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COMPARATIVE STUDY ON THERMAL MANAGEMENT SCHEMES WITH WASTE HEAT RECOVERY FROM ELECTRIC VEHICLE POWER TRAIN

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Christopher Roemmelmayer, Infineon, Germany
Jens Endrulat, Daimler, Germany
Outline

- Research Motivation
- HVAC Architectures
- Electro-thermally Coupled Models for Machine and Inverter
- Powertrain Specification
- Simulation Model
- Simulation Results and Discussion
- Conclusion
Cold weather condition (e.g. < 0°C)

- Heating power + Compressor power + Powertrain loss
- Consumes up to 50% of batteries’ capacity
- Mile range reduced by half
- Recover waste heat in the powertrain
HVAC Architectures (Heating Mode)

- **Conventional HVAC architecture**
  
  Evaporator, compressor, condenser, expansion valve
  Evaporator absorbs ambient energy, and condenser heats up cabin

- **Waste heat-only HVAC architecture**
  
  Chiller (working as evaporator), compressor, condenser, expansion valve
  Chiller absorbs waste heat from powertrain, and condenser heats up cabin

- **Dual heat source HVAC architecture**
  
  Chiller (working as evaporator), evaporator, compressor, condenser, expansion valve
  Chiller absorbs waste heat from powertrain, Evaporator absorbs ambient energy, and condenser heats up cabin
Waste Heat Recovery -- Waste Heat Only
Challenges:

- Electrical machine and inverter temperatures are subject to their losses.
- Machine and inverter losses are largely affected by their temperatures.

  a) Machine copper loss increases by 39% for every 100°C temperature rise (assuming same current);

  b) Inverter loss increases by ~20% for every 100°C temperature rise.
Electro-thermally Coupled Model for Electrical Machine

Schematic

- Torque
- Speed
- Machine core loss
- Machine current
- Machine efficiency
- Machine copper loss
- Electrical machine model
- Winding temperature
Electro-thermally Coupled Model for Electrical Machine

Machine phase current in A (RMS)

Machine core loss in kW
## Powertrain Specification

<table>
<thead>
<tr>
<th>Item</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kerb weight</td>
<td>1,708 kg</td>
</tr>
<tr>
<td>Gross weight</td>
<td>2,170 kg</td>
</tr>
<tr>
<td>Length</td>
<td>4,358 mm</td>
</tr>
<tr>
<td>Width</td>
<td>1,812 mm</td>
</tr>
<tr>
<td>Height</td>
<td>1,599 mm</td>
</tr>
<tr>
<td>Wheel base</td>
<td>2,699 mm</td>
</tr>
<tr>
<td>Wheel size</td>
<td>205/60 R16</td>
</tr>
<tr>
<td>Gear ratio</td>
<td>5.98 : 1</td>
</tr>
<tr>
<td>Axle ratio</td>
<td>1.12 : 1</td>
</tr>
<tr>
<td>Aerodynamic drag coefficient</td>
<td>0.28</td>
</tr>
<tr>
<td>Frontal area</td>
<td>2.55 m²</td>
</tr>
<tr>
<td>Tyre dynamic radius</td>
<td>316.4 mm</td>
</tr>
<tr>
<td>Cabin volume</td>
<td>3.5 m³</td>
</tr>
<tr>
<td>Window surface (for solar load)</td>
<td>1.4 m²</td>
</tr>
</tbody>
</table>
KULI – 1D simulation software for vehicle energy management

Components readily available: Cabin, compressor, heat exchanger, thermostatic expansion valve, blower, pump, electrical machine, inverter, battery, etc.
Conventional Powertrain and HVAC system
Simulation Model – Ambient Heat Only

Condenser
Refrigerant circuit
Evaporator
Compressor

Condenser in heat cable [1]

Battery coolant circuit

Motor

Battery

Cabin

Water/Glycol - Power Electronics & Motor

HT Circuit Coolant Pump

Coolant

Motor

Blower and fan

2 Stage

HVAC Blower

Inverter heat transfer coeff. vs. flow rate

HVAC heat transfer coeff. vs. flow rate

Coolant circuit

LV/HV Inverters

Condenser outlet temperature

Evaporator outlet temperature

Motor

Inverter (Low Volt Outputs)

Converter (Low Volt Outputs)

Pump

[Water/Glycol] - Power Electronics & Cooler

TXV

Compressor

Pump

Radiator

Coolant

Simulation parameters

Battery coolant circuit

Cabin

1. CAB

Therm Control

Motor Cooling

Battery Aux Calc.

Motor Cooling

Battery Cooling
Waste Heat Recovery -- Waste Heat Only

[Diagram of waste heat recovery system with labels for TXV, Chiller, Thermal Storage, ESS, PTC, EM, E-Pump, PE, Receiver, Compressor, Condenser, HX, Evaporator, Air flow, Refrigerant high temperature, Coolant high temperature, Refrigerant low temperature, Coolant low temperature.]
Simulation Model – Waste Heat Only
Waste Heat Recovery -- Dual Heat source
Cabin air average temperature

Condenser heat transfer rate

-10°C Ambient, 1 WLTC Driving Cycle
-10° C Ambient, 1 WLTC Driving Cycle

Compressor input speed

Compressor driving power

- Ambient heat only
- Waste heat only
- Dual heat source
-10° C Ambient, 1 WLTC Driving Cycle

COP

![Graph showing COP over time for different heat sources (Ambient heat only, Waste heat only, Dual heat source)]
-10° C Ambient, 1 WLTC Driving Cycle

**Machine stator temperature**

**Inverter temperature**
### Net energy gain

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Unit</th>
<th>Ambient heat only</th>
<th>Waste heat only</th>
<th>Dual heat source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compressor driving energy $W_{com}$</td>
<td>MJ</td>
<td>2.04</td>
<td>0.75</td>
<td>2.63</td>
</tr>
<tr>
<td>(including compressor loss)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Condenser energy $W_{con}$</td>
<td>MJ</td>
<td>5.33</td>
<td>2.88</td>
<td>6.46</td>
</tr>
<tr>
<td>(heat up cabin)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Evaporator energy $W_{eva}$</td>
<td>MJ</td>
<td>3.79</td>
<td>2.20</td>
<td>2.26 (Ambient heat) 2.25 (Waste heat)</td>
</tr>
<tr>
<td>(waste energy recovery)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Net energy gain $W_{net}$</td>
<td>MJ</td>
<td>3.29</td>
<td>2.13</td>
<td>3.83</td>
</tr>
<tr>
<td>($W_{net}=W_{con}-W_{com}$)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total energy consumption $W_{tot}$</td>
<td>MJ</td>
<td>17.96</td>
<td>15.07</td>
<td>18.93</td>
</tr>
<tr>
<td>(Consumed battery energy)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Net energy gain ratio $R_{net}$</td>
<td>%</td>
<td>18.32%</td>
<td>14.13%</td>
<td>20.23%</td>
</tr>
<tr>
<td>($R_{net}=W_{net}/W_{tot} *100%$)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average COP</td>
<td>-</td>
<td>2.61</td>
<td>3.84</td>
<td>2.46</td>
</tr>
</tbody>
</table>
10° C Ambient, 1 WLTC Driving Cycle

Cabin air average temperature

Cabin air entry temperature

- Ambient heat only
- Waste heat only
- Dual heat source
10°C Ambient, 1 WLTC Driving Cycle

Compressor input speed

Compressor driving power
## 10°C Ambient, 1 WLTC Driving Cycle

### Net energy gain

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Unit</th>
<th>Ambient heat only</th>
<th>Waste heat only</th>
<th>Dual heat source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compressor driving energy ( W_{com} ) (including compressor loss)</td>
<td>MJ</td>
<td>1.01</td>
<td>1.11</td>
<td>1.04</td>
</tr>
<tr>
<td>Condenser energy ( W_{con} ) (heat up cabin)</td>
<td>MJ</td>
<td>2.41</td>
<td>2.38</td>
<td>2.36</td>
</tr>
<tr>
<td>Evaporator energy ( W_{eva} ) (waste energy recovery)</td>
<td>MJ</td>
<td>1.82</td>
<td>1.56</td>
<td>0.56 (Ambient heat) 1.10 (Waste heat)</td>
</tr>
<tr>
<td>Net energy gain ( W_{net} ) ( (W_{net}=W_{con} - W_{com} ) )</td>
<td>MJ</td>
<td>1.40</td>
<td>1.27</td>
<td>1.32</td>
</tr>
<tr>
<td>Total energy consumption ( W_{tot} ) (Consumed battery energy)</td>
<td>MJ</td>
<td>16.83</td>
<td>15.85</td>
<td>16.99</td>
</tr>
<tr>
<td>Net energy gain ratio ( R_{net} ) ( (R_{net}=W_{net}/W_{tot} * 100%) )</td>
<td>%</td>
<td>8.32%</td>
<td>8.01%</td>
<td>7.77%</td>
</tr>
<tr>
<td>Average COP</td>
<td>-</td>
<td>2.39</td>
<td>2.14</td>
<td>2.27</td>
</tr>
</tbody>
</table>
Influence of ambient temperature

Net energy gain vs. ambient temperature

Net energy gain (%)

Ambient temperature (°C)

-15 -10 -5 0 5 10 15 20

Ambient heat only
Waste heat only
Dual heat source
Mean temperature rise rate before reaching 20°C target temperature

- Ambient heat only
- Waste heat only
- Dual heat source

Temperature rise rate (°C)

Ambient temperature (°C)
Conclusions and Future work

- Compared to the ambient heat only scheme, the dual heat sources scheme can work at lower temperatures, exhibits higher heating power and thus takes less time to reach thermal comfort temperature, and also has higher net energy gain.

- Compared to the waste heat only scheme, the dual heat source scheme can satisfy the thermal comfort without introducing new key components, has much higher heating power, and also higher net energy gain.

- The main trend of the net energy gain is decreasing with the increase of ambient temperature since the required energy for thermal comfort is lower at higher ambient temperature.

- The main trend of the temperature rise rate is increasing with the increase of ambient temperature because more ambient heat is available at higher ambient temperature.

- Experimental test will be performed after setting up the test rig and demo car.
Thank you for your attention!