A/C System Control Strategies for Major Refrigerant Options

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Introduction
AR selection and then ?

10 years to come to AR selection

- 10 years ago: 1st Phoenix meeting
- 5 years ago: 1st draft of the EU F-Gas regulation
- 1 year ago: HFO 1234-yf becomes the challenger of R744
- 0.5 year ago: EU commission proposal to have a regulation including “Minimum Efficiency requirements for MAC”

After AR option(s) selection due to direct emission issues
Energy efficiency is the main challenge
Agenda: major parts of the presentation

1. Referenced Test Results for 3 refrigerants
   - A/C system at bench
   - In cars at Climatic Wind Tunnel
   - LCCP analysis

2. A/C system control strategies and results
   - Methodology for torque estimation
   - Results for sub-critical refrigerants (R134a & 1234-yf)
   - Results for super-critical refrigerant (R744)
   - Conclusion
## Tested A/C system architectures

<table>
<thead>
<tr>
<th></th>
<th><strong>R744 A/C system</strong></th>
<th><strong>Enhanced R-744 system</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Compressor</td>
<td>28cc externally controlled</td>
<td>Optimized 28cc Externally controlled</td>
</tr>
<tr>
<td>Gas cooler</td>
<td>25 dm2, 16 mm width</td>
<td>25 dm2, 16mm width</td>
</tr>
<tr>
<td>Evaporator</td>
<td>6 passes, 5.3 dm2 (38 mm width)</td>
<td>6 passes, 5.3 dm2 (38 mm width)</td>
</tr>
<tr>
<td>Expansion valve</td>
<td>Fixed orifice + by pass</td>
<td><strong>New back pressure expansion valve</strong></td>
</tr>
<tr>
<td>IHX</td>
<td>Integrated IHX Accumulator (510 cc)</td>
<td>Integrated IHX Accumulator (510 cc)</td>
</tr>
<tr>
<td>Accumulator</td>
<td>110mm</td>
<td>110mm</td>
</tr>
<tr>
<td>Pulley</td>
<td>P/T sensor</td>
<td>Pressure sensor (condenser outlet)</td>
</tr>
<tr>
<td></td>
<td>Evaporator Air Temperature sensor</td>
<td>Evaporator Air Temperature sensor</td>
</tr>
<tr>
<td>System weight</td>
<td>14.5 kg</td>
<td>14.4 kg</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th><strong>R134a &amp; HFO 1234yf A/C system</strong></th>
<th><strong>Enhanced R134a &amp; HFO 1234yf A/C system</strong></th>
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</thead>
<tbody>
<tr>
<td>Compressor</td>
<td>171cc Externally controlled</td>
<td>171cc Externally controlled</td>
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<tr>
<td>IHX</td>
<td>None</td>
<td>High efficiency IHX</td>
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<tr>
<td>Gas cooler</td>
<td>23.5dm2, 16mm width + integrated receiver dryer</td>
<td>23,5dm2, 16mm width + integrated receiver dryer</td>
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<tr>
<td>Evaporator</td>
<td>6 passes (U-bends), 5.3 dm2 (60 mm width)</td>
<td><strong>New 6 passes (counter flow), 5.3 dm2 (48 mm width)</strong></td>
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<tr>
<td>Expansion valve</td>
<td>Thermostatic expansion valve</td>
<td>Thermostatic expansion valve (new settings)</td>
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<tr>
<td>Pulley</td>
<td>110mm</td>
<td>110mm</td>
</tr>
<tr>
<td>Sensors</td>
<td>Pressure sensor (condenser outlet)</td>
<td>Pressure sensor (condenser outlet)</td>
</tr>
<tr>
<td></td>
<td>Evaporator Air Temperature sensor</td>
<td>Evaporator Air Temperature sensor</td>
</tr>
<tr>
<td>System weight</td>
<td>12.4 kg</td>
<td>12.7 kg</td>
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</tbody>
</table>
Test bench facilities

Valeo system test bench is fully instrumented

Acceptance criteria for testing point is ± 5%

the air side cooling capacity is measured with a mixing chamber and compared to the refrigerant.
Method and test conditions at bench

Valeo Standard test conditions

<table>
<thead>
<tr>
<th>HVAC position</th>
<th>MAEI (kg/h)</th>
<th>TAEI (°C)</th>
<th>HRAEI (°C)</th>
<th>MAGI (kg/h)</th>
<th>TAGI (°C)</th>
<th>N (rpm)</th>
<th>TAEO (°C)</th>
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<tbody>
<tr>
<td><strong>High thermal loads</strong></td>
<td></td>
<td></td>
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<tr>
<td>Sizing 45</td>
<td>Fresh air</td>
<td>540</td>
<td>45</td>
<td>40</td>
<td>2300</td>
<td>45</td>
<td>1850</td>
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<tr>
<td>IDLE 45</td>
<td>Fresh air</td>
<td>540</td>
<td>45</td>
<td>40</td>
<td>1300</td>
<td>45</td>
<td>1000</td>
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<tr>
<td>IDLE 40</td>
<td>Fresh air</td>
<td>520</td>
<td>40</td>
<td>40</td>
<td>1000</td>
<td>40</td>
<td>1000</td>
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<tr>
<td>IH 45_35</td>
<td>Recirculation</td>
<td>465</td>
<td>35</td>
<td>30</td>
<td>1500</td>
<td>45</td>
<td>1500</td>
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<tr>
<td>IH 35</td>
<td>Fresh air</td>
<td>540</td>
<td>35</td>
<td>40</td>
<td>1500</td>
<td>35</td>
<td>1500</td>
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<tr>
<td><strong>Average and low thermal loads</strong></td>
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<tr>
<td>IH 35_25</td>
<td>Recirculation</td>
<td>465</td>
<td>25</td>
<td>40</td>
<td>1600</td>
<td>35</td>
<td>1600</td>
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<tr>
<td>IH 30</td>
<td>Fresh air</td>
<td>520</td>
<td>30</td>
<td>40</td>
<td>1600</td>
<td>30</td>
<td>1600</td>
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<td>IH 25</td>
<td>Fresh air</td>
<td>260</td>
<td>25</td>
<td>55</td>
<td>1600</td>
<td>25</td>
<td>1600</td>
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<td>IH 20</td>
<td>Fresh air</td>
<td>260</td>
<td>20</td>
<td>70</td>
<td>1600</td>
<td>20</td>
<td>1600</td>
</tr>
<tr>
<td>IH 15</td>
<td>Fresh air</td>
<td>180</td>
<td>15</td>
<td>90</td>
<td>1600</td>
<td>15</td>
<td>1600</td>
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<tr>
<td><strong>Cool down</strong></td>
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<tr>
<td>CD1</td>
<td>Recirculation</td>
<td>540</td>
<td>46,5</td>
<td>15,5</td>
<td>2300</td>
<td>46</td>
<td>2500</td>
</tr>
<tr>
<td>CD2</td>
<td>Recirculation</td>
<td>540</td>
<td>37</td>
<td>17</td>
<td>2300</td>
<td>46</td>
<td>2500</td>
</tr>
<tr>
<td>CD3</td>
<td>Recirculation</td>
<td>540</td>
<td>28</td>
<td>24</td>
<td>2300</td>
<td>46</td>
<td>2500</td>
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<tr>
<td>CD4</td>
<td>Recirculation</td>
<td>540</td>
<td>30</td>
<td>30</td>
<td>1600</td>
<td>46</td>
<td>1000</td>
</tr>
</tbody>
</table>

All the A/C systems are tested and compared with:

- The same test bench
- The same test matrix
Result at high thermal load: explore the limits

### Conditions

High load test points are the most severe conditions applied to the system in order to check the maximum cooling capacity:

- **Sizing & Idle 45**: 45°C and 40% RH (fresh air)
- **IDLE 40**: 45°C and 40% RH (fresh air)
- **IH45_35 (8°C/min)**: 45°C (recirculation 35°C, 30%)
- **IH35 (8°C/min)**: 35°C and 40% RH (fresh air)

### Conclusions

- **R134a** remains the most efficient for high loads conditions
- **R744 & 1234-yf w/o IHX** show limitation in cooling capacity in severe idle conditions
- For specific high load countries the use of an automatic recirculation HVAC function is recommended with **R744 & 1234-yf w/o IHX**
Result at medium & low thermal loads
Qualify the energy efficiency

Conditions

IH test points have been selected in order to evaluate the A/C loop efficiency according to the West European Climate test matrix.

The A/C loop control the blown air temperature between 8°C and 12°C (depending on the test conditions).

The A/C loop is always in capacity reduction so the cooling capacity is the same whatever the refrigerant.

Conclusions

- R744 becomes more efficient as far as the thermal load is reducing

- Calculated average values for EU climate shows that both systems are close in terms of efficiency with an advantage (6-9%) for R744 in this application
Results on cool down test points

Correlate bench and car tests

Conditions

Cool down test points have been defined in order to simulate the A/C loop behavior during the cool down procedure:
- CD1: conditions after 3’ (40 km/h III gear phase)
- CD2: conditions after 10’ (40 km/h III gear phase)
- CD3: conditions after 30’ (40 km/h III gear phase)
- CD4: conditions after 60’ (IDLE phase)

Conclusions

- R744 can bring a better cool-down than 1234-yf
- But this better cool-down leads to a slightly lower efficiency
In car results: Test in CWT (R-134a and HFO-1234yf)

LV Windtunnel tests - Valeo cooldown R134a vs. HFO 1234yf
Ambient air conditions 45°C & 40% RH (recirculation)

Additional configurations under tests: 171cc compressor + w & w/o IHX + new condenser
In car results: Test in CWT (R-744)

Wind tunnel tests - Valeo cool down R-134a baseline vs. R-744

Ambient air conditions 45°C & 40% RH (recirculation)

Breath level R-134a baseline
Vents outlet- R-134a baseline
Breath level R-744
Vents outlet R-744

1.6 gasoline engine

40 km/h - III gear (30')
IDLE - N (30')
90 km/h - V gear (20')

Temperature (°C)

0 300 600 900 1200 1500 1800 2100 2400 2700 3000 3300 3600 3900 4200 4500 4800

Time (s)

8.9°C
6.3°C
14.9°C
13.9°C
LCCP results

Main assumptions

Direct emissions: optimistic scenario
- < 6 g/y in EU as regular leak in use added to all others (service, accident, EoL,...) leading to little more than 1 charge lost along life time. Worst case being around 1,7 charge if no effort on R&R

Indirect emissions:
- Compressor shaft power: test bench results
- Electrical power: blower and fan powers according to Valeo control strategy

Conclusions

- Direct emissions of R134a leads to a 1/3 gap versus Low GWP refrigerants
- Indirect emissions between the 2 remaining AR options are in a small range < ±10% depending of climate basis
- On a worldwide basis 1234-yf shows the lowest global emissions
Methodology for Torque estimation:
control software based on physical models

<table>
<thead>
<tr>
<th>Inputs</th>
<th>Sequence of physical models</th>
<th>Controlled parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sub-critical</td>
<td></td>
<td></td>
</tr>
<tr>
<td>R-134a &amp; 1234-yf</td>
<td></td>
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<tr>
<td>Super-critical</td>
<td></td>
<td></td>
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<tr>
<td>R-744</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Inputs:
- Car speed
- Fan power
- PRCO
- TRCO
- Ncomp
- Ivalve
- PRCO
- TRCO
- Ncomp
- PRCO
- TRCO
- Text
- Ncomp
- Ivalve
- PRCO
- TRCO
- Ncomp

Sequence of physical models:
- Air flow Estimation
- Front end model
- Refrigerant Mass flow estimation
- Condenser model
- Suction pressure Estimation
- Compressor model
- Isentropic compressor enthalpy difference
- Suction temperature Estimation
- Compressor model
- Density estimation
- Mass flow Estimation
- Expansion valve model
- Suction pressure estimation
- Compressor model
- Suction temperature estimation
- Compressor model
- Compressor shaft power
- Compressor Model
- Shaft power estimation
- Compressor Model
- Torque Estimation
- Torque

Controlled parameters:
- Torque

Sub-critical:
- R-134a & 1234-yf
- Ncomp

Super-critical:
- R-744

Inputs:
- PRCO
- TRCO
- Text
- Ncomp
- Ivalve

Controlled parameters:
- Torque
Torque estimation and control results for R-134a
the same algorithm is used for 1234-yf with an adjusted tuning

R-134a Windtunnel test: 25°C/55%/250Kg/h
Torque estimation

Torque estimated with +/- 1.5 N.M accuracy
Torque estimation and control results for R-744

R-744 Wind tunnel test: 25°C/55%

Torque estimation

Torque estimated with +/- 1 N.M accuracy
Conclusions

A/C system control with torque estimation is the key function to deal with the energy efficiency challenge on MAC systems

This validated software approach brings key advantages:

- No new device needed vs existing ones ➔ **No additional cost**
- Same software structure and environment used ➔ **Development robustness**
- Fully adaptable technique to all MAC solutions and market constraints
  - Adapted and tested for all A/C cycles ➔ **R134a, R744, 1234-yf: multi-refrigerant**
  - Adapted to different compressor technologies ➔ **Market oriented: multi-sourcing**
  - Able to be tuned to local efficiency requests ➔ **Climate oriented: multi-region**
  - Able to adapt strategy (cool-down, stabilized,..) ➔ **Real life oriented: multi-usage**
- Engine control optimized thanks to the given real-time dynamic A/C torque value
Many thanks for your attention