Heat and cold accumulators in vehicles
Lämpö- ja kylmääkut kuljetusvälineissä

Pertti Kauranen, Project Manager
Lisa Wikström
VTT Technical Research Centre of Finland, Advanced Materials
P.O. Box 1300, 33101 Tampere
Tel. +358 20 722 111
Email: forename.surname@vtt.fi

Jorma Heikkinen, Mathematical modelling
VTT Technical Research Centre of Finland, Building Services and Indoor Environment
P.O. Box 1000, 02044 VTT

Juhani Laurikko, Vehicle applications
Tuomo Elonen, Exhaust gas heat recovery and field testing
VTT Technical Research Centre of Finland, Emission Control
P.O. Box 1000, 02044 VTT

Ari Seppälä, Supercooling studies, Research Scientist
Helsinki University of Technology, Applied Thermodynamics
P.O. Box 4400, 02015 TKK
Tel. +358 9 451 3977
Email: ari.seppala@tkk.fi

Abstract
Phase Change Material (PCM) based heat and cold accumulators have been tailored for transport applications including a mail delivery van as well as the cold chains of foodstuff and blood products. The PCMs can store relative large amount of thermal energy in a narrow temperature interval as latent heat of fusion of their melting and crystallization processes. Compact heat and cold accumulators can be designed using PCMs. The aim of the project has been to reduce the exhaust gas and noise emissions and improve the fuel economy of the transport systems and to improve the reliability of the cold chains studied by storing thermal energy in PCM accumulators.

Tiivistelmä


1 Background and objectives
The fuel economy of a VW Caddy 1.9 TDI mail delivery van decreases drastically during the cold winter months with subzero outdoor temperatures. As the average speed during a typical mail delivery driving cycle is low and includes plenty of idling, a modern diesel engine is not properly heating up. A diesel fuelled additional heater (e.g. Webasto) is needed both for the engine preheating during cold start and additional heating during the driving cycle which is increasing the total fuel consumption and exhaust gas emissions. A specific objective of the project has been to replace this additional heater by a heat accumulator. As there is not sufficient waste heat available in the diesel engine, an exhaust gas heat recovery system was designed to charge the heat
accumulator. Moreover, use of the supercooling phenomenon to control heat release from the accumulator and replacement of corrosive PCM salts by sugar alcohols was studied.

Diesel engine driven refrigerators are typically used for temperature controlled transportation of foodstuff. The transportation temperatures are regulated by international and national standards and can be roughly divided to cool (0–+10 °C) and frozen (< -18 °C) transportations. The objective of the project has been to study if PCM cold accumulators could be used to reduce the exhaust gas and noise emissions of food transportation in dense populated areas. The idea was to charge the cold accumulators while driving on highways and to temporarily switch off the refrigerator in city centres. Moreover, the cold accumulator could reduce the size of the refrigerator and reduce the total energy consumption.

Blood products are transported in dry ice or PCM accumulator tempered cold boxes by Red Cross Finland Blood Service. Different products are transported frozen, cool or at room temperature. The most important of these is room temperature which is used for whole blood and trombocytes. Commercial PCMs were evaluated and new materials developed for this application temperature of 22±2 °C.

Numerical mathematical modelling was used in all the applications to design the heat exchangers, verify the prototype performance and study the scale up from laboratory to the real application.

2.1 Mail delivery van

The design temperature for the heat accumulator was 80 °C. Commercial PCMs melting in this range were evaluated. As most of them are corrosive salts, an attempt was made to tailor a sugar alcohol for this temperature.

Most materials tend to solidify at the same temperature where they melt called as the melting point. However, some materials do not crystallize spontaneously and remain in liquid stage far below their melting point. The crystallization of such supercooled liquid can be initiated by adding some nucleation centres to the liquid. The latent heat is then released. The phenomenon could be used for long term heat storage and possibly for the control of the heat accumulator.

A 6 dm³ vacuum insulated open mouth stainless steel dewar flask was selected for the heat accumulator (HA) vessel. Two types of heat exchangers were studied for the accumulator: a brush and a tube heat exchanger, Figure 1. As the tube exchanger showed much faster response, it was selected for the prototype construction. The prototype performance was verified in an automated laboratory test bench.

Three types of gas to liquid heat exchangers were evaluated for the exhaust gas heat recovery (EGHR). The best one was an aluminium lamella type, Figure 2.

2 Project work programme

<table>
<thead>
<tr>
<th>Duration of the project</th>
<th>Funding of the project</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 July 2006–31 March 2009</td>
<td>Total 698,000 €, of which Tekes funding 468,000 €</td>
</tr>
</tbody>
</table>

| Project partners | VTT Technical Research Centre of Finland  
| Helsinki University of Technology |

| Participating companies | Lumikko Oy, VAK Oy, Eurocon Oy, Tuorette Oy, Itella Oy, Easy Km Oy, EHS Group Oy, Danisco Sweeteners Oy, Red Cross Finland Blood Service |

| International co-operation | Commercial PCM suppliers |
Figure 1. a) Schematic of the brush heat exchanger. The coolant is flowing in stainless steel tubes (red) with aluminium wires. b) The tube heat exchanger and the dewar flask.

The HA and the EGHR system were connected into the coolant loop of the mail delivery van without any active control, Figure 3. The accumulator was placed in the engine room and the heat recovery system under the floor of the van, Figure 4.

The van was tested in the VTT vehicle laboratory dynamometer using a simulated drive cycle and in real mail delivery operation in the city of Oulu (65 °N) in February 2009, Figure 5.

Figure 2. The aluminium lamella gas to liquid heat exchanger used for exhaust gas heat recover (EGHR).
**Figure 3.** The engine heating with heat accumulator (HA) and exhaust gas heat recovery (EGHR).

**Figure 4.** a) The heat accumulator in the engine room and b) the EGHR under the mail delivery van.

**Figure 5.** The mail delivery van a) on the VTT dynamometer and b) during field testing.
2.2 Temperature controlled transportation of foodstuff

Cool transportation of foodstuff at zero to +6 °C typical for ready made food was selected as the primary application. The first assumption was to cover the ceiling of the temperature controlled cargo space of a delivery lorry with a thin sheet of PCM. The PCM would be charged during driving on highways and temporarily switched off in city centres. The performance of a full size lorry was analyzed using the VTT House numerical simulation model.

A commercial latent heat paraffin with a melting point at +4 °C was selected as the PCM. A prototype cold accumulator plate was constructed out of a 2 m² aluminium honeycomb plate with a thickness of 10 mm into which the paraffin was packed. The prototype accumulator was tested in a 2.5 x 2.0 x 0.9 m³ insulated test cell with a refrigerator by Lumikko Ltd, Figure 6, and the test results were used for the model verification. The PCM was crystallized with the cold air from the refrigerator during the charging period. The refrigerator was stopped after the PCM was fully crystallized but the fan was still blowing in order to increase the convective heat transfer from the air to the PCM module during discharge. The temperatures in the test box and on the PCM module surface were continuously monitored.

Additional, testing and analyses were carried out for frozen goods.

2.3 Transportation of blood products

Commercial and internally developed PCM materials for room temperature transportation were first tested by differential scanning calorimetry (DSC). The most promising ones were packed into 1.0 kg plastic bags and tested in an empty Red Cross Finland Bloodservice cold box, Figure 7. The cold box was placed in a freezer at −26 °C for the PCM to freeze and in a heat chamber at +35 °C for the PCM to solidify. The surface temperature of the PCM accumulator was continuously monitored and the time the temperature remained between 20 and 24 °C was calculated.

Figure 7. The cold box and commercial PCM bags by Red Cross Finland Blood Service.

3 Project results

3.1 Mail delivery van

The eutectic mixtures of xylitol and erythritol and adonitol and d-arabitol were shown to melt at 82 and 81 °C respectively. However, the crystallization speed of these sugar alcohol mixtures is very low and they form an amorphous phase as they cool down. They could not be modified to speed up the crystallization for fast enough latent heat release for practical use.

Sodium acetate trihydrate (SAT) with a melting point of 57 °C was the only PCM which could be supercooled to subzero temperatures and remained in liquid form for prolonged periods of time, even over a year. The latent heat of SAT could be released by addition of solid crystals of the same material.
Trisodium phosphate dodecahydrate melting at 75 °C was selected as the PCM for the heat accumu- lator for it has high latent heat of fusion and high density. 4 kg of the salt was packed into 25 mm stainless steel tubes into the dewar flask, Figure 1 b. In addition to the salt tubes the dewar con- tained 2 dm³ of the coolant (a glycol water mixture). The cumulative energy of 11 charge dis- charge cycles in the laboratory test bench is shown in Figure 8. The stored energy is very close to the theoretical value of 700 Wh or 2.5 MJ.

Figure 8. Cumulative energy of the heat accumulator prototype in the laboratory test bench during 11 charge-discharge cycles. Every second peak is for charge and every second for discharge.

Figure 9. Driving speed and coolant temperature during 30 min dynamometer test drive cycles with the additional heater (AH) and/or exhaust gas heat recovery (EGHR) connected and heat accumulator (HA) charged or discharged.
The effects of the heat accumulator (HA) and the exhaust gas heat recovery (EGHR) on the coolant temperature of the delivery van during the 30 min dynamometer drive cycle at −10 °C are shown in figure 9. The test was performed both with the diesel fuelled additional heater (AH) connected and disconnected and the HA fully charged or discharged and compared with a standard van without HA or EGHR. When the AH was connected and the HA fully charged, the engine was heating up faster to 70 °C than without the HA and EGHR. Even then HA was discharged the EGHR was heating the engine up almost as fast as the standard van without HA and EGHR. The heat capacity of the fully charged HA was able to bring the coolant temperature to about 45 °C in 10 min but the desired 70 °C is only reached when the driving speed has increased to 80 km/h towards the end of the driving cycle.

Figure 10. a) CO, HC, NOx and b) CO₂ emissions during the first 20 min of the dynamometer drive cycle at −10 °C.
The engine exhaust gas emissions during the first 20 min of the dynamometer test cycles with the additional heater connected are compared in Figure 10. The CO and HC emissions are reduced by more than 80% and the NOx emissions by 50% when a fully charged HA and EGHR are used. The CO2 emission which is directly proportional to the fuel consumption is reduced by 13%. The measurements were repeated when the AH was disconnected and, surprisingly, it had no measurable effect on the engine emissions. This could be explained by the assumption that most of the emissions are produced during the first couple of minutes when the coolant (or engine) temperature is below 20 °C. As the fuel consumption and emissions of the additional heater are not included in the measurement, the real benefits would be even more pronounced.

The following temperatures were measured during the two week field test drive in real mail delivery operation: exhaust gas before and after the EGHR, coolant, HA, AH exhaust gas, outdoor and indoor (in the van). After one week driving

**Figure 11.** Mail delivery van temperatures when the additional heater was a) connected and b) disconnected.
the AH was disconnected, to see if the HA and EGHR would be sufficient to keep the engine warm without the AH. Typical results for one working day are presented in figures 11 a and b with the AH connected and disconnected, respectively. The AH was needed only for 20 min in the morning and the EGHR was sufficient to keep the coolant temperature above 70 °C for the rest of the day when the outdoor temperature was −7 °C. When the AH was disconnected, it took 15 min longer to reach the coolant temperature of 70 °C but once more the EGHR was sufficient to maintain the desired coolant temperature for the rest of the day although the outdoor temperature was −10 °C. In a comparative test drive without the HA and EGHR the previous winter, the AH was needed several times throughout the day and was operating for about 1.5 to 2 hours. It should be noted that the average driving speed in the field tests was higher than in the dynamometer and thus the HA and EGHR were working better due to higher exhaust gas temperature.

3.2 Temperature controlled transportation of foodstuff

The measured temperatures in the test cell of figure 6 during the discharge period of the cold accumulator panel are shown in figure 12 along with the simulated temperatures. The agreement is reasonable and it seems that the discharge period is fairly easy to predict with the computational model. A case with an empty test cell without PCM is also included in figure 12 to show that the heat capacity and the heat losses of the test cell have been modelled correctly.

The temperature of the test box was under the required +6 °C for nine hours. It was estimated that 3 hours could be attributed to sensible heat and 6 hours to the latent heat of the PCM.

The performance during the charge period is less satisfactory. To work during the discharge period as well, the PCM in the accumulator must be crystallized completely, as seen in figure 11.

![Figure 12. Measured and simulated temperatures in the test cell during the PCM discharge period.](image)
It turned out that the temperature of the supply air from the refrigerator for loading the PCM module in a reasonable time had to be about −10 °C. This temperature is far too low for the foodstuffs being transported, even if the air temperature in the cargo space is a few degrees higher than the air supply temperature. The crystallization of the test module was also tested with 0 °C air, but the crystallization took more than 8 hours, which is not acceptable. It remains a challenge to find other methods to crystallize the PCM without affecting the foodstuffs.

Based on the test results, the performance of a full-size empty lorry was estimated using the VTT House model. The empty lorry represents a worst case scenario as the precooled foodstuffs being transported increases the thermal capacity of the system. According to the simulations, a 5 mm-thick PCM cold accumulator in the ceiling of the lorry is able to keep the inside temperature within the desired limits for about 5 hours when the outdoor temperature is +30 °C and there is no air leakage to the cargo space. Figure 13 shows that the effect of air leakage through the loading doors can be remarkable.

Effective heat transfer from the cargo space to the PCM panels is essential in keeping the air temperature within the desired limits. It seems that natural convection heat transfer is not enough and a slight enhancement, for example with a fan, is needed to double the convective heat transfer coefficient. Radiation heat transfer is also important, covering about one-half of the heat flow to the panels.

### 3.3 Transportation of blood products

As the performance of commercial PCMs at room temperature of 22±2 °C was not satisfactory, a mixture of fatty acids was optimized for this temperature. The performance of this VTT prototype material as measured in the Red Cross Finland cold box is compared with the best available commercial PCM salt and paraffin in figure 14 and table 1. The VTT prototype PCM bag was shown to be stable at least for 50 cycles.
Table 1. The times the PCM accumulators maintained a surface temperature between 20 and 24 °C in the Red Cross Finland Blood Service cold box.

<table>
<thead>
<tr>
<th>PCM</th>
<th>Crystallization in a freezer at −26 °C</th>
<th>Melting in a heat Chamber at +35 °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Commercial salt</td>
<td>1.7 h</td>
<td>5.1 h</td>
</tr>
<tr>
<td>Commercial paraffin</td>
<td>4.4 h</td>
<td>6.8 h</td>
</tr>
<tr>
<td>VTT prototype</td>
<td>5.5 h</td>
<td>8.5 h</td>
</tr>
</tbody>
</table>

Figure 14. Comparison of the VTT prototype room temperature with commercial references in an empty Red Cross Finland Blood Service cold box. a) Crystallization at −26 °C and b) melting at +35 °C outdoor temperature.
4 Impact of the results

The results show that it is possible to heat up a modern diesel engine faster and maintain its temperature higher in cold climates by a simple exhaust gas heat recovery system recirculating heat from the tail pipe to the engine coolant loop. Addition of a heat accumulator to the system would store the recovered heat over short brakes and even overnight to the next cold start. A heat accumulator has a faster response than a diesel fuelled additional heater during the cold start and can reduce the exhaust gas emissions by 50 to 80%. The need for the diesel fuelled additional heater could be minimized or it could even be replaced by the proposed system.

In addition, the combination of a heat accumulator and exhaust gas heat recovery system has been shown to improve the fuel economy of a mail delivery van engine. The engine fuel savings can be up to 15%. When the emissions and fuel consumption of the additional heater were accounted for the effect would become even more pronounced. The results should be further confirmed by longer fleet testing preferably using commercial components and an optimized system.

A 5 mm thick PCM cold accumulator panel covering the ceiling of a temperature controlled cool transportation lorry could keep the cargo space of an empty lorry at desired temperature for 5 h. However, subzero air would be needed to charge the accumulator which was not feasible in the simple system studied. The PCM panels should be precharged outside the lorry or before loading the temperature sensitive goods or a more complex system where the cold air from the refrigerator is blown in a slot between the PCM panel and the ceiling of the lorry should be designed.

The performance of room temperature PCMs is limited. Improved materials are needed for this temperature where additional applications can be found in space heating and cooling.

5 Publications and reports


6 Bibliography