INVESTIGATION OF FUEL CONSUMPTION AND SYSTEM PERFORMANCE BY CHANGING COMPRESSOR TYPE, CONTROL METHOD AND REFRIGERANT

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  • Test Conditions
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Goal of this Study

The goal of these investigations is the comparison of:

- **different compressor types:**
  - R134a - TRS → Scroll fixed displacement
  - R134a - PXC → internal variable displacement (IVD), swash plate compressor
  - R134a - PXE → internal controlled displacement with external variable set points (CVD)
  - R744 - SLC → external controlled SANDEN LUK Compressor for CO₂

- **different refrigerant systems:** R134a and R744 (CO₂)

- **different system control methods:** fixed and variable set points for the HVAC modul

The fuel consumption and system performance was done with a Honda Civic 1.4 Vision in the climatic wind tunnel.
Tested Compressors

R134a Compressors

- TRS09
- PXE/PXC13

R744 (CO₂) Compressor

- SLC28
• Goal of this Study

• Vehicle Setup

• Test Conditions

• Test Results

• Summary

Fuel Consumption Measurement Equipment
R134a A/C Sensors Installation Points
CO₂ A/C Sensors Installation Points
Sensor List
Thermocouple grid evaporator air Inlet
Thermocouple grid evaporator air Outlet
Thermocouple grid air condenser/gas cooler Inlet
Torque measurement device
Compressor specification/Refrigerant and Oil Charge
Fuel Consumption Measurement Equipment from the company PLU (Pierburg Instruments GmbH)

Direct mass flow measurement

Fuel Consumption Measurement Equipment

1 - Fuel inlet
2 - Fuel return to tank
3 - Fuel outlet
4 - Fuel return from engine

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R134a A/C Sensors Installation Points

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CO₂ A/C Sensors Installation Points

- Condenser/Gas cooler
- Int. Heat Exchanger
- Compressor
- TXV
- Evaporator
- Receiver

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# Sensor List

<table>
<thead>
<tr>
<th>Temperatures R744</th>
<th>Temperatures R134a</th>
<th>Air Temperature</th>
<th>Voltages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compressor Out</td>
<td>Compressor Out</td>
<td>Evaporator front 1</td>
<td>Foot rear left</td>
</tr>
<tr>
<td>Gas Cooler Out</td>
<td>Condenser Out</td>
<td>Condenser grid 1</td>
<td></td>
</tr>
<tr>
<td>TXV in</td>
<td>TXV in</td>
<td>Evaporator front 2</td>
<td>Foot rear right</td>
</tr>
<tr>
<td>TXV out</td>
<td>TXV out</td>
<td>Condenser grid 2</td>
<td></td>
</tr>
<tr>
<td>Evaporator Out</td>
<td></td>
<td>Evaporator front 3</td>
<td>Foot front left</td>
</tr>
<tr>
<td>Compressor In</td>
<td></td>
<td>Condenser grid 3</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Evaporator front 4</td>
<td>Foot front right</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Condenser grid 4</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Evaporator front 5</td>
<td>Foot front right</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Condenser grid 5</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Evaporator rear 1</td>
<td>Head front left</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Condenser grid 6</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Evaporator rear 2</td>
<td>Head front middle</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Condenser grid 7</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Evaporator rear 3</td>
<td>Head front right</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Condenser grid 8</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Pressures R744</th>
<th>Pressures R134a</th>
<th>Current</th>
<th>Engine Speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compressor Out</td>
<td>TXV in</td>
<td>Louver left</td>
<td>measured at crankshaft</td>
</tr>
<tr>
<td>Gas Cooler Out</td>
<td>TXV out</td>
<td>Louver centre left</td>
<td></td>
</tr>
<tr>
<td>TXV In</td>
<td>Compressor in</td>
<td>Louver centre right</td>
<td></td>
</tr>
<tr>
<td>Evaporator Out</td>
<td>Condenser out</td>
<td>Louver right</td>
<td></td>
</tr>
<tr>
<td>Compressor In</td>
<td>Crankcase</td>
<td>Car Ventilation</td>
<td>Head rear middle</td>
</tr>
<tr>
<td>Crankcase</td>
<td></td>
<td>Head rear right</td>
<td>Head rear right</td>
</tr>
</tbody>
</table>

- **Test Points Equipped by Sanden**
- **Temperatures**
  - R744
  - R134a
- **Air Temperatures**
- **Voltages**
- **Pressures**
  - R744
  - R134a
- **Current**
- **Engine Speed**
Thermocouple Grid Evaporator Air Temperature Inlet

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Thermocouple Grid Evaporator Air Temperature Outlet
Thermocouple Grid Condenser / Gas cooler Air Inlet
Torque Measurement Device

A strain gauge was applied on the compressor shaft, a slip ring was used for the connection to the signal amplifier. This method is very sensitive due to high thermal stress. Only used for TRS and PXC tests.
• Goal of this Study
• Vehicle Setup
• Test Conditions
• Test Results
• Summary

Driving Conditions
Wind Tunnel Conditions and Car Settings
Cabin Temperature Calculation
Compressor / System Control Method
## Driving Conditions

<table>
<thead>
<tr>
<th>Test</th>
<th>Soaking</th>
<th>120kph phase</th>
<th>80kph phase</th>
<th>40kph phase</th>
<th>Idle Phase</th>
</tr>
</thead>
<tbody>
<tr>
<td>Driving Gear</td>
<td>-</td>
<td>5th gear</td>
<td>4th gear</td>
<td>4th gear</td>
<td>Idle</td>
</tr>
<tr>
<td>Duration</td>
<td>*)</td>
<td>Until stability is reached</td>
<td>Until stability is reached</td>
<td>Until stability is reached</td>
<td>Until stability is reached</td>
</tr>
<tr>
<td>A/C Setting</td>
<td>-</td>
<td>A/C Off</td>
<td>A/C Off</td>
<td>A/C Off</td>
<td>A/C Off</td>
</tr>
<tr>
<td></td>
<td></td>
<td>A/C On Blower Max</td>
<td>A/C On Blower Max</td>
<td>A/C On Blower Max</td>
<td>A/C On Blower Max</td>
</tr>
</tbody>
</table>

*) Time required to achieve a special under seat air temperature
### Wind Tunnel Conditions and Car Settings

<table>
<thead>
<tr>
<th>No</th>
<th>Ambient Temp. [°C]</th>
<th>Humidity [%]</th>
<th>A/C</th>
<th>Solar load</th>
<th>Intake</th>
<th>Blower Speed</th>
<th>Car Cabin Temp. [°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1a</td>
<td>5</td>
<td>60</td>
<td>on</td>
<td>no</td>
<td>Fresh</td>
<td>high</td>
<td>23</td>
</tr>
<tr>
<td>1b</td>
<td>5</td>
<td>60</td>
<td>off</td>
<td>no</td>
<td>Fresh</td>
<td>high</td>
<td>23</td>
</tr>
<tr>
<td>2a</td>
<td>10</td>
<td>75</td>
<td>on</td>
<td>no</td>
<td>Fresh</td>
<td>high</td>
<td>23</td>
</tr>
<tr>
<td>2b</td>
<td>10</td>
<td>75</td>
<td>off</td>
<td>no</td>
<td>Fresh</td>
<td>high</td>
<td>23</td>
</tr>
<tr>
<td>3a</td>
<td>20</td>
<td>60</td>
<td>on</td>
<td>no</td>
<td>Fresh</td>
<td>high</td>
<td>23</td>
</tr>
<tr>
<td>3b</td>
<td>20</td>
<td>60</td>
<td>off</td>
<td>no</td>
<td>Fresh</td>
<td>high</td>
<td>23</td>
</tr>
<tr>
<td>4a</td>
<td>30</td>
<td>60</td>
<td>on</td>
<td>no</td>
<td>Fresh</td>
<td>high</td>
<td>23</td>
</tr>
<tr>
<td>4b</td>
<td>30</td>
<td>60</td>
<td>off</td>
<td>no</td>
<td>Fresh</td>
<td>high</td>
<td>23</td>
</tr>
<tr>
<td>5a</td>
<td>40</td>
<td>60</td>
<td>on</td>
<td>930 W/m²</td>
<td>Recirc.</td>
<td>high</td>
<td>23</td>
</tr>
<tr>
<td>5b</td>
<td>40</td>
<td>60</td>
<td>off</td>
<td>930 W/m²</td>
<td>Recirc.</td>
<td>high</td>
<td>23</td>
</tr>
</tbody>
</table>
Cabin Temperature Calculation

The average car cabin temperature is calculated as follows*):

- 53% Head temperatures
- 23,5% Seat temperature
- 23,5% Foot temperatures

*) see also sensor list
Compressor / System Control Method

Ambient Temperature 20°C

Evaporator

Cabin Temperature 23°C

Heater

Air Temperature [°C]

20°C

10°C

4°C

23°C Car Cabin Temperature

Cool Down

PXE

Re-Heat

PXC (100% PWM)
Compressor / System Control Method

- **TRS**: clutch cycling
  \[ \Rightarrow \text{controlled by the temperature sensor at the evaporator in the HVAC module} \]

- **PXC**: clutch cycling, PWM signal 100% simulating an internal controlled compressor with fixed set point  \[ \Rightarrow \text{controlled by the temperature sensor at the evaporator in the HVAC module} \]

- **PXE**: change of PWM signal to reach average air temperature after evaporator = f(ambient)
  
  Ambient temperature:  
  \[ \begin{array}{cccc}
  5^\circ \text{C} & 10^\circ \text{C} & 20^\circ \text{C} & \text{higher than } 20^\circ \text{C} \\
  
  \end{array} \]

  \[ T_{av., \text{air, evaporator, outlet}}: \begin{array}{cccc}
  4^\circ \text{C} & 8^\circ \text{C} & 10^\circ \text{C} & \text{lowest setting} \\
  
  \end{array} \]

- **SLC CO\textsubscript{2} system**: reach the same average air temperature after evaporator = f(ambient)
  
  Ambient temperature:  
  \[ \begin{array}{cccc}
  5^\circ \text{C} & 10^\circ \text{C} & 20^\circ \text{C} & \text{higher than } 20^\circ \text{C} \\
  
  \end{array} \]

  \[ T_{av., \text{air, evaporator, outlet}}: \begin{array}{cccc}
  4^\circ \text{C} & 8^\circ \text{C} & 10^\circ \text{C} & \text{lowest setting} \\
  
  \end{array} \]
• Goal of this Study
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Fuel consumption
A/C related fuel consumption calculated from the fuel consumption difference between A/C on and A/C off
Pull Down Tests with R134a and CO₂
Fuel Consumption Difference  A/C on - A/C off

Only belt driven compressors. CO\textsubscript{2} electric compressor is externally supplied - no comparison of the FC differences possible.
Idle - Fuel Consumption Difference  A/C on - A/C off

CO₂ is worse at lower speed and higher temperature (See slide 63 and following).

At part load condition external controlled compressor (PXE) have significant advantages.

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40 kph
Fuel Consumption Difference  A/C on - A/C off

AC on / Blower high / 40 kph

CO₂ is worse at lower speed and higher temperature (See slide 63 and following).

At part load condition external controlled compressor (PXE) have significant advantages.

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80 kph
Fuel Consumption Difference  A/C on - A/C off

AC on / Blower high / 80 kph

At part load condition external controlled compressor (PXE) have significant advantages.

SLC is good at higher speed and higher temperature.

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120 kph
Fuel Consumption Difference  A/C on - A/C off

At part load condition external controlled compressor (PXE) have significant advantages.

SLC is good at higher speed and higher temperature.

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External controlled compressors (PXE) has at part load condition (10°C - 20°C) advantages due to variable evaporator temperature control.

- CO$_2$ is worse at lower speed and higher temperature, gas cooler performance seems to be very important.
- CO$_2$ SLC showed the lowest FC at high speed and high temperature.
Pull Down Test - R134a PXE

Car Cabin Temperatures

- Ambient Temperature: 40°C
- R.H.: 60%
- Sun Load: 930 W
- Refrigerant: R134a
- Compressor: PXE13
- REC
- 40 kph, 4th gear
- 100 kph, 5th gear
- 0 kph, Idle

19 minutes for 30 K cooling down of the average car cabin temperature

Temperature graph showing:
- Average Head
- Average Foot
- Average Louver
- Average Cabin

53.8 °C
25.0 °C

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Pull Down Test - CO₂ SLC

Car Cabin Temperatures

- 40 kph, 4th gear
- 100 kph, 5th gear
- 0 kph, Idle

Temperature [°C]

Time [hh:mm]

0:00 0:04 0:08 0:12 0:16 0:20 0:24 0:28 0:32 0:36 0:40 0:44 0:48 0:52 0:56 1:00 1:04 1:08 1:12 1:16 1:20 1:24 1:28 1:32 1:36 1:40 1:44 1:48 1:52 1:56 2:00 2:04 2:08 2:12 2:16 2:20 2:24 2:28 2:32 2:36 2:40 2:44 2:48 2:52 2:56 3:00

- Controlability need to be improved.
- 55 °C
- 25 °C

9 minutes for 30 K cooling down of the average car cabin temperature - much larger cooling capacity

Pull Down Test
Ambient Temperature: 40 °C
R.H.: 60%
Sun Load: 930 W
Refrigerant: R744
Compressor: SLC
REC

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Summary of Pull Down Tests

• The R134a system needs 19 minutes to reach 25°C cabin temperature.
• The CO₂ SLC system needs 9 minutes to reach 25°C cabin temperature.
• The results show an unnecessary high cooling capacity of the CO₂ SLC system (around 100% more).
• Optimising the CO₂ SLC system to a smaller system, means decreasing the maximum displacement. Probably it is still possible to have better performance, even at lower speed and higher temperature.