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Analysis of Possibilities to Use Phase Change Materials in Heat Exchangers-Accumulators

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Abstract. Phase Change Materials (PCMs) are utilized in different engineering fields, such as thermal storage of building structures, such as domestic hot water, heating and cooling systems, electronic products, drying technology, waste heat recovery, refrigeration and cold storage, and solar cookers. The biggest technological problems for the implementation of low and high temperatures PCM are the insufficient thermal conductivity of the available phase change materials, compatibility with the container material, cycling stability. In order to evaluate efficient and cost effective operation of thermal energy storage, different design concepts for PCM integration into heat exchanger/ accumulator should be investigated.

Keywords: Heat exchanger, Phase change material (PCM), Latent heat, Thermal energy storage (TES).

Conference topic: Energy for buildings.

Introduction

Thermal energy storage (TES) is a technology that stocks 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 and power generation. TES systems are used particularly in buildings and industrial processes.

There are three kinds of TES systems, namely: 1) sensible heat storage that is based on storing thermal energy by heating or cooling a liquid or solid storage medium (e.g. water, sand, molten salts, rocks), with water being the cheapest option; 2) latent heat storage using phase change materials or PCMs (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 (Thermal energy storage 2013).

In sensible heat storage (SHS), thermal energy is stored by raising the temperature of a solid or liquid. SHS system utilizes the heat capacity and the change in temperature of the material during the process of charging and discharging. The amount of heat stored depends on the specific heat of the medium, the temperature change and the amount of storage material (Sharma *et al.* 2007).

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. Phase change from liquid to gas has higher latent heat of phase transition but large changes in volume make the TES system complex and impractical (Sharma *et al.* 2007). During the melting process, the material absorbs heat, known as melting enthalpy, at constant temperature and correspondingly releases the same amount of heat during solidification, when the storage is discharged. Therefore, in latent heat storage large volumetric energy storage capacities are feasible within a very narrow temperature range around the melting temperature, as the heat of melting and solidification is used (Laing *et al.* 2012).

Thermochemical systems rely on the energy absorbed and released in breaking and reforming molecular bonds in a completely reversible chemical reaction. In this case, the heat stored depends on the amount of storage material, the endothermic heat of reaction and the extent of conversion (Sharma *et al.* 2007).

Sensible heat storage is relatively inexpensive, but its drawbacks are low energy density and variable discharging temperature. These issues can be overcome by PCM based thermal energy storage, which enables higher storage capacities and target oriented discharging temperatures. The change of phase could be either a solid/liquid or a solid/solid process (Thermal energy storage 2013). Melting processes involve energy densities in the order of 100 kWh/m^3 (e.g. ice) compared to a typical 25 kWh/m^3 for sensible heat storage options. Phase change materials can be used for both short term (daily) and long term (seasonal) energy storage, using a variety of techniques and materials. For example, 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 cool and solidify by night and melt during the day, thus cooling the walls and reducing or avoiding the need for electric chillers ("passive cooling"). Other applications for active cooling systems involve the use of macro-encapsulated PCMs that melt at an appropriate temperature. The 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. A number of R&D activities, most of them aimed at industrial applications, currently focus on high temperature PCM (above 150 °C) (Thermal energy storage 2013).

Phase change materials

Thermal energy can be stored nearly isothermally in some substances as the latent heat of phase change, as heat of fusion (solid–liquid transition) or heat of vaporization (liquid–vapour transition). In general, the term "latent heat" describes the heat of solid-solid, solid-liquid and liquid-vapour phase changes. However, the terms "latent heat storage" and "phase change material" are commonly only used for the first two kinds of phase changes and not for liquid-vapour phase changes. In a liquid-vapour phase change, the phase change temperature strongly depends on the boundary conditions and therefore the phase change is not just used for storage of heat alone (Mehling, Cabeza 2008). Storage systems utilizing PCM can be reduced in size compared to single-phase sensible heating systems. However, heat transfer design and media selection are more difficult and experience with low temperature salts has shown that the performance of the materials can degrade after moderate number of freeze–melt cycles. Phase change materials allow large amounts of energy to be stored in relatively small volumes, resulting in some of the lowest storage media costs of any storage concepts (Gil *et al.* 2010).

A large number of PCMs are known to melt with a heat of fusion in any required range. However, for their employment as latent heat storage materials these materials must exhibit certain desirable thermodynamic, kinetic and chemical properties. Moreover, economic considerations and easy availability of these materials has to be kept in mind. A large number of PCMs (organic, inorganic and eutectic) are available in any required temperature range. A classification of PCMs is given in Figure 1.

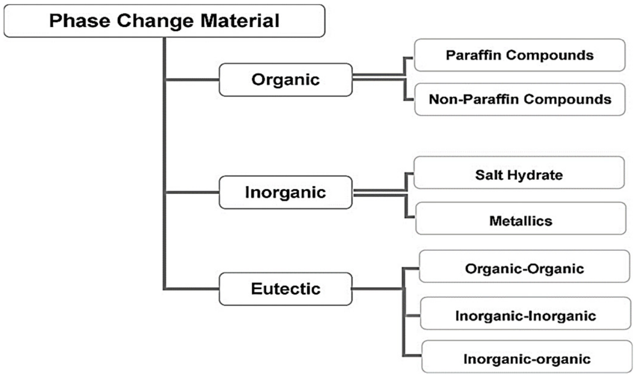


Fig. 1. Classification of PCMs (Sharma *et al.* 2007)

A suitable phase change temperature and a large melting enthalpy are two obvious requirements on a phase change material. They have to be fulfilled in order to store and release heat at all. However, there are more requirements for most, but not all applications. These requirements can be grouped into physical, technical, and economic (Mehling, Cabeza 2008): suitable phase change temperature, large phase change enthalpy, reproducible phase change (also called cycling stability), little subcooling, good thermal conductivity, low vapor pressure, small volume change, chemical stability of the PCM, compatibility of the PCM with other materials, safety constraints, low price, good recyclability. Schematic temperature change of PCM heating and cooling cycle is shown in Figure 2.

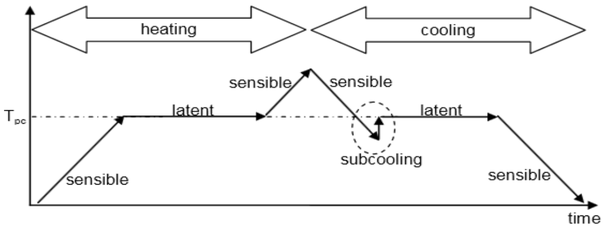


Fig. 2. Schematic temperature change during heating (melting) and cooling (solidification) of a PCM with subcooling (Mehling, Cabeza 2008)

The biggest technological problem for the implementation of low temperatures PCM is the insufficient thermal conductivity of the available phase change materials. Most salts provide a thermal conductivity around 0.5 W/mK. During the discharge process, the energy released by solidification of the storage material must be transported from the solid-liquid interface through the growing solid layer to the heat exchanger surface (Fig. 3). Therefore the heat transfer coefficient is dominated by the thermal conductivity of the solid PCM. So the main task in the heat exchanger design process is to identify cost effective options to increase the effective heat conductivity within the storage material (Laing *et al.* 2009).

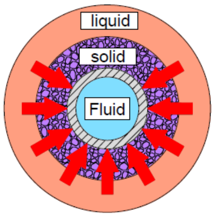


Fig. 3. Solidification of PCM around heat exchanger tube during discharging (Tamme 2007)

Once the PCM has been selected based primarily on the temperature range of application, the next most important factors to consider are the geometry of the PCM container and the thermal and geometric parameters of the container required for a given amount of PCM.

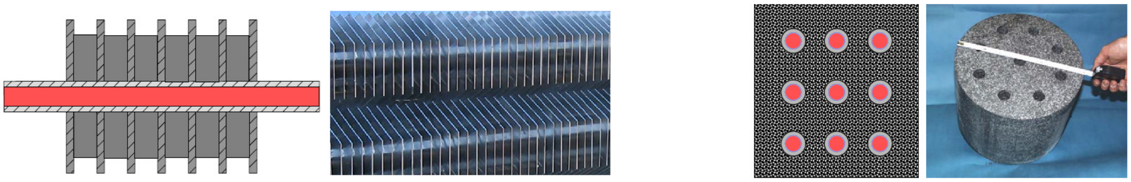
Each of these factors has a direct influence on the heat transfer characteristics in the PCM and ultimately affects the melt time and the performance of the PCM storage unit. To ensure long-term thermal performance of any PCM system, the size and shape of the PCM container must correspond to the melting time of the PCM (Agyenim *et al.* 2009).

Concept for PCM heat exchange system

Generally, the heat transfer depends on the heat transfer area, the mode of heat transfer (convection, conduction, radiation) and the corresponding heat transfer coefficient, and the temperature gradient. When trying to improve the heat transfer, it is therefore straightforward to increase the heat transfer area. For storages with heat transfer on the storage surface this can be done by adding fins to the surfaces of the storage. Usually more efficient is the use of internal heat transfer surfaces. Storages with heat transfer on internal heat transfer surfaces use a heat transfer fluid (HTF) to transport heat in and out of the storage. Such storages are able to transfer heat faster to the supply side and/or on the demand side. There are number of options to construct storages with heat transfer on internal surfaces. Basic storage types could be (Mehling, Cabeza 2008):

- Heat exchanger type – the most common kind of storage with heat transfer on internal surfaces. It is derived directly from the construction principle of any kind of heat exchanger to exchange heat between two fluids. To build storage on one side of the heat exchanger the fluid is replaced by the PCM.
- Direct contact type – the heat transfer fluid is in direct contact with PCM and this eliminates the thermal resistance of the heat exchanger wall. The direct contact concept takes advantage of convection and actually enforces it. In addition, it can also solve the problem of phase separation in PCM that do not melt congruently.
- Module type – it uses macro-encapsulated PCM modules for heat storage. Using macro-encapsulated PCM modules is a big advantage regarding manufacturing and marketing. Instead of heat exchanger that separates the PCM from the heat transfer fluid, the PCM is macro-encapsulated. The PCM modules are placed in the storage tank and the heat transfer fluid flows in the tank exchanging heat with the PCM modules.

Different concepts are investigated at German Aerospace Center (DLR) to overcome the limitations resulting from PCMs low thermal conductivity. There are two basic solutions (Buschle *et al.* 2006a, 2006b): increase of the heat transfer area, Figure 4a; and increase of the effective thermal conductivity, Figure 4b.



a) b)

Fig. 4. Heat transfer enhancement (Laing *et al.* 2009; Buschle *et al.* 2006b)

A concept to increase the heat transfer area is the macro-encapsulation of the storage material. The capsules filled with PCM are stored in a pressure vessel filled with heat transfer fluid. Macro-encapsulation can be done with flexible or stiff capsules. Because of the variations in specific volume of up to 10% during phase change, the tubes are not filled completely with the PCM. A gas volume fraction of about 20% is required inside the stiff capsules to limit the increase of pressure during the melting of the PCM. Due to the corrosive behaviour of the selected salt as PCM, a minimum wall thickness is necessary and no flexible encapsulation is possible.

The thermal conductivity of the PCM can be increased by integrating layers of highly conductive materials into the PCM. The layers are arranged in the direction of heat transport. A promising material for these layers is expanded graphite due to its high thermal conductivity (150 W/mK) and its corrosion resistance. The higher price of expanded graphite mass unit compared to stainless steel or carbon steel is compensated by its low density and high thermal conductivity. The investment costs for extended heat transfer structures made of graphite foil are expected to be significantly lower than for steel.

Another way to increase the thermal conductivity of the PCM is by mixing the PCM with a material of high thermal conductivity. Composite materials are manufactured by compression of a powder mixture of technical salts and ground expanded graphite. Expanded graphite is chosen because of its high thermal conductivity and chemical stability. An important aspect here is the cyclic behaviour of the composite material. After repeated charging and discharging cycles, the separation of the components must not occur (Buschle *et al.* 2006a).

These heat transfer enhancement concepts can be grouped in the following categories (Medrano *et al.* 2009; Al-Abidi *et al.* 2013): 1) having the PCM inserted in a metal; 2) adding metallic particles with higher thermal conductivity than the PCM; 3) macro and micro encapsulating the PCM; 4) using a PCM-graphite composite material; 5) using finned tubes with different configurations; 6) using multitubes; 7) using bubble agitation when the movement of steam bubbles induces convection during PCM melting; 8) employing multiple families of PCMs when the HTF temperature changes during charging process and different melting temperature of PCM is required in the same TES.

In Figure 5 classification of PCM storage concepts investigated in the DISTOR project is presented (IEA ECES 2010).

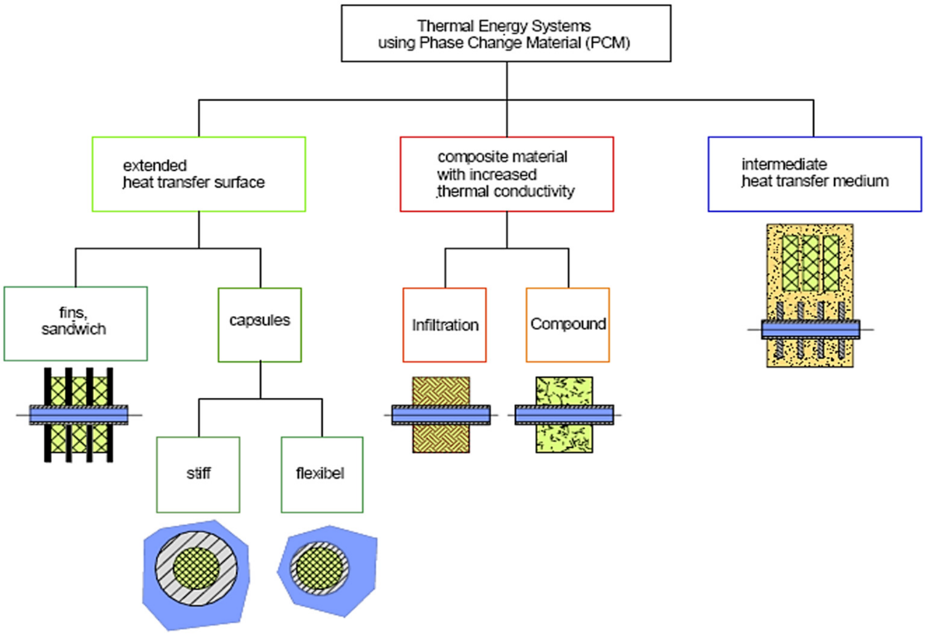


Fig. 5. Classification of PCM storage concepts (IEA ECES 2010)

Different options have been investigated to overcome the limitation resulting from the low thermal conductivity of the storage material. The sandwich concept has been identified as the most promising option to realize cost-effective latent heat storage systems. In this concept fins enhance the heat transfer within the storage material. The heat transfer area is increased by mounting the fins vertically to the axis of the tubes. The characteristic height of these fins exceeds the dimensions which are commercially available as finned tubes. Decisive for the successful implementation of this approach is the selection of the fin material. Steel fins seem to be a straightforward solution, since they are clearly compatible to the steel tubes. Instead, graphite foil or aluminium could be chosen as fin material due to their favourable heat conductivity. As shown in Figure 6, steel fins showing the same heat transport performance as fins made of graphite foil demand much more volume. Therefore the costs for steel fins are significantly higher, also due to the higher density. The application of fins made of expanded graphite offers several advantages besides good thermal conductivity. Expanded graphite shows good chemical stability in nitrates and nitrites at temperatures up to 250 °C and galvanic corrosion does not occur in contact with steel tubes. Since graphite foils, often used as sealing material, show a high flexibility, a close contact between tubes and fins can easily be realized. Aluminium fins are applicable for temperatures up to 330 °C. The mounting of the fins on the tubes is an essential issue for the sandwich concept. Galvanic corrosion of aluminium with carbon steel and sodium nitrate has been analysed, showing no critical corrosion. A good mechanical contact between fins and tubes is important (Laing *et al.* 2009).

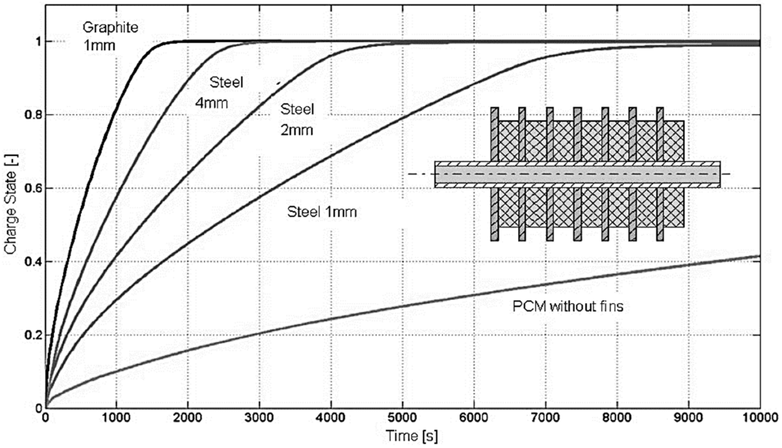
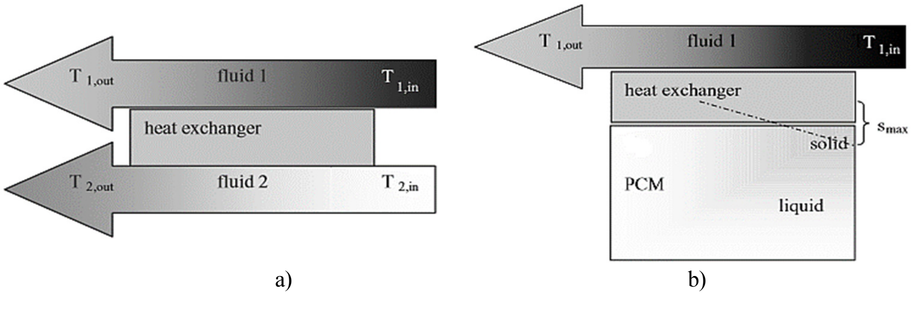


Fig. 6. Comparison of charge state for PCM without fins, with steel fins of different thickness and with graphite fins (Laing *et al.* 2009)

Development of the heat exchangers/accumulators

Heat transfer in a heat exchanger usually involves convection in each fluid and conduction through the wall separating the two fluids. In the analysis of heat exchangers, it is convenient to work with an overall heat transfer coefficient U that accounts for the contribution of all these effects on heat transfer. The rate of heat transfer between the two fluids at a location in a heat exchanger depends on the magnitude of the temperature difference at that location, which varies along the heat exchanger (Cengel, Ghajar 2015).

If one of the fluids is replaced by a PCM, as shown in Figure 7, the heat exchanger becomes heat exchanger type heat storage. As a first approach it is useful to assume a constant temperature equal to the phase change temperature along the heat exchanger and constant with time (Mehling, Cabeza 2008).



a) b)

Fig. 7. Heat exchanger transferring heat from fluid 2 to fluid 1 (a) and approximation of a heat storage by a heat exchanger (b). s_{max} – maximum distance of the phase front to the heat exchanger (Cengel, Ghajar 2015, Thermal Energy Storage 2007)

The PCM based thermal energy storages have complex heat transfer aspects and have difficulty in tracking and predicting the solid-liquid interface during the phase change process making it a really challenging problem. These complexities and challenges can be summarized as (Bashar 2016): 1) Nonlinearity in the phase transition resulting from the unpredictable motion of the solid-liquid interface during phase change; 2) Inadequate knowledge of the heat transfers within the liquid domain and across the solid-liquid interface; 3) Unpredictable volume changes and structural behavior within the PCM upon phase transition especially during solidification, such as formation of void/cavities, super cooling (subcooling), nucleation, etc. that may arise in the solid phase and can significantly reduce the heat transfer rate both during melting and solidification cycles.

One of the ongoing projects where PCM based heat exchange/accumulation systems will be developed and integrated to overall energy recovery system is Sustainable Production of Industrial Recovered Energy using energy dissipative and storage technologies (SusPIRE).

Main objective of the SusPIRE project is to achieve a 20% saving of the global energy consumption in an industrial manufacturing company specifically representative of the iron & steel process, but generally of different processes and segment markets by an effective integrated energy recovery system (Equipment's & methodology) (Fig. 8) with a pay back of less than 3 years.

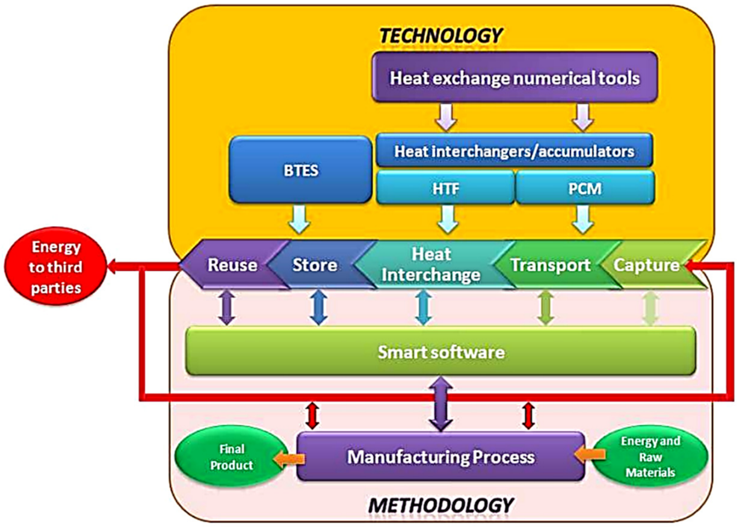


Fig. 8. SusPIRE project concept

Overview of SusPIRE approach:

- Energy recovery of industrial heat streams that run parallel to manufacturing process;
- Specific software to control key variables and key indicators to achieve the best results in energy efficiency without disturbing the manufacturing process or product quality;
- Heat exchangers and accumulators aided by heat exchange numerical tools;
- Increasing the actual existing energy recovery rates by using phase change material (PCM) and heat transfer fluids (HTF).

Results and discussion

Based on the SusPIRE project requirements for heat recovery/accumulation system, different materials and geometries of the PCM based thermal energy storage were analysed. Some of the results from the designing and simulation stage of low temperature heat recovery/accumulation system of SusPIRE project are presented in this chapter.

The main technological challenge is to design heat exchanger/accumulator which will be able to store in a brief period of time a high quantity of heat. Measurement data of low temperatures residual heat stream from one of the technological processes is shown in Figure 9. The graph shows that the PCM charging (melting) cycle must be no longer than 540 seconds.

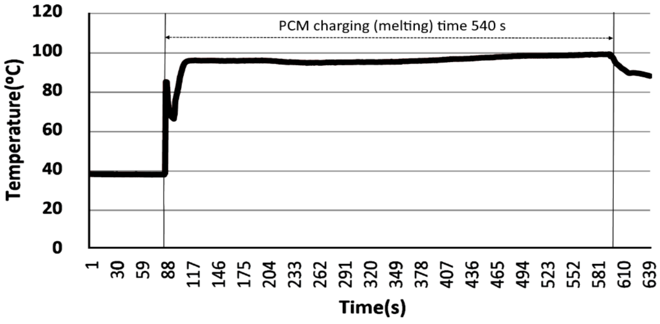
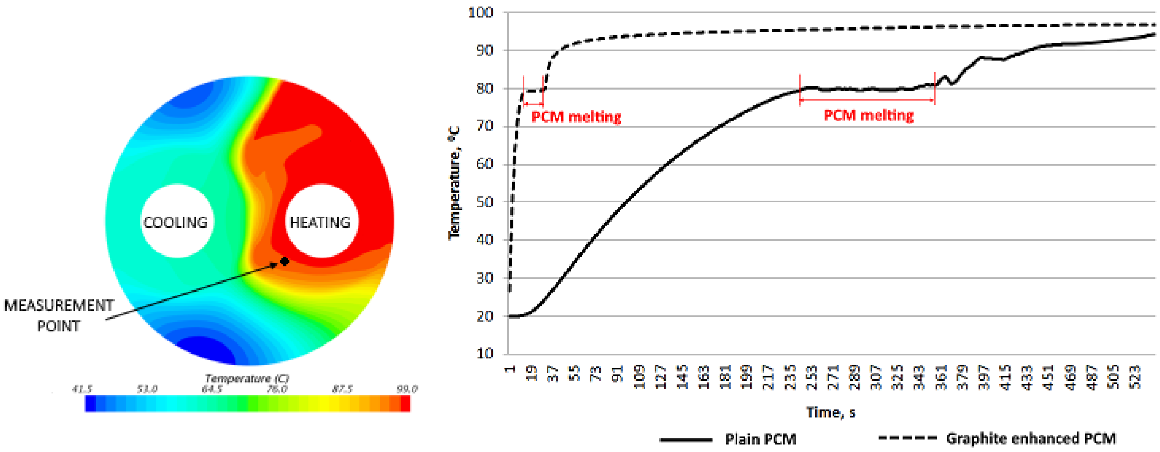


Fig. 9. One cycle of residual heat stream (*Source*: SusPIRE project)

In order to achieve high heat transfer rate of heat exchanger and short PCM charging/discharging time external arrangement (TES consists of a storage vessel that contains the storage medium and an internal heat exchanger) of PCM was selected for further development. The design of heat exchanger/accumulator is based on shell-and-tube type heat exchanger. Due to the low thermal conductivity of PCM, heat transfer area is increased by integrating fins from highly conductive material (copper) perpendicularly to the axis of the heat transfer tubes. Moreover, thermal conductivity is increased by mixing the PCM with graphite. Paraffin based PCM with melting temperature of around 77–82 °C was used. Thermophysical properties such as density, thermal conductivity, specific heat of the PCM are changing depending on solid and liquid phases. The results of the simulation (PCM melting process) are presented in Figure 10.



a) b)

Fig. 10. Temperature distribution of PCM after 540 seconds (Source: SusPIRE project)

Figure 10 a shows temperature distribution in the graphite enhanced PCM after 540 seconds of heating in the specific part of heat exchanger – heating and cooling pipes with heat transfer fluid surrounded by PCM. In this case "hot" fluid is steam and the "cold" fluid is water. The charging (heating) of PCM was performed at constant mass flow rate of steam and average temperature of 99 °C was applied to the heating pipe (as shown in Fig. 9). There is no cooling process (no water flow) in the cooling pipe and PCM temperature in the beginning of the heating process is 20 °C.

Figure 10b shows temperature distribution of plain and graphite enhanced PCM in the specific point (measurement point). The graph shows that from the beginning of the heating process until 240 sec. temperature of plain PCM increases. In this case we have sensible heat storage and the amount of heat stored depends on the specific heat of PCM in solid phase, temperature difference and mass of material. After 240 sec. the temperature of PCM remains constant until 350 sec. It means that PCM is changing phase from solid to liquid and latent heat is stored. In this case amount of heat stored depends on the melting enthalpy and on the amount of storage material. There is no change in temperature. When PCM is completely melted, temperature begins to rise (350–540 sec.) close to the temperature of the heat source (99 °C). Again the sensible heat is stored, but in this case the amount of heat stored depends on the specific heat of PCM in liquid phase. The same charging process can be seen in the case of graphite enhanced PCM (dotted line), but due to much higher thermal conductivity significantly less time is required for heating and melting of the PCM.

Conclusions

The analysis of possibilities to use phase change materials in heat exchanger type thermal energy storages shows that the effectiveness of the PCM based TES highly depends on application and thermophysical parameters of materials. Different requirements such as physical, technical and economic must be carefully evaluated before starting the design and production process.

The low thermal conductivity of most PCMs which causes a long time for the melting and solidification process, especially when fast dynamic of TES is needed, leads to development of complex geometries of heat exchangers. One of the most common heat transfer enhancing methods is increase of heat transfer area (e.g. integration of fins), but this solution also has its drawbacks as a large number of fins decrease capacity of PCM based thermal energy storage.

The test module has been analysed to determine charging rate of heat exchanger type PCM based thermal energy storage developed in SusPIRE project. Graphite enhanced PCM shows much better results compared to plain PCM.

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Disclosure statement

Authors declare that they have no any competing financial, professional, or personal interests from other parties

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