NTNU – Trondheim
Norwegian University of
Science and Technology

Analysis and design of systems for thermal-energy storage at moderate temperatures based on Phase Change Materials (PCM)

Martina Trogrlic

Master's Thesis
Submission date: July 2014
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MASTER THESIS

for

Student Martina Trogrlić

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Analysis and design of systems for thermal-energy storage at moderate temperatures based on Phase Change Materials (PCM)

Analyse og design av systemer for lagring av lavtemperatur termisk energi basert på faseskifte materialer (PCM)

Background and objective

In many cases heat, such as released from some of the renewable energy sources (e.g. thermal solar panels or geothermal energy sources) or waste heat recovered from energy conversion or industrial processes, cannot be directly used at the time of its generation. Therefore, facilities for thermal-energy storage 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 (PCM).

The primary goal of this study is to propose up to three different systems for thermal-energy storage based on the use of PCM materials, at relatively low temperatures of the incoming heat transfer fluid (HTF) in the range such as arising in the building heating systems. The work will include the following:

- design of the PCM container for thermal-energy storage,
- choice of an appropriate kind of heat transfer from HTF to PCM and vice versa,
- selection of an appropriate PCM-material,
- dimensioning of the storage system in accordance with its prospect application (e.g. thermal solar heating).

Additionally, it would be beneficial to predict (using appropriate mathematical models) the heat storage capacity, as well as the charging and discharging times for the proposed storage-system design variants. Finally, the proposed variant systems should be discussed regarding their pros and cons.

This assignment is realised as a part of the collaborative project "Sustainable Energy and Environment in Western Balkans" that aims to develop and establish five new internationally recognized MSc study programs for the field of "Sustainable Energy and Environment", one at each of the five collaborating universities in three different WB countries. The project is funded through the Norwegian Programme in Higher Education, Research and Development in the Western Balkans, Programme 3: Energy Sector (HERD Energy) for the period 2011-2014.

The following tasks are to be considered:

1. Review of the state-of-the-art progress in applying the PCM material for moderate temperature level heat storage and opportunities of their applications. This work should also take into account the previous works (e.g. Master thesis) performed at the NTNU on energy storage.
2. Propose solutions for up to three different systems for low temperature thermal-energy storage based on the use of PCM materials
3. Select appropriate mathematical models for analysis of the proposed solutions for low temperature thermal-energy storage PCM systems.
4. Analyse the proposed solutions for moderate temperature thermal-energy storage PCM systems and discuss their feasibility.
5. Make a draft proposal (8-10 pages) for a scientific paper based on the performed work in the master thesis.

-- " --

Within 14 days of receiving the written text on the master thesis, the candidate shall submit a research plan for his project to the department.

When the thesis is evaluated, emphasis is put on processing of the results, and that they are presented in tabular and/or graphic form in a clear manner, and that they are analyzed carefully.

The thesis should be formulated as a research report with summary both in English and Norwegian, conclusion, literature references, table of contents etc. During the preparation of the text, the candidate should make an effort to produce a well-structured and easily readable report. In order to ease the evaluation of the thesis, it is important that the cross-references are correct. In the making of the report, strong emphasis should be placed on both a thorough discussion of the results and an orderly presentation.

The candidate is requested to initiate and keep close contact with his/her academic supervisor(s) throughout the working period. The candidate must follow the rules and regulations of NTNU as well as passive directions given by the Department of Energy and Process Engineering.

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The final report is to be submitted digitally in DAIM. An executive summary of the thesis including title, student's name, supervisor's name, year, department name, and NTNU's logo and name, shall be submitted to the department as a separate pdf file. Based on an agreement with the supervisor, the final report and other material and documents may be given to the supervisor in digital format.

☐ Work to be done in lab (Water power lab, Fluids engineering lab, Thermal engineering lab)
☐ Field work

Department of Energy and Process Engineering, 21. February 2014

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Abstract

In this thesis, sensible and latent heat storage are described, as well as phase transformations of materials. Some properties of some phase change materials (PCM) are introduced, including sub-cooling phenomenon. Computer simulation program TRNSYS is briefly described, as well as water tank model in TRNSYS, TYPE 840. In order to compare sensible and latent heat storage characteristics, water tank is compared to water tank with PCM modules for heat charging and heat discharging process, using simulation program. PCM modules in cylindrical and spherical shape are compared one to another, in heat charging and heat discharging processes. Furthermore, three systems containing PCM modules (system with electric heater, solar thermal system and portable heat battery system) are described, analyzed, and results are presented.

This assignment is realized as a part of the collaborative project Sustainable Energy and Environment in Western Balkans that aims to develop and establish five new internationally recognized MSc study programs for the field of Sustainable Energy and Environment, one at each of the five collaborating universities in three different Western Balkan countries. The project is funded through the Norwegian Programme in Higher Education, Research and Development in the Western Balkans, Programme 3: Energy Sector (HERD Energy) for the period 2011-2013.

Keywords: PCM, latent heat storage, simulation, heat charging, heat discharging.

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Nomenclature

Symbol	Quantity	Unit
c_p	Specific heat capacity	J/kgK
$c_{p,l}$	Specific heat capacity of liquid phase	J/kgK
$c_{p,s}$	Specific heat capacity of solid phase	J/kgK
D	Diameter	m
d_O	Outer diameter	m
H	Height	m
h	Enthalpy	J/kg
h_j	Enthalpy of node j	J/kg
h_m	Enthalpy of melting	J/kg
ΔH_{PCM}	Enthalpy of melting for PCM	J/kg
j	Node	-
L	Length of pipe for HX	m
m	Mass	Kg
m_j	Mass flow for node j	kg/s
N	Number of PCM modules	-
P	Power	W
p	previous time step	s
p+1	new time step	s
Q	Amount of thermal energy stored or released	W
Q_{aux}	Amount of thermal energy given by auxiliary heater	W
Q_{coll}	Amount of thermal energy obtained on solar collector	W
Q_{cond}	Amount of thermal energy given by conduction to adjoining node	W
Q_{dp}	Amount of thermal energy given to node by mass flow through double port	W
Q_{HX}	Amount of thermal energy given to node by internal heat exchanger	W
Q_{loss}	Amount of thermal energy lost to ambient through system envelope	W
Q_{LOSSES_SIMUL}	Amount of thermal energy lost to ambient obtained with simulation	W
Q_{module}	Amount of thermal energy exchanged with PCM in tank	W
Q_{PCM_SIMUL}	Amount of thermal energy given to PCM module, obtained with simulation	W
Q_{soll}	Amount of thermal energy available in environment due to insolation	W
Q_{TOTAL}	Total amount of thermal energy exchanged in a system	W
Q_{TOTAL_SIMUL}	Total amount of thermal energy exchanged in a system, obtained with simulation	W
Q_{WASTE}	Amount of thermal energy let out in environment from certain system	W
Q_{WATER_SIMUL}	Amount of thermal energy given to water in a system, obtained with simulation	W
T_{AMB}	Temperature of the ambient	K
T_f	Final temperature of a process	K
Ti	Initial temperature of a process	K
T_{INLET_HX}	Inlet temperature in heat exchanger	K
$T_{INITIAL\_TANK}$	Initial temperature of water tank	K
ΔT_{hyst}	Temperature difference present with hysteresis phenomenon	K
ΔT_{sc}	Temperature difference present with sub-cooling	K
T_m	Melting temperature of material	K
V_{HX}	Mass flow into heat exchanger	kg/s
V_{PCM}	Volume of PCM in tank	m^3

V_{TOTAL}	Total volume of water tank	m^3
V_{WATER}	Volume of water in the tank	m^3
u_{WATER}	Speed of heating of tank with water	kWh/h
$u_{WATER+PCM}$	Speed of heating of tank with water and PCM	kWh/h
η	Efficiency of the system	%
λ	Thermal conductivity of material	W/mK
ρ	Density	kg/m^3
$\Delta\tau$	Size of the time step	s

Subscripts

AMB	Ambient
aux	Auxiliary
coll	Collector
cond	Conduction
DP	Double port
f	Final
HX	Heat exchanger
hyst	Hysteresis
i	Initial
j	Node
l	Liquid
loss	Losses
m	Melting
o	Outer
PCM	Phase Change Material
s	Solid
sc	Sub-cooling
simul	Simulation
soll	Solar
w	Water

Acronyms

CO_2	*Carbon Dioxide*
DLL	*Dynamic Link Library*
DP	*Double Port*
HX	*Heat Exchanger*
HVAC	*Heating, Ventilation and Air-Conditioning*
LHS	*Latent Heat Storage*
LHTES	*Latent Heat Thermal Energy Storage*
PCM	*Phase Change Material*
PV	*Photo Voltaic*
SDHW	*Solar Domestic Hot Water*
SHS	*Sensible Heat Storage*
TSC	*Thermo-Chemical Storage*
TRNSYS	*Transient System Simulation*

1 Introduction

Because human population is growing at such a high rate, as well as the energy consumption per person, new ways of preserving and efficiently using available energy must be explored. Until new and abundant energy sources are found and means of their exploitation developed, research attention should be focused on finding ways of proper and safe use of what is nowadays available.

In that sense, storage of thermal energy plays an important role both in heating and/or cooling applications, such as in residential or commercial buildings, and in industrial processes. Some of the technical solutions are based on phase change materials (PCM) which can help to preserve and to increase the efficiency of energy use when used at right temperature levels at which PCMs change their phase. Thus in just a few degrees of temperature difference, a large quantity of energy can be stored. PCMs might find their application in fixing the energy storage problems in different fields, for they represent a kind of thermal battery. PCM may allow keeping the temperature of the room stable because of their high density of energy storage. PCMs can help keeping the temperature level of a water tank at a certain point. The successful usage of PCMs is not only a question of energy storage density, but on the other hand it is a question of proper charge and discharge of the energy stored with power suitable for the desired application [1].

The aim of this work is to design and analyze up to three different systems for thermal energy storage based on application of PCMs and, where applicable, examine their performance in comparison with water used as a storage fluid. In order to do this simulation program TRNSYS is used. TRNSYS model TYPE 840 is used for representation of water storage tank with PCM material included. Model TYPE 840 is validated in the work of other authors [3]. Different experiments are simulated in order to investigate feasibility of the use of PCM modules in these systems.

The following applications of thermal storage are considered in this work:

- a tank with an electric heater,
- a tank in a solar thermal application, and
- a simple heat exchanger with a PCM module inside, that might be used as a portable thermal accumulator (battery).

For the first and second system, simulation in TRNSYS is done to evaluate the features of PCM incorporation in a water tank and for the third system, a simulation is also done to show the characteristics of the heat exchanger designed.

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.

There are three kinds of TES systems, namely:

1) 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,
2) latent heat storage using phase change materials (PCM) e.g. from a solid state into a liquid state, and
3) thermo-chemical storage (TCS) using chemical reactions to store and release thermal energy [2].

2.1 Sensible heat 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:

$$Q = \int_{T_i}^{T_f} m \cdot c_p \cdot dT, \tag{2.1}$$

or:

$$Q = m \cdot c_p \cdot (T_f - T_i), \tag{2.2}$$

where Q [J] is the amount of thermal energy stored or released in form of sensible heat, T_i is the initial temperature of medium, T_f is the final temperature of medium, m [kg], is the mass of material used to store thermal energy, and c_p [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.

Gases have very low volumetric heat capacity and are not used for sensible heat storage. Water is the best SHS liquid available because it is inexpensive and has a high specific heat capacity. However above the boiling point of water (which is pressure and temperature dependent), the steam has relatively low heat capacity. Hence, oils, molten salts and liquid metals, etc. are used for systems with working temperatures above the boiling point of water.

Sensible heat storage is relatively inexpensive compared to PCM and TCS systems and is applicable to domestic systems, district heating and industrial needs. However, in general sensible heat storage requires large volumes because of its low energy density (i.e. three and five times lower than that of PCM and TCS systems, respectively). Furthermore, sensible heat storage systems require proper design to discharge thermal energy at constant temperatures [2].

2.2 Phase transformations and latent heat storage

Phase change of a certain material can be in the following form: solid– solid, solid– liquid, solid– gas, liquid– gas and vice versa.

In *solid–solid* transitions, heat is stored as the material is transformed from one crystalline to another. These transitions generally have smaller latent heat and smaller volume changes than solid–liquid transitions. Solid–solid PCMs offer the advantages of less stringent container requirements and greater design flexibility [4].
Solid–gas and *liquid–gas* transition have higher latent heat of phase transition, but their large volume changes on phase transition at (nearly) constant pressure are associated with the containment problems and rule out their potential utility in thermal-storage systems. Large changes in volume make the system complex and impractical [5].
Solid–liquid transformations have comparatively smaller latent heat than liquid–gas. However, these transformations involve only a small change in volume (about 10% or less). Therefore, solid–liquid transitions have proved to be economically attractive for use in thermal energy storage systems. PCMs themselves cannot be used as heat transfer medium. A separate heat transfer medium must be employed with heat exchanger in between to transfer energy from the source to the PCM and from the PCM to the load.

The most widely used heat transfer fluid in solar hot water systems is pure water. Many different fluids have been tried over the years. Propylene glycol-water mix, ethylene glycol-water mix, synthetic oil and silicone oil are some examples. Propylene glycol-water mix is in many ways considered the standard heat transfer fluid of the industry [6]. The reason to resort to propylene glycol-water mix instead of pure water is in order to prevent the liquid from freezing solid and bursting the pipes. In all other aspects, water is by far the superior heat transfer fluid. One of the most important advantages is that it has high specific heat capacity as well as high thermal conductivity.
This makes it very desirable for storing and transferring thermal energy. It is also inexpensive, easily attainable and its properties will not alter or change over time [7].

Propylene glycol-water mix, though essentially non-toxic, can still cause deterioration and damaging of the system. Over time, it will lose and alter its properties. As this happens, it will become more acidic and its antifreeze properties will wear out [6].

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:

$$Q = \int_{T_i}^{T_m} m \cdot c_{p,s} \cdot dT + m \cdot a_m \cdot \Delta h_m + \int_{T_m}^{T_f} m \cdot c_{p,l} \cdot dT, \quad \textbf{(2.3)}$$

or:

$$Q = m \cdot [c_{p,s} \cdot (T_m - T_i) + a_m \cdot \Delta h_m + c_{p,l} \cdot (T_f - T_m)], \quad \textbf{(2.4)}$$

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 [7].

Note that c_p in Eq. (2.3) and (2.4) has different values for the solid state ($T_i < T < T_m$) and the liquid state ($T_m < T < T_f$), which is denoted by the indices *s* and *l*.

The first term in Eq. (2.4) represents the heat transfer between the storage material and the heat transferring fluid before the PCM crystalizes. The second term represents the energy exchanged during phase change and the last term represents the sensible energy transferred between the solid PCM to the heat transferring fluid.
In a change of aggregate state a large amount of energy, the latent heat, can be stored or released at an almost constant temperature. Thus, a small difference in temperature can be used for storing and releasing the stored energy.
The system with PCM depends on the phase change of the material for capturing and releasing the energy. Processes such as melting/solidifying and evaporation/condensation require energy inlets or outlets. Heat is absorbed or released when the material changes phase from solid to liquid and vice versa.

Therefore, PCMs readily and predictably change their phase with a certain input of energy and release this energy at a later time. Compared to the storage of sensible heat, there is almost no temperature variation during the process in the storage [3].
There are a vast number of published materials available for latent heat storage. An overview of the materials and their properties is done, among others, by Milisic (2013).

3 Materials for LHTES

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

- a melting temperature lying in the practical range of operation,
- melt congruently 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. Depending on the applications, the first criteria for PCMs should be their melting temperature. Materials that melt below 15 ˚C are used for storing cooled air in air-conditioning applications, while materials that melt above 90 ˚C are used for absorption refrigeration. All other materials that melt between these two temperatures can be applied in solar heating and for heat load leveling applications [8].

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 [1].

Sensible heat storage is relatively inexpensive, but its drawbacks are its low energy density and its variable discharging temperature [2]. These issues can be overcome by PCM-based TES. Melting processes involve energy densities about 100 kWh/m^3 (e.g. ice-water) compared to a typical 25 kWh/m^3 energy density for sensible heat storage in water.

Fig. 3.1 compares the achievable storage capacity at given temperature difference for a storage medium with sensible heat storage and with latent heat storage.

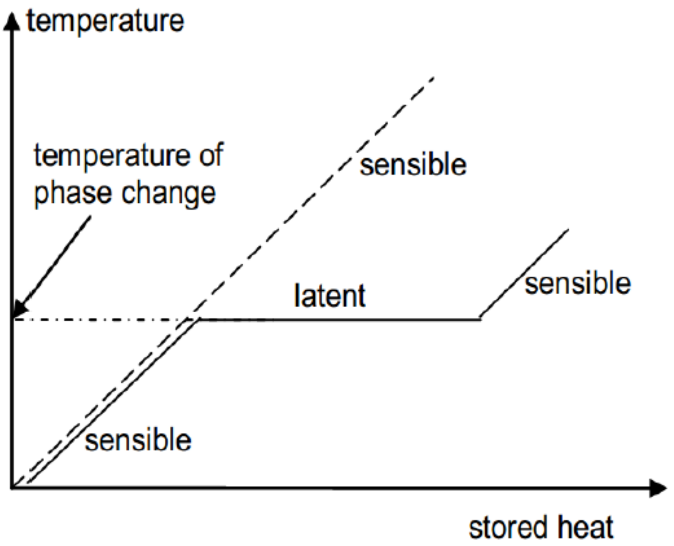

Figure 3.1 Heat storage as latent heat for the case of solid – liquid phase change [9]

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/m³], i.e. a high volumetric melting enthalpy [J/m³].

As shown in Table 3.1, there are two main groups of PCMs, *paraffins* and *salt hydrates*. Paraffins have an excellent stability concerning the thermal cycling, i.e. a very high number of phase changes can be performed without a change of the material's characteristics. On the other hand, the drawback of their usage come in a form of their flammability and their relatively low melting enthalpy and density compared to salt hydrates.

Salt hydrates tend to corrode and don't have a large the cycling stability, unless certain conditions are met. Another drawback of salt hydrates is the so called *sub- cooling*. That means that the material does not crystallize at the melting temperature, but at a lower temperature. The sub- cooling can be reduced by adding so called nucleators into the PCM [1].

Table 3.1 : Advantages and disadvantages of PCMs [10]

Organic (paraffins)	Inorganic (salt hydrates)
Advantages: • Not corrosive • Chemically and thermally stable • No or little sub cooling	Advantages: • High melting enthalpy • High density
Disadvantages • Lower melting enthalpy • Lower density • Flammable	Disadvantages: • Sub cooling • Corrosive • Cycling stability

Table 3.2 shows some of the mostly used PCMs with melting temperature in different ranges with their melting enthalpy and density.

Table 3.2: PCM thermal storage properties [2], [11]

PCM	**Melting Temp. [˚C]**	**Melting Enthalpy [kJ/kg]**	**Density [g/cm^3]**
Ice	0	333	0.92
Natrium- acetate Trihydrate	58	250	1.3
Paraffin	-5 to 120	150-240	0.77
Erytritol	118	340	1.3
Sodium Acetate + Graphite	56 to 60	240	1.35

The incorporation of micro-encapsulated PCM materials (e.g. paraffin wax) into gypsum walls or plaster can considerably increase the thermal mass and capacity of lightweight building walls. The micro-encapsulated PCMs can cool and solidify by night and melt during the day, thus cooling the walls and the room, and reducing (or avoiding) the need for electric chillers (”passive cooling”).

Other applications for active cooling systems with PCMs involve the use of macro-encapsulated salts that have an appropriate melting temperature. PCM can be stored in the building’s air vent ducts and cold air can be delivered via large-area ceiling and floor ventilation systems.

PCM slurries are a promising technology. For example, ice-slurries or water-paraffin dispersions can be used for building or industrial cooling purposes. As slurries can be pumped, they can be used for either storing or distributing thermal energy [2].

One of the major drawbacks of latent thermal energy storage is the low thermal conductivity of the materials used as PCMs, which limits the power that can be extracted from the thermal energy storage.

There are mainly two ways of solving this problem. On one hand, the distances for heat transfer by conduction in the PCM can be shortened. This can be done by encapsulating the PCM into relatively small capsules, or by highly dispersed heat exchangers with low distances between fins or pipes.

On the other hand, the thermal conductivity can be enhanced by embedding structures of materials with high thermal conductivity into the PCM.

This can be done by adding graphite powder into the PCM, which not only increases the thermal conductivity of the PCMs by a factor of 10-20, but also creates a kind of carrier structure that inhibits the segregation of salt hydrates and therefore improves their cycling stability [1].

3.1 Sub-cooling

For many PCMs, the consideration of sub cooling and hysteresis effects is necessary. Sub-cooling is the process of material crystallization at a temperature that can be much lower than its melting temperature. After the crystallization finishes, the temperature of PCM increases until it reaches the melting temperature, at which the latent heat is set free. For some materials the temperature does not increase up to the melting temperature, instead the latent heat is set free at a slightly lower temperature. Both the effect of sub-cooling and the temperature difference between crystallization temperature and the melting temperature are referred to as hysteresis.

Fig. 3.2 shows the enthalpy-temperature functions for heating and cooling processes for a PCM, with the sub-cooling ΔT_{sc} and the hysteresis ΔT_{hyst} [12].

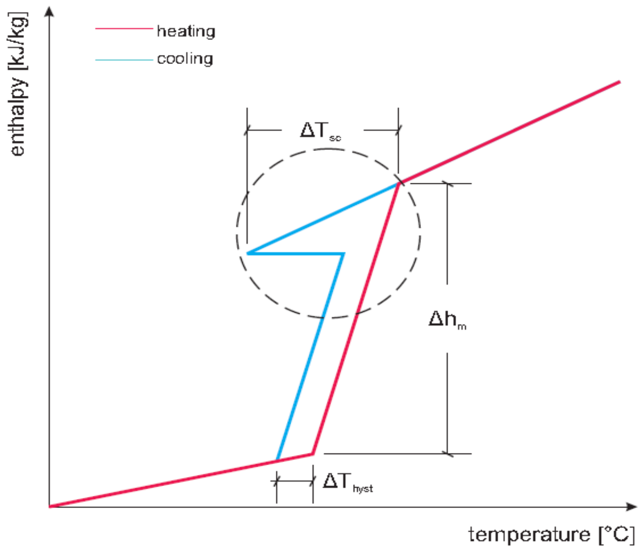

Figure 3.2: Enthalpy-temperature functions of a PCM with the sub cooling ΔTsc and the hysteresis ΔThyst [12]

The effects of sub-cooling and hysteresis are modelled in the program used in this thesis for system analysis. The modelling is done by using different enthalpy-temperature functions for heating and cooling of the material.
If the temperatures of all PCM nodes are higher than $T_{critical\ 2}$ the whole module is assumed to be fully melted. This means a transition from the heating to the cooling function, which is identical to the heating function for temperatures higher than $T_{critical\ 2}$.Thus the temperatures of the nodes are not changing due to this transition [12].

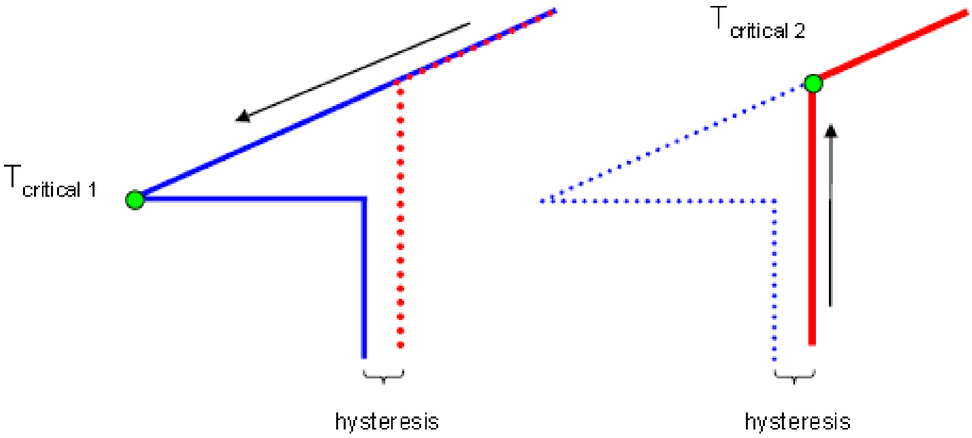

Figure 3.3: Critical temperatures for the transition between the enthalpy- temperature function for heating and cooling [12]

If the temperature of any node in the PCM module falls below $T_{critical1}$ during the cooling process, the transition from the cooling to the heating function is done. In case of a material with a hysteresis a modified heating function is used (parallel shift of the phase change temperature range to lower temperatures by ΔT_{hyst} - Fig. 3.3) [12].

4 Computer simulation program

In this study the computer program TRNSYS is used to analyze the proposed solutions with PCM application for three systems.

TRNSYS is a simulation environment for the transient simulation of systems, including multi-zone buildings. It can be used to validate new energy concepts, from simple domestic hot water systems to the design and simulation of buildings and their equipment, including control strategies, occupant behavior, alternative energy systems (wind, solar, photovoltaic, hydrogen systems), etc.

It has an open, modular structure. The source code of the kernel as well as the component models is delivered to the end users. This simplifies extending existing models to make them fit the user's specific needs [15].
The Dynamic Link Library (DLL) based architecture allows users and third-party developers to add custom component models, using all common programming languages (C, C++, PASCAL, FORTRAN, etc.). In addition, TRNSYS can be connected to many other applications, for pre- or post-processing or through interactive calls during the simulation (e.g. Microsoft Excel, Matlab, COMIS, etc.).

TRNSYS applications include:

- solar systems (solar thermal and PV),
- low energy buildings and HVAC systems with advanced design features (natural ventilation, slab heating/cooling, double façade, etc.),
- renewable energy systems,
- cogeneration, fuel cells.

In Fig. 4.1, the graphical user interface of TRNSYS simulation studio is shown, illustrating the model of solar domestic hot water (SDHW) system. Different models have been connected together to help simulate this system:

- weather data,
- pump,
- water tank,
- controllers of temperature,
- mass flow and temperature inlet data,
- solar collector,
- outlet data providers (printers), etc.

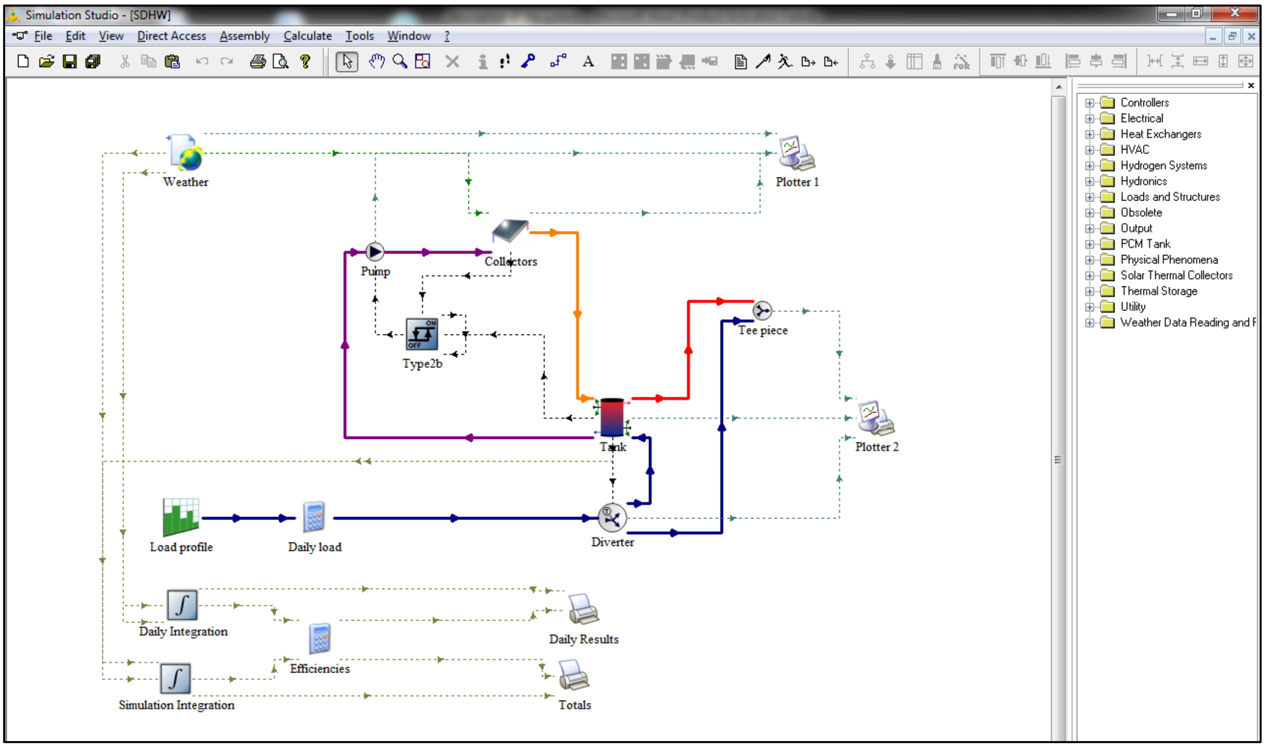

Figure 4.1: The simulation Studio outlook in TRNSYS- SDHW system is simulated in TRNSYS [13]

The TRNSYS simulation engine is programmed in FORTRAN. The engine is compiled into a Windows Dynamic Link Library, TRNDLL. The TRNSYS kernel reads all the information on the simulation (which components are used and how they are connected) in the TRNSYS input file. It also opens additional input files (e.g. weather data) and creates output files [13].

4.1 Modeling the water tank with PCM

In simulation studio- TRNSYS, TYPE 840 is a model for water tank with possibility of PCM modules inclusion. It can help give insight into capabilities and behavior of PCM incorporated in certain system. It can also be used to show the thermal characteristics of PCM material.

Modelling of phase change process with PCM has a theoretical approach because the thermal properties of PCM change during the phase change of the PCM. The model for the water storage tank has been implemented into the simulation environment as a multi-node storage model where the nodes are obtained by subdividing the PCM storage in vertical direction [9].

An energy balance equation for each storage node is formulated in order to calculate the time evolution of enthalpy and temperature. Fig.4.2 shows that the storage volume is divided into N horizontal segments (nodes). Each node is characterized by the enthalpy h_j, the temperature T_j and the mass m_j of the storage fluid in the node (j).

Eq. (4.1) is the energy balance equation for any (and each) storage node and it gives the enthalpy h_j for j-th node and also the temperature T_j of the given j-th node:

$$m_j \frac{h_j^{p+1} - h_j^p}{\Delta t} = \dot{Q}_{dp}^p + \dot{Q}_{hx}^p + \dot{Q}_{aux}^p + \dot{Q}_{cond}^p + \dot{Q}_{loss}^p + \dot{Q}_{module}^p \, . \tag{4.1}$$

The left side of the Eq. (4.1) describes the evolution of the enthalpy in the node (j) from the previous time step (p) to the new time step (p+1), where Δt is the size of the time step. The right side expresses the heat flows in and out of the respective node.

In Eq. (4.1), $\dot{Q}_{dp}$ [W] denotes the heat flow due to the mass flow through a double port (direct connection to the tank), $\dot{Q}_{HX}$ [W] is the heat flow exchanged with an internal heat exchanger, $\dot{Q}_{aux}$ [W] represents the heat input coming from a built-in electric heater, $\dot{Q}_{cond}$ [W] is the heat conduction to adjoining storage nodes, $\dot{Q}_{loss}$ [W] represents the heat losses to the ambient and $\dot{Q}_{module}$ [W] denotes the heat exchange with built-in PCM modules [12].

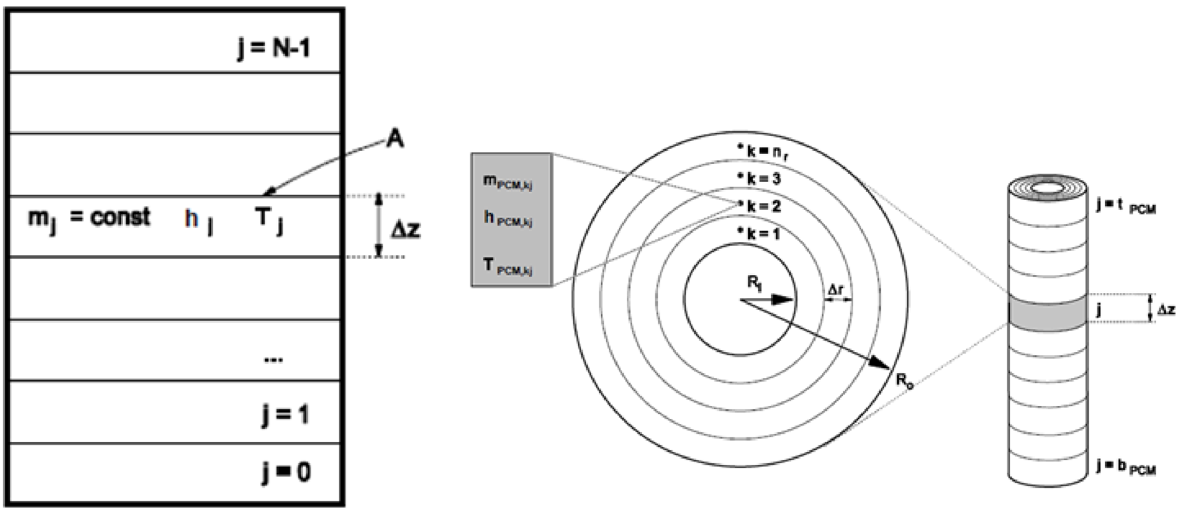

Figure 4.2: Multi-node storage model with N nodes with the height Δz and the top and lower cross sectional area A; the j_{th} node has the mass mj the enthalpy hj and the temperature Tj (left), and nodal network of a cylindrical PCM module (pipe module) with the vertical nodes (j) and the radial nodes (k) (right) [12]

The evolution of the enthalpy with time is determined with the explicit approach as shown in Eq. (4.2):

$$h_j^{p+1} = h_j^p + \frac{\Delta t}{m_j} \cdot \sum \dot{Q}^p \tag{4.2}$$

Thus the enthalpy in the time (p+1) results explicitly out of the respective terms in the time (p). [3]

In the TYPE 840, the thermal properties of the PCM materials are read from ASCII data files. The enthalpy h, the density ρ and the thermal conductivity λ of the materials are provided as a function of the temperature. A maximum of 100 values for 100 different temperatures can be given. The properties in-between these values are determined by means of linear interpolation [12].

For every system, that is going to have a PCM modules included, the volume of PCMs had to be divided into cylinders, spheres or cuboids. Calculation of diameter D [m] of cylindrical PCM modules is done using Eq. (4.3) and Eq. (4.4):

$$D=\sqrt{\frac{4V}{N\pi H}}\ , \tag{4.3}$$

$$V=ND^2\pi\frac{1}{4}H\ . \tag{4.4}$$

V [m^3] represents the total volume of PCM material inside the tank, N is the number of PCM modules, H [m] is the height of modules.

In the case of spherical module, Eq. (4.5) and Eq. (4.6) are used:

$$D=\sqrt[3]{\frac{6V}{N\pi}}\ , \tag{4.5}$$

$$V= D^3\pi\frac{1}{6}N. \tag{4.6}$$

The volume V of PCM modules is set to be constant in this thesis (30% of total tank volume) - diameter D and number N of modules are changed. The values obtained for the diameter are used in water tank model. Table 4.1 and Table 4.2 give insight into all the parameters and outputs of this model- TYPE 840.

4.2 Validation of model

The storage tank model TYPE 840 has been validated with measurements carried out at the Institute of Thermal Engineering of TU Graz and by measurement data provided by their project partners of IEA SHC Task 32. The validations include

- a tank filled with PCM slurry (charging and discharging via an internal heat exchanger and via a double port),
- a tank with spherical PCM modules,
- and a tank with cylindrical PCM modules (different PCM materials).

The results of this work have been published in (Puschnig et al., 2005) and (Schranzhofer et al., 2006). Concerning the results obtained with water tanks (Solé, 2006) the model was compared to a well validated water storage model (Drück, 2000).

Table 4.1: List of TYPE 840 outputs [12]

Model Outputs		
	Output parameter name	**Parameter unit**
1	Outlet temperature 1,2,3,4,5	C
2	Total energy of store	kWh
3	Energy of storage fluid	kWh
4	Energy in internal HX1,HX2,HX3,HX4,HX5..	kWh
5	Energy in PCM module1, 2, 3	kWh
6	Energy in PCM container1, 2, 3	kWh
7	Power through double port1, 2, 3, 4, 5	kW
8	Heat loss rate to ambient	kW
9	Power by electric heater	kW
10	Heat transfer rate to PCM1, 2, 3	kW
11	Temperature sensor 1, 2, 3, 4, 5	C
12	Fluid temperature 1 bottom	C
13	Fluid temperature 2, 3, 4, 5, 6, 7, 8, 9	C
14	Fluid temperature 10 top	C
15	PCM temperature 1 bottom	C
16	PCM temperature 2, 3, 4, 5, 6, 7, 8, 9	C
17	PCM temperature 10 top	C

Table 4.2: List of TYPE 840 parameters [12]

Model Parameters & Inputs			
	Parameter name	**Parameter unit**	**Value scope**
1	Volume of storage	m^3	
2	Height of storage	m	[0;10]
3	Heat loss rate	W/K	[0;1000]
4	Fluid number of storage fluid	-	[0;3]
5	Number of nodes	-	[1;200]
6	Initial temperature of store	C	[0;100]
7	Position of aux. heater (top)	-	[0;1]
8	Position of aux. heater (bottom)	-	[0;1]
9	Effective vertical thermalt conductivity	W/m.K	[0;100]
10	Number of temperature sensors	-	[1;10]
11	Position of top sensor	-	[0;1]
12	Position of bottom sensor	-	[0;1]
13	DP1: type	-	[0;1]
14	DP1: fluid number	-	[0;3]
15	DP1: inlet height	-	[0;1]
16	DP1: outlet height	-	[0;1]
17	DP1: height of temperature sensor	-	[0;1]
18	DP1: Length of HX pipe	m	[0;200]
19	DP1: Inner diameter of HX pipe	mm	[0;100]
20	DP1: Outer diamter of HX pipe	mm	[0;100]
21	DP1: Therm. Cond. of pipe wall	W/m.K	[0;5000]
22	DP1: Heat transfer per pipe length	W/m.K	[-50;200.0]
23	PCM1: number of modules	-	[0;+Inf]
24	PCM1: fluid number	-	[0;3]
25	PCM1: geometry 0 = cyl, 1 = sph	-	[0;1]
26	PCM1: Inner diameter (cyl)	mm	[0;500]
27	PCM1: Outer diameter	mm	[0;500]
28	PCM1: Number of radial nodes	-	[1;20]
29	PCM1: position in tank (top)	-	[0;1]
30	PCM1: position in tank (bottom)	-	[0;1]
31	PCM1: thickness container	mm	[0;10]
32	PCM1: therm. cond. Container	W/m.K	[0;5000]
33	PCM1: c_p of container material	J/kgK	
34	PCM1: mass density of container material	kg/m^3	
35	inlet temperature 1,2,3,4,5…	C	
36	inlet mass flow rate 1,2,3,4,5..	kg/hr	
37	Ambient temperature	C	
38	Electric heater power	W	

5 Comparison of SHS and LHS

The goal of this thesis is to investigate feasibility of the PCM usage for thermal storage in three different technical applications. In order to get insight into the differences arising in the heat storage using both SHS and LHS, a simple case is investigated.

5.1 Water tank

A 300 l tank filled only with water is compared to a 300 l tank filled with 70 % of water and 30% of PCM. Different operating scenarios are simulated using TRNSYS simulation program. The model TYPE 840 is used to simulate both the water tank and water tank with PCM modules. In Fig. 5.1, the outlook of the water tank is presented, with parameters adopted in simulation. The division of tank into nodes is illustrated also in Fig. 5.1, as well as position of double ports.

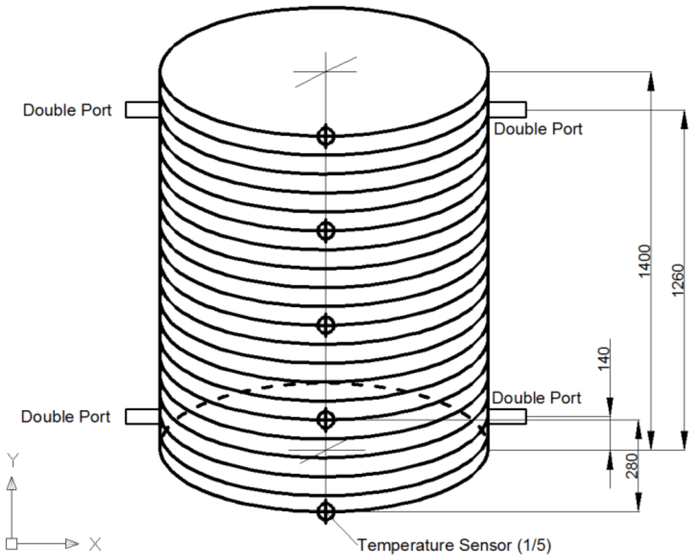

Figure 5.1: Schematic representation of water tank in TRNSYS, divided vertically in nodes

The initial temperature of the water in the tank is 50 ˚C. The tank contains heat exchanger (HX) pipe that occupies 0.007598 m^3 of tank volume (2.53 % of tank volume). Hot water is let through the HX pipe and it heats the tank water. The inlet temperature of the water through the HX pipe is 65 ˚C. Additional simulation parameters can be found below in Table 5.1.

Table 5.1: Simulation parameters

Water tank and simulation parameters	
Tank storage fluid volume	$0.3m^3$ (water)
Tank height	1.4 m
Simulation time	24h
Simulation time step	0.05 h
Number of nodes of the tank	20
T_{INLET_HX}	65 ˚C
V_{HX}	300 kg/h
Number of temperature sensors	5
$T_{INITIAL\_TANK}$	50˚C
T_{AMB}	20˚C
Heat exchanger dimensions	
Outer Diameter of HX pipe, D_O	22 mm
Length of HX pipe, L	20 m
Heat exchanger total volume	0.007598 m^3
Total tank volume	0.3076 m^3

The parameters for water tank given in Table 5.1 are selected to satisfy the needs of four member family. The height of the tank and the heat exchanger dimensions are chosen according to manufacturing recommendations for this volume of the tank [16].

The working temperature interval was chosen to enclose the melting temperature of PCM given with the TYPE 840- Sodium Acetate + Graphite (thermal characteristics data available in Table 2). After having multiple simulations with TYPE 840 run, the number of nodes and the number of temperature sensors are chosen so it would give the optimal accuracy of the results as well as the time of simulation.

The initial temperature of the tank is set to 50 ˚C. The goal is to heat the tank water up to 65 ˚C. This temperature range is chosen in order case to compare the results with the case of the tank that contains PCM modules for the best usage of PCM is around their phase change temperature.

Expected heat stored with water is:

$$Q = V \cdot \rho \cdot c_p \cdot \Delta T = 5.18 \text{ kWh}. \quad \textbf{(5.1)}$$

The time history of the heat stored in water, obtained from TRNSYS is shown in Fig. 5.2. The final heat stored in water amounts to 4.9 kWh.

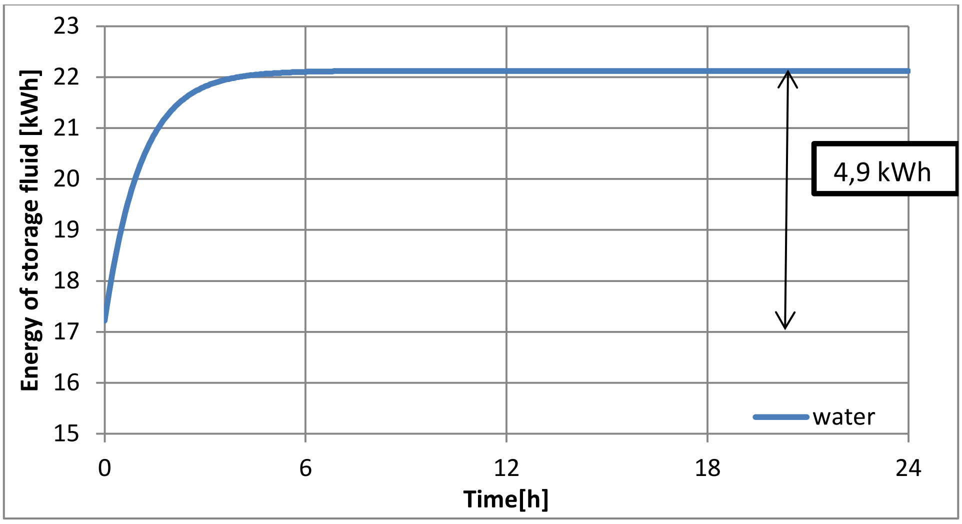

Figure 5.2: Variation of the energy of the storage fluid (water) in time

The results of simulation in TRNSYS give approximately expected quantity of stored heat. The reason why the simulated heat stored in the tank is lower than analytically calculated amount of heat is that TRNSYS takes the heat losses into account. Therefore, the predicted accumulated heat turns out to be less than the theoretical amount described by the Eq. (5.1).

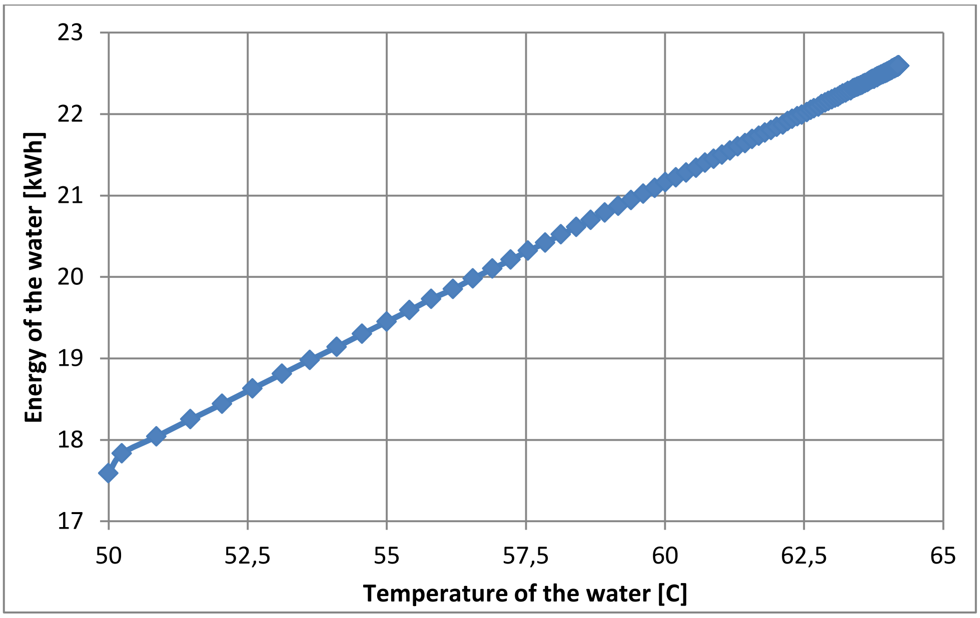

Figure 5.3: Energy of the water rises with temperature increase since the heat is stored as sensible heat

In Fig. 5.3, variation of the stored heat with temperature of the water can be observed. It has linear trend, as expected according to Eq. (5.1).

5.2 Water tank with cylindrical PCM modules

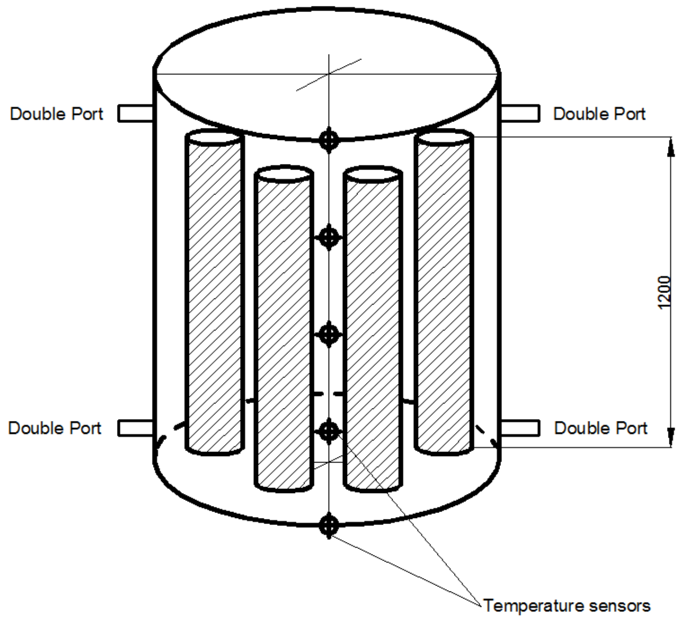

Figure 5.4: Water tank with cylindrical PCM modules inside

In Fig. 5.4, water tank with PCM modules inside is presented. Cylindrical modules are chosen to be the shape of PCM modules because they have manufacturing and installation advantages over other shapes e.g. spherical PCM modules.

5.2.1 Charging process

In the next simulation tank filled with both water and PCM is observed. Simulation results of this case are compared to the results of the previous section (tank filled up only with water). The new simulation parameters are shown in Table 5.2, and all the rest parameters are taken from the previous section, and can be found in Table 5.1.

Table 5.2: Simulation parameters

PCM Total Volume	0.09 m^3= 30% of tank storage volume
Number of nodes in PCM (radial)	4
Number of nodes (vertical)	20
PCM shape	Cylinders
Height	1.2 m
Number of modules	8
Diameter of module	109.3mm
PCM material	Sodium Acetate + Graphite

Heat stored with water is expected to be:

$$Q_W = V \cdot \rho \cdot c_{p,w} \cdot \Delta T = 3.55 \text{ kWh} \quad \textbf{(5.2)}$$

Heat stored with both PCM and water can be estimated as:

$$Q_{W+PCM} = [V \cdot \rho \cdot c_{p,w} \cdot \Delta T]_W + [V \cdot \rho \cdot c_{p,s} \cdot \Delta T]_{PCM\_SEN1} + Q_{LAT\_PCM} + [V \cdot \rho \cdot c_{p,l} \cdot \Delta T]_{PCM\_SEN2} \quad \textbf{(5.3)}$$

$$Q_{W+PCM} = 8.825 \text{ kWh} \quad \textbf{(5.4)}$$

Note that in Eq. (5.3) the values for $c_{p,s}$ and $c_{p,l}$ are adopted to be equal, 2.5 kJ/kg K. In reality, there is a difference between the $c_{p,s}$ and $c_{p,l}$ for PCMs. However, in this study for simplicity no difference has been made.

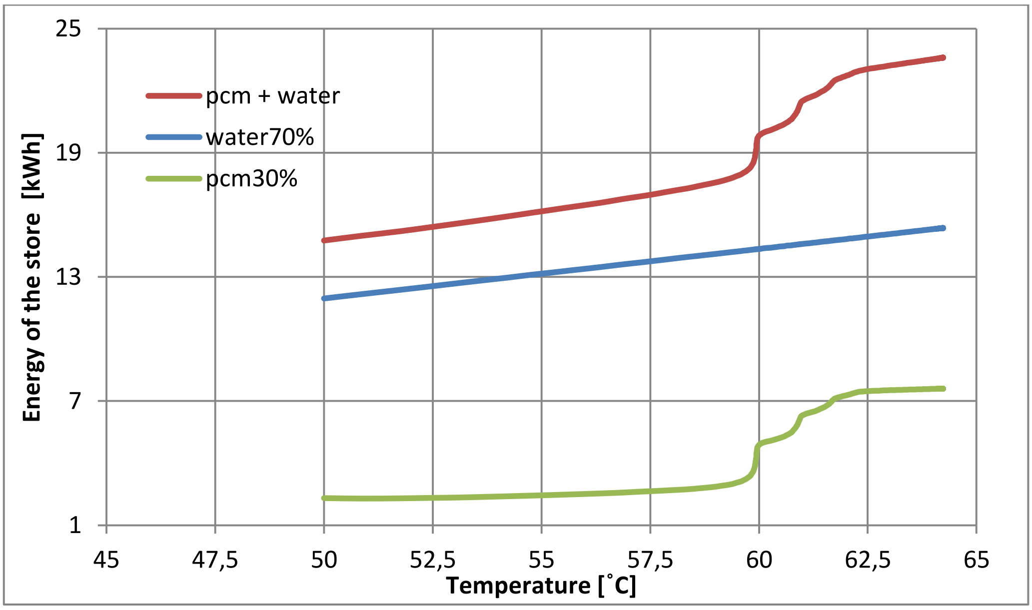

Figure 5.5: Energy stored depending on of temperature of water in the tank

In Fig. 5.5, the dependence of energy stored in storage fluids of temperature change is given. The topmost curve represents the total energy stored in storage fluids of the tank (both water and PCM). The bottom two curves represent the heat stored in water and in PCM, separately. The heat stored in PCM during the phase change is 3.63 kWh in the temperature range of approximately 2 ˚C. Using water, in the same temperature interval 0.6 kWh can be stored.

The topmost and the lowermost curves at approximately 58 ˚C start to have a greater inclination. This goes on until around 62 ˚C, and the amount of energy rises up faster in this area of temperatures. In this part is the latent heat stored inside the PCM modules.

The curve of energy stored with PCM in the phase change temperature interval is expected to be vertical in the Fig. 5.5.

The almost horizontal landings that appear in the places where the curve is expected to be vertical (no temperature difference expected during the phase change of PCM) can be explained with the fact that the heat is going to be stored with some temperature change.

The heat needs time to progress through the material of the PCM module. While the surface parts of cylinder go through the phase change, the center of the module stores the heat in the form of sensible heat. By the time the center of the module collects enough heat to go through the phase change, the outermost (the surface) parts of the cylinder module have already gone through the phase change and are, again, storing the heat in the form of sensible heat.

The greater the diameter of the cylinder, the more time will be needed for the heat to progress to the center of the module. Therefore, in real situations, there is in fact no possibility of getting instantaneous phase change of the entire PCM modules, unless the diameter of modules is very thin.

Note that in this graph the energy change curve for PCM is shown in dependence of the temperature of the water in the tank.

It is also important to observe that after the phase change the PCM material can store less heat via sensible heat than water can. This is explained by the fact that the specific heat capacity of the water is greater than the specific heat capacity of PCM.

Note that the volume of water in the case with PCM is smaller than in the tank with water only, in order to fit the PCM modules in the tank, keeping the same total volume occupied. In Table 5.3 the latent and total heat stored in PCM, obtained with simulation, are presented.

Table 5.3 Quantity of heat stored in PCM

Latent heat stored in PCM	Q_{LAT_PCM}= 3.63 kWh
Total heat stored in PCM	Q_{PCM}= 5.29 kWh

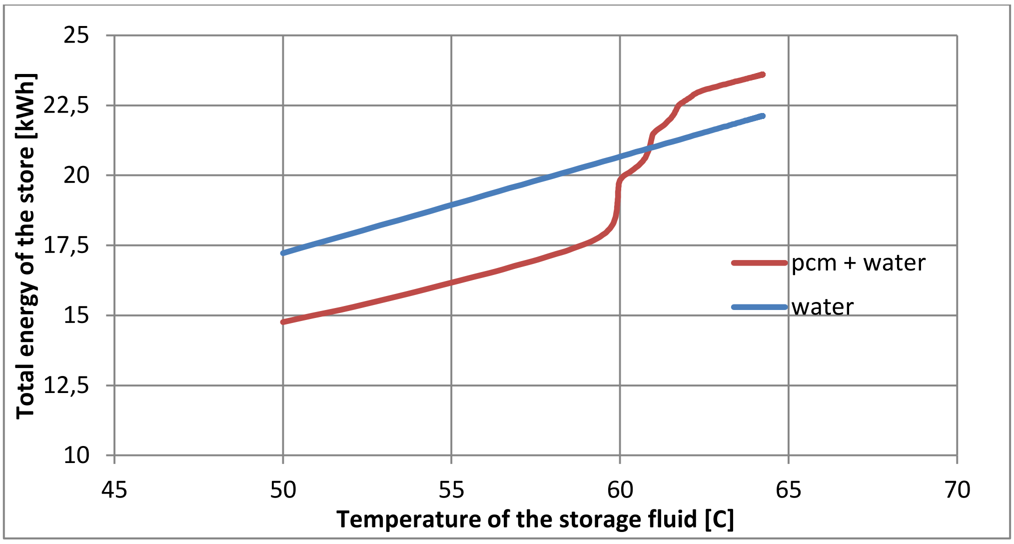

Figure 5.6: Total energy of the store in dependence of water temperature

In Fig. 5.6, total energy of the store in dependence of the temperature of the storage fluid (water) is compared for the two cases: (i) with water only, and (ii) water and PCM. It can be seen that in the temperature range where PCM goes through the phase change (56˚C- 60˚C) the heat stored in the tank with both water and PCM, with just a few degrees of temperature difference, is much greater than the heat stored in the tank that contains only water.

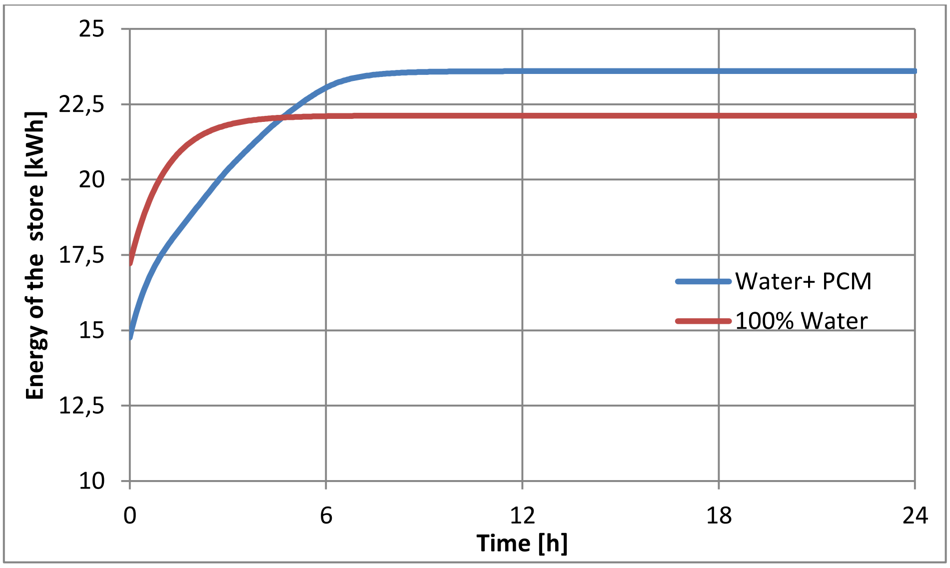

Figure 5.7: Total energy of storage fluid in dependence of time

In Fig. 5.7, another characteristic of using PCM modules in the tank can be seen. The time needed to charge the storage material in the case of the tank with both PCM and water is greater than in the case of the tank filled with only water. Time needed to load the tank with water as a storage fluid in this case is 4.5 h, and the time needed to load the tank with both PCM and water is 6.75 h.

However, in the tank that contains both water and PCM the so called speed of charging, is greater compared to the tank with only water. The speed of charging is the ratio of heat accumulated in the storage fluid and the time needed to achieve that. For the tank with water, this parameter can be expressed as:

$$u_{WATER} = \frac{\Delta Q_{WATER}}{\Delta\tau} = \frac{22.05 - 17.22}{4.5} = 1.0733\ {}^{kWh}/_{h.} \qquad \textbf{(5.5)}$$

And for the tank with water and PCM the speed of charging is 15.6% larger:

$$u_{WATER+PCM} = \frac{\Delta Q_{WATER+PCM}}{\Delta\tau} = \frac{23.35 - 14.76}{6.75} = 1.2726\ {}^{kWh}/_{h.} \qquad \textbf{(5.6)}$$

Eq. (5.5) and (5.6) show even though more time is needed to heat up the tank with PCM, the quantity of heat accumulated per unit of time is greater in this tank.

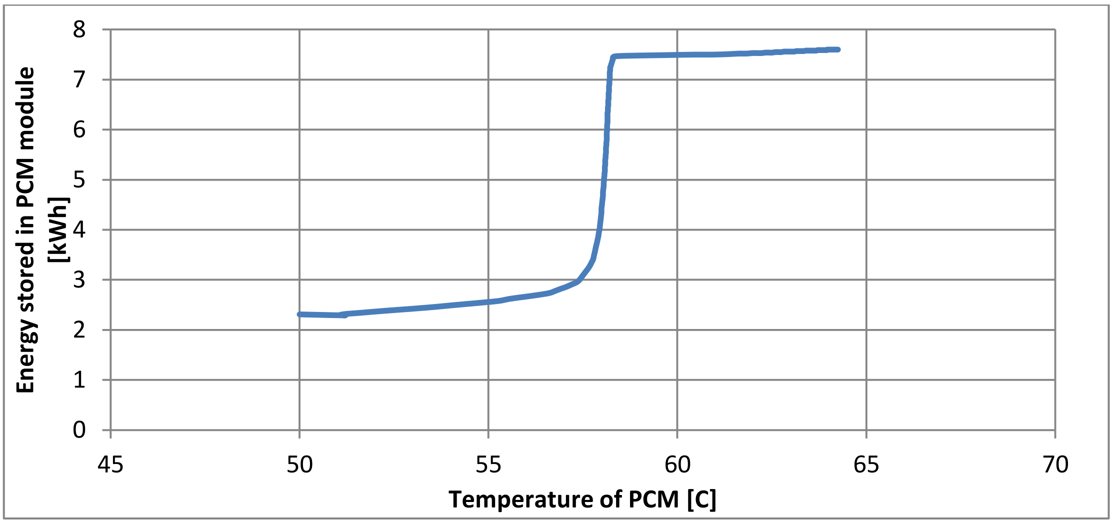

Figure 5.8: Energy stored in PCM modules in dependence of temperature of PCM modules

Energy change in PCM modules depending on the temperature of the PCM is shown in Fig. 5.8. During the phase change of PCM in the modules, the curve is almost vertical. Before and after the phase change temperature of PCM is reached, the heat is stored in PCM via sensible heat. It can clearly be seen that unless the right temperature range is chosen the usage of PCM becomes ineffective. The right temperature range is the interval of temperatures that encompasses PCM's phase change temperature for it is in that range that the full potential of PCM is used.

Total heat stored with PCM in this case is 5.29 kWh, and 3.63 kWh of that heat is stored within the phase change temperature interval. That leaves 1.66 kWh of heat stored via sensible heat, meaning that 68.6 % of heat stored with this volume of PCM is during the phase change, and the 31.3 % is via sensible heat, before and after the phase change.

It should be noted that if water is used in the temperature intervals before and after phase change of PCM, the heat stored in the water would be greater than the amount of heat stored with the PCM (1.66 kWh).

The cause of this is the specific heat capacity of each material (water and PCM). The specific heat capacity of water is greater than the specific heat capacity of PCM used (4.187 kJ/kg K > 2.5 kJ/kg K).

5.2.2 Discharging process

In the next experiment, the tank discharge is simulated. Again, two cases are observed and compared one to another. In the first case, storage tank contains only water, and in second case it contains 70 % of water and 30 % of PCM. The HX is used to release the heat from the tank. Tank initial temperature in both cases is 65 ˚C, and the temperature of the water let through the HX is 50 ˚C. All the additional parameters are equal to the previous cases, and can be found in Table 5.1.

Table 5.4: Simulation parameters

Parameter	**Value**
T_{INLET_HX}	50 ˚C
$T_{INITIAL\_TANK}$	65˚C

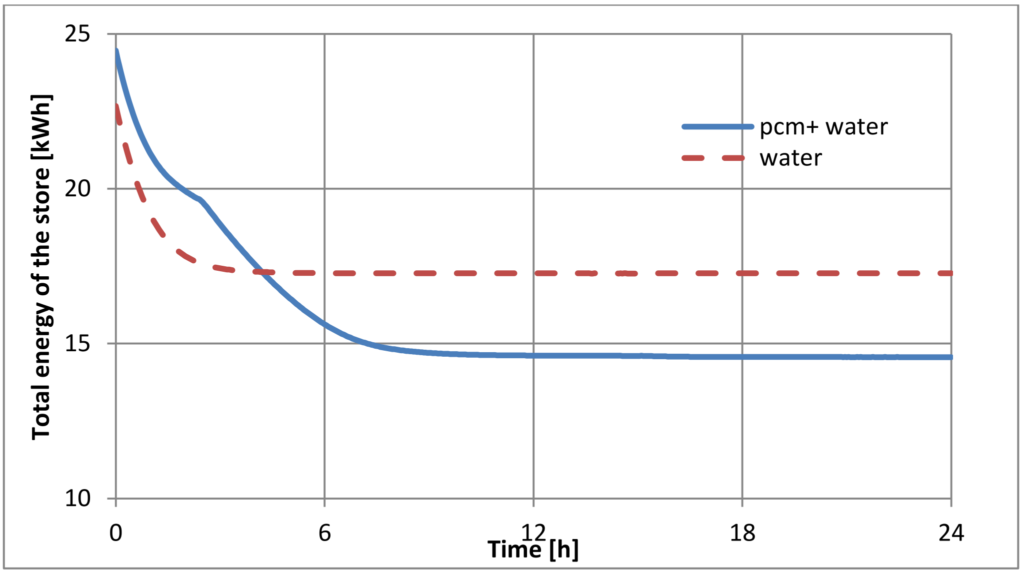

Figure 5.9: Total energy of the storage fluid in dependence of time

In Fig. 5.9, energy change during the discharging of heat process is presented for two cases mentioned. Initial energy of the tank with water and PCM is greater compared to the tank that contains only water. Since the temperature of the tank in the simulation is set to be 65 ˚C, and the melting point of PCM is between 56 ˚C and 60 ˚C, the PCM in modules is therefore initially in liquid state. So, with cooling it with colder water via internal HX the material in modules is going through the phase change and the latent heat from the PCM is released and given to the water.

It can be seen that the tank with both PCM and water releases heat slower and that it can give out more heat than the tank filled just with water.

The difference between these two processes is caused by the presence of PCM modules in the tank. While cooling the tank with PCM and water, the heat stored in PCM is transmitted to the surrounding water, and the water in the tank is both being cooled by the HX and heated by the PCM. This process goes on until the temperature of the PCM becomes equal to the temperature of the water. Then, the water continues cooling until its temperature drops down to the temperature of the water in HX (50 ˚C).

The total amount of the heat given to HX in the tank with water and PCM is 9.9 kWh, and in the tank with water is 5.4 kWh. Time needed to finish these processes is in the case of the tank with water and PCM around 7 h, and in the case of the tank with water around 2h. This gives an insight into possibilities of PCM application in processes of heat preservation.

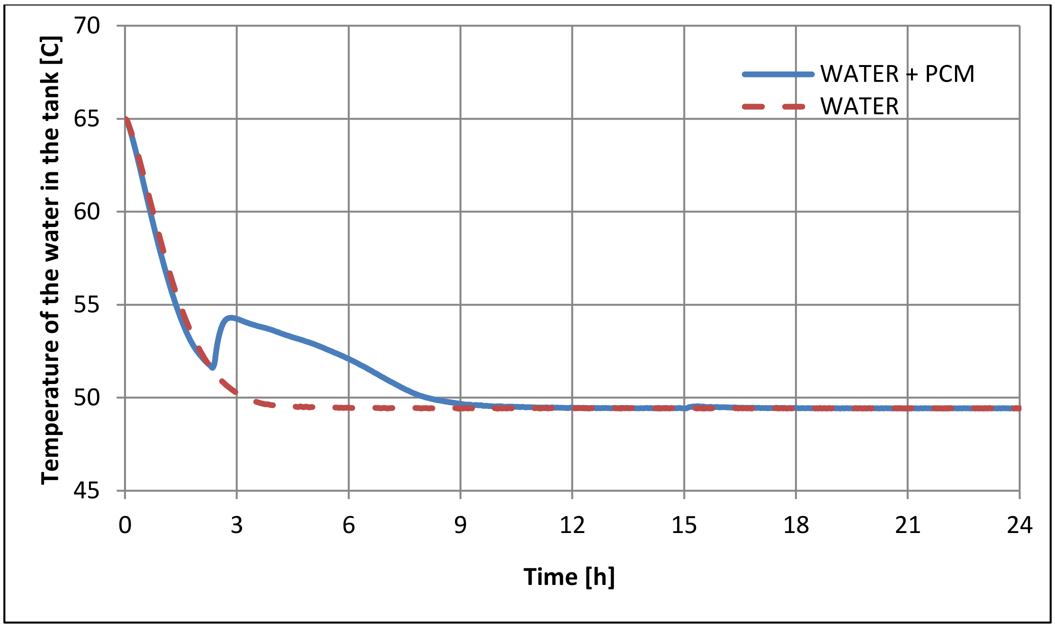

Figure 5.10: Temperature of the water in dependence of time

Fig. 5.10 is the result of the same simulation of tank discharging and it shows how the temperature of the water changes in time. The initial temperature of the tank water is 65 ˚C and it is being cooled with internal HX.

The temperature change of the water in the tank that contains only water is described with dotted curve, and it can be seen that the temperature drops down uniformly. Meanwhile, the temperature of the water in the tank that contains both water and PCM has a different progress because the PCM has the tendency to sub- cool. Sub- cooling process causes the material not to crystallize at its melting point, but at a lower temperature. In the Fig. 5.10 it can be seen that at one point the temperature of the water starts to increase. This can be explained with the fact that after the crystallization process starts, the temperature of PCM increases until it reaches the melting temperature, at which point the latent heat is set free, and crystallization process is finished.

For some PCMs the latent heat is set free at a temperature slightly lower than their melting point.

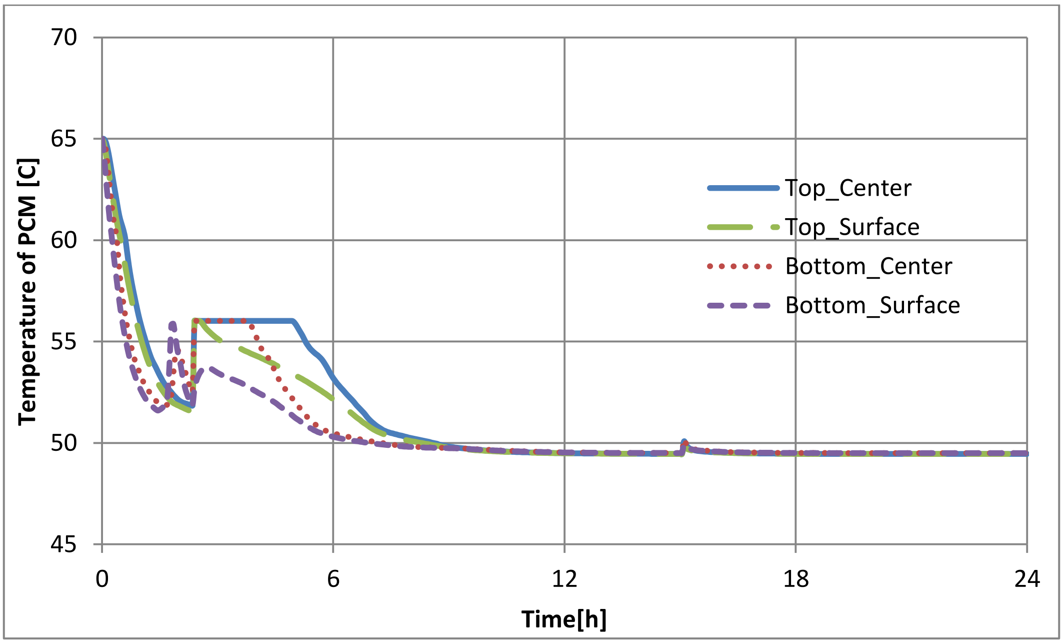

Figure 5.11: Temperature of PCM modules at different positions of temperature sensors in the modules in dependence of time

In Fig. 5.11, temperature change of PCM material at different points is shown. The effect of sub-cooling can be noted. Temperature sensors, in simulation model, are set at the top center and on the top surface layer, as well as on the bottom center and bottom surface layer of PCM cylinder modules, and this is depicted in Fig. 5.12.

Because the heat needs time to progress through the PCM modules, the outer layers of the modules are going through the sub-cooling process sooner than the center parts. The temperature of the PCM is rising from 52 ˚C to 56 ˚C and then the latent heat is being released.

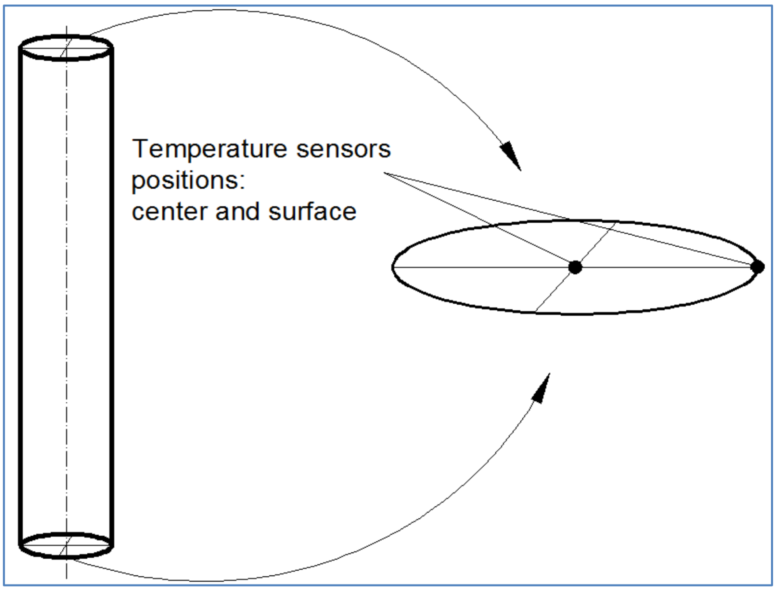

Figure 5.12 Temperature sensors positions

5.3 Water tank with spherical PCM modules

5.3.1 Charging process

Since the simulation model TYPE 840 allows the user to change the shape of PCM module container, this program option is analyzed in this master thesis. In graphs presented below, tank containing water and spherical PCM modules is compared to the tank containing only water, as well as to the tank containing PCM module in cylindrical shape. In all cases presented, the total storage volume is $0.3m^3$. In the tank containing water and the PCM modules (cylindrical or spherical), the total volume of the PCM material is 0.09 m^3 (30 % of the total tank storage volume). In order to satisfy the constant volume of the PCM in the tank, the formulas presented below are used. Additional simulation parameters can be found in Table 5.1.

Table 5.5: Simulation parameters

PCM shape	Cylinders
Number of modules	8
Diameter of module	109.3mm
PCM shape	Spheres
Number of modules	10
Diameter of module	258.1mm

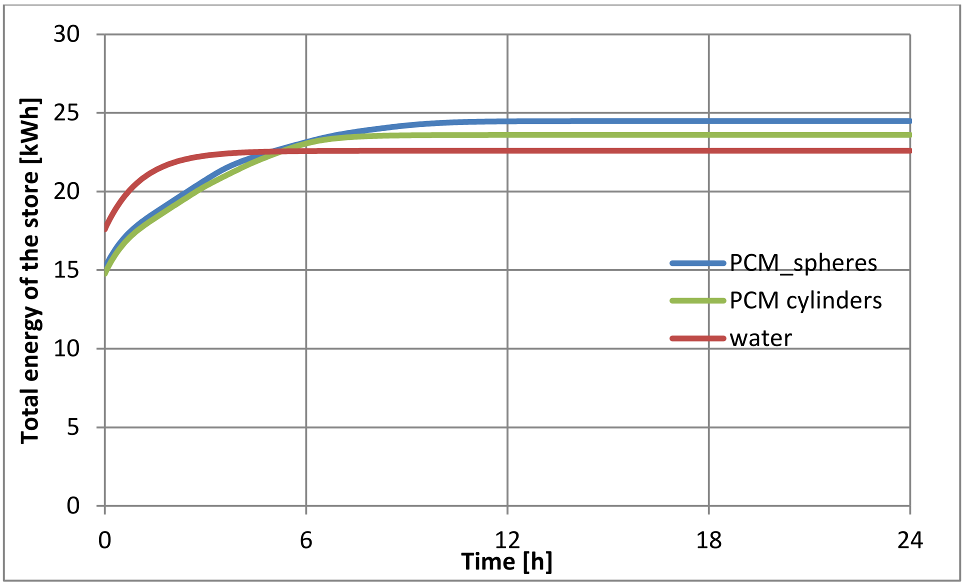

Figure 5.13: Variation of total energy of the tank storage fluid in time

In Figure 5.13, total energy of the tank progress in time is presented. Three cases are observed: tank with water, tank with water and PCM modules in cylindrical shape, and tank with water and PCM modules in spherical shape. Just as in the cases before, the first thing to notice is that more energy is stored in cases with PCM modules application as well as that more time is needed to load the tanks with PCM modules.

Apparently, more energy can be stored in tank with water and PCM modules in spherical shape: 9.37 kWh is stored in the tank with spherical modules, and in the simulation with cylindrical PCM modules 8.84 kWh of heat is stored with the same volume of PCM.

Even though PCM spheres do store more heat, the difference compared to PCM cylinders is not very significant. Considering installation and manufacturing challenges of PCM modules, cylinders will be given advantage in later examples of this thesis, for this shape minimizes these problems.

5.3.2 Discharge process

In the next case, the tank discharge is simulated. Three cases are observed and compared. In the first case, storage tank contained only water, and in second and third case it contained 70 % of water and 30 % of PCM. In the second and third case the shape of PCM modules is altered (cylinders compared to spheres). HX is used to unload the tank. Tank initial temperature in all cases is 65 ˚C, and the temperature of the water let through the HX is 50 ˚C.

Table 5.6: Simulation parameters

Parameter	Value
T_{INLET_HX}	50 ˚C
$T_{INITIAL\_TANK}$	65˚C
PCM characteristics	
PCM shape	Cylinders
Diameter of module	109.3 mm
PCM shape	Spheres
Diameter of module	258.1 mm

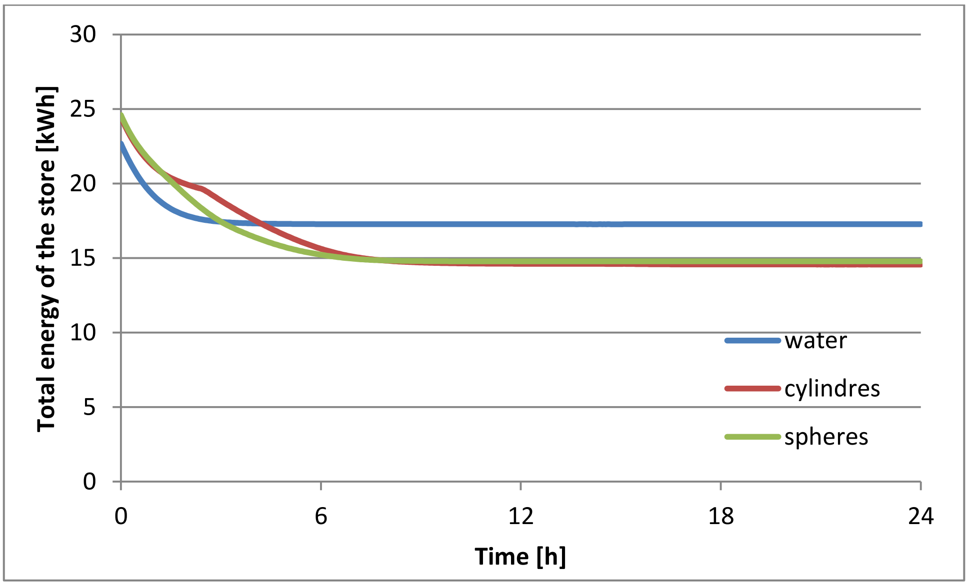

Figure 5.14: Total energy of the storage fluid in dependence of time

In Fig. 5.14, total energy change of the tank storage material is presented. The energy stored in the tank that contained only water is compared to the energy stored in tanks with PCM.

Simulation results show that 9.8 kWh of heat can be released from the tank with spherical PCM modules. In the case of cylindrical PCM modules 9.9 kWh of heat can be released. This shows that there is no significant difference between these two cases, and because cylindrical PCM modules are less difficult to manufacture and install, this gives them an advantage. Quantity of heat released from the tank with only water is the same as in Fig. 5.9- 5.4 kWh.

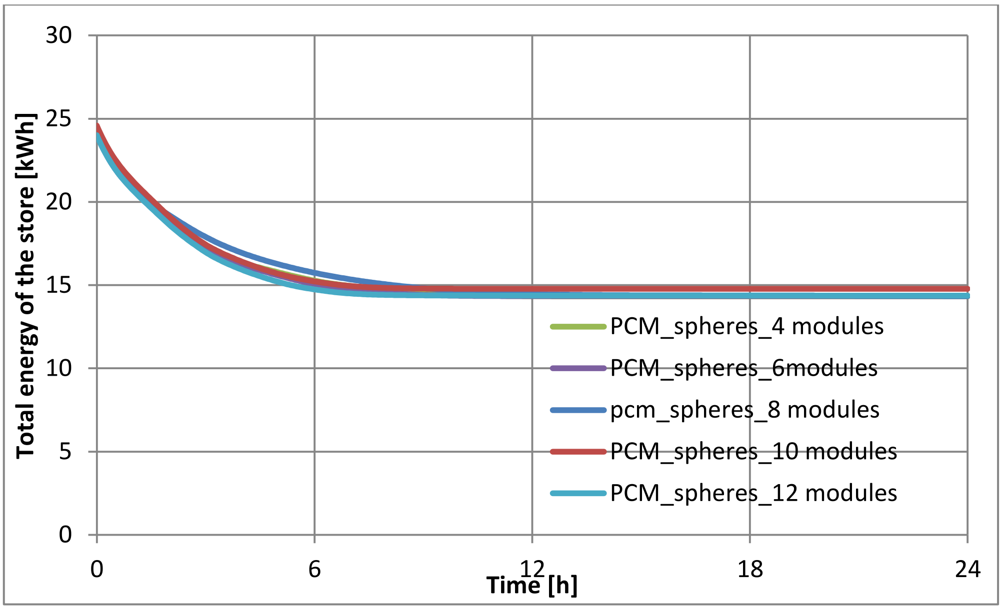

Figure 5.15: Total energy of storage fluid in dependence of time

In Fig. 5.15, total energy change of the storage fluid in the tank is presented. The idea for the simulation in Fig. 5.15 is to see how the diameter of the PCM spheres influences the quantity of heat stored. The energy released in the tank with number of modules changed can be clearly seen in Table 5.7.

Table 5.7: Energy released in discharge process with number of PCM modules and module diameter altered

Number of modules	Diameter [mm]	Energy released [kWh]
4	350.35	9.72
6	306.03	9.7
8	278.05	9.7
10	258.1	9.68
12	242.9	9.64

Although there is some difference between these results, it is not significant, meaning that the certain volume of PCM can store, more or less certain quantity of the heat.

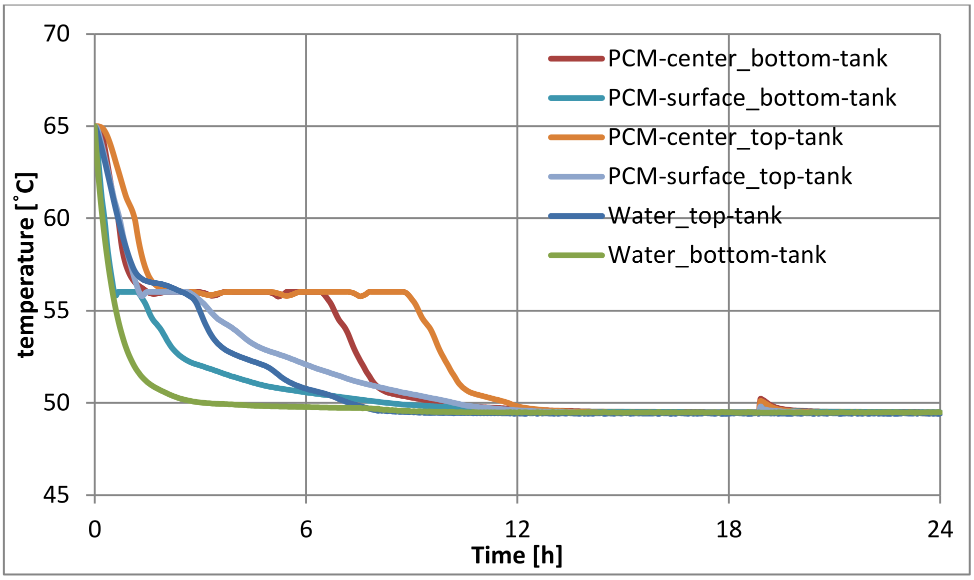

Figure 5.16: Temperature of storage fluid in dependence of time

In Fig. 5.16, the temperature change of the storage fluid in the tank is shown. The simulation tank model TYPE 840 allows temperature sensors to be placed in different locations in the tank and on the PCM modules.

The six curves in Fig. 5.16 are result of measuring temperature of the water in top and bottom of the tank, as well as measuring temperature of PCM at two locations on the spherical module: in the center point and on the surface of the module.

The HX inlet is simulated to be in the bottom of the tank, and outlet in the top of the tank. Therefore, the water in the bottom layers of the tank is losing heat more rapidly since it is directly exposed to the cold water inlet.

The water in the top layers of the tank is exchanging heat with the water in HX that has been heated up by the lower layers of water so it stays warmer for the longer period of time. The curve of temperature change in the center of PCM module shows that the center of PCM needs more time to release the heat, compared to the surface part of modules. In addition, the modules located in the bottom of the tank lose heat faster than modules in the top of the tank.

6 Application of PCM

In this part of the thesis, three different systems with PCM modules are analyzed. The three systems are:

- system with electric heater,
- system for solar domestic hot water,
- system with portable heat battery.

In order to analyze the characteristics of PCM in systems, system with electric heater is compared to the equivalent one containing only water as a storage fluid. Other than analysis of the systems, dimensioning of the water tank with modules is done for second and third example, in a sense of determining the number and dimensions of PCM modules, their shape and location in the tank. The dimensions of water tanks are taken from the catalogues to make sure they are standardized. Inlet data used for every case is taken to be close to real situations.

6.1 System with electric heater

A water tank with electric heater is taken to be a simple example of possible PCM usage. This kind of water tanks is often found in domestic hot water systems. The idea is to use the electric energy available at lower cost periods during the day-night cycle. For that purpose, it is assumed that 2 kW of power is available during 3.5 h at lower cost, within one day.

Two cases of tank are observed: one with water as a storage fluid, and the other with water and PCM modules put in the tank. In both cases, volume of the tank is 0.3 m^3.

As it was already done in the examples shown in Chapter 5, where it resulted in a good performance of the PCM storage, the amount of the PCM filling in the tank is adopted to be 30% of total tank volume. The total tank volume is selected to satisfy an average family needs for hot water.

In Fig. 6.1, water tank with electric heater used in this example is presented. In the first case, the tank is filled only with water, and in the second case, the volume of water is set to be 0.21 m^3 and the volume of PCM in the tank is set to be 0.09 m^3.

PCM volume is distributed in 8 modules, 1.2 m high and with 109.3 mm wide diameter. Additional parameters of the simulation can be found in Table 5.1. Efficiency of the heater is adopted to be 91.5% according to the data available in the model documentation [12].

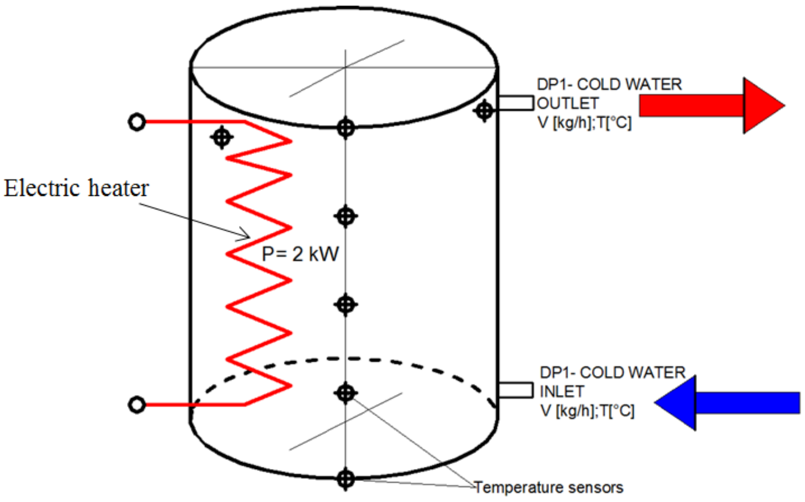

Figure 6.1 : Water tank with electric heater

Table 6.1: Simulation parameters

Parameter	Value
Electric heater power	2 kW
Simulation time	3.5 h

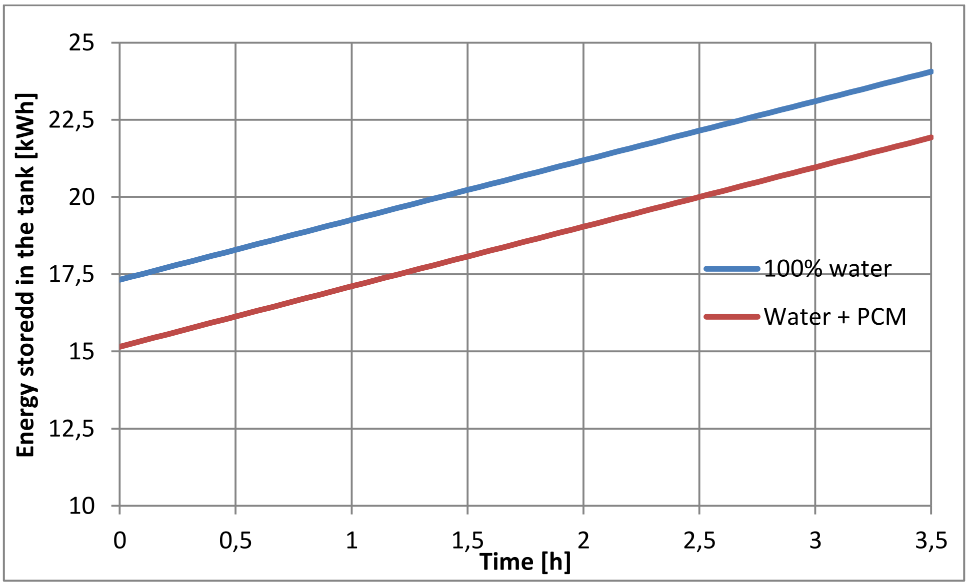

Figure 6.2 Energy stored in the water tank for two cases observed

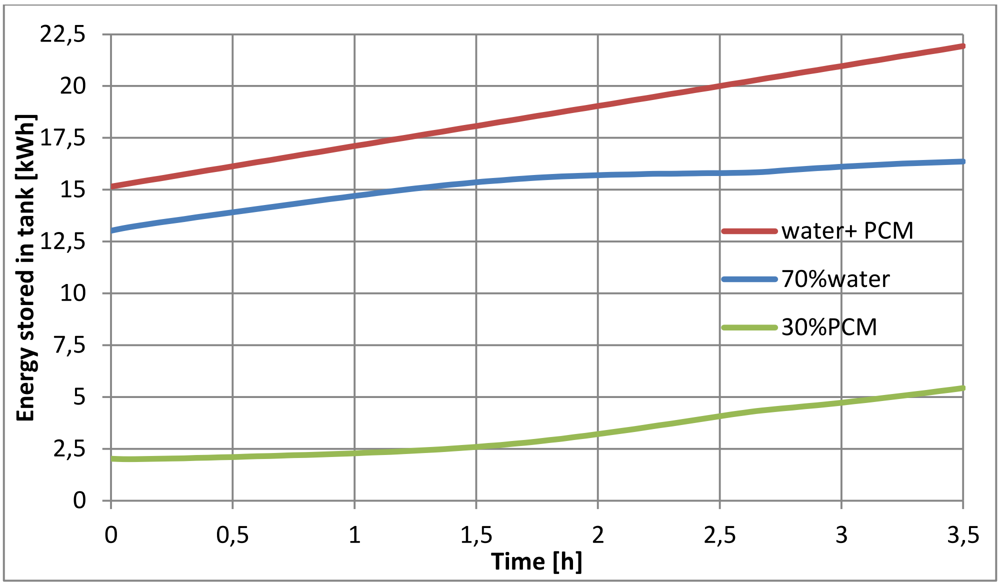

Figure 6.3: Energy in tank storage fluids in dependence of time

In Fig. 6.2 comparison of simulation of heating water tank is done for two cases. First case is tank with water and second case is tank with water and PCM. In Fig.6.3 energy distribution between storage materials for tank with water and PCM is presented.

As it is shown in Fig. 6.2, in the case of the tank with only water inside 6.74 kWh of heat is stored, and results of the simulation show that 6.78 kWh is stored with water and PCM tank. In the both cases, energy given by the electric heater is 7 kWh.

In Fig. 6.3, the first curve represents the total energy stored, with both water and PCM in the tank. The second curve represents energy stored with the 70% of the water that is in the tank, and the third curve represents energy stored with 30% PCM. Different ratios of energy stored in the tank can be seen. With 70% of water 3.34 kWh is stored, and with 30% of PCM 3.41 kWh of heat is stored.

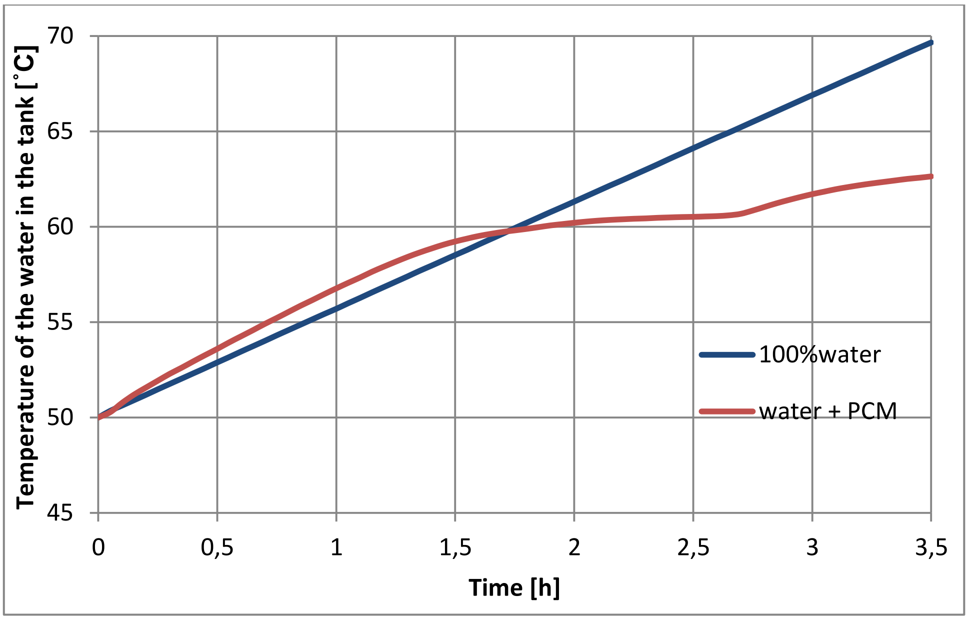

Figure 6.4: Total energy of the store in dependence of temperature of water

In Fig. 6.4, it can be seen how temperature of the water in the tank changes for the case with water, and for the case of the tank with water and PCM modules. Fig. 6.4 represents an illustration of the sensible heat storage, on the top curve, as well as an example of latent heat storage, on the other curve. The part of the curve of water and PCM that is horizontal represents the latent heat stored in the PCM modules.

Because the amount of heat stored with water and PCM is not significantly greater than the amount of heat stored in the tank with 100% of water ($\mathrm{Q_{WATER}} = 6.74\ \mathrm{kWh}, \mathrm{Q_{WATER+PCM}} = 6.78\ \mathrm{kWh}, \mathrm{Fig.}\ 6.2$), the advantage of PCM in these systems has to be questioned, especially considering the space taken by the modules, as well as relatively high costs of PCM modules.

However, in Fig. 6.5 the advantage of PCM presence in the tank might be shown.

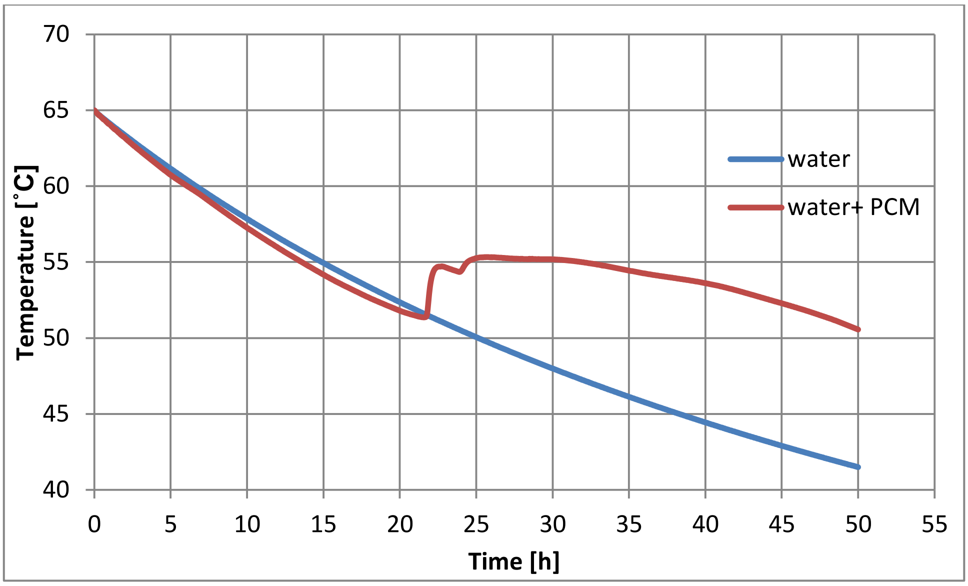

Figure 6.5: Temperature of water in dependence of time for two cases of tank: the first for the tank with only water, and the second for the tank with water and PCM modules; experiment: heat discharge

In Fig 6.5, the temperature change of water in the tank is shown. The idea behind this simulation is to check how the temperature of water in the tank is dropping down due to heat losses to the ambient for two cases of the tank storage fluids mentioned above.

The tank temperature is set to be 65˚C, and the tank isn't heated, it is let to cool down in time. In the case of the tank with water as a storage fluid, after 25 h water temperature dropped down to 50 ˚C, and in the case of the tank with both water and PCM it took more than 50 h to cool down the water to 50 ˚C. All data of the simulation parameters rests equal to the previous case.

So, if the electric heater is controlled by the temperature of water in the tank and a thermostat to keep the temperature of the water at a certain level, the advantage of PCM might be found. Because the temperature of the water in the tank with no PCM present is dropping down almost two times faster compared to the tank with PCM modules inside, less power would be taken from electric heater to keep the temperature of the water in specified interval.

The interesting thing shown in the Fig. 6.5 is that at one point the temperature of the water is rising. After 20 h of cooling, the temperature of water that surrounds PCM modules in the tank is risen from 51 ˚C up to 55 ˚C. This is the result of PCM inside the tank crystallizing and sub- cooling. PCM is releasing the latent heat to the water around it, and it is because of this that the temperature if water is rising. If the case of hot domestic water is presented, the PCM in the tank would cause the temperature of water to rise after the hot water is drawn out and cold water is let inside.

So, the advantage of PCM modules presence inside the tank can be seen here: with the right temperature interval the opportunities of PCM application come in the form of smaller amount of power spent using electric heater over certain time period, the temperature of the water in the tank is kept at relatively constant level, and finally, more energy is stored in the tank.

Other than these characteristic of the system with PCM, one more can be presented. Since there is certain amount of heat stored with PCM modules, that part of energy can be deducted from water as a storage fluid, causing smaller amount of water needed in the tank. This causes the dimensions of the tank to be smaller while the amount of heat remains the same. With this, the losses to the ambient through the tank surface are lowered as well.

In this example, 3.41 kWh of heat is stored with PCM material, and the temperature of the water in the tank had risen from 50 ˚C to 69.66 ˚C. With this data, the mass and volume of water that can be replaced with PCM can be calculated in order to determine the new total volume of the tank. Of course, this only applies for the systems where it can be allowed to reduce the amount of hot water, that is, for the systems where the quantity of heat stored is the most important thing.

The quantity of water that can store 3.41 kWh of water with 19.66 K of temperature difference is presented in Eq. (6.1):

$$\mathrm{m_{WATER}} = \frac{\mathrm{Q}}{\mathrm{c_{pWATER}} \cdot \Delta\mathrm{T}} = \frac{3.41 \cdot 3600}{4.187 \cdot 19.66} = 149.132 \text{ kg}. \qquad \textbf{(6.1)}$$

This gives the volume of water calculated with Eq. (6.2):

$$\mathrm{V_{WATER}} = \frac{\mathrm{m_{WATER}}}{\mathrm{\rho_{WATER}}} = \frac{149.132}{990} = 0{,}151 \text{ m}^3. \qquad \textbf{(6.2)}$$

Of course, not all of this water can be removed from tank, since the total volume of tank is 0.3 m^3. This amount of water is result of the high quantity of energy that can be stored with PCM during its phase change, opposite to the amount of heat stored with water in the same temperature range. Water doesn’t go through the phase change between 50˚C and 65˚C, and it stores energy in a form of sensible heat. Nevertheless, this shows a great advantage of PCM: when adequately used, in the right temperature ranges, PCM can store great amounts of energy.

The suggestion of the outlook of water tank with PCM and electric heater is given in Fig. 6.6. Other characteristics can be found in Table 6.2.

Table 6.2: Water tank characteristics for system with electric heater

Tank volume	$0.3m^3$
Tank height	1.4 m
Tank diameter	650 mm
Tank isolation material	Glass wool
Tank isolation thickness	50 mm
PCM container material	Stainless steel
PCM container thickness	1.5 mm

Most of the dimensions in Fig. 6.6 are adopted according to the real water tanks dimensions, such as height, tank diameter, and isolation material and thickness [20]. The distribution of PCM modules in the tank has been adopted by arbitrary choice. Total volume of PCM has been distributed in modules according to Eq. (4.3) and (4.4).

Other than the parts of the tank in Fig. 6.6, additional parts are going to be needed to complete the system, such as valves, safety valves, manometers, thermometers, thermo regulators, etc.

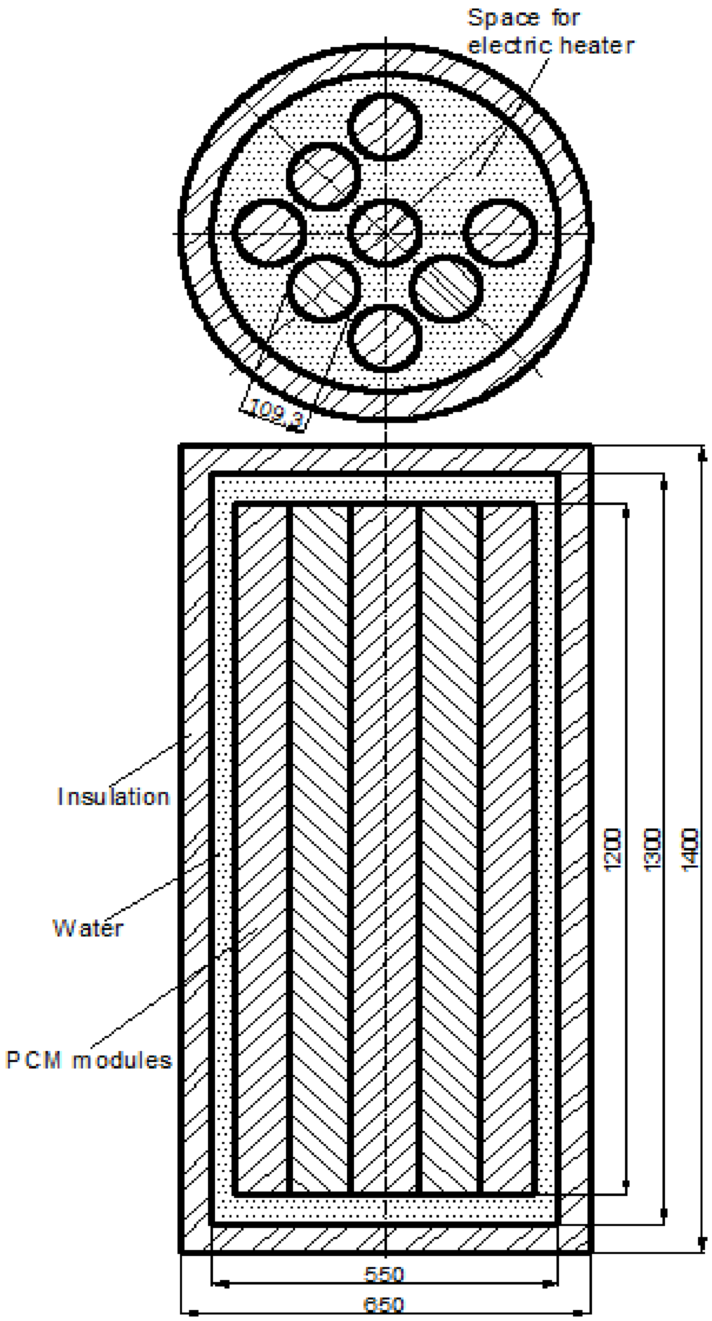

Figure 6.6: Drawing of water tank with PCM modules. Up: cross section of the tank with visible space left for electric heater; Down: Position of PCM modules in the tank, with tank insulation and water for domestic use enhanced.

6.2 Solar- thermal system with PCM modules included

Solar- thermal system simulated in this section includes known quantity of heat collected with solar collector and hot water storage tank with PCM modules. Hot water that is generated in the pipes of solar collector heats up the water in the storage tank. Hot water from the collector is let in the storage tank through an internal heat exchanger. PCM modules are present in the tank. Total volume of PCM modules corresponds to the quantity of the heat collected with the solar collector.

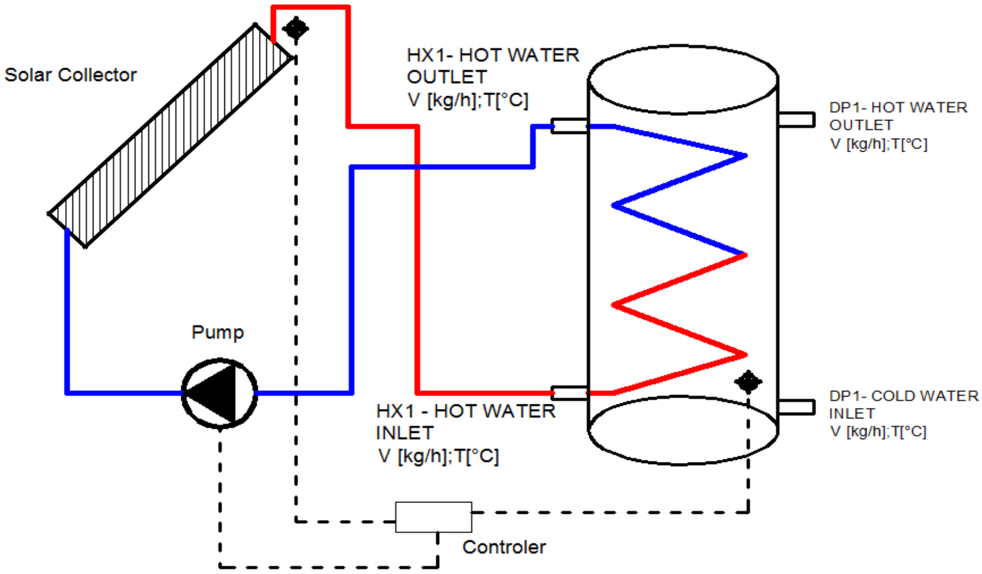

Figure 6.7: Solar- thermal system with water tank

The heat collected with the solar collector is simulated for one day period. The data is taken for an average day in June in Bosnia and Herzegovina [18]. The energy given to the collector has been modeled to behave by the sinus semi- period, and energy peak is set to be at 13:00 PM.

Water storage tank is dimensioned to be able to satisfy average four member family needs, so it has space for 120 l of water and extra space to fit the PCM modules [20].

The idea is to design water tank that contains PCM modules inside. In order to do this, volume of PCM had to be calculated to receive a certain amount of energy [kWh] obtained with a solar collector. The average monthly solar ground insolation for Bosnia and Herzegovina for June is taken in order to make the simulation more realistic. In June, in Bosnia and Herzegovina, average possible amount of heat to collect is 19,512 MJ/m^{2}d [18], [19]. This is equal to 5,42 kWh/ m^{2}d.

The goal is to calculate how much PCM is needed to store a certain amount of energy provided by solar collectors. In order to design the system the total volume of PCM modules is calculated with Eq. (6.3):

$$\mathrm{V_{PCM}} = \frac{\mathrm{Q_{COLL}}}{\Delta\mathrm{H_{PCM}} \cdot \rho_{\mathrm{PCM}}}\ [\mathrm{m}^3], \tag{6.3}$$

where $\mathrm{Q_{COLL}}$ [kWh] represents the heat collected with solar collector, $\Delta\mathrm{H_{PCM}}$ [kJ/kg] represents the latent heat of PCM, and ρ_{PCM} [kg/m^3] represents density of PCM.

$$\mathrm{Q_{COLL}} = \mathrm{Q_{SOLL}} \cdot \eta \tag{6.4}$$

Eq. (6.4) shows that heat given by the Sun- $\mathrm{Q_{SOLL}}$ will not entirely be transferred to the water for heating purpose. It will be reduced by the system efficiency factor η. In this example $\mathrm{Q_{COLL}}$ is the value assumed to be previously decreased by the value of η.

If two collectors are taken, with total area of 2 m^2, 10.84 kWh/ m^{2}d can be collected.

Not all energy will be stored with PCM material, for there has to be space left for the hot water that will be consumed. If 120L of hot water at 65 ˚C is needed to satisfy the needs of a family, then the quantity of heat required to achieve this is:

$$\mathrm{Q_{WATER}} = \mathrm{m_W} \cdot \mathrm{c_{pW}} \cdot \Delta\mathrm{T} = 120 \cdot 4.187 \cdot 30 = 15120\ \mathrm{kJ} = 4.2\ \mathrm{kWh}, \tag{6.5}$$

ΔT=30K here because the initial temperature of the tank is set to be 35 ˚C and desired temperature of water is 65˚C.

In reality, the rest of the heat (6.64 kWh) would be stored in a form of both sensible and latent heat with PCM material.

Note that this is an approximate calculation, and the sensible heat stored with PCM before and after the phase change will be neglected, as well as the heat losses to the ambient.

The total amount of heat will be distributed between sensible heat of water, and latent heat of PCM.

Therefore, if all of the rest of the heat is to be stored with PCM in a form of latent heat, the volume of PCM in the tank can be calculated with Eq. (6.6):

$$\mathrm{V_{PCM}} = \frac{\mathrm{Q_{PCM}}}{\Delta\mathrm{H_{PCM}} \cdot \rho_{\mathrm{PCM}}} = \frac{6.64 \cdot 3600}{240 \cdot 1350} = 0.07377\ [\mathrm{m}^3]. \tag{6.6}$$

The data for the PCM melting enthalpy and density can be found in Table 3.2.

Now the tank can be designed to fit all the water, the PCM modules, heat exchanger pipe and other elements. Total volume of the tank can now be approximately given by Eq. (6.7):

$$V_{TOTAL} = V_{WATER} + V_{PCM} + V_{HX} , \tag{6.7}$$

where V_{WATER} [m^3] represents total volume of water in the tank (120l), V_{PCM} [m^3] represents volume of all PCM modules present in the tank, and V_{HX} [m^3] is volume of the heat exchanger.

V_{HX} can be calculated with Eq. (6.8) :

$$V_{HX} = \frac{d_O^2 \cdot \pi}{4} \cdot L, [m^3] = 0.0103\ m^3, \tag{6.8}$$

where d_O = 0.022 m represents the outer diameter of heat exchanger pipe, and L=27 m, is the length of heat exchanger pipe. This data can be defined in the model TYPE 840, and is taken from the catalogues for water tanks [17].

The total amount of tank volume, given by Eq. (6.7):

$$V_{TOTAL} = 0.2041\ m^3$$

So, the tank total volume is 0.2041 m^3 = 204.1 l. To make the calculation simpler, tank volume of 205 l can be taken. Height of the tank is going to be 1200 mm, taken from the literature [21].

Volume of PCM modules can be distributed into cuboids, spheres or cylinders. Cylinders are chosen here for their manufacturing and handling advantages. So now, the dimensions and the number of PCM modules have to be determined.

If height H (H=1 m) and number of modules N (N=15 modules) are chosen, diameter d can be calculated using Eq. (6.9):

$$d = \sqrt{\frac{4 \cdot V}{\pi \cdot N \cdot H}} [m] = \sqrt{\frac{4 \cdot 0.07377}{\pi \cdot 15 \cdot 1}} = 0.07915 m = 79.15 \text{ mm} \quad \textbf{(6.9)}$$

Number of the modules can be determined by repeating the simulation until finding the optimal number. The optimal number of modules is the one that gives roughly equal temperature profile in all the radial slices of the modules, in a certain time interval.

If the diameter of the modules is too large, or if the number N of the modules is too small, the outer parts of the module will go through the phase change, while the center part stays solid, during the heat charge process. The model TYPE 840 gives insight into temperatures of modules in different radial positions, including center and surface, so the optimal number of the modules can be found.

In order to check if this method of designing heat exchanger is useful, a simulation of the process was done in TRNSYS. The diameter calculated with Eq. (6.9), as well as the number of modules, has been used in simulation. Heat inlet of 10.84 kWh of available solar energy is simulated to heat up the system.

The expected outcome of the simulation is to have tank storage material store the heat input, as it has been analytically calculated with Eq. (6.5).

Some parameters of the simulation can be found in the Table 6.3:

Table 6.3: Simulation parameters for SDHW system

Parameter	**Value**
Tank volume	205 l
Tank height	1.2 m
$T_{INITIAL\_TANK}$	35 ˚C
Heat inlet	10.84 kWh
PCM shape	Cylinder
Diameter of module	79.15 mm
Number of modules	15
PCM material	Sodium Acetate + Graphite
V_{HX}	200 kg/h
T_{IN}	Sinus semi period function
Simulation time step	0.05 h
Simulation time	8 h

Results of simulation are presented below in Fig. 6.9 and Fig. 6.10.

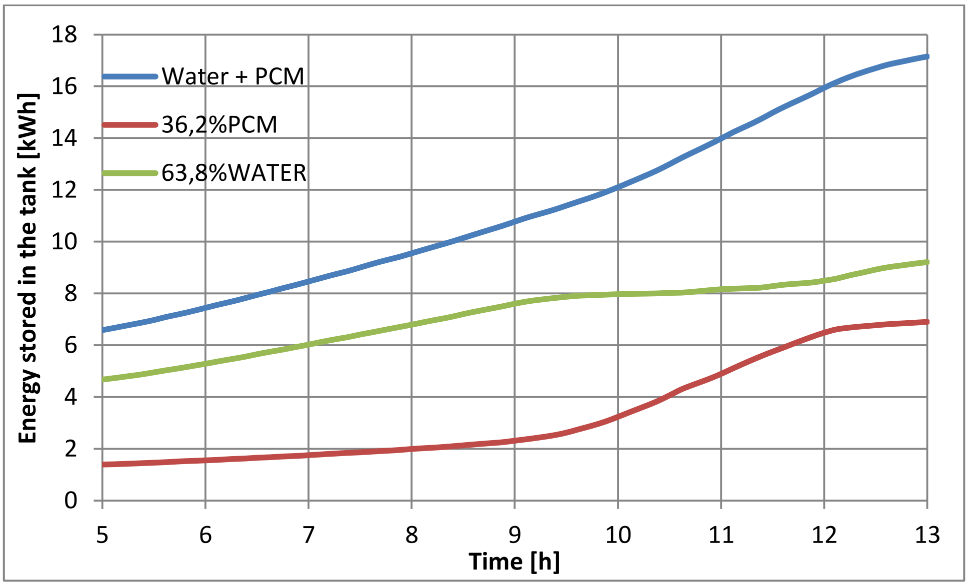

Figure 6.8: Energy stored in PCM modules in dependence of time

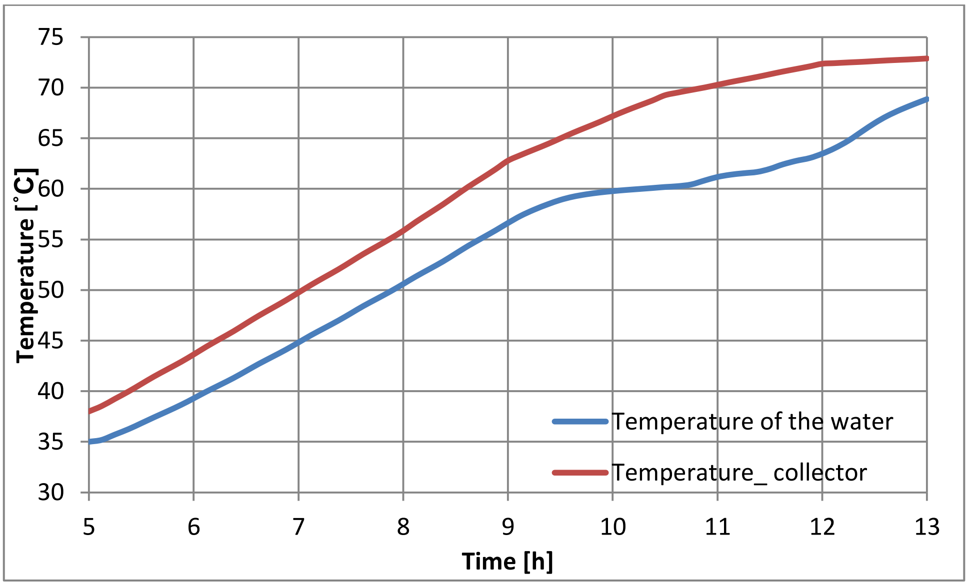

Figure 6.9: Temperature of the tank water and water provided with collector in time

In Fig. 6.8 and 6.9, energy and temperature change depending on time are shown. Results of simulation will be analyzed until water in the tank is reached 65 ˚C, as that value is taken into calculation of tank dimensions (simulation time-12:25 h).

Table 6.4: Comparison of analytical results and simulation results

Analytical predictions	
Energy expected to be stored	$Q_{TOTAL} = 10.84$ kWh
Simulation results	
Total energy stored	$Q_{TOTAL\_SIMUL} = 9.32$ kWh
Energy stored with PCM	$Q_{PCM\_SIMUL} = 5.29$ kWh
Energy stored with water in the system	$Q_{WATER\_SIMUL} = 4.03$ kWh
Heat losses to the ambient	$Q_{LOSSES\_SIMUL} = 0.15$ kWh

The mismatch between the results ($\Delta Q = Q_{TOTAL} - Q_{TOTAL_{SIMUL}} - Q_{LOSSES_{SIMUL}} = 1.37$ kWh) can be explained with neglected heat stored in sensible form in PCM. Energy is needed for PCM to come from the solid state at 35 ˚C, to the state where it is about to change its phase, at around 58 ˚C.

Then, there are other mechanisms of heat transfer inside tank that can more precisely characterize the whole process, and that haven't been taken into consideration here. To improve this method of tank dimensioning, iterations are suggested to be made, with a goal to decrease the amount of PCM in water tank, so the volume of PCM really stores all the inlet heat. In other words to make the mismatch, ΔQ , minimal.

This method of designing a water tank with PCM modules had a quantity of inlet heat known, and it is shown, by the simulation results, to be useful when approximately determining dimensions of system.

6.3 Portable energy storage with PCM - Heat battery

In this example, a theoretical scenario of heat storage with PCM is studied. Assuming that the waste heat from different processes can be captured (power plants, bakeries, engine cooling systems in the passenger cars etc.), it would be beneficial to store it in an appropriate system with portable storage modules allowing thus for the remote use of the stored heat. The idea considered in this work is to charge PCM module in a heat exchanger until the PCM is completely melted, then to replace PCM module with solid one, and to repeat the process. The melted PCM module could be used for remote heat storage as a portable device, e.g. it could heat up the systems located in nearby area, water for different purposes etc.

Here, a system including the cylindrical PCM modules is observed. To start this analysis a quantity of inlet heat is needed to be known in order to design the system. If, for the purpose of this project, 1 kWh of waste heat is taken to heat the system than the volume of PCM required can be calculated with following equation:

$$V_{PCM} = \frac{Q_{WASTE}}{\Delta H_{PCM} \cdot \rho_{PCM}} \; [m^3] \, , \qquad \textbf{(6.10)}$$

where Q_{WASTE} represents the waste heat from a system considered, ΔH_{PCM} [J/kg] represents the latent heat of PCM, and ρ_{PCM} [kg/m^3] represents density of PCM.

PCM material assumed is Sodium Acetate + Graphite. Its thermal characteristics can be found in Table 3.2.

Therefore, the volume of PCM required is:

$$V_{PCM} = 0.0111 \text{ m}^3 = 11.1 \text{ l}. \qquad \textbf{(6.11)}$$

In order to use the overall surface of the PCM for heat transfer in the heat exchanger, PCM module will have to be submerged into water. Three different configurations of tank will be taken in order to test this example. Number of PCM modules N is 1. Diameter of PCM module is altered, and height and volume of heat exchanger are calculated. Water tank drawing with planned dimensions is presented in Fig. 6.10.

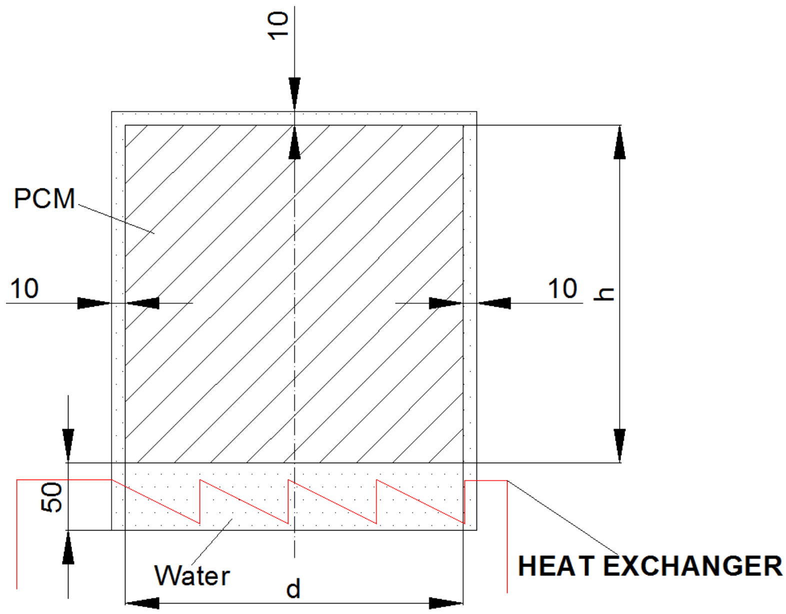

Figure 6.10: Water tank drawing (dimensions are given in mm)

In water tank, 10 mm space is always left on top of the tank and around PCM module in order to surround the module with water that will transfer heat. At the bottom of the tank, 50 mm from bottom is left to place the heat exchanger. In Table 6.6, dimensions of water tank are presented. Volume of tank is augmented in order to fit in the heat exchanger. Volume of heat exchanger is calculated below:

$$V_{HX} = \frac{d_O^2 \cdot \pi}{4} \cdot L\ [m^3] = \frac{0.022^2 \cdot \pi}{4} \cdot 10 = 0.0038\ m^3 = 3{,}8\ l \qquad \mathbf{(6.12)}$$

In Eq. (6.12) d_O^2 [m] represents the outer diameter of the heat exchanger pipe, and L [m] represents the total length of heat exchanger pipe. Dimensions of heat exchanger are adopted.

Table 6.5: Dimensions of water tank

Volume of PCM [l]	Diameter of PCM [mm]	Height PCM [mm]	Volume of tank [l]	Tank height [m]
11.1	150	622.78	19.49	682.78
11.1	200	350.32	19.79	410.32
11.1	250	224.20	20.36	284.24

Table 6.6 Simulation parameters

Simulation time	2 h
Simulation time step	0.05 h
Number of nodes of the tank	5
T_{INLET_HX}	65 ˚C
V_{HX}	200 kg/h
Number of temperature sensors	5
$T_{INITIAL\_TANK}$	20 ˚C
T_{AMB}	20 ˚C

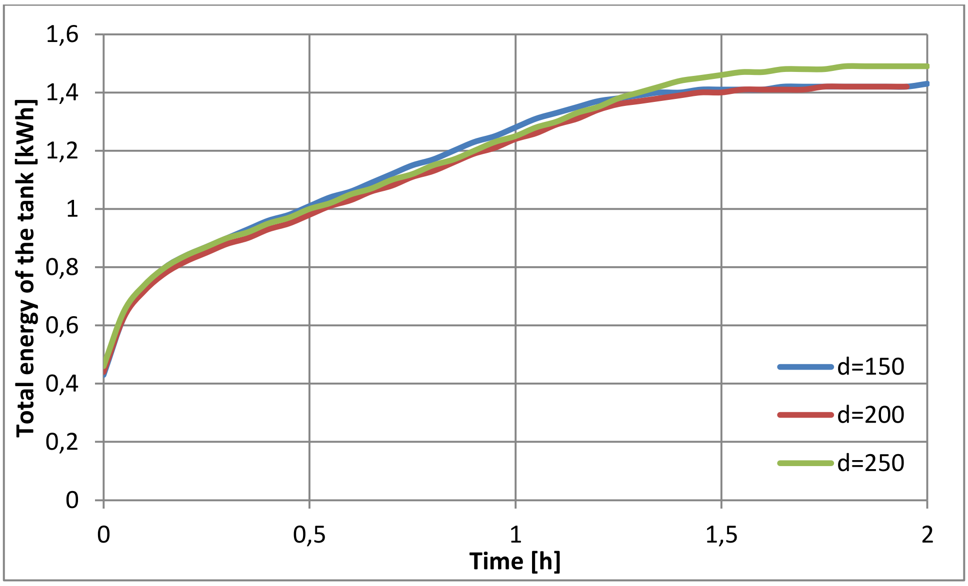

Figure 6.11 Energy of the tank for three cases of the PCM diameter

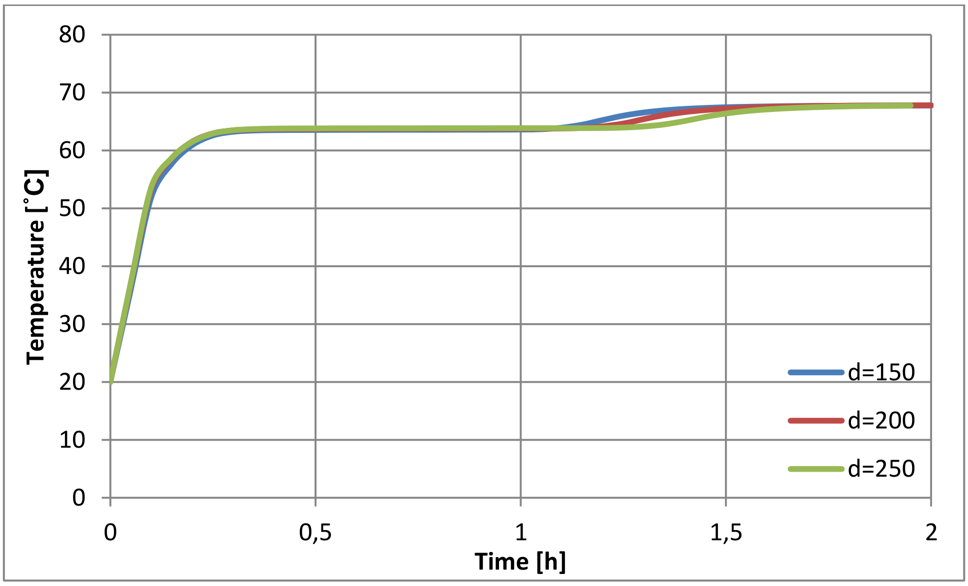

Figure 6.12 Temperature of tank water for three cases of the PCM module diameter

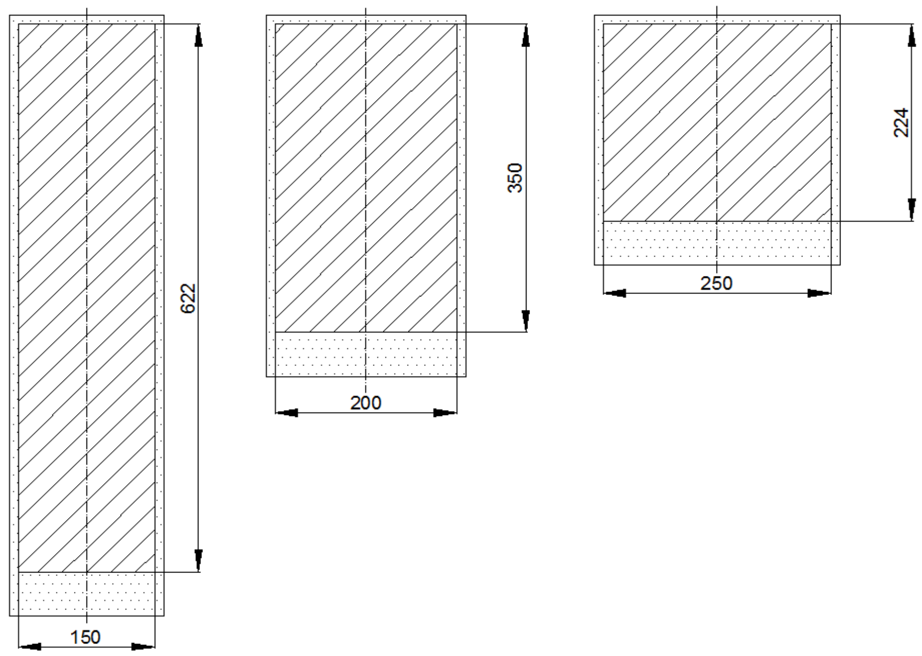

Figure 6.13 Different configurations of water tank

In Fig. 6.11 and 6.12 results of simulation of this case are presented. In every scenario of the tank parameters, the amount of the stored heat seems to be approximately the same (about 1kWh as expected according to the initial estimation of the storage volume), since the storage time was sufficiently long. Slightly higher stored energy, and thus slightly higher storage rate is achieved in the case of the PCM module with the largest diameter of 250 mm.

So, the parameter that influences the amount of stored heat the most is the total volume of PCM present in the tank, and not so much its aspect ratio.

In Fig. 6.13 different configurations of water tank used in simulation are presented, with diameter and height altered.

The storage rate (approximately 0.67 kWh/h) is less than obtained in the case from the Chapter 5 (see Eq. 5.5 and 5.6) which may be addressed to differences in the amount and the flow velocity of the water.

7 Concluding remarks

In the past few decades, LHS has been explored intensively in order to increase the efficiency of the thermal systems. PCM materials have been analyzed and tested in order to be applied in systems they correspond to the best. In this master thesis comparison of sensible and latent heat storage is done. Systems containing PCM modules were analyzed in order to show water tank heat charging and discharging times, and quantity of stored/ released heat. Analysis has been done using simulation program TRNSYS. Results obtained with few cases analyzed in this work can be used as an introduction into behavior and possibilities of PCMs in thermal energy systems.

Analysis of three systems with PCM is done by comparing the characteristics of these systems (charging and discharging times, and quantity of stored heat) to the equivalent systems with no PCM. Additionally, dimensioning of systems is done in a sense of determining the volume of PCM in tank in order to store a certain amount of inlet thermal energy.

In all examples of systems with PCMs, analyzed in this work, PCMs have shown both improvements and drawbacks of their incorporation into these thermal systems. In general, improvements, or advantages, of having PCMs present in water tank are found in having more energy stored (Fig. 5.6), having the temperature of water in tank more stable (Fig. 6.5), and in storing energy that can't be used in given moment, for later use (instead of releasing it into environment). The phenomenon that comes with PCM inclusion in systems, and that is considered to be drawback here, is the time needed to heat the tank, which is always longer compared to systems without PCMs (Fig. 5.7). It is necessary to emphasize that not all of mentioned characteristics have to be labeled as system advantages or disadvantages, because this depends on system requirements.

The conclusions made in this work are greatly dependent on simulation results obtained with TRNSYS. Simulations of processes and models of real objects are dependent on measurement results. Even though simulation of a system is a great way of avoiding all difficulties of conducting an experiment, in order to have system dimensioned more accurately, simple experiment is recommended to be made, and those results to be compared with simulation results. This would give more meaningful and convincing results, and it would show water tank with PCM model accuracy. Other than this, it is recommended to conduct a cost analysis of a system with PCM, include possible energy savings with PCM application, and find investment return period.

Additionally it would be good to do work with different applications of PCMs in systems, not only in water tanks. A good example of PCM application is wall incorporation of micro-encapsulated PCM materials (e.g. paraffin wax). Analysis of thermal comfort satisfaction and air conditioning needs reduction of a room with these types of walls could be done.

Other than this, it is recommended to experiment (simulate) systems with different PCMs. In all examples in this work, only Sodium Acetate + Graphite is used.

This work aims to give readers a glance into possibilities of PCMs as a new tool of concurring high energy demands on one side, and unreasonably low energy efficiency measurements on the other side.

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Appendix

I Draft proposal for scientific paper: *Thermal energy storage with PCM materials*

Abstract

Energy is released from different processes into environment every day across the globe. With the augmentation of the population it isn't realistic to expect the energy demand to decrease, therefore currently available energy should be used more efficiently. In that sense, latent heat storage (LHS) has been popularized in last few decades because it can improve energy savings of thermal energy systems. The present paper contributes in showing the effects on system of including phase change materials (PCM) in a thermal energy system. System analyzed here is hot water tank for domestic use purposes. Analysis of system has been done using simulation program TRNSYS. Results come in a form of graphs that show charging and discharging times, quantities of energy stored, and temperature profile of water tank.

Keywords: Phase change materials (PCM), thermal energy storage (TES), model of water tank, latent heat storage (LHS), sensible heat storage (SHS)

1. Introduction

Phase change materials change their aggregate phase when exposed to heat. This process occurs at different temperatures- it depends on chemical composition of the material. The use of this process is made by incorporating PCMs into different thermal energy systems where rejected heat from the systems can be stored in PCMs in form of latent heat. This is called latent heat storage, and it is becoming popular in thermal energy storage (TES) because of large amount of energy that can be stored in PCMs during the phase change.

There are different systems that could use PCMs and benefit from it: (i) air conditioning systems, (ii) internal combustion engines, (iii) solar domestic hot water system, (iv) waste heat recovery from different systems, (v) off peak power utilization, (vi) heat pump systems, (vii) space applications, (viii) computer cooling, etc. [1]

In this paper, characteristics of incorporating PCMs into system with water tank will be analyzed.

2. Materials for LHS

There is a vast number of PCMs available today. PCM material should be selected for certain application considering the system working conditions. Depending on the application, first criteria for PCM selection should be based on their melting temperature. Materials that melt below 288 K are used in air conditioning applications, while materials that melt above 363 K are used for absorption refrigeration. Materials that melt between these two temperatures can be applied in solar heating and for heat load leveling applications.
Materials that are used for latent heat thermal energy storage (LHTES) should have a large latent heat and high thermal conductivity.

They should also have high storage density in a relatively small volume, high melting enthalpy [J/kg] and a high density [kg/m³], i.e. a high volumetric melting enthalpy [J/m³]. Most commonly used type of phase change is solid- liquid phase transformation, because of small change in volume during the process and its energy density [1].

PCM material adopted for analysis performed in this paper is Sodium Acetate + Graphite, and its thermal characteristics are presented in Table 1.

Table 1: PCM thermal storage properties [2]

PCM	Sodium Acetate + Graphite
Melting Temperature [˚C]	56 to 60
Melting Enthalpy [kJ/kg]	240
Density [g/cm³]	1.35

3. Modeling the water tank with PCM

In simulation studio- TRNSYS, TYPE 840 is a model for water tank with possibility of PCM modules inclusion. It can help give insight into capabilities and behavior of PCM incorporated in certain system. It can also be used to show the thermal characteristics of PCM material.

Modelling of phase change process with PCM has a theoretical approach because the thermal properties of PCM change during the phase change of the PCM. The model for the water storage tank has been implemented into the simulation environment as a multi-node storage model where the nodes are obtained by subdividing the PCM storage in vertical direction [3].

An energy balance equation for each storage node is formulated in order to calculate the time evolution of enthalpy and temperature. Fig.1 shows that the storage volume is divided into N vertical segments (nodes). Each node is characterized by the enthalpy h_j, the temperature T_j and the mass m_j of the storage fluid in the node (j). Eq. (1) gives the energy balance equation for any (and each) storage node and it gives the enthalpy h_j for j-th node and also the temperature T_j of the given j-th node:

$$m_j \frac{h_j^{p+1} - h_j^p}{\Delta t} = \dot{Q}_{dp}^p + \dot{Q}_{hx}^p + \dot{Q}_{aux}^p + \dot{Q}_{cond}^p + \dot{Q}_{loss}^p + \dot{Q}_{module}^p. \quad \mathbf{(1)}$$

In Eq. (1), $\dot{Q}_{dp}$ [W] denotes the heat flow due to the mass flow through a double port (direct connection to the tank), $\dot{Q}_{HX}$ [W] is the heat flow exchanged with an internal heat exchanger, $\dot{Q}_{aux}$ [W] represents the heat input coming from a built-in electric heater, $\dot{Q}_{cond}$ [W] is the heat conduction to adjoining storage nodes, $\dot{Q}_{loss}$ [W] represents the heat losses to the ambient and $\dot{Q}_{module}$ [W] denotes the heat exchange with built-in PCM modules [3].

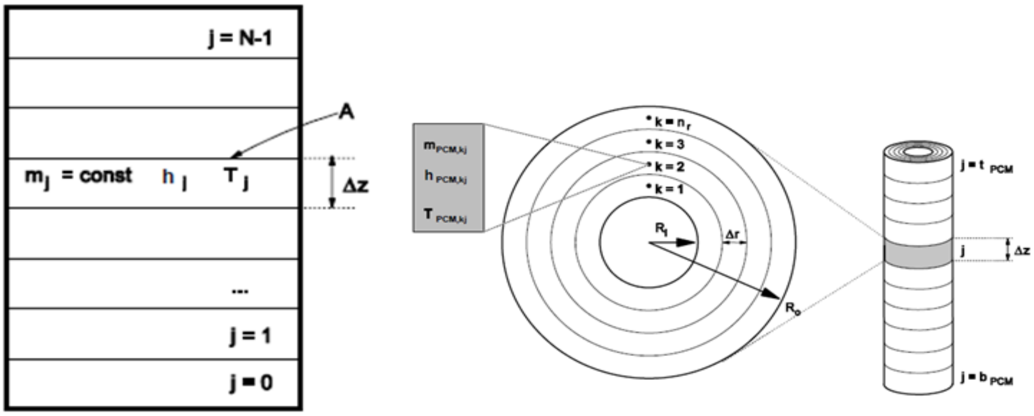

Figure 1: Multi-node storage model with N nodes with the height Δz and the top and lower cross sectional area A; the jth node has the mass mj the enthalpy hj and the temperature Tj (left), and nodal network of a cylindrical PCM module (pipe module) with the vertical nodes (j) and the radial nodes (k) (right) [3]

The evolution of the enthalpy with time is determined with the explicit approach as shown in Eq. (2):

$$h_j^{p+1} = h_j^p + \frac{\Delta t}{m_j} \cdot \sum \dot{Q}^p \tag{2}$$

Thus the enthalpy in the time (p+1) results explicitly out of the respective terms in the time (p). [3]

4. Comparison of SHS and LHS

In order to get insight into the differences arising in the heat storage using both SHS and LHS, a simple case is investigated. A 300 l tank filled only with water is compared to a 300 l tank filled with 70 % of water and 30% of PCM. Heat charging scenario is simulated using TRNSYS simulation program. The model TYPE 840 is used to simulate both the water tank and water tank with PCM modules. In Fig. 2, the outlook of the both water tank is presented, with parameters adopted in simulation. The division of tank into nodes is illustrated also in Fig. 2, as well as position of double ports, and PCM modules present in tank are schematically illustrated. Shape of PCM modules is chosen to be cylinder, over sphere, because it has both manufacturing and installing advantages.

Simulation parameters used in TRNSYS for tank with only water are presented in Table 2. In Table 3 simulation parameters for the case of tank with both water and PCM are given. Basic simulation parameters are equal for both cases; the only difference is storage material (water vs water and PCM).

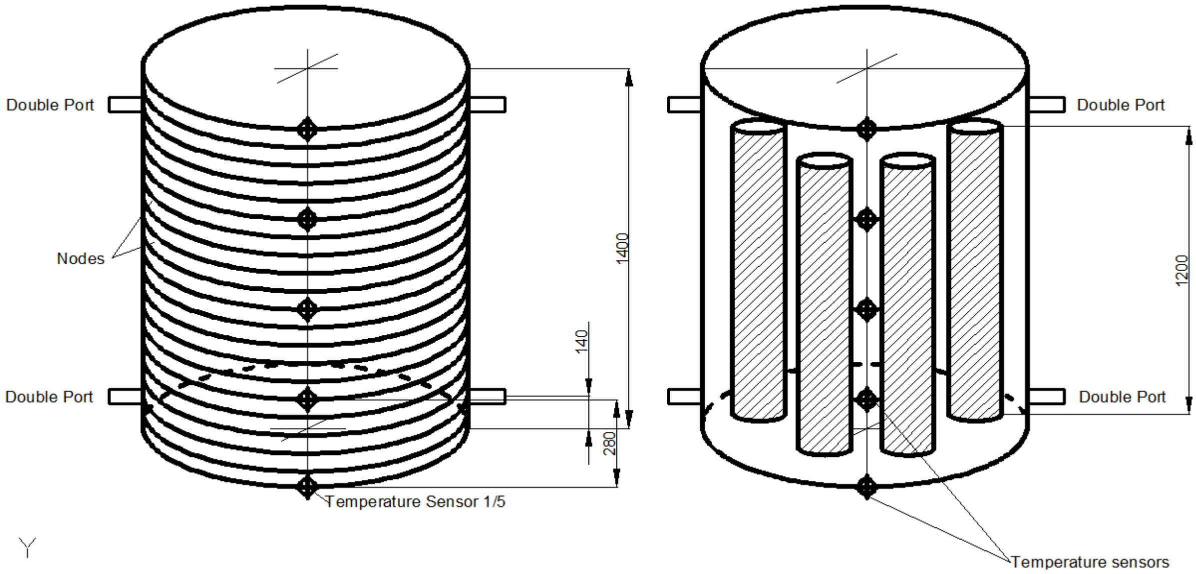

Figure 2: Left: schematic representation of water tank in TRNSYS, divided vertically in nodes; Right: water tank with PCM modules inserted, filling ratio of PCM is 30% [4]

Table 2: Simulation parameters for tank with only water

Water tank and simulation parameters	
Tank storage fluid volume	0.3 m^3 (water)
Tank height	1.4 m
Simulation time	24 h
Simulation time step	0.05 h
Number of nodes of the tank	20
T_{INLET_HX}	65 ˚C
V_{HX}	300 kg/h
Number of temperature sensors	5
$T_{INITIAL\_TANK}$	50˚C
T_{AMB}	20˚C
Heat exchanger dimensions	
Outer Diameter of HX pipe, D_O	22 mm
Length of HX pipe, L	20 m
Heat exchanger total volume	0.007598 m^3

Heat is delivered to system through internal heat exchanger (HX). Its dimensions, as well as temperature and mass flow rate of hot inlet water, are given in Table 2.

Table 3: Simulation parameters for tank with water and PCM

Water volume	0.21 m^3= 70% of tank storage volume
PCM Total Volume	0.09 m^3= 30% of tank storage volume
Number of nodes in PCM (radial)	4
Number of nodes (vertical)	20
PCM shape	Cylinders
Height	1.2 m
Number of modules	8
Diameter of module	109.3mm
PCM material	Sodium Acetate + Graphite

Quantity of heat expected to be stored in tank with 100% of water is:

$$Q = V \cdot \rho \cdot c_p \cdot \Delta T = 5.18 \text{ kWh.} \quad \textbf{(3)}$$

Heat stored with both PCM and water can be estimated as:

$$Q_{W+PCM} = [V \cdot \rho \cdot c_{p,w} \cdot \Delta T]_{w} + [V \cdot \rho \cdot c_{p,s} \cdot \Delta T]_{PCM\_SEN1} + Q_{LAT\_PCM} + [V \cdot \rho \cdot c_{p,l} \cdot \Delta T]_{PCM\_SEN2} = 8.825 \text{ kWh} \quad \textbf{(4)}$$

Note that in Eq. (4) the values for $c_{p,s}$ and $c_{p,l}$ are adopted to be equal, 2.5 kJ/kg K. In reality, there is a difference between the $c_{p,s}$ and $c_{p,l}$ for PCMs. However, in this study for simplicity no difference has been made.

1. Results

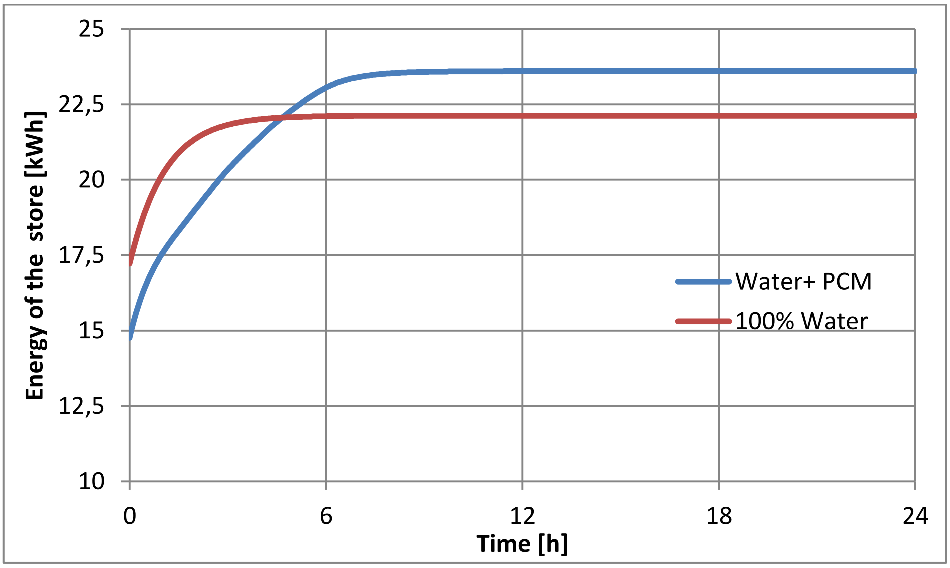

Figure 3: Total energy of storage fluid in dependence of time for two types of water tank [4]

Table 3: Quantity of heat stored in two tanks

Heat stored in tank with water	4.9 kWh
Heat stored in tank with water	8.84 kWh

The results of simulation in TRNSYS give approximately expected quantity of stored heat as in Eq. (3) and Eq. (4). In Fig. 3, a characteristic of using PCM modules in the tank can be seen. The time needed to charge the storage material in the case of the tank with both PCM and water is greater than in the case of the tank filled with only water. Time needed to load the tank with water as a storage fluid in this case is 4.5 h, and the time needed to load the tank with both PCM and water is 6.75 h.

However, in the tank that contains both water and PCM the so called speed of charging, is greater compared to the tank with only water. The speed of charging is the ratio of heat accumulated in the storage fluid and the time needed to achieve that. For the tank with water, this parameter can be expressed as:

$$u_{WATER} = \frac{\Delta Q_{WATER}}{\Delta\tau} = \frac{22.05 - 17.22}{4.5} = 1.0733\ {}^{kWh}/_{h.} \tag{5}$$

And for the tank with water and PCM the speed of charging is 15.6% larger:

$$u_{WATER+PCM} = \frac{\Delta Q_{WATER+PCM}}{\Delta\tau} = \frac{23.35 - 14.76}{6.75} = 1.2726\ {}^{kWh}/_{h.} \tag{6}$$

Eq. (5) and (6) show that, even though more time is needed to heat up the tank with PCM, the quantity of heat accumulated per unit of time is greater in this tank.

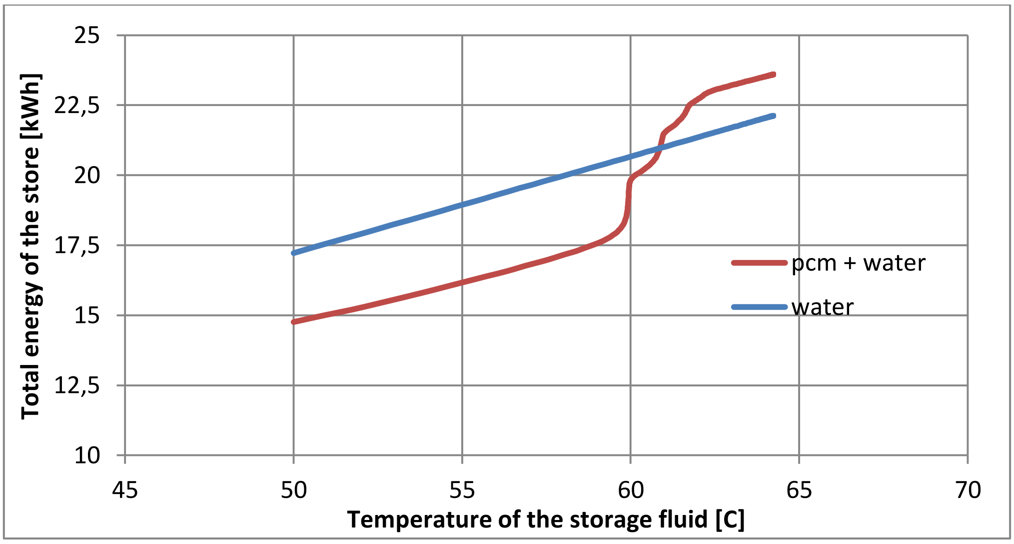

Figure 4: Temperature of water in tank for two types of tank [4]

In Fig. 4, total energy of the store in dependence of the temperature of the storage fluid (water) is compared for the two mentioned cases of water tanks: (i) with water only, and (ii) water and PCM.

It can be seen that in the temperature range where PCM goes through the phase change (56˚C-60˚C) the heat stored in the tank with both water and PCM, with just a few degrees of temperature difference, is much greater than the heat stored in the tank that contains only water.

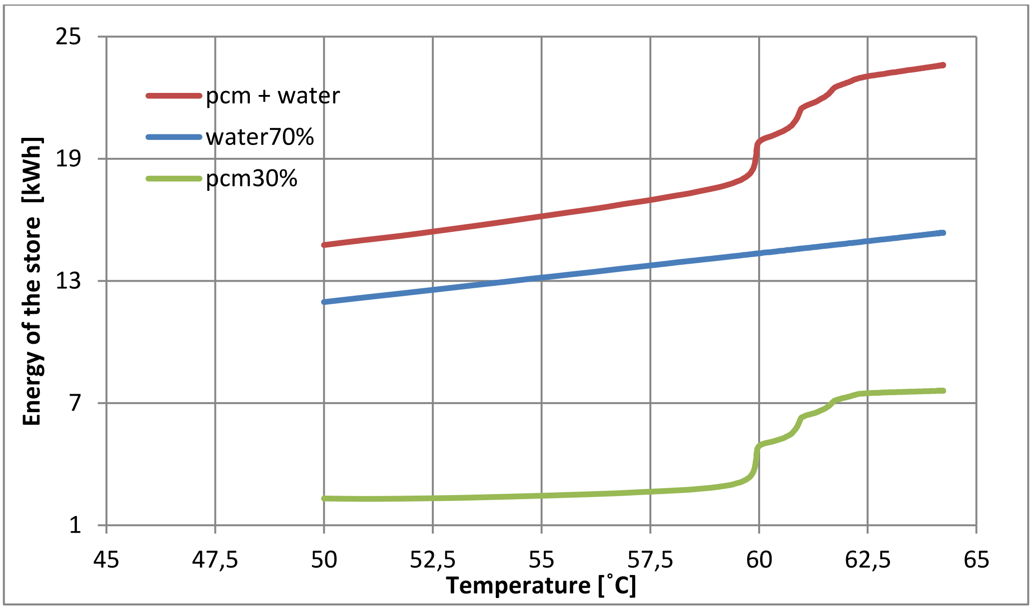

Figure 5: Energy stored in tank with PCM modules separated into segments [4]

In Fig. 5, the energy stored in storage fluids, for the tank with water and PCM, depending on temperature of tank water is presented. The topmost curve represents the total energy stored in storage fluids of the tank (both water and PCM). The bottom two curves represent the heat stored in water and in PCM, separately. The heat stored in PCM during the phase change is 3.63 kWh in the temperature range of approximately 2 ˚C. Using water, in the same temperature interval 0.6 kWh can be stored.

The topmost and the lowermost curves at approximately 58 ˚C start to have a greater inclination. This goes on until around 62 ˚C, and the amount of energy rises up faster in this area of temperatures. In this part is the latent heat stored inside the PCM modules.

It is also important to observe that after the phase change the PCM material can store less energy via sensible heat than water. This is explained by the fact that the specific heat capacity of the water is greater than the specific heat capacity of PCM.

Note that the volume of water in the case with PCM is smaller than in the tank with water only, in order to fit the PCM modules in the tank, keeping the same total volume of tank. In Table 4 the latent and total heat stored in PCM, obtained with simulation, are presented.

Table 4: Heat stored in tank with water and PCM

Total heat stored in tank (water + PCM)	Q_{TOTAL}= 8.84 kWh
Sensible heat stored in tank (70%water)	$Q_{SENSIBLE\_W}$= 3.4 kWh
Latent heat stored in PCM	Q_{LAT_PCM}= 3.63 kWh
Total heat stored in PCM (sensible + latent)	Q_{PCM}= 5.29 kWh

The difference between $Q_{SENSIBLE\_W} + Q_{PCM}$ and Q_{TOTAL} can be explained with quantity of heat lost into ambient,Q_{loss}, that is taken into account by water tank model in simulation program TRNSYS.

1. Conclusion

In this paper comparison of sensible and latent heat storage is done. Results obtained in this work can be used as an introduction into behavior and possibilities of PCMs in thermal energy systems. In general characteristics of having PCMs present in water tank are expressed in having more energy stored, having the temperature of water in tank more stable, storing energy, that can't be used in given moment, for later use (instead of releasing it into environment). When PCM modules are included in system, the time needed to heat the tank is always longer compared to systems without PCMs. However, the speed of charging (the ratio of heat accumulated in the storage fluid and the time needed to achieve that) is greater for the case of tank with water and PCM. This paper shows that, when used in adequate temperature range, PCMs can help improve thermal energy system.

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Acronyms

DP	*Double Port*	PCM	*Phase Change Material*
HX	*Heat Exchanger*	SHS	*Sensible Heat Storage*
LHS	*Latent Heat Storage*	TRNSYS	*Transient System Simulation*
LHTES	*Latent Heat Thermal Energy Storage*		