Energy Consumption Of Battery Cooling In Hybrid Electric Vehicles

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Energy consumption of battery cooling in hybrid electric vehicles

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ABSTRACT

Lithium ion cells are presently the most promising technology for the use in hybrid vehicles. The cells heat up due to internal heat generation. This may lead to premature aging and necessitates an efficient thermal management. The heat sink for the cells is the automotive refrigeration cycle. The cells can be cooled by evaporation of the refrigerant or via a secondary coolant loop.

Models for battery cooling systems are added to an existing Modelica library in order to examine the influence of battery cooling on the complete air-conditioning cycle. The lithium ion cells are also modeled with Modelica, making an analysis of the complete system possible. The library can serve as a design tool for the battery cooling system.

In this study, the thermal load caused by the battery during the New European Drive Cycle (NEDC) is calculated for a hybrid vehicle. Results are presented for direct evaporative cooling of the cell. The study is carried out for the refrigerants R134a and R1234yf. The impact of the battery cooling on the refrigerant cycle and the resulting additional load on the compressor are determined for two climatic conditions.

The energy demand of the compressor is increased by up to 10\% depending on the climatic conditions and the refrigerant. In hot weather conditions, the thermal comfort of the passengers is reduced if the battery cooling is switched on.

1. INTRODUCTION

Electric drive trains are a promising alternative to combustion engines due to high efficiencies, a favorable torque characteristic and local zero emissions. At present, powerful accumulators are still missing so that the range of electric vehicles is a lot smaller than for conventional vehicles. Hybrid electric vehicles (HEVs) use a combination of electric and combustion drive trains which offers a high range due to the high energy density of gasoline and a low CO2 emission due to regenerative braking and energy storage.

Lithium ion cells are currently the storage technology that looks most promising for the use in HEVs due to their high power and energy densities. However, thermal management is necessary to prevent premature aging and subsequent loss of capacity. The cell temperature should be kept between 25 and 30°C. The maximum temperature within the cell should exceed 40°C in exceptional cases only. If the temperature rises above 70°C, the cell is at risk of thermal runaway that may lead to failure of the cell or to damage of the whole battery. Temperature differences within the cell lead to mechanical stress. One measure of this stress is the maximum temperature difference, which should not exceed 5 K (Jossen and Weydanz, 2006).

The automotive refrigeration cycle is the only heat sink that allows a sufficient cooling at high ambient temperatures. Three different cooling systems are possible in a hybrid vehicle:

\begin{itemize}
  \item Air cooling: conditioned air is provided by the air conditioning system,
  \item Evaporative cooling: the battery heat exchanger is integrated into the refrigeration unit
  \item Secondary loop cooling: a coolant is circulated in an additional loop that is connected to the refrigeration cycle
\end{itemize}
Bad heat transfer at the cell surface and low heat conductivity inside the cell necessitate very high air mass flows, so that air cooling is not recommended for lithium ion cells. Evaporative cooling is a very compact solution as the battery heat exchanger can be integrated directly into the refrigeration cycle of the air conditioning. Only few additional components are needed. But as soon as the battery temperature reaches critical values, the refrigeration cycle has to be switched on even if the cabin of the car doesn’t need air conditioning.

This can be avoided in a secondary loop cooling system. On cold days, the coolant can be cooled by ambient air using an additional air/coolant heat exchanger so that the refrigeration cycle doesn’t have to be operated. As a secondary coolant loop consists of many components, it is only profitable if parts of the electric drive trains can be cooled with it, too.

In a hybrid car, the requirements for the climatic comfort are the same as for a common vehicle. So the air conditioning is to be constructed so that the cells as well as the passengers can be kept in their particular comfort zone. In this paper, a Modelica library is presented that complements the commercial AirConditioning Library and allows the user to examine the influence of the battery cooling system on the comfort of the refrigeration cycle. The influence on the energy consumption is of interest as well: How much of the energy that can be saved due to the efficient drive train is consumed by the battery cooling system?

The following section describes the parts of the Modelica library for the Lithium ion cell and the cooling system. In Section 3, the chosen parameters for the use case are presented. In Section 4, the results for the two cooling systems are compared. Conclusions are drawn in the final section.

2. MODELING

The battery cooling system library presented in this paper consists of models for battery heat exchangers, Li-Ion cells and controllers. The number of discrete elements can be varied for most of the models. The geometry of the models can be changed by using replaceable data records.

The whole library is written in Modelica. Modelica is an object-oriented, descriptive language that is suited for multi-domain modeling. In order to simulate the models, the simulation environment Dymola 2012 FD is used. The models for further components of the coolant and the refrigerant cycle are taken from commercial Modelica libraries.

2.1 Vehicle

The vehicle model calculates the required drive power from the total driving resistance $F_{\text{tot}}$ and the velocity $v$ given by the drive cycle model. The total driving resistance results from the rolling resistance $F_{\text{roll}}$, the accelarative resistance and the air resistance $F_{\text{air}}$:

$$F_{\text{tot}} = F_{\text{roll}} + F_{\text{air}} + m \cdot a = f \cdot m \cdot g + \frac{1}{2} c_w A v^2 + m \cdot a \quad (1)$$

The model determines with the implemented driving strategy how the drive power is shared between the electric and the combustion motor. The driving strategy depends on the hybridization degree and the structure of the hybrid drive train. It considers the state of charge of the battery and decides, whether the battery has to be charged or can be discharged and used for electric driving. As long as the state of charge (SOC) of the battery exceeds the minimum SOC, the battery can be discharged.

In this model it is assumed that the braking energy can be converted completely into chemical energy up to the maximum load of the generator with consideration of efficiencies. The load current is not limited.

<table>
<thead>
<tr>
<th>Table 1: vehicle parameter</th>
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<tbody>
<tr>
<td><strong>Parameter</strong></td>
</tr>
<tr>
<td>Mass</td>
</tr>
<tr>
<td>Projected area</td>
</tr>
<tr>
<td>Air drag coefficient</td>
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<tr>
<td>Specific rolling resistance</td>
</tr>
</tbody>
</table>
2.2 Drive Cycle
The drive cycle model delivers the velocity as a function of time. They are used to calculate the gasoline consumption of vehicles. The library contains several drive cycles e.g. NEDC, Artemis Urban, FTP-75 etc. Further drive cycles can be easily created if their data are provided as a function of time.

2.3 Battery
For the cell, several thermal models of different degree of detail are created. The finite volume and finite element method are used for more detailed models; these cannot be used in system simulations as they slow down the simulation. For the simulation of the whole cycle, a simple lumped capacity approach is used as a thermal model. The thermal capacity and conductivity is calculated from literature data (Al-Hallaj et al 2000, Chen et al 2006, Julien and Stoynov 2000).
Input is the electric power provided or required by the electric drive train. The model delivers the cell temperature that serves as an input for the controller of the compressor and the battery valve as well as the State of Charge that is delivered to the vehicle model.
Heat loss due to charge/discharge can be calculated by using a fixed efficiency or by using a current depending function.

2.4 Battery Heat Exchanger
The battery heat exchangers look similar for the refrigerant and the coolant case, only their piping differs. They consist of a ripped plate that contains pipes for the fluids. The solid of the plate is modeled with finite volumes in order to be able to consider the complex geometry. Due to the object oriented approach, the model of the solid can be used for both coolant system models, only the pipe has to be replaced. The pipe models are deviated from the AirConditioning Library and the Hydronics Library and are adapted to the specific geometry and heat transfer behavior given by measurements. As for the batteries, there are simple models for the system simulation as well as more complex models for detailed examinations of temperature distribution.

2.5 Chiller
The chiller is a plate heat exchanger that is used to cool down the coolant of the secondary coolant loop with the refrigerant.
The geometric data are calculated with the equations given in VDI Wärmeatlas 2006. The heat transfer coefficient relations are adapted to given measurement data.

2.6 Refrigeration and Coolant Cycles
For the remaining components of the cycle, common models from the AirConditioning Library (Tummescheidt et al 2005) and the Hydronics Library as well as internal libraries are used with adapted geometry records. All component models are arranged on the graphic user interface of Dymola and can be connected. Similar models have been presented in various studies, e.g. by Prölß et al. 2006. Figure 1A and B show the flow scheme for both cooling systems.

![Diagram](image-url)

**Figure 1:** flow scheme for battery cooling systems (A) evaporative cooling (B) secondary loop cooling
2.7 Battery Temperature Control
The battery temperature is controlled by a valve that opens the branch of the battery heat exchanger (evaporative cooling) or the chiller (secondary coolant loop) only if the temperature rises above 37°C. An integrated hysteresis function block reduces the number of switches.
The numerical stability of the models has to be ensured even for very low mass flows in order to simulate the shut off of the battery cooling branch. Due to numerical reasons the mass flow isn’t exactly zero if the valve is closed. But it is less than 1e-7 kg/s so it is considered as nearly zero.

3. USE CASE

3.1 Climate
Two climatic conditions are chosen for the simulations. On the one hand a hot weather condition in order to examine the power capabilities of the refrigeration cycle, on the other hand a milder climate. The parameters for air temperature at condenser inlet, evaporator inlet temperature, evaporator air mass flow and set point temperature at evaporator outlet are given in table 2. The revolution number $n$ of the compressor is limited to 8000 1/min.
The air mass flow through the condenser depends on the velocity of the vehicle. In system simulations, this value is often kept constant. To evaluate the relation between heat load of the battery and varying air mass flow through the condenser, a function for the condenser air mass flow depending on the car velocity is developed. Data from a CFD simulation of the underhood flow for a Mercedes S (provided by Daimler AG) are used as reference points to convert the velocity of the car into a corresponding air mass flow through the condenser. The correlation is shown in figure 2. Up to a velocity of 5m/s the mass flow is kept constant at about 0.6kg/s, it rises then with the velocity.

<table>
<thead>
<tr>
<th>Table 2: Climatic conditions</th>
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<tbody>
<tr>
<td>Hot weather condition</td>
</tr>
<tr>
<td>$T_{\text{air,cond}}$</td>
</tr>
<tr>
<td>$T_{\text{L,V}}$</td>
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<tr>
<td>$\dot{m}_{\text{L,V}}$</td>
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<tr>
<td>$T_{\text{Set}}$</td>
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<tr>
<td>$n_{\text{max}}$</td>
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**Figure 2:** condenser air mass flow as a function of the vehicle velocity

3.2 Drive Cycle
The New European Drive Cycle (NEDC) is chosen for the simulation. This drive cycle consists of an urban part that is repeated four times and the extra urban part with the maximum velocity of 120 km/h (see figure 3). The accelerations and decelerations are constant. During 260s of the 780s urban part, the car is at rest ($v=0$). Little changes in the velocity mean little recuperation potential and therefore only little heat loss in the battery. But the effects of the battery cooling on the whole refrigeration cycle can be shown more clearly with the NEDC, whereas more realistic cycles e.g. Artemis Urban (see figure 4) tend to hide important information due to their strong dynamic character.
3.3 Hybrid Car
The car model in this study is a Mild Hybrid. It has a start-stop-system, regenerative braking and a boost function. Pure electric driving is not possible. The power of the electric motor/generator is set to 15kW. The battery consists of 30 spirally wound cylindrical cells with a nominal voltage of 3.6V and a nominal capacity of 10Ah each. The amount of savable energy is 1080 Wh. The battery has at the beginning a state of charge of 85%. For a Mild Hybrid the SOC-swing is fairly low, this means that the difference between minimum and maximum SOC is fairly low, in this study it is 20%.

3.4 Refrigerants
The two refrigerants R134a and R1234yf are compared in this paper. R134a will be replaced by R1234yf in mobile air conditioning systems as legal regulations of the European Commission specify that the GWP of refrigerants has to be lower than 150. The GWP of R1234yf is 4, its physical and thermodynamic characteristics are similar to those of R134a. This means that only little modifications of the common components of a refrigeration cycle are necessary.

The p-h-diagram of the two refrigerants is drawn using Refprop (fig.5). The vapor pressure curves have nearly the same inclination. The specific evaporation enthalpy of R1234yf is lower, the two-phase region is about 18% smaller. The higher density and the lower pressure ratio of R1234yf can compensate the lower evaporation enthalpy such that almost the same COP can be reached if R134a is replaced by R1234yf in a refrigeration cycle. Medium models for the refrigerants R134a and R1234yf are included in the AirConditioning library.
3.5 Refrigeration Cycle
The refrigeration cycle in this study consists of a condenser with integrated receiver, an internal heat exchanger, a thermal expansion valve, and a flat tube evaporator. The electric scroll compressor’s power is revolution controlled. The pipe to the battery heat exchanger branches off after the internal heat exchanger. The mass flow to the battery heat exchanger is limited by the battery temperature control valve. Figure 6 shows the cycle model for the evaporative cooling. The cycle models a prototypic concept, the models for the components are delivered and validated by the suppliers. As these models are encrypted, no geometric details can be provided. A refrigerant cycle model without battery cooling system has been built up for comparison, too.

3.6 Simulation
The same simulations have been run for both weather conditions. The initial conditions have to be the same for all simulation runs so that the compressor work can be compared for the cycles with and without battery cooling. Battery heat load and the condenser mass flow are therefore kept constant until all dynamic effects of the initialization have vanished. Once steady state conditions are reached, the drive cycle is activated. The thermal power loss and the condenser air mass flow vary now due to the varying velocity. The valve to the battery cooling branch is closed at simulation start.

4. RESULTS

4.1 Heat loss
Figure 7 shows the heat loss inside the lithium ion cells for the NEDC. The peaks of the heat loss reach up 4kW to at the beginning, in the end up to 5kW. The charge and discharge of the battery happens very fast, so that heat losses are only generated during short time periods. The percentage of constant velocities is quite high in the NEDC, so that there are long periods where the heat loss is equal to zero. Figure 8 shows the heat loss for the more realistic Artemis Urban drive cycle for a comparison. Its characteristic is more dynamic and has thus a higher heat load.

Each load peak shows as a rise in the slope of the mean battery temperature graphs in figure 9 and 10. All temperature curves show a similar run because the heat load is the same for both climatic conditions. As soon as the battery temperature reaches the upper temperature limit, the battery valve opens and the curve kinks at about 700s. The temperature curves run parallel for both refrigerants in hot weather conditions, after the valve opening, the curve of the R134a cycle declines a bit steeper, rises then faster than for the R1234yf cycle and ends in a temperature that is 2 K lower for the battery in the R1234yf cycle. The battery temperature in the R134a cycle is slightly lower than the one in the R1234yf cycle, the battery valve closes again so that the battery temperature rises
faster until the temperature reaches the upper limit and the valve opens again (see next section). The limit of 40°C can be kept for both refrigerants in hot weather conditions.

For the mild weather conditions, the temperature rises above the limit, although the battery valve is opened. The compressor controller does not consider the battery temperature, so that the compressor speed is not adapted to the higher heat load. The final temperature of the battery is 42°C for the R134a cycle and 48°C for the R1234yf cycle. The heat load will be lower in reality than the heat load calculated in this use case. The full recuperation potential cannot be used as the number of loading cycles is restricted for a battery and the vehicle dynamics are more complex in reality. This means, that real cell temperatures are a lot lower than the simulated temperatures. But it must be pointed out that the calculated temperature is only a mean temperature. Cells that are in the area of superheated refrigerant can have a lot higher temperature than cells in the two-phase heat transfer area. With the lumped capacity assumption, it can only be verified, if the temperature limits of the battery can be respected at all, if the cooling power is big enough and how the additional components influence the whole air conditioning system. Detailed design studies with the more detailed library models of battery as well as the battery heat exchanger must be carried out for a detailed layout of the controllers and the battery heat exchanger itself.

4.2 Effects of Battery Cooling on Refrigerant Cycle

The temperature limit of the battery control valve is not reached at the same time for both refrigerants in both weather conditions even though the heat flow into the battery is the same. As written above, the refrigerant mass flow can not be reduced to zero e.g. there is a small refrigerant mass flow through the battery heat exchanger and thus a small heat flux out of the battery into the refrigeration cycle. The heat flux is dependent on the mass flow and the refrigerant, therefore the valve doesn’t open at the same time. The refrigerant mass flow in the battery branch is shown in figure 11 and 12. When the battery temperature falls below the lower limit of the controller valve, the valve closes and the mass flow through the battery branch is interrupted as shown for R134a in figure 10. The lower temperature limit cannot be reached in the other cases, the valve stays open until the end of the drive cycle.

**Figure 9**: Battery temperature for hot weather condition  
**Figure 10**: Battery temperature for mild weather condition

**Figure 11**: Refrigerant mass flow in battery branch for hot weather condition  
**Figure 12**: Refrigerant mass flow in battery branch for mild weather condition
The refrigerant mass flow through the battery branch is about 5.5g/s in case of hot weather conditions and 3g/s in case of mild weather when the valve is open. As the refrigerant mass flow cannot be set exactly to zero, the minimum mass flow varies around 0g/s when the valve is “closed”.

In hot weather conditions, the mass flow of R1234yf in the battery branch is higher than for R134a because the density of R1234yf is slightly higher than for R134a and the compressor speed is at maximum during the whole simulation. In mild weather conditions, the mass flow of R134a is higher, this is because the COP of the R134a cycle is in this case lower than the COP of the R1234yf cycle such that the compressor of the R1234yf cycle is run at a lower speed.

The total refrigerant mass flow rises in all cases after the opening of the battery control valve (see fig. 13 and 14). The variable air mass flow through the condenser has little influence on the resulting total mass flow. The high air mass flow at the end of the NEDC (after 900s) lets the refrigerant mass flow go down in all cases.

Figure 13: Total refrigerant mass flow for hot weather conditions

Figure 14: Total refrigerant mass flow for mild weather conditions

Figure 15 and 16 show the influence of the battery cooling on the air temperature at the evaporator outlet. For hot weather conditions, the difference between the temperatures for the cycles with and without battery cooling is about 1K. When the valve opens, the difference is increased by 1K. For R134a, the temperature sinks, when the battery valve is closed again at 900s. The temperature rises then again, when the valve opens again. In the hot case, the compressor turns already at maximum speed, there is no more reserve to compensate the additional cooling load of the battery.

In the mild case the battery cooling has hardly any influence on the average value of the evaporator outlet temperature. The opening and closing of the valve causes little peaks of about +/-0.5K which is corrected by the compressor controller.

The varying air mass flow through the condenser leads to remarkably higher variations in the cycle with hot weather conditions than in the mild weather.

Figure 15: Air temperature at evaporator outlet for hot weather conditions with/without battery cooling

Figure 16: Air temperature at evaporator outlet for mild weather conditions with/without battery cooling
The additional energy consumption of the cycle with battery cooling in comparison to a cycle without battery cooling is shown in figure 17. As a comparison, the energy consumption for the more heat intense drive cycle Artemis Urban is shown as well. The numbers in figure 17 indicate the relative increase of the energy need of the compressor. The additional energy consumption for battery cooling during one NEDC is about 150 kJ for the R1234yf cycles and 60 kJ for the R134a cycles.

In case of mild weather conditions the relative increase is a lot higher because the additional heat loss of the battery is larger in relation to the total cooling demand of the cycle. As the temperatures limits cannot be kept for the mild weather conditions due to the controller that does not consider the battery temperature, it can be assumed that the necessary additional energy is about the same as for hot weather conditions, this would raise the relative increases to 17.3% for the Artemis Urban cycle.

### Figure 17: Additional energy consumption of the cycles with battery cooling

![Figure 17: Additional energy consumption of the cycles with battery cooling](image)

#### 5. CONCLUSIONS

Several drive cycles are provided for dynamic studies of battery cooling. Effects of the additional cooling demand of batteries in hybrid electric vehicles on the refrigeration cycle can be determined with the help of thermal battery and heat exchanger simulation models.

High power losses and thus high thermal loads are damped partly by the thermal capacity of the battery, such that high charge rates of the battery are possible even though the refrigeration capacity of the refrigeration cycle is limited.

In hot weather conditions, the comfort of the passenger is affected by the battery cooling: the evaporator air outlet temperature rises by 1 K when the battery cooling is switched on.

The energy consumption of the refrigerant cycle rises by up to 11%. It depends strongly on the weather condition and the drive cycle.

### NOMENCLATURE

<table>
<thead>
<tr>
<th>F</th>
<th>force (N)</th>
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<tbody>
<tr>
<td>m</td>
<td>mass (kg)</td>
</tr>
<tr>
<td>a</td>
<td>acceleration (m/s²)</td>
</tr>
<tr>
<td>g</td>
<td>gravity constant (m/s²)</td>
</tr>
<tr>
<td>c</td>
<td>drag air coefficient</td>
</tr>
<tr>
<td>A</td>
<td>area (m²)</td>
</tr>
</tbody>
</table>

| Subscripts | tot | total | roll | rolling |
REFERENCES


