Thermal energy storage system applicable to vehicles

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Abstract. The paper presents the state of the art for thermal energy accumulators using the latent heat phase change usable in cars with either internal combustion engine or electric. The new materials with high storage capacity are presented and the most important achievements in this field of thermal energy storage on vehicles. The case study presented in the paper brings some information necessary for the development of thermal accumulators, with phase change materials, showing the important parameters and characteristics and what values they must have (e.g.: required and accumulated energy; charging and discharging time; latent heat, geometric characteristics). The paper presents a possible classification of these types of batteries, thus facilitating the development of products specific to the applications in which they are included. The work will continue with numerical and experimental studies on models developed based on the case study described here. If at present, in the case of electric cars, a reduction of approx. 20% of electricity was obtained by implementing thermal batteries with phase change material, then studies or research become necessary to accelerate their development on an industrial scale in competitive economic conditions.

1. Introduction
The automotive and the energy production industries are in a period of continuous development and optimization, the main trends being the reduction of carbon emissions with of course, an increase in efficiency and a reduction in operating costs, which dethrones the combustion engines in the favor of electric ones. “Phase change material heat exchanger shows that the objective of extending winter driving range by 20% using a 2.7 [kWh] thermal energy storage system is possible” [5]

Given that the new legislation provides for an energy efficiency target of approx. 40% by 2030, with a revision clause in 2023 compared to 1990 levels, whether we are referring to vehicles with internal combustion engines, those with electric motors (electric batteries or fuel cells) or hybrid ones, a more efficient management of thermal energy is necessary, thus reducing the overall energy consumption for the same mode of operation having as consequence the increase of the comfort and especially for the electric ones increasing the autonomy.

In the case of combustion or hybrid engines, the main sources of thermal energy are the exhaust gases and the coolant, whose heat could be stored and used to reduce fuel consumption, e.g. when starting the cold engine.

In the case of electric motors, batteries are an important source of heat, but an additional energy consumption is needed, from that accumulated in electric batteries to produce heat in the cabin. In this case, the accumulation of thermal energy at the level of the vehicle is further justified. Thermal recharging can be accomplished with grid electricity, plug-in system, once the electric battery charges,
but also by recovering heat from the battery runtime. It is important for electric vehicles with batteries not to use, as much as possible, the energy from electric accumulators to heat the cabin. Because is a constant mismatch between the supply and the demand of the thermal energy, the problem is not the lack of energy, but finding solutions to store and then supply the energy when is needed [1].

To increase the efficiency of heat flow in vehicles the problematic element to be considered is the thermal energy accumulator, with a supporting role between periods of energy supply and energy demand.

Several methods of thermal energy storage are currently known using: sensible heat, latent heat and reversible chemical reactions (metal hydrides react very fast at low temperatures), but the efficiency and the field of use depends primarily on the materials used to store the energy and also to isolate that energy from the environment.

A version that the scientific community appreciates through the continuous development of new, increasingly high-performance materials with low temperature phase change, would be the method using the latent heat, to store thermal energy.

Phase change materials can absorb or release great amounts of latent heat, at nearly constant temperature, during the phase transitions.

There are three categories of phase change materials, depending on the phase change: liquid-gas (because of the large volume required in the storage system, these are impractical for vehicles where we need a compact ), liquid-solid (alkanes, are the most used materials in latent heat storage, because of their high energy storage capacity and limited volume variation) and solid-solid (polyalcohols, less volume variations, no leakages problems, are renewable, non-toxic, non-flammable and compatible with a lot of materials, but are expensive and the lowest latent heat of the three categories). [2]

2. Materials and systems used for thermal energy storage in vehicles

The three main characteristics required for thermal energy storage systems, regardless of the type of engine, are: Low volume and mass, High storage capacity and Short loading / unloading times. Currently developed systems use sensitive heat [3] or latent heat [2] but also combinations between them [3].

In order to optimize these systems, it is necessary first of all to develop materials with the required characteristics. Mainly it is chosen to make composite materials thus obtaining materials with different properties (e.g. increasing the thermal conductivity of the material to reduce loading and unloading times is reduced from the storage capacity for the same volume).

An example of material usable in the automotive industry is studied at German Aerospace Center at the Institute of Vehicle Concepts, which develops Metallic Phase Change Materials (m_phase change material). With the use of m_phase change material, both the sensible and latent thermal energy is used to enable high energy densities [3].

In [2] is presented another type of material called shape-stabilized phase change material (ss_phase change material) using polyalcohols (Neopentyl Glycol) with solid-solid phase transition as active supporting matrix for n-alkanes (Docosane). It is well-established that the use of ssphase change material avoids leakage and increases stability and easy handling of solid-liquid phase change materials. The resulting composite exhibits a loss of heat storage capacity due to the volume occupied by the supporting material, which does not contribute to latent heat storage. [2]

Most studies in the literature focus on improving the materials and determining parameters like latent heat, or comparisons between two or more substances and less on complete systems (battery and control system) using the known materials, not only for storing but also for capturing as well as for insulating and releasing the heat when needed as efficiently as possible.

Oak Ridge National Laboratory and Mahle Behr Troy Inc. presents in [5] a concept of electrical phase change material Assisted Thermal Heating System, figure 1.
For the liquid-solid phase change material, several composites were made having the thermic properties noted in figure 2, (most of the conventional phase change materials used in basic applications have the latent heat a little over 200 [J/g]).

Other variants of plug-in charging systems of thermal accumulators during stationary, with the control system, are also presented in [3], figure 3 and in [6] respectively.

As shown in Figure 4, the energy required to maintain a comfortable temperature in the cabin of a small passenger car is about 3 [kWh] for a duration of 50 minutes (average duration of a city trip), for an outside temperature of -10 [℃].
This paper presents constructive solutions for the design of thermal energy storage systems for vehicles, using phase-change materials of the solid-liquid type, with a latent heat of approx. 340 [J/g] and a melting temperature of 68 [°C], which meet the following requirements:
- can be thermally charged from the grid, during parking, and by the heat recovered either from the combustion engine or from the batteries of the electric motors.
- must be able to supply at least 2.7 [kWh] mentioned above.
- stationary phase change material, without being included in the system additional pump and tank for the phase change material.
- compact construction, i.e.: the battery and the heat exchanger to be a common body.
- modular so they can be connected several modules mounted in different areas of the car body.
- possibility to install the system only in winter.

3. Theoretical approach
It is chosen in this case study as phase change material: DPT68 from figure 2, considering a density, in liquid state, of 780 [kg/m³].

For charging as well for discharging the thermal battery, from the well-known equation of the thermal balance, in which we impose a necessary thermal flow in the present application, of 6.5 [kW]:

\[ Q_{\text{coolant}} = Q_{\text{DPT68}} \]

where:
\( Q_{\text{coolant}} \) - the thermal flow of the thermal agent.
\( Q_{\text{DPT68}} \) - the thermal flow of the phase change material.

The mass flow of the required thermal agent results:
\[ \dot{m}_{\text{coolant}} = \frac{Q_{\text{coolant}}}{c_{\text{p}, \text{coolant}} \cdot \Delta t_{\text{coolant}}} = 0.03 \ldots 0.15 \text{ [kg/s]} \] (2)

\( c_{\text{p}, \text{coolant}} \) – specific heat of water (4180 J/kg·K).
\( \Delta t_{\text{coolant}} \) - the temperature difference between the inlet and the outlet of the thermal agent (10 to 50 [K]).

From the expression of the thermal flux in phase change material, results the necessary mass, for the material in which the energy is stored:
\[ m_{\text{DPT68}} = \frac{Q_{\text{DPT68}}}{c_{\text{p}, \text{DPT68}} \cdot \Delta t_{\text{DPT68}} + L_{\text{DPT68}}} = 17 \ldots 20 \text{ [kg]} \] (3)

\( c_{\text{p}, \text{DPT68}} \) – specific heat of phase change material in solid state (2130 [J/kg·K]).
\( \Delta t_{\text{DPT68}} \) – temperature difference between melting point and solid-state temperatures (10…50 [K]).

The area required for heat exchange:
\[ S = \frac{Q_{\text{coolant}}}{k \cdot \Delta t_{\text{log}}} \approx 3 \text{ [m²]} \] (4)
where: \( k = 84.5 \, [\text{W/m}^2\cdot\text{K}] \), global heat transfer coefficient.

and

\[
\Delta t_{\log} = \frac{\Delta t_{\text{max}} - \Delta t_{\text{min}}}{\ln \frac{\Delta t_{\text{max}}}{\Delta t_{\text{min}}}} = 25 \, [\text{K}]
\]  

(5)

The amount of heat stored in the battery by heating the phase change material from 5 to 80 \(^\circ\text{C}\), is calculated with the relation:

\[
Q = m_{DPT68} \cdot \left( c_{P,DPT68,\text{solid}} \cdot \Delta t_{DPT68,\text{solid}} + L_{DPT68} + c_{P,DPT68,\text{liquid}} \cdot \Delta t_{DPT68,\text{liquid}} \right)
\]  

(6)

For this case study, presented in the paper, a mass of 20 \([\text{kg}]\) of phase change material, having a melting point of 68 \(^\circ\text{C}\) and a total temperature difference from 5 to 80 \(^\circ\text{C}\) are considered. The total stored energy would be: 10177 \([\text{kJ}]\) or 2.82 \([\text{kWh}]\), enough to a typical trip. The duration in which the battery can give up this heat being 1560 \([\text{sec.}]\).

Although the additional mass of the heat accumulator must be counted into the engine consumption. For internal combustion engines, the additional energy consumption for the transport of the thermal batteries can be determined according to figure 5.

![Figure 5. Increased fuel consumption depending on mass addition [6]](image)

4. Thermal energy storage system concepts

Depending on the thermal agent with which the heat transfer takes place, the heat accumulators can be made with the heat exchange between phase change material and:

- Gas; example: exhaust gases for charging the battery; fresh air introduced into the cabin for heating)

- Liquids; example: the coolant from the internal combustion engine or from the batteries, for charging the accumulators; liquid conveyed in another water-air heat exchanger with which the interior or the engine or the electrical batteries of the vehicle are heated.

- Mixed; example: The engine coolant charges the heat accumulator with energy and an airflow takes the heat, when is needed, and introduces it into the cab of the vehicle or for preheating the engine or electrical batteries.

The modes in which the thermal batteries are charged can be classified into several categories:

- Plug-in, charging is done with electricity from the network during parking, through electrical resistors embedded in the battery.

- Onboard, the energy transformed into heat by motors or electrical batteries is taken up by a fluid and transferred to the phase change material.
- Mixed.
  The stored energy can be used for:
  - Preheating the engines with internal combustion, in cold season.
  - Heating the passenger compartment of the car. - Maintaining an optimal temperature for electrical batteries.
  - Electricity production.

  The thermal flux must be managed with the help of a control system based on the signals from the temperature sensors inside the passenger compartment, the outside air, the thermal accumulator phase change materials, the flowrates and temperatures of the primary thermal agent, etc. But for optimal control, charging and discharging the thermal batteries should be based on information on distance and duration of the trip, obtained from the car's navigation system or even based on the weather forecast and how often the car is used.

  An important role in the efficiency of the thermal batteries is of course also played by its thermal insulation. Good results were obtained in [5], with vacuum panels, approx. 10% loss at every 8 hours.

  Figure 6 shows a constructive variant, to be realized as an experimental model in a future study, of a thermal accumulator with a capacity of 2.8 [kWh], using as phase change material the DPT68 and as primary thermal agent a liquid, which circulates through a network of 135 pipes connected to each other (10x10x0.5 [mm], length approx. 550 [mm]), thus obtaining a heat transfer surface of approx. 3 [m²]. Of course, the material, the shape and the dimensions used have a great importance in the overall efficiency.

![Figure 6. Heat Accumulator for vehicles](image)

5. Conclusions
The development of materials usable as thermal energy storage media further required the realization of design solutions/concepts and management systems for thermal energy accumulators, so that the best results can be put into practice for widespread use.

  The obtained results determine us to perform in the future, for a first phase, numerical simulations to optimize the design of the thermal accumulator and then the realization of an experimental model for carrying studies with different materials (see Figure 2) for both storage and isolation (vacuum insulated panels), implementing also the control system.

  The potential offered by high latent heat phase change materials requires new studies on the production of such energy accumulators. An optimization of the design and in terms of production (the choice of materials and manufacturing technology that declares the lowest costs ex. deformations by stamping, robotic welds) as economical as possible can be of interest in the future.
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