Analysis of heat storage using Phase change material

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Abstract. In many cases heat released from some of the renewable energy sources, cannot be directly used at the time of its generation. Therefore, facilities for thermal-energy storage (TES) which would allow delayed use of the harvested heat are very important for increase of the total process efficiency. An approach to thermal-energy storage is based on the use of the latent heat of phase-change materials (PCMs). The use of PCMs as thermal storage has a theoretical advantage over the sensible one because of their high latent heat that is released or accumulated during the phase-change process.

The advantage of PCM in thermal energy storage is in applications that needs narrow temperature range of supplying and storing thermal energy. The focus of the paper is on the analysis of thermal energy storage devices based on macroencapsulated PCM. The aim of this paper is to design a latent heat storage (LHS) system with spherical modules filled with PCM. Several measurements were performed on the experimental system under constant input conditions which shows that PCMs improve the release of heat from thermal storage and can supply heat or cold at a desired temperature level for longer time periods. With the help of the computer simulation program TRNSYS, a validation of the simulation model of the latent heat storage system Type 840 was carried out with the initial and boundary conditions of the experimental system. Finally, a parameter analysis for different diameters of the spherical modules was carried out using the simulation model.

Keywords. Energy storage, Latent heat storage, Phase change materials, Optimization, Parametric analysis.
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1. Introduction

Nowadays, as global warming is becoming one of the most urgent problems in the world, we need to find a better way to utilize energy: not only in the field of energy production, transmission, distribution, and consumption, but also in the area of energy storage (1).

Current energy production in the EU comes from five different sources, namely oil and petroleum products (36%), natural gas (8,5%), solid fossil fuels (15%), nuclear energy (32%) and renewables (15%) (2,3). Of this, the household, together with services, consumes 40% of the total energy produced, of which 80% energy is used for heating and cooling (4).

Buildings' CO_2 operational emissions account for 30% of the total energy-related carbon emissions (2,3). Indeed, the decarbonization of the building sector plays a central role in the action against climate change. To reduce greenhouse gas emissions by at least 40% (Paris Agreement), the EU has introduced a new directive (2010/31 / EU) as one of the ways to increase the energy efficiency of buildings, for which it has invested heavily in their renovation (5, 6). The EU's goal is to become carbon neutral by 2050. The process of decarbonization of greenhouse gases is primarily part of the building sector in the fight against global warming. Reducing carbon emissions in the building sector goes through improving energy efficiency and the use of renewable energy sources (7).

In order to achieve better energy efficiency of buildings, new ways need to be explored energy storage and efficiency. The focus of the paper is on the analysis of thermal energy storage devices based on macroencapsulated PCM (4,8). The aim is to design a latent heat storage (LHS) system with spherical modules filled with PCM. Several measurements were performed on the experimental system under constant input conditions which shows that PCMs improve the release of heat from thermal storage and can supply heat or cold at a desired temperature level for longer time periods. With the help of the computer simulation program TRNSYS, a validation of the simulation model of the latent heat storage system Type 840 was carried out with the initial and boundary conditions of the experimental system. Finally, a parameter analysis for different diameters of the spherical modules was carried out using the simulation model.

2. Thermal energy storage

Thermal energy storage (TES) is a technology that accumulates thermal energy by heating or cooling a storage medium so that the stored energy can be used at a later time for heating and cooling applications or power generation. TES systems can help balance energy demand and supply on a daily, weekly and even seasonal basis. They can also reduce peak demand of energy, energy consumption, CO2 emissions and costs, and increase overall efficiency of the system(10).

There are three different types of TES systems, namely:

a. *Sensible heat storage* – technology based on storing thermal energy by heating or cooling mostly a liquid or solid storage medium (e.g. water, sand, molten salts, rocks), where water is the cheapest option;

b. *Latent heat storage* using phase change materials (PCM) e,g from a solid state into a liquid state, and;

c. *Thermo-chemical storage* using chemical reactions to store and release thermal energy.

The well-known consequence is an increase in temperature (sensible heating) or change of phase (latent heating) is shown in **Error! Reference source not found.**. Starting with an initial solid state at point A, heat addition to the substance first causes sensible heating of the solid (region A–B) followed by a solid–solid phase change by crystalline structure change (region B–C), again sensible heating of the solid (region C–D), solid–liquid phase change (region D–E), sensible heating of the liquid (region E–F), liquid–gas phase change (region F–G) and sensible heating of the gas (region G–H).

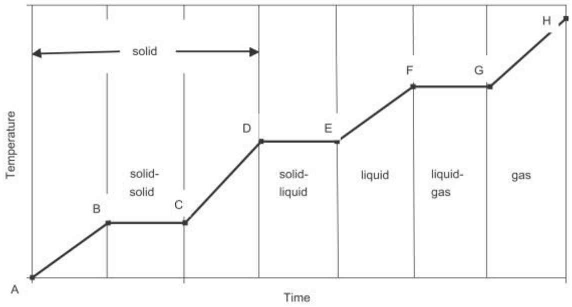

Fig. 1: Temperature-time diagram for the heating of substance*(9).*

The total amount of energy stored can be written as:

$$Q = m\left[\int_{Ta}^{Td} Cps(T)dT + L_p + L + \int_{Te}^{Tf} Cpl(T)dT + L_g + \int_{Tg}^{Th} Cpg(T)dT\right] \quad \textbf{(Eq. 1)}$$

where m is the mass of material, Cps specific heat of material in solid phase, Cpl specific heat of material in liquid phase, Cpg specific heat of material in gas phase, Lp is latent heat of solid–solid phase change, L is latent heat of solid–liquid phase change and Lg is the latent heat of liquid–gas phase change(9)..

2.1 Sensible thermal energy storage

In sensible heat storage (SHS), thermal energy is stored by raising the temperature of a material, typically a solid or liquid. SHS system depends on the heat capacity and the change in temperature of the material during the process of charging and discharging heat. The amount of heat stored depends on the specific heat capacity of the medium, temperature change and the amount of storage material. Heat transferred to the storage medium leads to a temperature increase of the storage medium. A sensor can detect this temperature increase and the heat stored is than called sensible heat. The amount of heat stored in or released form a material can be described as:

$$Q = m\int_{T_i}^{T_f} c_p dT \quad \textbf{(Eq. 2)}$$

where Q [J] is the amount of thermal energy stored or released in form of sensible heat, Ti is the initial temperature of medium, Tf is the final temperature of medium, m [kg], is the mass of material used to store thermal energy, and cp [J/kgK] is the specific heat capacity of material used to store thermal energy [3]. SHS is often used with solids like stone or brick, or liquids like water, as storage material(11).

2.2 Latent thermal energy storage

In case of latent thermal energy storage, thermal energy is stored through phase change of storage medium. During phase change of medium thermal energy can be released at nearly constant temperature. Materials used in latent thermal stages are known as phase change materials (PCMs).

The storage capacity of the material depends on both its specific heat and latent heat values. Thus, it is desirable for the storage medium to have high specific heat capacity and latent heat value. Latent heat storage may be classified on the basis of the phase change process as solid–solid, solid–liquid, solid–gas and liquid–gas.

Latent heat storage (LHS) is based on the heat absorption or release when a storage material undergoes a phase change from solid to liquid or liquid to gas or vice versa. The storage capacity of the LHS system with a PCM medium is:

$$Q = m\left[\int_{T_i}^{T_m} c_{p,s}\,dT + a_m \Delta h_m + \int_{T_m}^{T_f} c_{p,l}\,dT\right] \quad \textbf{(Eq. 3)}$$

where T_m is the melting temperature, $c_{p,s}$ [J/kg K] is the specific heat capacity of solid PCM, $c_{p,l}$ [J/kg K] is the specific heat capacity of liquid PCM, a_m is the fraction of PCM melted [-] and Δh_m [J/kg] is the heat of fusion per mass unit. Note that c_p has different values fort he solid state $(T_i < T < T_m)$ and the liqud state$(T_m < T < T_f)$, which is denoted by the indices s and l.

2.3 Materials for latent heat thermal energy storage LH

Materials that are used for LHTES should have a large latent heat and high thermal conductivity. These materials are expected to fulfil some requirements, such as:

- A melting temperature lying in the practical range of operation,
- Melt congruent with minimum sub-cooling,
- To be chemically stable,
- Low cost,
- Nontoxic and noncorrosive

Materials that have been studied during the last 40 years are hydrated salts, paraffin waxes, fatty acids and eutectics of organic and non-organic compounds. The idea to use PCMs for the purpose of storing thermal energy is to make use of the latent heat of a phase change, usually between the solid and the liquid state, to store a high quantity of energy. Since a phase change involves a small temperature changes, PCMs are used for temperature stabilization and for storing heat with large energy densities in combination with rather small temperature changes(13).

Error! Reference source not found. compares the achievable storage capacity at given temperature difference for a storage medium
with sensible heat storage and with latent heat storage.

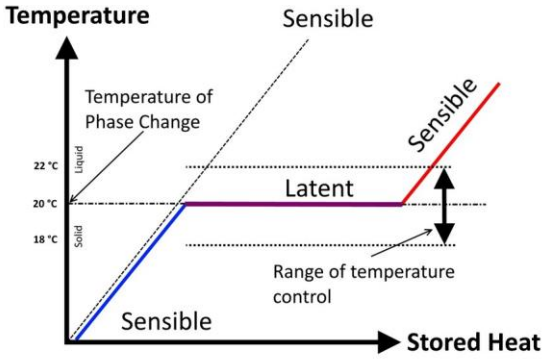

Fig. 2: Heat storage as latent heat for the case of solid-liquid phase change*(12).*

Because one of the goals of LHTES is to achieve a high storage density in a relatively small volume, expected thermal characteristics for PCMs are a high melting enthalpy [J/kg] and a high density [kg/m^3], i.e. a high volumetric melting enthalpy [J/m^3].

3. Experimental investigation

The purpose of this experiment was to investigate improvement in increased energy density for thermal energy storage by integrating PCM modules in water storage tank. The influence of integrated modules on time of providing heat demand and the maximum heat output ha also been studied.

3.1 Experimental system

The experimental system was designed according the standard *VID 2146 – PCM energy storage systems in building services.* With experimental system we have an opportunity to make measurements of charging, discharging and standby of energy storage under different initial conditions.

The storage tank of volume 0,1 m^3 was used. A large part of time has been dedicated to selection of the right shape of the modules. There are different forms in which PCMs can be inserted into the storage tang, e.g. pack, panels, balls (spherical modules), cylindrical shape etc. According to the standard parameters, the spherical modules *FSS PCM HS24* were used in our system, as shown in **Fig. 3.**

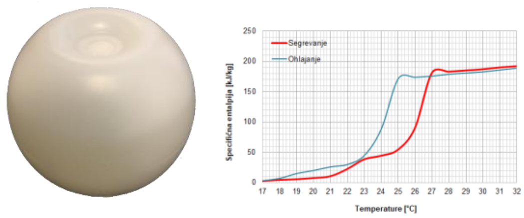

Fig. 2: Spherical modules filled with PCM and enthalpy-temperature function of PCM of FSS PCM HS24.

The temperature was measured with thermocouples, which were arranged along the height of the system and at the inlet and outlet of storage tank. For charging and getting propriate inlet temperate we used 4 kW electric heater. For discharging of storage tank was used the Omega air TAE 031 water cooler.

The scheme of the experimental system is shown in Fig.***4***, with the charging process being shown in red, with blue colour shows the process discharging system. On the diagram are presented all the hydraulic connections and locations of temperature sensors, shut-off valves and circulation pump for each circle.

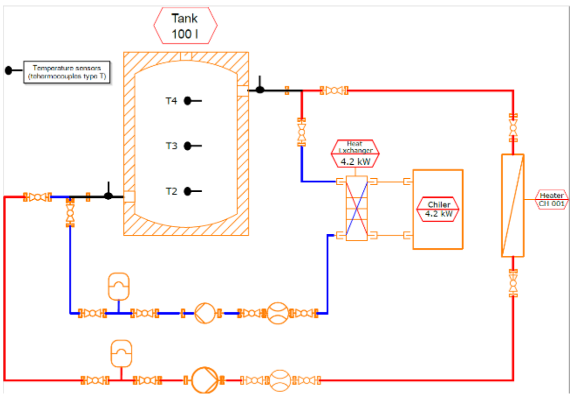

Fig. 4: Scheme of experimental setup.

3.2 Measurements

Two sets of measurements were performed, charging process with temperature of inlet water of 35 and 45°C and discharge process with temperature of inlet water of 16°C.

On the **Fig. 5** and **Fig. 6** can be seen that with higher inlet temperature we need shorter time of changing storage tank. In our case we can see that for inlet temperature of 35° C time of phase changing is $\Delta t = 164\ min$ and $\Delta t = 118\ min$ for inlet temperature of 45° C. From here we can make a concussion that inlet temperature has significant affect to the operation of the LHS.

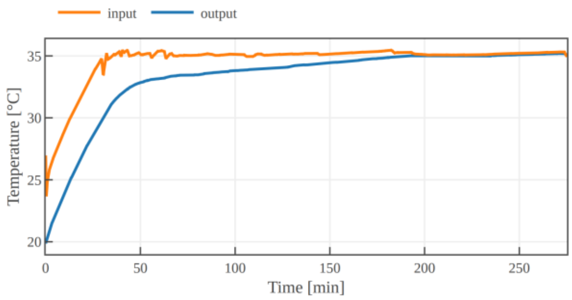

Fig. 5 Charging of LTS with inlet temperature of 35° C.

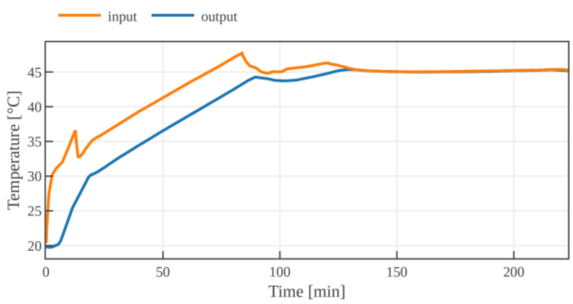

Fig. 6: Charging of LTS with inlet temperature of 455° C.

On the ***Fig.7***, shows changing of absorbed energy during different inlet parameters. We can noted that absorption of energy depends exponentially of temperature. Due to larger temperature difference, the maximum accumulated energy is 4kWh. For reaching this energy we need approximately 130min. on the other side, maximum accumulate energy for inlet temperature of 35° C is 2.5kWh for 200min.

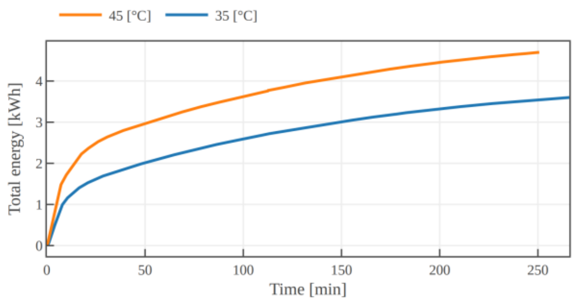

Fig. 7. Storage energy in different charging temperature of 35 and 45 ° C.

During the discharging process were made the same measurements with max. flow rate of the water of $q_v = 490\ {}^{kg}/_{h}$. On **Fig. 8** is shows that time that we need for discharging all system was 135 min.

And from the **Fig. 9** is shown energy released during the time of discharging of LTS. From the fig. we can say that the in the period of 250 min we released 4,7 kWh of energy. This amount of energy was released when the LHS was charge with inlet temperature of 45°C.

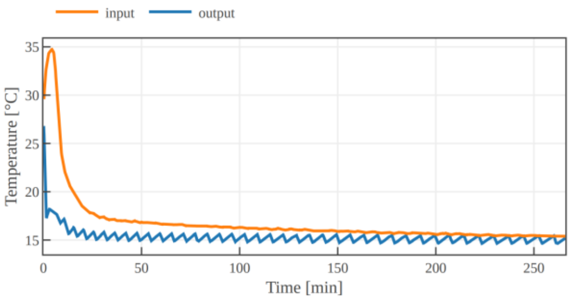

Fig. 8. Discharging of LTS with inlet temperature.

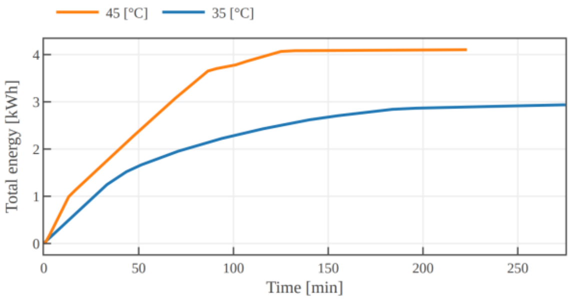

Fig. 9. Heat released during discharging of LHS.

4. Results and discussion

With the help of the computer simulation program TRNSYS, a validation of the simulation model of the latent heat storage system Type 840 was carried out with the initial and boundary conditions of the experimental system.

On the **Fig.10** shows the schematic of TYPE 840 simulation model that was built by team from TU Graz. The scheme consists of the following sets: latent storage tank, a module for the implementation of experimental data and a module for plotting graphs and printouts of the results of a numerical model. A comparison of the temperatures inside the heat accumulator and the outlet temperatures between the simulation and the experiment was made during the melting process as well as during the solidification process of the FSS.

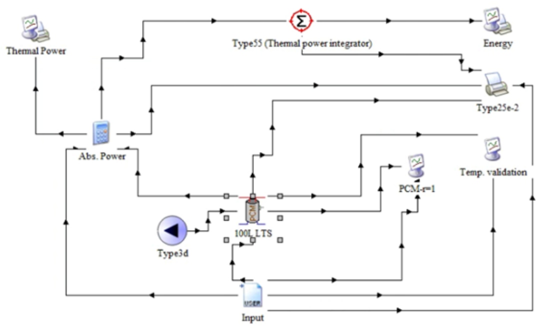

Fig. 10: Schematic of simulation system TYPE 840 in the Trnsys software environment.

For validation of our model, we made comparation of measuring and simulated temperatures data. Validation was made regarding to relative error on the outlet temperature and the temperature inside the storage tank. On **Fig.11** and **Fig.12** are shows relative errors between outlet temperature and temperature inside storage tank during process of charging and discharging of the system.

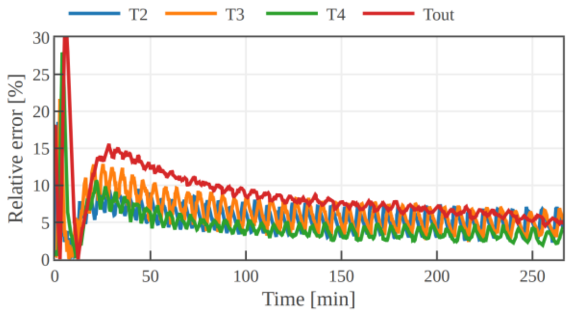

Fig. 10: Relative errors between simulation and measuring results during the process of discarding.

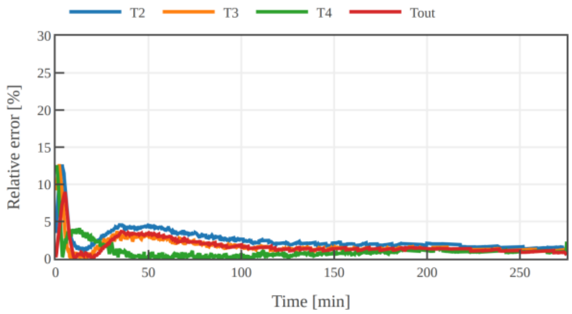

Fig. 10: Relative errors between simulation and measuring results during the process of charging with inlet temperature of 35^0C.

The most important parameter is outlet temperature. According to the relative errors shows in the **Fig.11** and **Fig.12,** we can say that the numerical model during charging is presenting results with relative error of 3% and 5% during discharging the system.

One of the reasons why the relative error is higher is due to the placement of thermocouples inside the LHS. The thermocouples were attached to a tube inserted in the middle of the tank. To prevent contact between the thermocouples and the pipe wall, the thermocouples were moved a few centimetres' away from the pipe. In addition to the basic reasons, deviation is also greatly influenced by the inaccuracy of temperature measurements within the modules, which would give us an accurate start data. The results show that the smallest difference is in the middle of the tank, and the largest at the top. Similar to the outlet temperature, the numerical model better describes the processes during the charging than in discharging of the system.

Finally, a parameter analysis was made for different diameters of the spherical modules was carried out using the simulation model. For analysis we use different diameters PCM $D = [50, 75, 100, 120]mm$. Number of the PCM modules (N) can be determined by following equation:

$$N = \frac{6V}{D^3 \pi} \qquad \textbf{(Eq. 2)}$$

Where V is a volume of the tank and D represent the dimeter of the module.

We made 2 different simulation, charging the system with flow rate of $q_v = 350\, {}^{kg}/_{h}$ and discharging with flow rate of $q_v = 490\, {}^{kg}/_{h}$.

On the **Fig.13** shows that the temperature inside the tank is changing proportional to the size of the modules. Time required for to equalizing to the inlet temperature of 35⁰C is $\Delta = 190min$ for the FSS diameter of 50 mm, and for diameter 120 mm $\Delta = 437min$.

On the **Fig.14** showing variation of outlet temperature in time. From the chart we can see that we have logarithmic temperature scale in time.

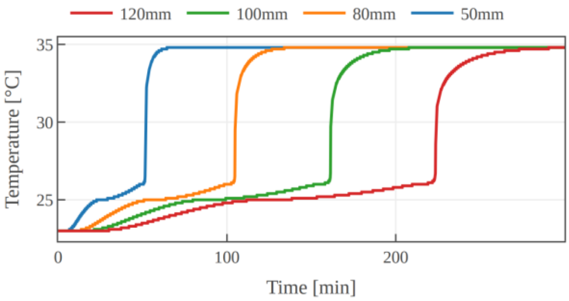

Fig. 13: Temperature inside the storage tank in time during the process of charging.

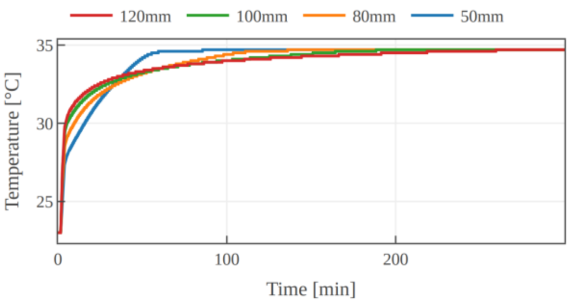

Fig. 14: Outlet temperature during the process of charging.

In the next two charts **Fig.15** and **Fig.16** are showed changing the temperature in time during the process of discharging. From the **Fig.15** we can see that we required time for to equalizing inside temperature with to the inlet temperature of 16⁰C is $\Delta = 120min$ for the FSS diameter of 50 mm, and for diameter 120 mm $\Delta = 324min$.

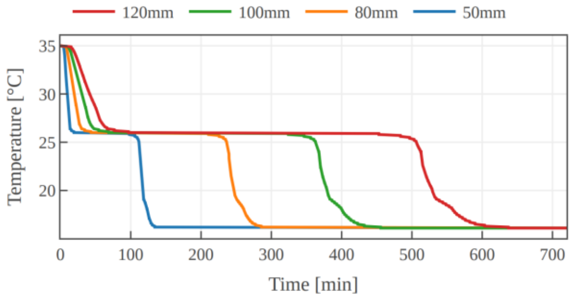

Fig. 15: Temperature inside the storage tank in time during the process of discharging.

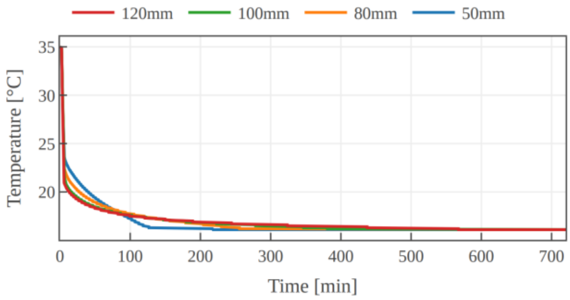

Fig. 16: Outlet temperature during the process of discharging.

5. Conclusions

Energy storage is one of the key areas in which more attention and projects will need to be focused to better address the challenges of energy efficiency and the integration of renewable energy sources into heat storage systems in the future.

The paper focused on improvement of latent energy storage with PCMs where its main advantages have been reviewed and researched. One of the advantages of using PCMs for energy storage is there low thermal conductivity, which has a direct effect at the time of charging and discharging the storage tank. As part of the work, we performed the following steps and came to the following conclusions:

1. When we charge the storage tank with an inlet water temperature of 45 ⁰C, we were able to accumulate energy of 4 kWh and it took 130 min. When we were performing a discharge of system we were able to relesed maximum energy in the amount of 4.7 kWh for 250 min.

2. With used TRANSYS software as a tool where the numerical model LHT Type 840 was adjusted to the initial and boundary conditions of the experimental system and validated with the measurement results. Validation of the numerical model was performed on the basis of calculated relative errors between measured and simulation results. From the obtained results we can say that the numerical model

better describes the process of charging LHS for both temperatures (35⁰C and 45⁰C) and the relative error is less than 3%. In the process of charging with 45°C, the relative error is lower than 5%, while in the case of discharging the LHS it is less than 35° C, the relative error is between 5% and 10%.

3. Based on a validated numerical model, we performed a parametric analysis of LHS with different boundary conditions. The analysis was performed at the maximum number of modules that can be inserted into the storage tank, at different diameters $D = [50, 75, 100, 120] mm$. From the results we can see that in the case of melting and solidification of FSS the outlet temperature changes logarithmically in time for different size of modules. The inlet temperature significantly affects the melting time of the PCMs when using larger modules. However, in the process of emptying the LHS, the temperature inside the storage tank does not significantly affect the required solidification time of the PCMs.

4. To summarize the results obtained, the Type 840 simulation model is an excellent tool for performing various analyses for the LHT area of operation. In order to achieve the minimum charging and discharging time of the system, it makes sense to use a smaller diameter PCMs modules.

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