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Ingolstadt, 26.09.2013
Engine Cooling only

[Image of an old car with a sign that says "Shirley Horton Ford"]

/ftp://pdphoto.org/PictureDetail.php?mat=pdef&pg=7906/
Vehicle Thermal Management

Electric Powertrain and Passenger Comfort
Content

- Road map and definitions Thermal management

  - Temperature levels
  - Engine thermal management
  - MAC – mobile air conditioning
    - Working fluids
    - Functionalities
  - Waste heat recovery
  - Future fuel
  - Conclusion
Road Map
Vehicle Thermal Management

- future fuel
- electric powertrain
- waste heat recovery
- A/C with new refrigerants
- engine thermal management
- air conditioning (A/C)
- engine cooling and heating
- engine cooling only
Content

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• Future fuel

• Conclusion
Temperature Levels

Combustion Engine

Heat Source
- Engine exhaust gas
- Engine coolant

Heat Sink
- A/C
- Ambient
- Heater
**Electric Vehicle**

**Heat Source**
- Range Extender
- Thermal Storage (HT)
- E - Motor
- AC Inverter, DC-DC
- Battery

**Heat Sink**
- Heater
- Thermal Storage (LT)
- Ambient
- Battery

**Temperature Levels**

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Fuel Cell Electric Vehicle with LH₂ Tank

Temperature Levels

Heat Source:
- Fuel Cell
- Thermal Storage (HT)
- E - Motor
- AC Inverter, DC-DC
- Battery
- A/C

Heat Sink:
- Heater
- Ambient
- Thermal Storage (LT)
- Battery
- LH₂ Tank

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• **Automotive cooling systems**
  - designed for the highest necessary heat rejection
  - this operating state is reached only during 3-5% of operation
  - in most cases the thermal situation is subcritical
  - the engine is overcooled

• **A demand-responsive engine cooling system provides:**
  - 3 to 5% reduced fuel consumption
  - increased passenger comfort .. faster heat-up
  - environmental compatibility .. reduced tail pipe emissions

• **specific components**
• **specific control strategies**
• **demand-responsive cooling system**
Components of a Thermal Management System - Overview

climate control
climate blower
auxiliary water pump
latent-heat accumulator
starter/alternator
fan module
radiator shutter
main water pump
valve

exhaust gas heat exchanger
auxiliary heating
engine management

/ SAE Technical Paper 1999-01-0238/
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Air conditioning only

- Refrigerant: R134a
- HVAC Evaporator
- Frontend Condenser
- Belt driven compressor
  - variable capacity
  - fixed capacity
Automotive Air Conditioning

R134a system
Automotive Air Conditioning

- Passenger comfort
- Performance .. cool down
- Environment .. ozone depletion ✓
- Environment .. global warming
- Enhanced efficiency .. fuel consumption => credits
- Extended functionality .. heat pumping, el. powertrain cooling (battery, inverter, DC/DC)

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Automotive Air Conditioning

- Refrigerants: Transition CFC-12 to HFC-134a
  - Omission of ozone depletion
  - Significant reduction of global warming effect

F-gases: effect of globally produced F-gases as Gt CO₂ equivalent (grey: CFC and HCFC, red: HFC)
• 0.11% of total global greenhouse emissions are due to the HFC refrigerants used in mobile air conditioning (MAC)

- 1 January 2011: no type-approval for vehicle fitted with an A/C system designed to contain fluorinated greenhouse gases with a GWP > 150

- 1 January 2017: new vehicles fitted with an air-conditioning system designed to contain fluorinated greenhouse gases with a GWP > 150:
  (a) certificates of conformity no longer considered
  (b) registration refused and sale & entry into service prohibited

GWP (global warming potential): R134a: 1430, R1234yf: 4, CO₂: 1 /IPCC/
Automotive Air Conditioning

Refrigerants:

- **HFO 1234yf**
  - Properties and behavior close to R134a
  - GWP: 4 /IPCC/ resp. <1 /Reviews of Geophysics; Volume 51, June 2013/
  - Serial vehicles already in the market
  - Mildly flammable
    - Ignition in presence of oil @ 600 .. 800 °C
    - Decomposition products include hydrogen fluoride (HF, LC50 = 966 ppm) and carbonyl fluoride (COF₂, LC50 = 360 ppm) /Graz, 2008/
  - R1234yf:
    - Ignition of refrigerant in a test car after a simulated accident with a refrigerant leakage
    - (some do some do not ignite)
Refrigerants:

- **Natural refrigerants**
  - hydro carbons, e.g. propane (R290) GWP = 3
  - CO₂ (R744) GWP = 1

- **Propane:**
  - Similar pressure levels and components
  - Efficient refrigerant
  - Used already in not OEM approved „retrofit“
  - Highly flammable
    => Secondary fluid needed
    => Reduced efficiency
Automotive Air Conditioning

Refrigerants:

- **CO₂ (R744):**
  - Transcritical cycle
  - Pressure level 120 to 160 bar (25 to 32 bar with R134a)
  - All new components and control
  
  - Also interesting for heat pump function

  - Higher efficiency than R134a at lower ambient temperature
  - Lower efficiency than R134a at high ambient temperature

  - Development of application for MAC had been terminated in 2005
Cycle and Process with CO₂ (R744)

CO₂ system

transcritical process

\[ p_{\text{krit}} = 7.38 \text{ MPa} \]

\[ t_{\text{krit}} = 30.98 ^\circ \text{C} \]
Process with CO₂ (R744)

Cooling

Specific enthalpy

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Process with CO₂ (R744)

Specific enthalpy

Heating

20 bar

35 bar

120 bar

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Cool Down Performance
R744 / R134a

 Ambient temp.: 43 °C, RH: 40 %, Sunload: 1000 W

\[ \Delta T: 6 \text{ K} @ 10 \text{ min} \]
Efficiency R744 / R134a (SAE ARCRP 1)

Pedrag Hrnjak, VDA-Wintermeeting 2007/

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An approach:

- Restart of development
- Building base of serial suppliers
- Enhance efficiency and NVH (competitive to current R134a)
- Development
- Serial project development
- Process and industrialization
- Of tool samples
- Full validation
- SOP
- **DIRECTIVE 2006/40/EC:**
  phase out of R134a in all new cars by 1 January 2017
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CO$_2$ Air / Air Heat Pump Cycle

Cooling Mode

4-Way-Valve

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CO$_2$ Air / Air Heat Pump Cycle

Heating Mode

4-Way-Valve

“flash fogging”
Flash Fogging

Limited Vision

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Advanced Heat Pump Cycle

Cooling Mode

engine

/SAE Phoenix 2004/
Wind tunnel test: -20 °C
heating mode: after 5 min
### Fuel Consumption

-20 °C, after 30 min., 50 km/h

<table>
<thead>
<tr>
<th>effect on</th>
<th>head temp.</th>
<th>fuel consumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>el. heater</td>
<td>+ 4.2 K</td>
<td>+ 0.69 lt./100km</td>
</tr>
<tr>
<td></td>
<td>+ 7.3 K</td>
<td>+ 1.21 lt. (100%)</td>
</tr>
<tr>
<td>heat pump</td>
<td>+ 7.3 K</td>
<td>+ 0.79 lt. (-35%)</td>
</tr>
</tbody>
</table>
Electric Powertrain
Assumption:

- Heating demand: 3 kW
- Distance: 180 km @ 60 km/h
- Energy Heating 9 kWh
- 45% of a 20 kWh battery
Heat Pump for electric Vehicle

Assumption:

- Heating demand: 3 kW
- Distance: 180 km @ 60 km/h
- Energy Heating 9 kWh
- Heat pump @ a COP of 3
- 15 % of a 20 kWh battery
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Waste Heat Recovery

- **Waste heat of a combustion engine**
  - Development of components and system
e.g.: turbo, piston or scroll expander
  - Concept:
    Rankin Cycle with natural working fluid
  - Savings:
    up to 5% fuel consumption (long distance truck)
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# Hydrogen Storage

<table>
<thead>
<tr>
<th>Compressed Gas</th>
<th>Cryo-compressed</th>
<th>Liquid</th>
<th>Solid storage</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="" alt="Image" /></td>
<td><img src="" alt="Image" /></td>
<td><img src="" alt="Image" /></td>
<td>• Physisorption</td>
</tr>
<tr>
<td>1 kg - 6 kg one or more pressure vessels</td>
<td>4 kg - 12 kg insulated cryogenic pressure vessel</td>
<td>7 kg - 12 kg insulated cryo-vessel</td>
<td>• Metal hydrides</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Complex hydrides</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Chemical hydrides</td>
</tr>
</tbody>
</table>
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Summary

- Management of different heat sources and heat sinks

- at different temperature levels
  - From 22 K (LH$_2$)
  - Around ambient temperature
  - Up to 800 K (exhaust gas)

- for powertrain component thermal management and climate control
  - Conventional and electric powertrain
  - Sustainable A/C and heat pump refrigerants

- Benefit
  - Efficiency
  - Function and durability
  - Passenger comfort and safety