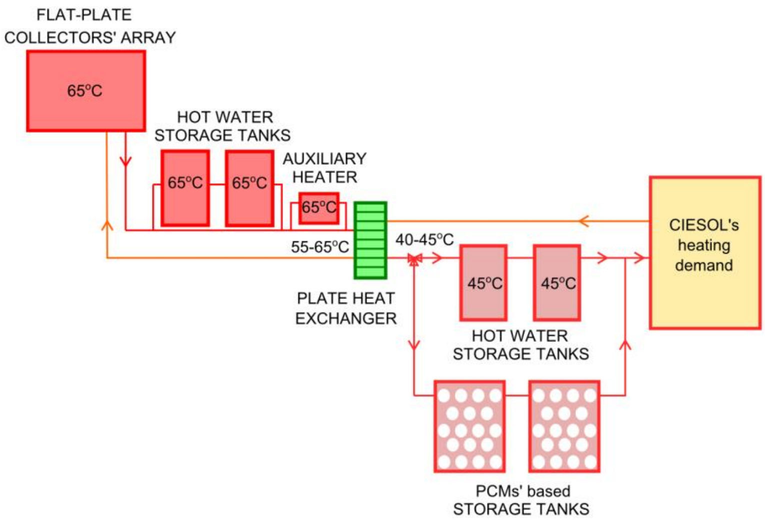

Fig. 1: Scheme of the heating system in the CIESOL building in Almeria

In literature, there are papers concerning the modelling of tanks in which the PCM is enclosed in spheres (Lee et al., 2019). However, the experimental tanks are usually filled with bottles (Ibanez et al., 2006) or, e.g. tubes

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(Mousaa et al., 2019), and those filled with the PCM spheres can only be found in small sizes, such as in (Huanga et al., 2019). Companies are reluctant to offer tank solutions with a capacity of several thousand litres that are filled with spheres, and instead they offer cube-shaped modules that are not described in literature.

The basis for carrying out the work is the task undertaken as part of the project *ERANet-LAC 2nd Joint Call on Research and Innovation called Thermal Energy Storage with Phase Change Materials for Solar Cooling and Heating Applications: A technology viability analysis (PCMSOL)*. As part of these activities, the possibility of using PCM tanks as a replacement for water tanks that cooperate with the installation of solar collectors, and which are used to cover heating demands is examined.

The installation, the heating scheme of which is shown in Figure 1, is situated in the campus of the University of Almeria in Spain. There is a Mediterranean climate with average temperatures in winter and high temperatures in summer. Heating installations works in this building ensure thermal comfort for its users - mainly the scientific and teaching staff of CIESOL. The current system is equipped with two tanks with a capacity of 2000 litres and 3000 litres, which are filled with water. These tanks are designed to ensure stable operation of the system.

The system works correctly, but the amount of accumulated energy is small and in the period of high-energy demand lasts for a very short time. In addition, in the morning, when the installation is starting after an overnight break, there is an increased demand for energy in order to quickly restore thermal comfort. This means that despite the large size of water tanks, they are quickly discharged. Therefore, the concept of using accumulators filled with PCMs, for which the phase transformation process can be treated as isothermal (Sharma et al., 2009), allows smaller accumulators, which accumulate more energy, to be used for the accumulation of heat.

The purpose of the work is to determine the thermal power of storage tanks filled with phase-change materials and to also determine the thermodynamic parameters of the accumulation material during discharging of the storage tanks.

2. Assumptions

When performing the heat balance of a building, the heating and cooling demands in the analysed facility can be determined. Such a balance was carried out for the CIESOL building in (Gil et al., 2019), and Figure 2 shows its thermal demands whilst at the same time indicating the maximum demand for heat and cold. It can be noticed that the maximum cooling demands are nearly three times higher than the heating demands for the assumed constant temperature of thermal comfort inside the utility rooms. Therefore, the amount of PCM for the accumulation of heat should be selected whilst taking into account this fact.

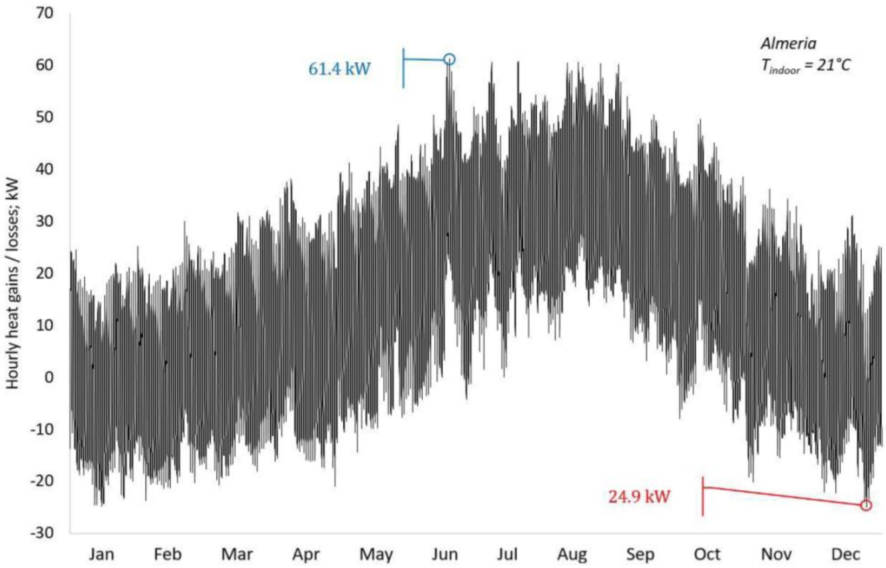

Fig. 2: Heat gains for the analysed set of rooms in the analysed building (Gil et al. 2019)

When creating a model of heat transfer inside a tank that is filled with PCM, some assumptions should be made. The calculation model takes into account the assumptions resulting from the work of the installation and the current state of knowledge about phase change materials. The assumptions include:

- the insulation of the storage tanks is 3 cm and the thermal conductivity of insulation is 0.034 W/(m·K),
- each tank is filled with high-temperature PCM and low-temperature PCM. Parameters are described by PCMProducts Company (PCMProducts information, 2019) as S46 and S10,
- the convective heat transfer coefficient on the PCM side $\alpha_{PCM} \rightarrow \infty$ (is neglected),
- the water flow rate depends on the pump capacity, and the maximum value is 25 m^3/h,
- nodules with the high-temperature PCM and the low-temperature PCM are arranged randomly,
- for heating mode, the initial temperature of the PCM is equal to 50 °C,
- for heating mode, the temperature of water flowing into tank 1 is equal to 40 °C,
- the temperature of water flowing out of tank 1 is the same as the temperature of the water flowing into tank 2,
- the time step is equal to 1 second,
- the PCM is enclosed in 3 mm thick hexagonal nodules, and the heat transfer coefficient is equal to 13 W/(m·K),
- used nodules of 500 x 250 x 32 mm are described by PCMProducts Company (PCMProducts information, 2019) as ICEFlat.

In utility rooms, comfort temperatures are set to be equal to 21 ºC (Fig. 2). The heating system that heats the building is located in a research laboratory, in which there are no strict rules regarding temperature control. In the summer it can be as high as 28 ºC. However, in the winter season, although the room is not intentionally heated, due to the machinery and installed equipment, such as e.g. the described heating system with water tanks and PCM tanks, the temperature in the laboratory is about 20 ºC, and this was adopted for the further calculations.

3. Solving the process

The calculation algorithm consisted of 30 balance equations describing one storage tank, which gives 60 equations describing the process and 30 unknown values for one storage tank, which in turn gives 60 unknown values for the process. Unknown values arising from the thermal balance of the tank are: $\dot{Q}_{side}$, $\dot{Q}_{top}$, $\dot{Q}_{bottom}$, $\alpha_{con\_side\_out}$, $\alpha_{con\_top\_out}$, $\alpha_{con\_bottom\_out}$, $\alpha_{con\_side\_in}$, $\alpha_{con\_top\_in}$, $\alpha_{con\_bottom\_in}$, Nu_{side_out}, Nu_{top_out}, Nu_{bottom_out}, Nu_{side_in}, Nu_{top_in}, Nu_{bottom_in}, T_{side_out}, T_{top_out}, T_{bottom_out}, T_{side_in}, T_{top_in}, T_{bottom_in}, $\alpha_{rad\_side\_out}$, $\alpha_{rad\_top\_out}$, $\alpha_{rad\_bottom\_out}$. These parameters are shown in Figure 3.

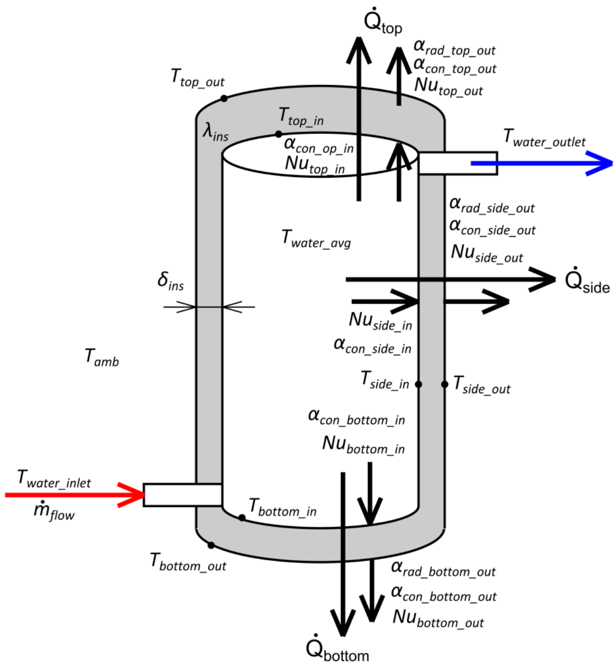

Fig. 3: Thermal parameters describing the heat loss process from the storage tanks

Equations for the heat transfer through a partition described in (Wiśniewski, 2014) were used for the determination of the tank's balance. Heat losses through the cylindrical side surface and the bottom and top were determined whilst taking into account heat transfer through the tank's wall with an applied insulation, free convection on its external side and forced convection on its internal side. This issue was described in detail by the authors in (Nemś et al., 2017), however with a difference that the balance was determined for a cube-shape accumulator through which the air flowed.

The process of heat exchange between the water flowing through the tank and PCMs was described in the same way as the tank's balance. The heat transfer through the surface of a single nodule is described by a forced convection on the side of water, the conduction through the wall of the nodule, and the conduction through the PCM. It was assumed that the process of heat release only occurs from the place of phase change. This means that transport in the PCM is only through the thickness s of the constant phase, which changes over time along with the released heat. Unknown values in the heat transfer process between the water in the tanks and PCMs are: $\dot{Q}_{water\_PCM\_1}$, $\dot{Q}_{water\_PCM\_cold\_1}$, $T_{water\_outlet\_1}$, T_{PCM_1}, $T_{PCM\_cold\_1}$, $\dot{Q}_{water\_PCM\_2}$, $\dot{Q}_{water\_PCM\_cold\_2}$, $T_{water\_outlet\_2}$, T_{PCM_2}, $T_{PCM\_cold\_2}$, S_1, S_2. These parameters are shown in Figure 4. Due to the fact that there are two tanks in the system, the indexes concerning the first one were designated as "1", and the second one as "2". The above-mentioned 36 unknowns were determined using Mathcad 15 software from 36 equations that describe the heat balance for an accumulator filled with PCMs.

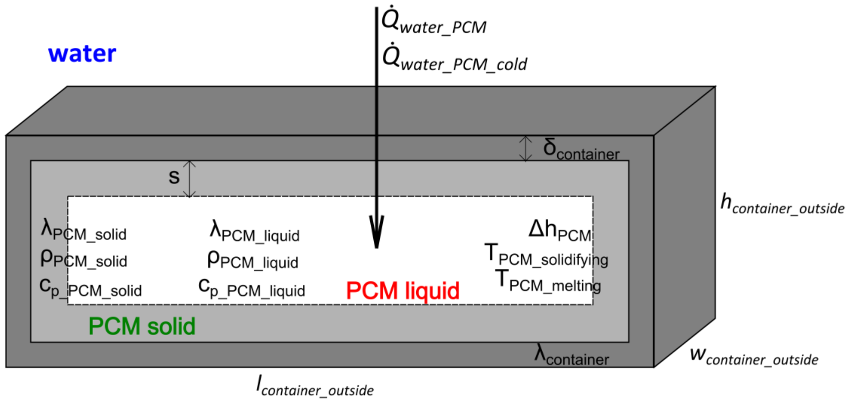

Fig. 4: Thermal parameters included in the model of heat exchange between water and the PCM

The used storage tanks enable the use of 180 PCM nodules, the arrangement of which is adopted as in Figure 5. The relations of the number of nodules in 2000-liter tanks and the proportions of quantities S46 and S10 adopted for the analysis are shown in Table 1.

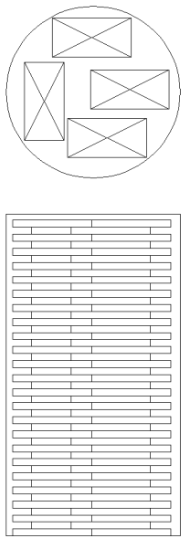

Fig. 5: Arrangement of PCM nodules in 2000 litre capacity tanks

Tab. 1: Number of nodules with the used PCMs as a function of their shares in a 2000-liter nodule

PCM \ Proportions	50-50	30-70	10-90
S46	90	54	18
S10	90	126	162

Due to the fact that in storage tanks, in addition to nodules, there is almost 1250 litres of water, the heat accumulated in them as sensible heat should also be considered. The flux of released heat is then dependent on the mass intensity of the flowing water and the temperature difference between the incoming and outgoing water. Figure 6 shows the dependence between the thermal power and the time of operation of the heat accumulators. The water temperature reduces from 50 °C to 40 °C according to the previous assumptions. The initial value of the thermal power is in this case dependent on the maximum flow rate of the circulation pump and is equal to 292 kW. However, with time, this power decreases. This is due to a decreasing temperature of the water in the tanks.

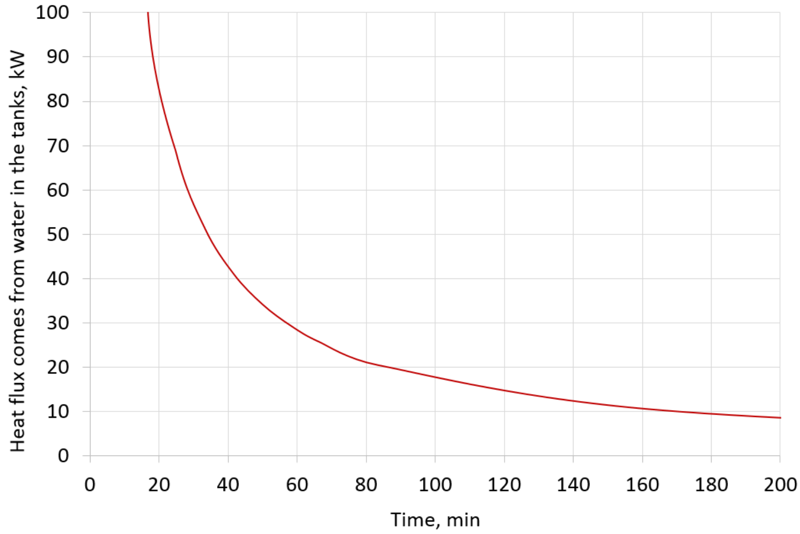

Fig. 6: Heat flux only released by the water contained in two 2000-litre tanks

In further analyses, it was assumed that heat will be first taken from the energy accumulated in the water, and when the heat flux is too low, it will then be collected from the PCMs. This assumption allows a better analysis of the process of the heat transfer between the PCMs and water, while at the same time providing information on the accumulation possibilities of a tank filled with PCMs.

4. Results

The calculations were made for two operation modes, however for the purpose of this article, only the heating mode that aims to cover the heating demands in winter was analysed. Due to this fact, the accumulation material was meant to be heated to 50 °C.

The thermal power of the heat accumulator was chosen as the basic parameter of its operation because the power shortage results in a lack of thermal comfort in a building. In addition to the thermal power, the temperature of the water flowing out of the tanks is important as it affects the operation of other elements of the system, such as radiators or floor heating. Therefore, this parameter has also been analysed. The PCM temperature and the mass share of the PCMs that undergo phase transformation were also considered as significant. The combination of the last two parameters with the thermal power of the tanks and the temperature of the water flowing out of them should provide the necessary knowledge to understand the relationships in the analysed heat exchange process.

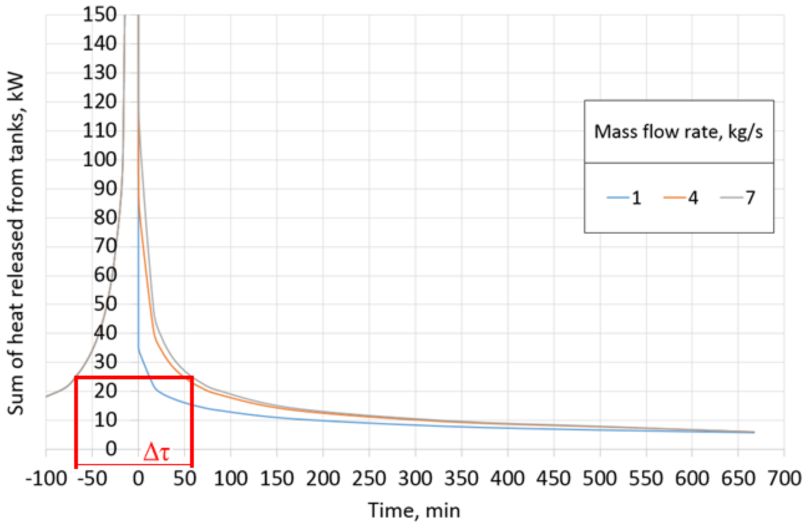

Fig. 7. Heat flux released from two 2000-liter tanks for 50-50 % proportions of S46 and S10

Figures 7 to 18 show variations of the 4 discussed parameters with regards to different amounts of PCM for the accumulation of heat and cold. In the first case, the proportions of S46 and S10 were 50 % of each, and the changes in the released heat flux, water outlet temperature, PCM temperature and mass share of the constant phase for S46 are shown in Figures 7 to 10.

In Figures 7, 11 and 15, the tanks power curve from heat accumulated from only water was added, as shown in Figure 6. This action enables the time Δτ, in which the heat released from the tanks will cover the thermal demands of the building (for a maximum water flow rate and heat demand of 24.9 kW), to be accurately determined, as shown in Figure 7. In addition, the separation of the tanks' power, which results from the heat accumulated in the water and PCM, allows the process of releasing heat stored in the PCM to be thoroughly analysed.

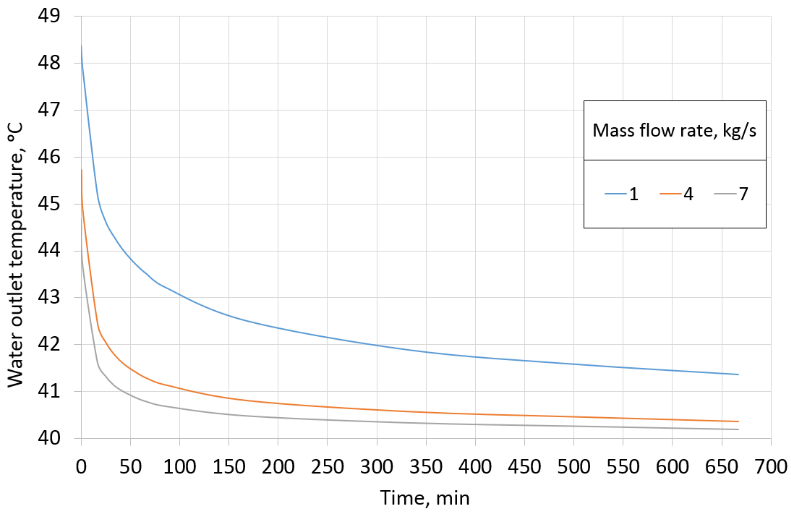

Fig. 8. Water temperature outflowing from the second of two 2000-liter tanks for 50-50 % proportions of S46 and S10

As can be seen from Figure 7, the released heat flux increases with an increase in the mass flow rate. This is because of a decreasing thermal resistance on the side of the water. This flux decreases in time due to a decreasing temperature difference between the PCMs and the water flowing through the tanks. There is also a visible drop in the thermal power of the tanks when the phase transition begins. This is due to the increasing thermal resistance that results from the increasing distance of the PCM phase change front from the surface of the tank.

It can be seen in Figure 8 that the temperature of the water flowing out of the tanks changes over time, and after a few hours approaches the temperature of the water entering the tanks. This is due to the decreasing flux of heat transfer between the PCMs and the water (for a constant flow of water through the tank).

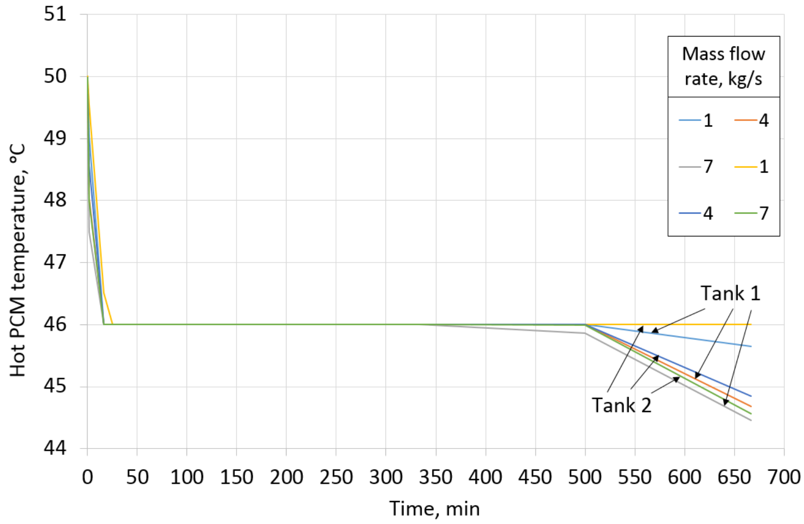

Fig. 9. Temperature of S46 inside two 2000-liter tanks for 50-50 % proportions of S46 and S10

It can be seen in Figure 9 that the temperature of the PCM in the first tank changes faster than in the second tank, and the same situation occurs in the case of the phase transition process, which also takes place faster. This is due to the larger temperature difference between the PCM and the water in the first tank. The effect of this is also a higher thermal power of the first tank and its faster discharge.

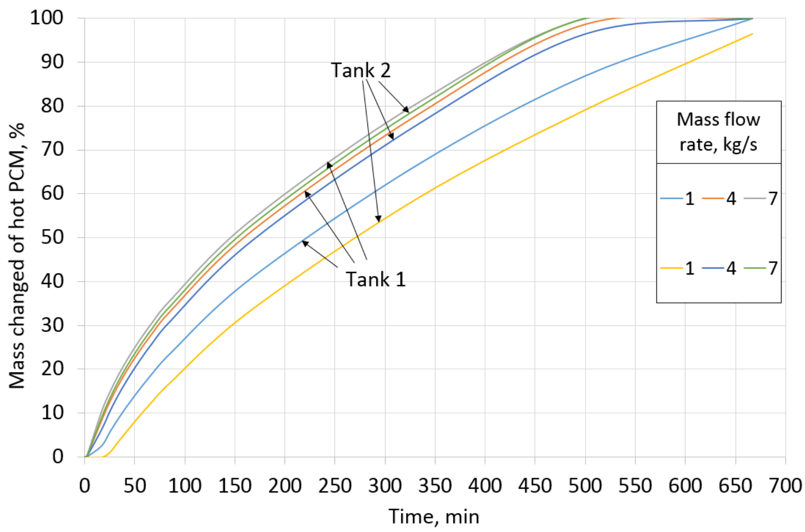

Fig. 10. Mass changed of S46 inside two 2000-liter tanks, for 50-50 % proportions of S46 and S10

The change of the S46 phase starts just after the PCM temperature drops to 46 °C. The phase change process then proceeds dynamically in the first few minutes. Afterwards, it slows down due to the increasing thermal resistance on the PCM side. It is worth noting that for small mass flow rates of water, the phase change process takes even longer than 10 hours.

Figures 11 to 14 show the same operating parameters for S46 and S10 in a ratio of 30 to 70 % respectively.

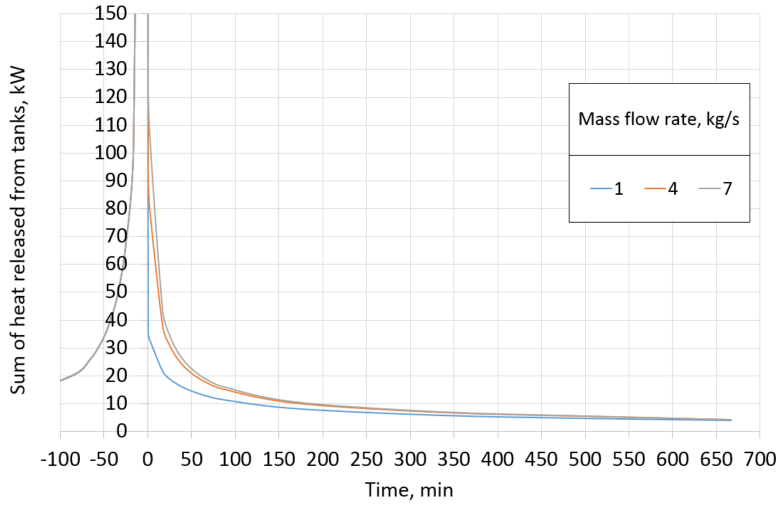

Fig. 11. Heat flux released from two 2000-litre tanks for 30-70 % proportions of S46 and S10

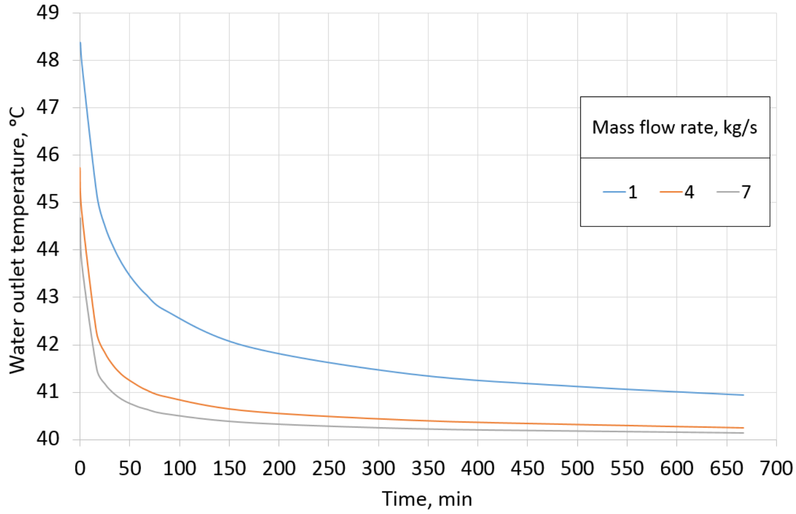

Fig. 12. Water temperature flowing out of the second of two 2000-litre tanks for 30-70 % proportions of S46 and S10

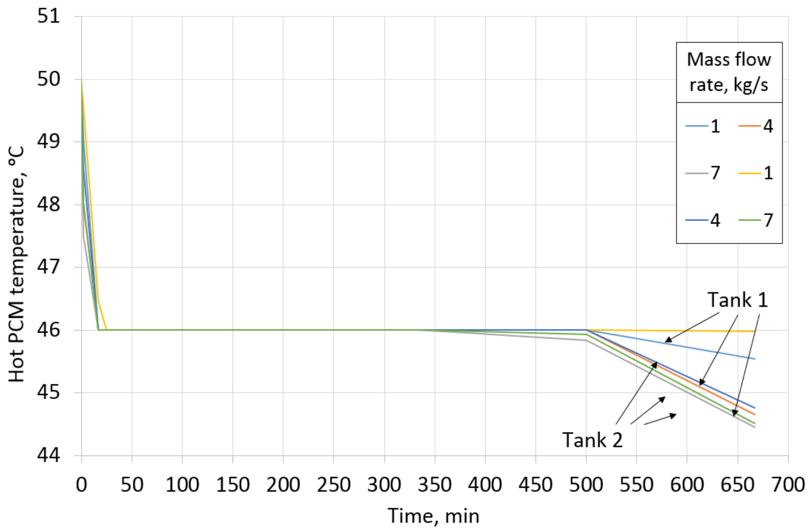

Fig. 13. Temperature of S10 inside two 2000-litre tanks for 30-70 % proportions of S46 and S10

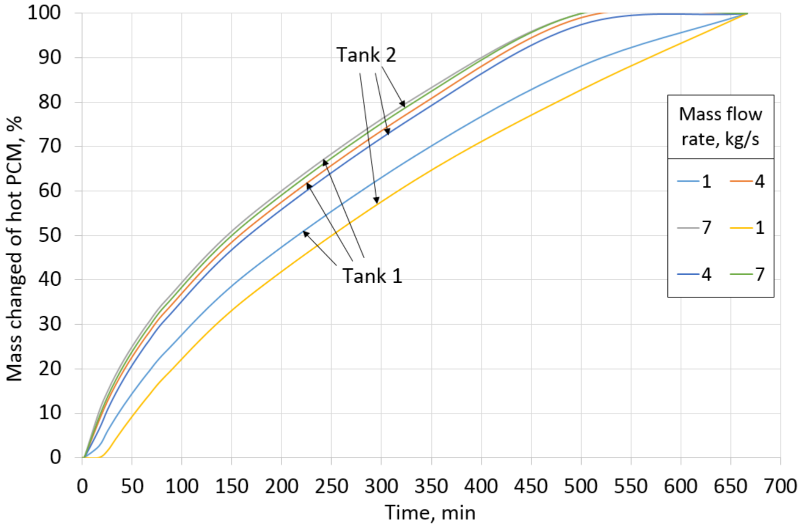

Fig. 14. Mass change of S10 inside two 2000-litre tanks for 30-70 % proportions of S46 and S10

The last 4 diagrams (Figs. 15-18) show the process parameters of the water and PCMs, but with the PCM contribution to heat accumulation of 10 %. The remaining part involved PCM for the accumulation of cold.

As can be seen from Figures 7, 11 and 15, the released heat flux by the storage tanks changes slightly with the change in the PCM proportions for the accumulation of heat and cold. For example, after 25 minutes it is equal to 19.46 kW, 18.86 kW and 18.13 kW for the ratios of 50-50 %, 30-70 % and 10-90 %, respectively.

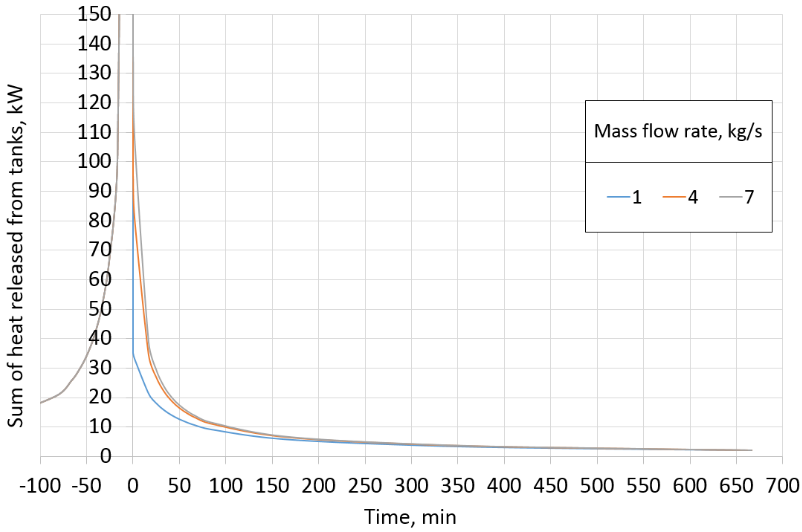

Fig. 15. Heat flux released from two 2000-liter tanks for 10-90 % proportions of S46 and S10

The increase in the amount of S10 at the expense of S46 results in a faster decrease of the temperature of water flowing out of the tanks. However, these changes are hardly visible in Figures 8, 12 and 16 because e.g. for the time of 25 minutes they are equal to 44.63 °C, 44.49 °C and 44.31 °C. This is due to a smaller amount of energy accumulated at a given temperature and a smaller amount of material that undergoes a phase change.

Under the given conditions, the phase change process takes a very long time in all the analysed cases (as shown in Figures 9, 13 and 17). For low water flow rates through tanks, even a long tank discharging time did not complete the phase change process in the second tank, as shown in Figures 10, 14 and 18.

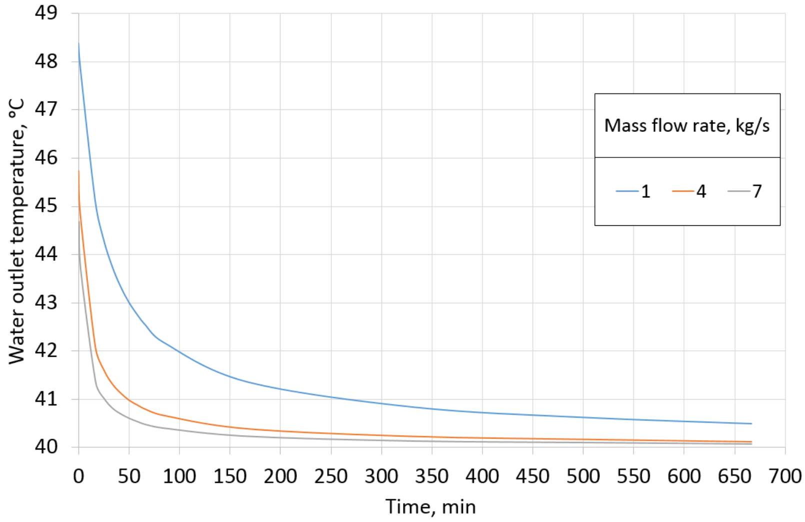

Fig. 16. Water temperature outflowing from the second of two 2000-liter tanks for 10-90 % proportions of S46 and S10

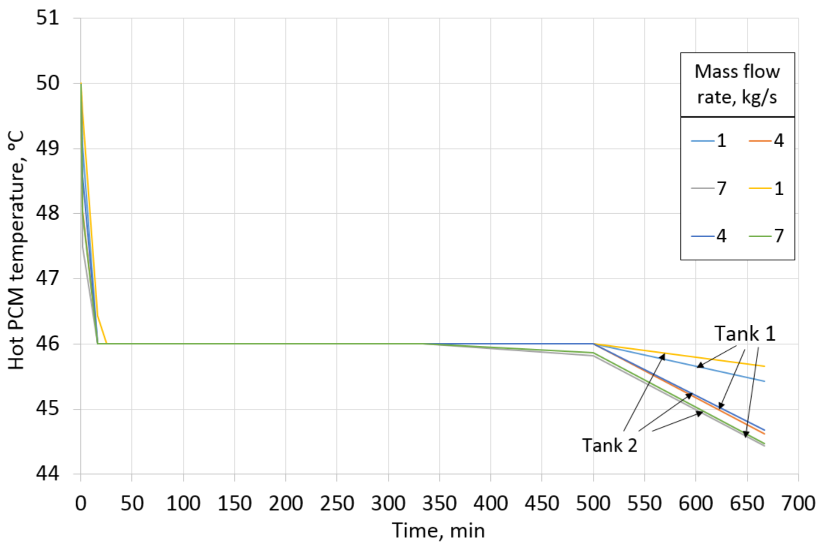

Fig. 17. Temperature of S46 inside two 2000-liter tanks for 10-90 % proportions of S46 and S10

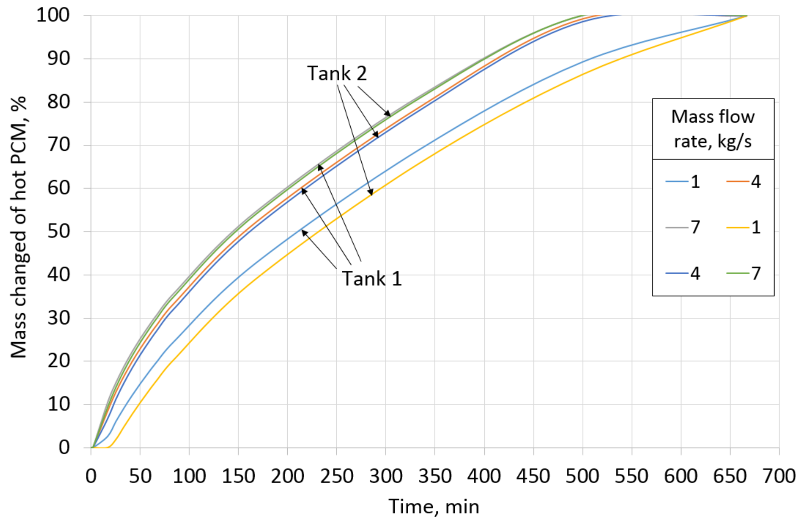

Fig. 18. Mass changed of S46 inside two 2000-liter tanks for 10-90 % proportions of S46 and S10

5. Conclusions

The presented results of the model, despite the adopted assumptions, provide information on problems related to heat accumulation in PCM filled tanks. Although phase-changing materials allow for the accumulation of more energy, the release of this energy is difficult.

From the above analysis, the following can be concluded:
- the flux of released heat increases with an increase of the mass flow rate,
- this flux decreases over time (in time), due to the decreasing temperature difference between the PCM and water flowing through the tanks,
- there is a very significant drop in the thermal power of the tanks when the phase transition begins. This is due to the increasing thermal resistance, which is caused by the increasing distance of the front of the PCM phase transition from the container's surface,
- the temperature of water that flows out of the tanks changes over time, and after a few hours it approaches the temperature of the water that enters the tanks. This is because of the decreasing flux of transferred heat between the PCM and water.

In addition, the obtained results show that the change in the ratio of the PCM to the accumulation of heat and cold has a slight effect on the thermal power of the tanks. However, due to the greater cooling demands, variants with a greater proportion of S10 material will be further analysed.
The presented results were made with an assumption that the convective heat transfer coefficient for the PCM is neglected. This simplification resulted in lower accuracy of the obtained results. Therefore, the next important step is to determine it as a function of existing variables and improve the calculation algorithm using this parameter.

6. Acknowledgments

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Appendix

Nomenclature:
Nu – Nusselt number, -
$\dot{Q}$ – heat flux, W
S – the distance between the front of the phase change and a nodule's wall, m
T – temperature, K
α – heat transfer coefficient, W/(m·K)

Indexes:
bottom – bottom surface
cold – PCM for the accumulation of cold
in – inside the heating tank
out – outside the heating tank
rad – radial
side – side surface
top – top surface
1, 2 – number of storage tank