TESS – Thermal Energy Storage System

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Abstract

The presentation provides an overview of emission reduction/ fuel efficiency technologies from the view of a chemical company.
Main focus is on thermal management of the Powertrain with the example of TESS - Thermal Energy Storage System. With TESS, it is possible to capture otherwise lost thermal energy from the exhaust gas, to store this energy over a period of time, and to release it on demand to various areas of the powertrain in order to enable a shorter warm-up period - therefore enabling lower fuel consumption and/ or faster passenger cabin warm-up.
TESS also has benefits for electric- and plug-in vehicles (EV, PHEV), enabling a longer electric drive range especially in cold conditions.

Key Words: thermal management; latent heat storage; waste heat recovery; cabin heating; EV; PHEV; HEV; cold start mitigation; fuel efficiency; fuel consumption reduction; CO_2 emission reduction

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1 Introduction

The long term imbalance between oil supply and demand requires new concepts for energy utilization and disposition. This imbalance leads to:

- Huge outflow of national wealth & capital
- Trade deficits
- Reliance upon other nations on a strategic material - oil
- Economic consequences of feedstock volatility

In addition, global warming resulting from CO_2 emissions is concerning.

To address both problems, low cost solutions are required to reduce oil consumption and dependency. The automotive industry as one of the big oil and fuel consumers needs to make a contribution towards reducing fuel consumptions and CO_2 emissions.

2 New Energy Management Concepts for Vehicles

2.1 Motivation and Consequences

The necessity for improving fuel efficiency and emissions has already led to new developments of Powertrain systems and –concepts to address these issues. The listed technologies are representative examples of new technologies:

- Hybrid- and plug-in vehicles (HEV, PHEV)
- Electric vehicles (EV)
- Alternative fuels (CNG, LPG, H_2, bio-fuels,..)
- Fuel cells

Objective of the development of Powertrains and necessary modifications are:

- Maximising vehicle range
- Minimising battery demand
- Increased efficiency of internal combustion engines
- Reduced battery packaging space
- Reduction of vehicle mass

In addition, legislation of increasingly stringent CO_2 emissions for individual vehicles and vehicle fleets, especially in Europe, Japan, China and the United States require strenuous technology efforts to increase fuel efficiency and CO_2 emission reduction.

2.2 Advances in Energy Management Technologies

In the area of energy management technologies, considerable progress has already been achieved in certain areas:

- Battery technology (NiMH, lithium-ion batteries)
- Waste heat recovery systems
- Engine pre-heat; cold start mitigation
- Thermo-electric generation (TEG)
- Braking power recuperation
- Vehicle integrated solar technologies (PV)
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- and TESS (Thermal Energy Storage System) – the latent heat storage device of Dow Chemical as an enabler/ enhancement of the approaches above

2.3 Heat Energy – a Missed Opportunity

Starting with the energy content of typical fuels (gasoline, diesel), only ca. 30% are being used for vehicle propulsion and operation of electrical consumers. This means, ca. 70% of the energy content of the originally fuel are being radiated as waste heat into the environment.
Capturing, storage and target-oriented utilisation of waste heat energy, enables to date unexploited applications. Advanced waste heat energy technologies can increase the overall efficiency of a vehicle and reduce fuel consumption/ CO_2 emissions.

In figure 1, waste heat flows are represented – based on the energy content of gasoline (=100%). Via the exhaust system, 40% of the heat energy is emitted to the environment. 30% are emitted via the engine coolant radiator; 5% due to friction losses and radiation. Merely 25% of the energy content of gasoline is effectively used for the propulsion of the vehicle.

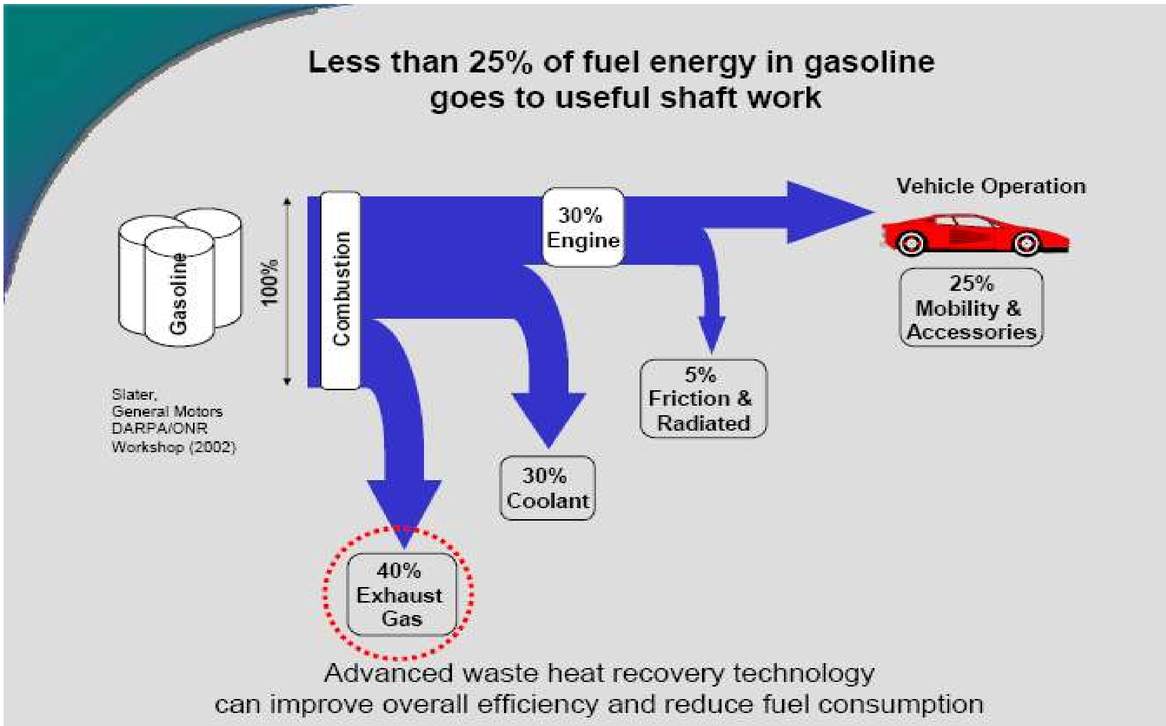

Figure 1: Fuel energy distribution in traditional vehicles [5]

3 Latent Heat Storage

3.1 Function of TESS

The latent heat storage device of Dow Chemical (TESS – Thermal Energy Storage System) enables new applications and has advantages compared to previous heat energy storage systems and distribution due to improved waste heat utilization at vehicles with internal combustion engine. For electric vehicles (EV), cabin heating is enabled without consuming electric energy from the vehicle battery. Especially during the cold seasons, this increases the electric drive range of these vehicles.

TESS Functions:

1. *Capture thermal energy from a heat source, e.g. exhaust gas*
2. *Store a large amount of thermal energy within a small device*
3. *Release of stored thermal energy into a targeted heat recipient*

The schematic structure of the latent heat storage device within the vehicle architecture is described in figure 2. Heat energy is extracted from the exhaust system or generated electrically during the battery charging period, once the battery is plugged into the power grid. The heat energy stored in TESS can be distributed e.g. to the engine coolant circuit, engine- and gear box oil and/ or passenger cabin, depending on the operation strategy.

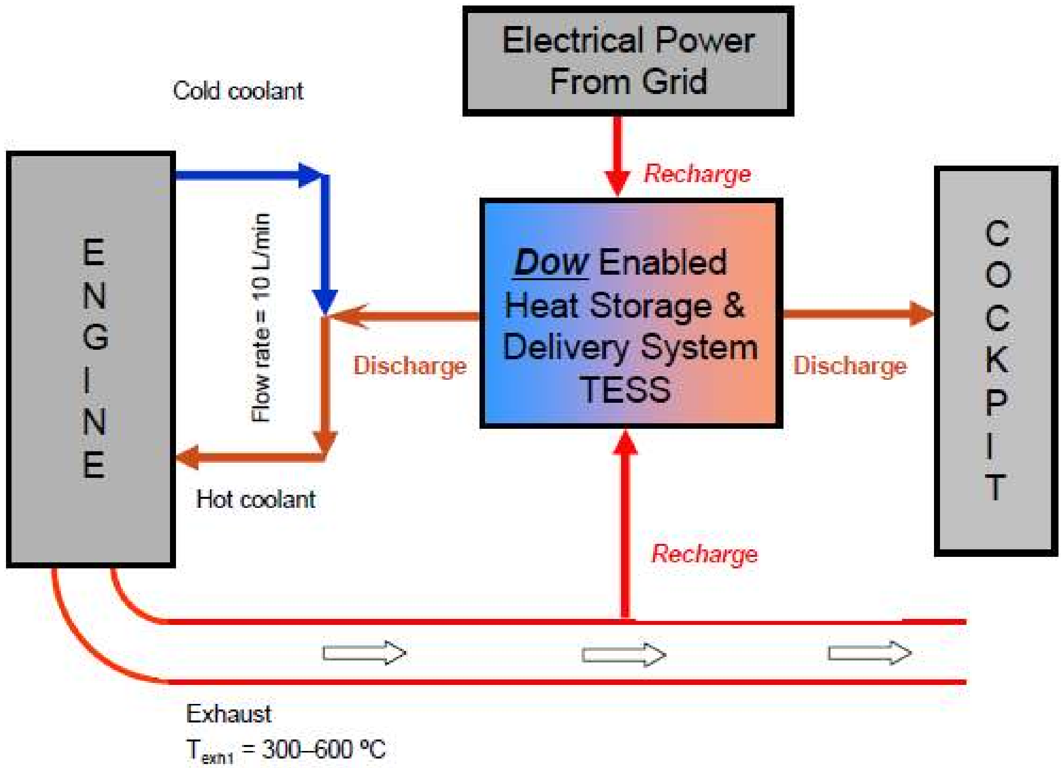

Figure 2: Functional schematic of a TESS in a vehicle

4 The new PCM, Laboratory Trials & Simulation

4.1 Dow Chemical's Approach

Aim of the efforts at Dow Chemical is the development of differentiated products and solutions to reduce fuel consumption and CO_2 emissions. A phase change material has been developed that yields high heat storage density over the relevant temperature range and the appropriate PCM encapsulation technology to enable development of novel PCM-based heat exchangers.

4.2 The PCM Heat Storage Material

The PCM developed by Dow Chemical is a highly efficient rechargeable energy storage material, hermetically sealed in a metal heat exchanger.

In the relevant temperature range between 50ºC and 300ºC, the PCM has a thermal energy density of:

Volumetric	1.3 MJ/l	= 0.36 kWh/l	of liquid PCM
Gravimetric	0.69 MJ/kg	= 0.19 kWh/kg	

During laboratory trials with a prototype heat exchanger using 4 mm thick PCM sheets, an average power density over 30 seconds of 22 kW/l into cold water has been achieved.

PCM density: 2.3 g/cm³ (20ºC, solid) 1.9 g/cm³ (200ºC, liquid)

Therefore, the PCM is capable of storing large amounts of thermal energy, which can provide advantages to a variety of applications:

- Comfort
  - Fast cabin heating
  - Defrosting of windscreen
  - Emission-free vehicle heater

- Mitigation of cold-start emissions
  - Faster engine coolant circuit warm-up
  - Faster engine and gear box oil warm-up
  - Warm-up of the catalyst system
  - Melting/warm-up of AdBlue/urea additive for NO_x SCR

4.3 The PCM in Comparison

In Figure 3, a number of known heat storage materials are shown in comparison to the new PCM developed by Dow Chemical. Erythritol – a sugar alcohol – shows interesting heat storage behaviour, but in the absence of nucleators loses the latent heat storage capability already after a few cycles and is therefore not suitable for vehicle usage. $Ba(OH)_2 \cdot 8H_2O$ is also not suitable due to its aggressive nature against metals. Paraffins show only a minor improvement in heat energy storage capability versus pure engine coolant (blue curve). The new PCM developed by Dow Chemical demonstrates a much higher heat storage capability and is, to our opinion, the optimal material for applications running vehicle drive cycles, e.g. NEDC.

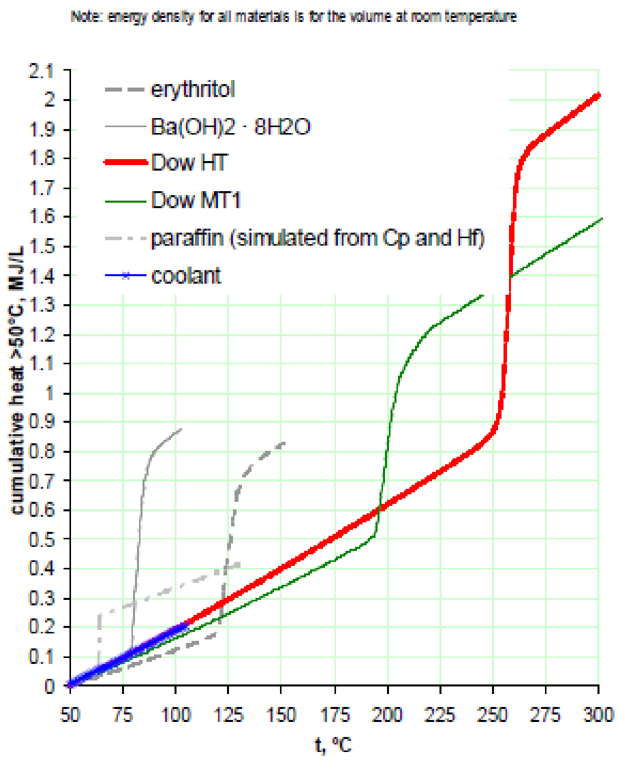

Figure 3: Volumetric energy densities of heat storage materials

The PCM developed by Dow Chemical has a very high volumetric thermal energy density and at the same time a low density. Furthermore, this PCM has demonstrated high thermal stability during a few thousand melt-freeze cycles and is therefore well suited for automotive applications.

The Dow PCM exhibits very little supercooling and thus does not depend on a trigger of crystallization to release its thermal energy. This behaviour allows for a precise and controlled release of the stored thermal energy and is in contrast to a typical pocket-warmer PCM, which requires a crystallization trigger and whose heat release is difficult to control.

4.4 The PCM Sheet Geometry

As already mentioned, the PCM is placed into embossed pockets and welded with a cover sheet. The PCM pocket geometry is designed to bring about the static mixer effect and thus to promote heat exchange. The PCM pocket geometry has been optimised for heat transfer using 3D Computational Fluid Dynamics (CFD) calculations. Figure 4 shows the geometry of a PCM sheet and sheet stack.

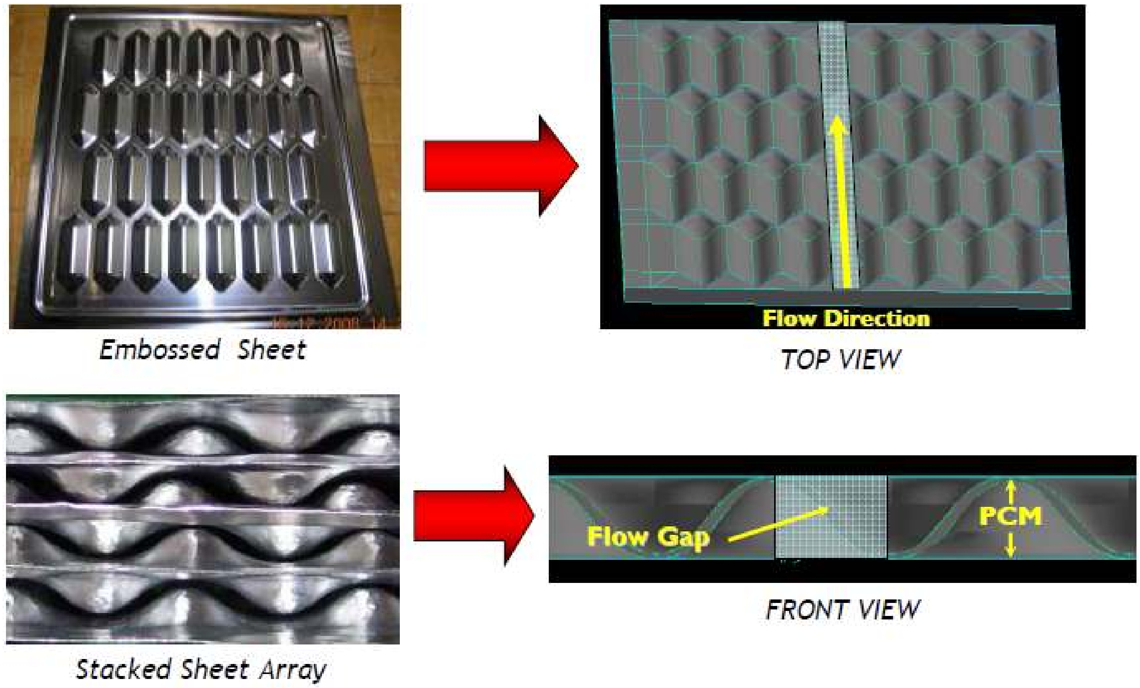

Figure 4: PCM sheet stack geometry

4.5 Laboratory Trials

Figure 5 shows the set-up at the laboratory. The photo on the left shows the open heat exchanger filled with eight PCM sheets. The picture on the right hand side shows the closed heat exchanger with the heat gun which heats up the PCM sheets to the desired temperature. The set-up has been equipped with 6 thermocouples along the flow of the fluid.

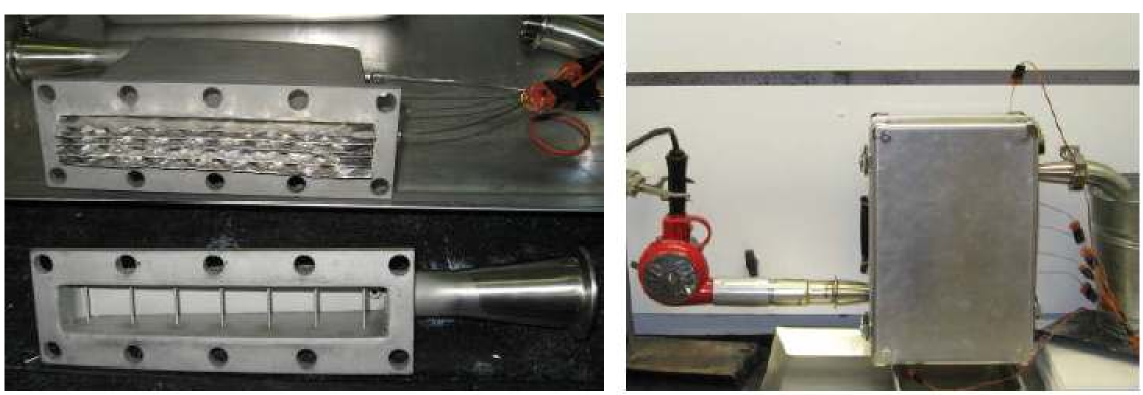

Figure 5: Laboratory set-up

After reaching the desired temperature level inside the heat exchanger, the inlet of the heat exchanger is immediately switched to a cold water line, and cold (7º C) water is passed through the heat exchanger and collected in a bucket. An average temperature increase of the cold water of 33 K has been observed. A 30 second average power density of 22 kW/l has been calculated for the heat exchanger. Related to the PCM sheets, a thermal energy density of 0.58 MJ/kg, respectively 1.1 MJ/l has been measured.

To simulate vehicle cabin heating, the trial has been repeated with the discharge of the stored thermal energy into room-temperature air pumped through the heat exchanger by the same heat gun switched to the "cold" mode. The device demonstrated its effectiveness as an air heater by keeping the outlet temperature of the above pumped air above 60 °C for about 20 min.

5 Applications and Previous Evaluations

5.1 Applications

The stored thermal energy can be utilised for various applications in vehicles. Figure 6 shows applications for vehicles with internal combustion engines and hybrid vehicles.

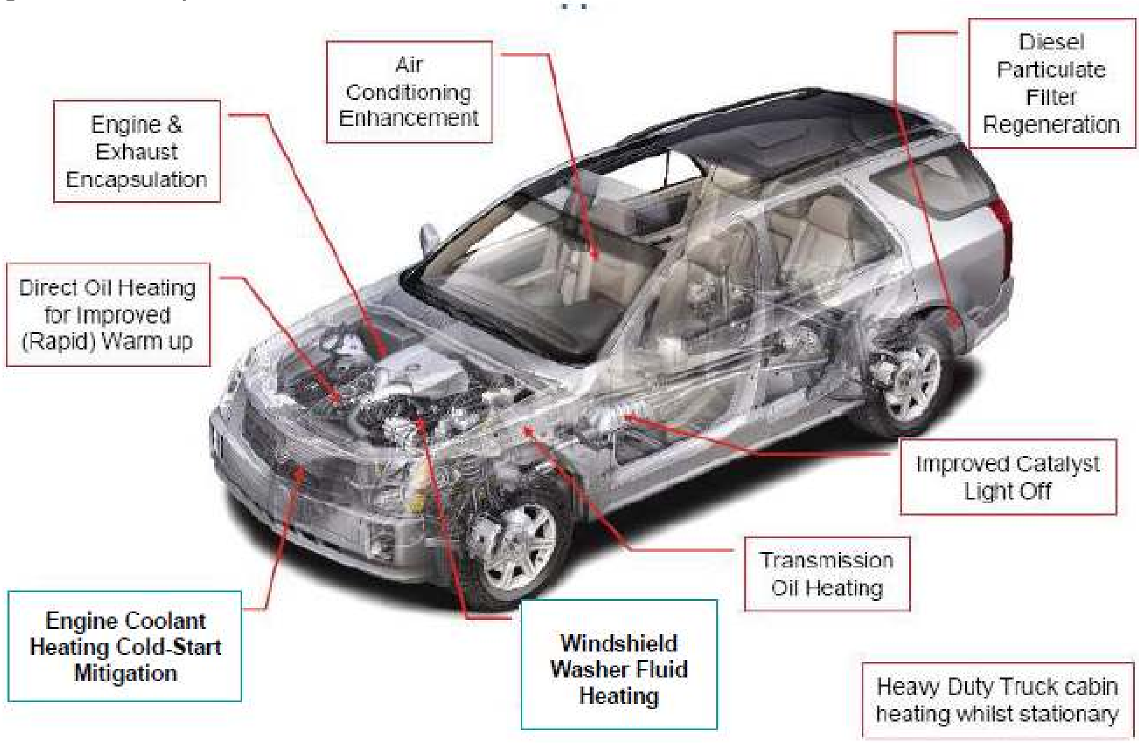

Figure 6: Applications in vehicles with internal combustion engines

Figure 7 shows applications for electric vehicles (EV) and plug-in hybrids (PHEV).

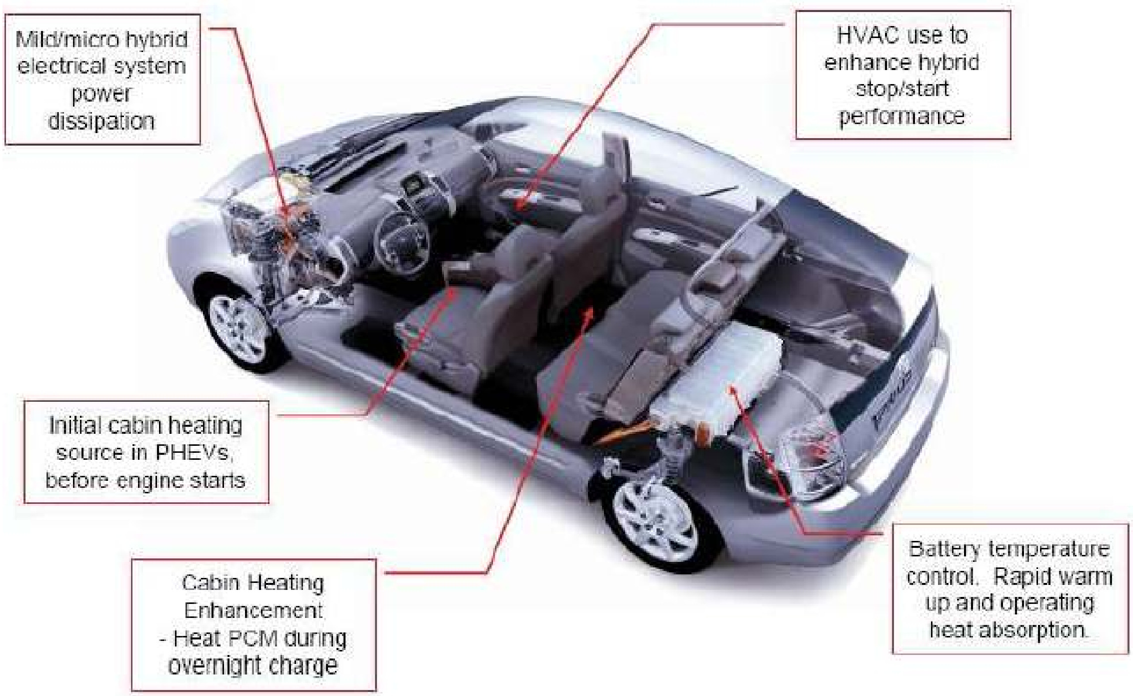

Figure 7: Applications in EV and PHEV

5.2 Cold Start Effects on Fuel Consumption

It is undisputable that fuel consumption - and as a consequence thereof emissions – increases with decreasing ambient temperatures. Cold start during the NEDC at +24ºC ambient temperature results in ca. 10% higher fuel consumption versus a vehicle running the same cycle already at operating temperature [2]. This vehicle dependent difference represents therefore the theoretical maximum fuel consumption reduction potential by applying latent heat energy storage.

During the North American FTP cycle, two available hybrid vehicles were exposed to different ambient temperatures [3]. Fuel consumption of the two hybrid vehicles at -7ºC increased by 17% respectively 12% versus tests performed at +24ºC. Additional utilisation of electric consumers and cabin heating at -7ºC ambient temperature increased fuel consumption by 43% respectively 35%.

Earlier studies with an engine coolant latent-heat-storage device [4] resulted in fuel consumption reduction during the FTP of already 2% at +24º ambient temperature and 8% at -6ºC. If the engine coolant circuit is activated already one minute before engine start, the fuel consumption reduction at both ambient temperatures increased to 4% (+24ºC), respectively 12% (-7ºC).

Results of the above mentioned studies are clear and authoritative evidence of the positive effects of a latent heat storage device on fuel consumption reduction, showing to advantage the colder the ambient temperature gets.

5.3 Considerations for Electric Vehicles

The goal of electric vehicles (EV + PHEV) is emission-free propulsion, at least for the initial part of the trip for PHEV. The air heaters in these vehicles should be no different from their powertrains in terms of emissions, i.e. they should be emission-free. Current difficulty of electric vehicles is the short electric drive-range due to low energy density of lithium-ion batteries, having boundaries due to weight and especially cost.

Recent field trials with electric vehicles and various simulations showed a reduction of electric drive-range of ca. 50% during the winter period. This is caused to a large extent by the cabin heating system, having to use battery energy for heating purposes due to the lack of an existing heat source e.g. internal combustion engine. This consumed heating energy cannot be utilised for electric propulsion.

This issue can be avoided with the described latent heat storage system. During the battery charging period, where the vehicle is plugged to the electric power grid, the heat storage device can be charged in parallel or after the propulsion battery is charged. This heat energy is then available for cabin heating during drive mode, without drawing energy from the propulsion battery, resulting in an increased electric drive-range.

A side benefit of the described latent heat energy storage system is the possibility to maintain the propulsion battery warm when the vehicle is parked in a cold location with no grid power. Otherwise, the battery has to consume its own electric energy for self-heating in order to enable sufficient electric power delivery to the electric motor.

6 Summary and Outlook

The majority of thermal energy storage materials have a melting point below 120ºC and exhibit relatively low thermal energy densities. Dow's new encapsulated PCM promises higher energy density with low space constraints.

Insufficient durability of PCM encapsulation – caused by corrosion and leakage – has been a limiting factor of earlier attempts of TESS implementations and must be addressed for new attempts.

Performance targets and system design have been defined for building-up a prototype system in 2010 for vehicle and engine bench testing, to quantify benefits with respect to fuel consumption and emissions reduction.

References

[1] Weilenmann M. et al.; Atmospheric Environment 39 (2005) 2433 - 2441.

[2] Kunze K., Wolff S., Lade I., Tonhauser J., SAE Publication 2006-01-1450; "A Systematic Analysis of CO2-Reduction by an Optimized Heat Supply during Vehicle Warm-up".

[3] US EPA Document EPA420-D-06-2002; 2006: Table III.A-22 Fuel Economy of 2 Hybrids.

[4] Piotrowski G., Schäfer R., US EPA White Paper, "Evaluation of a Schatz Heat Battery on a Flexible Fuel Vehicle", September 1991.

[5] Figure 1 "Waste heat flows in vehicles" from General Motors

[6] Figures 6 + 7 Applications for stored heat from Ricardo