Modeling the Thermal Management of a Plug-In HEV Powertrain

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Agenda

- Motivation
  - Modeling approach
  - Thermal modeling of electric drive train components
    - Battery
    - E-Motor
    - Inverter
  - Simulation of different cabin heating concepts
- Conclusion and outlook
Heating impact on energy consumption

Simulation based on FEV Liona electric vehicle, heating demand 3kW
Display analog Beidl et al., 32. Internationales Wiener Motorensymposium 2011
Measures to improve thermal management

Active thermal management
- Waste heat recovery from electric drive train
- Heat pump
- Usage of ICE or fuel cell for heating
- Additional vehicle heater (e.g. ethanol burner)
- Heat storage (e.g. PCM)
- Pre-conditioning at charging station
- Optimized cabin thermal management
  - Control of fresh air rate
  - Local thermal conditioning (radiation etc.)

Passive thermal management
- Lowering of cabin heating/cooling demand
  - Insulation
  - Reflective glazing
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Modeling approach

Objective: Investigation of energy saving potential for different thermal management concepts for Plug-In HEVs

Variable start and boundary conditions

- Drive cycles
- Ambient temperatures
- Battery SOC
- etc.

Vehicle model

Cooling system

Cabin model

cabin heating / cooling demand

component heat generation
Validation of vehicle model using FEV Liiona EV

Comparison of vehicle measurement and simulation in NEDC

(Electrical power calculated from current and voltage measurement)

Vehicle mass: 1260 kg
Passenger mass: 100 kg
Drag coefficient: 0.325
Frontal area: 2.09 m²
Rolling resistance factor: 0.01
Total gear ratio: 6.54
Possible cooling system layout for a PHEV

- ICE radiator
- Battery radiator
- E-drive radiator
- E-motor(s)
- Battery
- Air
- Cabin
- Cabin HX
- A/C condensor
- A/C evaporator
- PTC heater
- Power electronics
- Air
- Battery
- Heater

Circuit temperatures:
- HT circuit 90-120 °C
- NT circuit 50-70 °C
- Refrigerant circuit
- Battery circuit 20-40 °C
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Temperature sensitivity of Li-ion batteries

Source: Aachener Kolloquium „Fahrzeug- und Motorentechnik“ 2009
Electrical and thermal model of a Li-ion cell

Simple equivalent circuit model

Extended equivalent circuit model

Heat generation model
\[ \dot{Q} = I(U_0 - U) - IT \frac{dU_0}{dT} \]

- Joule heat
- Reversible heat
Battery Power Prediction in GT-Suite

Max. battery power depending on:
- Max. charge/discharge current
- Max. charge/discharge voltage

\[
P = (U_0 - R_i \cdot I) \cdot I
\]

\[
U_0^2 \over 4R_i
\]

Assumption: \( U_0 = 3.7 \text{ V}, R_i = 2 \text{ mOhm} \)
Heat transfer model for a battery module

Heat transfer model

- Lumped thermal mass for Li-Ion cell and busbar
- Equivalent thermal conductivity from cell to cooling plate to model heat transfer and homogeneous heat generation inside cell active material using lumped model

![Diagram of heat transfer model](image)

Top busbar

Li-Ion cell

Bottom busbar

Interface material flexible, thermally conductive, electrically isolating

Cooling plate
Battery module simulation results
Thermal model of E-motor

Heat generation
- Calculated from efficiency map

Heat transfer
- Lumped thermal mass
- Heat transfer to coolant through GT Flow model of coolant jacket
Thermal model of inverter

Heat generation
- Calculated from efficiency map

Heat transfer
- Modeling of different materials and heat transfer properties in IGBT module and cooling plate
- GT Flow model of cooling plate

Source: Mitsubishi
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Simulation of cabin heating during electric driving mode

Analysis of different cabin heating concepts for compact class vehicle
- Air PTC heater
- Water PTC heater in electric motor + power electronics cooling circuit
- Water PTC heater in independent heating coolant loop

Realistic driving cycles

![Graph showing Artemis Urban Cycle and Artemis Road Cycle](image-url)
Air PTC heater concept

Example of HV PTC air heater

Source: Eberspächer

Electric driving at 0°C ambient
Air PTC heating and cabin HX
NEDC and different Artemis cycles

- --- without cabin HX (all cycles)
- NEDC
- Artemis Road
- Artemis Urban + Road
Water PTC heater concepts

Electric driving at 0°C ambient
Water PTC heater
Artemis urban + road cycle

Concept A: Separate cooling circuit for water PTC
Concept B: Water PTC in series with EM and power el.

Heat transfer cabin HX / W

Zeit / s

0 120 240 360 480 600

0 500 1000 1500 2000 2500 3000 3500

4 kW PTC (Concept A)
4 kW PTC (Concept B)
6 kW PTC (Concept B)

Electrical power PTC / W

0 2000 3000 4000 5000 6000 7000

Energy consumption PTC / kWh

0.0 0.4 0.8 1.2 1.6 2.0

Time / s

0 300 600 900 1200 1500 1800 2100

Energy Consumption

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Comparison of heating concepts

- NEDC
- Artemis Urban + Road
- Artemis Road
- Artemis Urban

Energy demand / kWh/100km

- Without electrical heating
- Separate 4 kW water PTC
- 4 kW water PTC in LT cooling circuit
- 6 kW water PTC in LT cooling circuit
- Air PTC with cabin HX in LT cooling circuit
- Air PTC without cabin HX in LT cooling circuit

- - 6.4 %
- - 4.4 %
- - 4.6 %
- - 9.7 %
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Conclusion and outlook

- Cooling and heating can decrease electric range by more than 50%
  - Lowering of cabin cooling / heating demand essential for efficient future vehicles
  - Waste heat recovery from electric drive train only useful for longer trips
  - New concepts like heat pump have to be evaluated

- GT-Suite suitable for holistic thermal management modeling
  - Easy coupling of mechanical, electrical and thermal models

- Further cooling system concept studies to be performed
  - Usage of both electric drive train and combustion engine for cabin heating
  - Optimization of operating strategies
Thank You.

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