Environmental Assessment of Latent Heat Storage Technology

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Abstract. The potential for the use of renewable energy sources in heating or cooling systems increases with the possibility to store heat or cold when they are available. Latent heat storage (LHS) technology using phase change materials (PCMs) has significantly higher storage density compared to sensible heat storage. The solid-liquid phase change of PCMs with appropriate phase change temperature is preferred for building applications. In practice, there is often a lack of credible information about properties of LHS materials and their environmental impacts. Most of the common methods for evaluation of environmental impacts are based on Life-Cycle Assessment (LCA) principles. LCA is developed for several decades already. It can be used for evaluation of any product system. In this paper it is used for evaluation of environmental aspects of LHS technology, specifically selected heat storage materials.

1. Introduction

Efficient utilization of energy from renewable sources such as solar radiation (heat) depends on the solving of mismatch between energy generation and demand. Therefore some kind of heat storage must be implemented in the energy systems. Generally, there are three common approaches to heat storage: sensible heat storage (SHS), latent heat storage (LHS) and thermochemical heat storage. LHS technology is characterized by significantly higher heat storage capacity compared to the commonly used sensible heat storage in structural materials and water. Amount of heat stored in SHS materials depends on their thermal capacity in solid or liquid state, weight and temperature difference. Added value of LHS technology is heat storage during the melting of the storage medium, which is accompanied by consumption of large amount of heat in narrow temperature interval. On the other hand heat is released without any significant temperature change during solidification in LHS technology.

Application of LHS materials enables weight reduction of the heat storage system while retaining the same storage capacity compared to SHS materials. Most research activities in last decades were therefore focused on the substitution of heavy-weight (SHS) building structures by lighter ones with integrated LHS materials. Thermal energy storage systems (TES) using LHS materials integrated in building structures are designed in combination with well insulated building envelopes to ensure sufficient thermal inertia, reduction of primary energy and better thermal comfort for occupants and equipment without air-conditioning in summer season [1].

Life-Cycle Assessment (LCA) is one of the well-known methods for evaluating of environmental impact of any product or system. As the title suggests, LCA evaluates all phases of product life cycle, i.e. extraction of the raw materials, manufacturing process, transportation, use and maintenance as well as end-of-life. The method is applied for evaluation of environmental impacts of different PCMs and their comparison with common building materials in this paper. The reason for this LCA is lack of...
detailed information in literature. Only a handful of research papers describing application of PCMs for LHS in buildings were released during last decade, [2]. Most of them (e.g. [3]) deal only with specific parts of the PCMs life cycle. Others (e.g. [4]) utilize only general data which reduce accuracy of their assessment. Such inconsistency is unfortunate as environmental benefits such as savings of CO₂ emissions or primary energy could be a differentiating factor for spreading of (currently rather expensive) LHS systems in buildings. Therefore this paper presents detailed evaluation of environmental impacts related with partition walls utilizing LHS and their comparison with a common masonry-based partition.

2. Materials and Methods

2.1. Basics of PCMs and LHS systems

LHS utilizes solid-liquid, solid-gas, solid-solid, and liquid-gas transformation depending on the change of state [5]. Solid-liquid transformation is recommended and widely applied in building applications. LHS represents efficient method of thermal energy storage with higher heat storage capacity (compared to SHS) in narrow temperature interval. Materials for LHS technology in required temperature range are referred as Phase Change Materials (PCMs). PCMs are divided into three main groups according to their chemical substantiality [6]:

- organics:
  - paraffins (alkanes mixtures), high density polyethylene, palmitic acid, capric acid, fatty acid;
- inorganics:
  - salt hydrates, metallics;
- eutectic mixtures:
  - organic – organic, inorganic – inorganic, inorganic – organic.

From the installation potential point of view the selection of particular PCM depends on the desired temperature melting range, heat of fusion and possibility to be encapsulated without any undesirable interactions between the PCM and material of the container. There is a number of commercially available PCMs that are applied in common installations. The reason is that their properties are well-known, which simplifies calculation of heat storage capacity of the whole system and prediction of its performance.

Compatibility between PCM and the material of the container is a crucial parameter for the design of LHS system. This is one of the reasons that initialized the research presented in this paper. Our research team has experience with testing and evaluation of compatibility of selected organic and inorganic based PCMs and various plastics and metals.

2.2. Evaluated heat storage structures

Three heat storage partitions applicable (for example) in office buildings are evaluated in this paper. S1 represents typical non-bearing partition made of solid bricks and mortar with plaster on both surfaces. Such 0.15m thick partition could be advantageously used as a SHS structure. It serves as a reference base for the comparison with two light-weight partitions integrating PCMs in this paper.

Light-weight partitions S2 and S3 are the opposite of S1 in this paper. They both share the same basic composition: plasterboard panels on metal frame with mineral wool (acoustic insulation) infill. Interior-facing side (oriented to the heated or cooled space) of these partitions incorporates encapsulated PCMs as a substitution of heavy-weight structure with similar heat storage capacity. Partition S2 incorporates inorganic PCMs – Rubitherm SP21EK which is encapsulated in polypropylene containers. Partition S3 incorporates commercially available combination of organic Rubitherm RT21 encapsulated in aluminium containers. All three partitions have similar acoustic and heat storage parameters. Thickness of LHS layer in S2 and S3 was calculated so that the partitions it is equivalent to sensible heat storage capacity of the S1 partition. Estimated range of heat storage process was 15 °C
(from 13 °C up to 28 °C). This interval corresponds with theoretical heat storage capacity of selected PCMs. Heat storage capacity of selected structures within above mentioned interval is approx. 4.5 MJ·m⁻².

Table 1. Characteristics of the selected PCMs [7], [8]

| PCMs    | Heat storage capacity [kJ/kg] | Melting area [°C] | Density solid [kg·m⁻³] | Density liquid [kg·m⁻³] |
|---------|-------------------------------|-------------------|------------------------|------------------------|
| RT21    | 155                           | 18-23             | 880                    | 770                    |
| SP21EK  | 170                           | 22-23             | 1500                   | 1400                   |

Proposed pairing of PCMs with particular containers is based on the results of previous experiments [9] focused on the compatibility of inorganic and organic PCMs and selected plastic and metal samples representing potential containers. One of the experiments focused on evaluation of permanent weight increase of the plastic samples caused by penetration of the PCMs into the matrix of the plastics in time. Plastic samples immersed in organic PCMs have shown higher gradual weight increase than samples immersed in inorganic PCMs in this experiment. Another experiment evaluated corrosion rates of metal samples immersed in PCMs. The highest corrosion rate was observed on metal samples immersed in inorganic PCMs containing hydrated salts. Significant visual changes were observed especially on copper and aluminium samples. Two combinations of PCM and container material are selected for the study presented in this paper based on these results. First is inorganic PCM Rubitherm SP21EK encapsulated in Polypropylene containers. Second is organic PCM Rubitherm RT21 encapsulated in aluminium containers.
2.3. Life Cycle Assessment (LCA)

Environmental impacts of the partitions are calculated using LCA method as specified in ISO 14040 [10] and EN 15978 [11] standards. Presented LCA follows the life cycle of the partitions from raw material processing to final waste disposal. This corresponds with standardized template provided in EN 15978. This standard divides life cycle into four stages (Product stage, Construction process stage, Use stage and End of life stage) and 16 modules. Product stage (modules A1 Raw material supply to A3 Manufacturing) and Construction process stage (modules A4 Transport and A5 Construction-installation process) are included in this LCA as a whole. Use stage is represented only by module B4 (Replacement). Environmental impacts in other modules in this stage are considered negligible (e.g. module B1 Use), irrelevant (e.g. module B7 Operational water) or overlapping with module B4 (e.g. module B3 Repair) for the purpose of this assessment. All modules representing End-of-life stage (C1 Deconstruction-Demolition to C4 Disposal) are also included. However environmental impacts in module C3 (Waste processing) are merged into module C4 due to limitations in input data.

Functional unit in the presented assessment is 1m² of the evaluated partitions (with almost identical heat storage capacity) during hypothetical 50-year service life. This service life reflects common design practise in Czechia. The assessment presumes that only the bricks and mortar in S1 would be able to retain its function during whole 50 years. One replacement of plasters in S1 and complete replacement of partitions S2 and S3 is modelled in B4 to limit effects of hypothetical wear and tear.

The assessment is performed in GaBi software. Two impact categories predefined in the software are selected to represent the environmental impacts: Global Warming Potential (GWP; calculated with CML characterization factors) and Primary Energy (PE) consumption. The selection is based on reviewed literature.

Most data on environmental impacts of individual materials and processes considered during the assessment are based on ecoinvent database incorporated in GaBi software. Only exception is data on PCMs, which are based on literature [12]. It should be noted that the ecoinvent database does not include datasets corresponding with all materials considered in the assessment. Therefore some simplifications are necessary (especially in modules A1 to A3 of the LCA). For example the steel profiles supporting the plasterboard in partitions S2 and S3 are modelled with available datasets RER: steel, low-alloyed, at plant, RER: sheet rolling, steel and RER: zinc coating, pieces. Another example of the simplifications is transport. The hypothetical building site is placed in the centre of Brno. Real transport distances to material producers and other facilities are utilized in the LCA. Subsequently, environmental impacts of all transport are calculated using ecoinvent dataset RER: transport, lorry >16t, fleet average. Lastly, it should be noted that module C4 considers landfilling as only way of waste disposal in this LCA. It is considered a worst-case scenario, as it has higher environmental impacts than recycling or reuse of waste.

3. Results and Discussion

Charts in Figure 4 show overall results of the assessment in both impact categories. Total environmental impacts are divided into individual life cycle modules (as defined in EN 15978) in the charts. Moreover environmental impacts in module B4 are further divided to highlight the fact that the modules consists of multiple parts corresponding with other life cycle modules. Generally, both charts show that most demanding parts of the life cycle of all partitions is manufacturing of construction materials. Modules A1-A3 and corresponding part of module B4 have between 91% (in S2) and 94% (in S3) share on total environmental impacts in GWP. The shares are more varied in PE: between 76% (in S1) and 97% (in S3). In contrast, module C1 (and corresponding part of module B4) that describes demolition works have less than 2% share on total environmental impacts in both GWP and PE.

Figure 4 indicates that the importance of material production is a key factor especially, when durability (represented by the length of the service life) is considered. Partition S2 incorporating inorganic PCM has the lowest “initial” environmental impacts in modules A1-A5 in both evaluated impact categories. The “initial” difference between S2 and brick-based S1 is 48% in GWP and 12% in PE. On the other hand, the “initial” difference between S3 with organic PCM and S1 is negligible in
GWP. S3 even has the highest environmental impacts in PE. However the initial advantage of PCM-incorporating S2 is significantly reduced or completely turned later due to modelled replacement of materials in module B4: Replacement of plaster finishes in S1 is related with significantly lower environmental impacts than replacement of whole partitions in S2 and S3. S2 still retains the lowest environmental impacts overall in GWP, but the difference between S1 and S2 is only 13%. The order is reversed in PE, where S1 has 29% lower overall environmental impacts than S2. S3 fares much worse in the overall comparison. Its overall environmental impacts are 38% or 71% higher compared to S3 in GWP or PE respectively.

Figure 4. Total environmental impacts of the evaluated partitions divided according to EN 15978 framework.

Figure 5 shows different view of the environmental performance of the evaluated partitions. It divides the overall environmental impacts among individual construction materials. This helps with understanding of the differences between the partitions. First of all it shows that S3 is the worst in the comparison due to high environmental impacts of the organic PCM and its aluminium casing. Overall environmental impacts connected with these materials in GWP are 7% higher than environmental impacts of whole S1. Their combined performance is even worse in PE, where they have almost 3.5 times or 2.5 times higher environmental impacts than whole S1 or S2 respectively. In contrast the environmental impacts of inorganic PCM and its polypropylene containers in S2 are lower than environmental impacts of the rest of the light partition in both impact categories. The difference between the environmental impacts of both PCMs is 71% in GWP and 90% in PE in favour of inorganic PCM in S2. Also the polypropylene containers in S2 have noticeably lower environmental impacts than their aluminium counterparts in S3: the difference is 63% in GWP and 21% in PE. This makes (from environmental perspective) the evaluated inorganic PCM and its plastic containers much better option for application of LHS in the interior partition walls. It has a potential for replacing the traditional construction materials if installed on more durable supporting structure.
4. Conclusion

Several conclusions regarding the environmental efficiency of evaluated partitions could be drawn from the results presented in previous section. The results show that utilization of PCMs for LHS could be more environmentally sound than SHS in traditional construction techniques. This is true especially for inorganic PCM, whose embodied environmental impacts are significantly lower than environmental impacts of ceramic bricks with the same heat storage capacity. However this advantage heavily depends on frequency of replacements of the PCM and its supporting structure. Figure 4 shows that brick-based partition S1 has the lowest total environmental impacts in PE due to the fact that it requires less material replacements during the modelled 50-year life cycle. It should be noted that PCMs have a key role in this result as they have up to 82% share on total environmental impacts of S2 and S3 partitions. This somehow contradicts literature [2], which says that application of paraffin PCM increased environmental impacts of the test “cubicles” only by 18%.

Another important result of the presented research is that organic PCM has the highest environmental impacts of all evaluated materials. Its environmental impacts are several times higher than environmental impacts of inorganic PCM. Also the environmental impacts of aluminium container are (unsurprisingly) higher compared to the polypropylene container. This makes S3 the least desirable partition in the comparison. Moreover the fact that organic PCM has major share on the environmental impacts of S3 means that changes of the partition itself would not bring any notable improvement.

Above mentioned issues indicate several future research prospects in the field. Firstly, research should focus on improving of the durability or reusability of the PCM and its container that would reduce its embodied environmental impacts. Second research goal should be optimization of the supporting structure. The structure should be durable (to reduce its embodied operational impacts), but it also has to comply with thermal, acoustic, fire safety and other requirements. Lastly the research could focus on finding more efficient composition of organic PCMs, for example through utilization of organic wastes or other renewable material sources.
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