TLK-Thermo GmbH

Investigation of fuel reduction potential of a capacity controlled HVAC system for buses using virtual test drives

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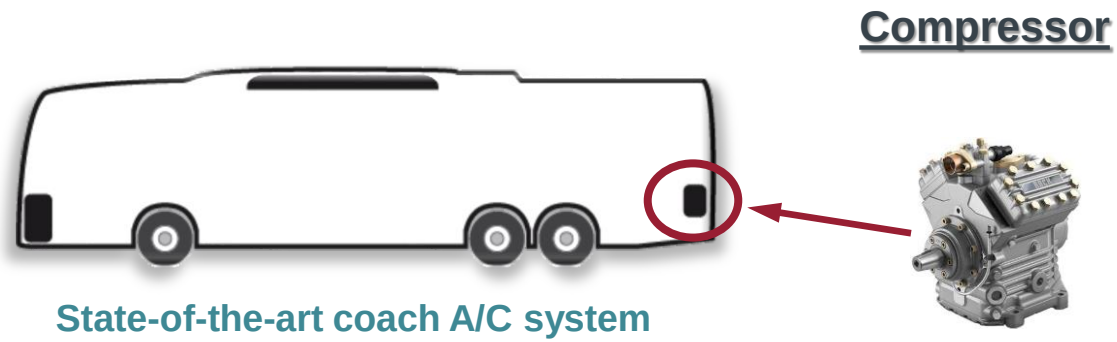
Motivation

- Emission by AC systems
  - Direct emission
    - Refrigerant leakage (GWP, ODP)
  - Indirect emission
    - Fuel consumption
- Possible measures
  - Alternative refrigerant R-744 (CO_2)
  - Improve AC efficiency: Control compressor capacity
- Measures have impact on many subsystems of the vehicle
  - Full vehicle simulation
  - Realistic use cases

Starting situation

State-of-the-art coach A/C system

Starting situation



State-of-the-art coach A/C system

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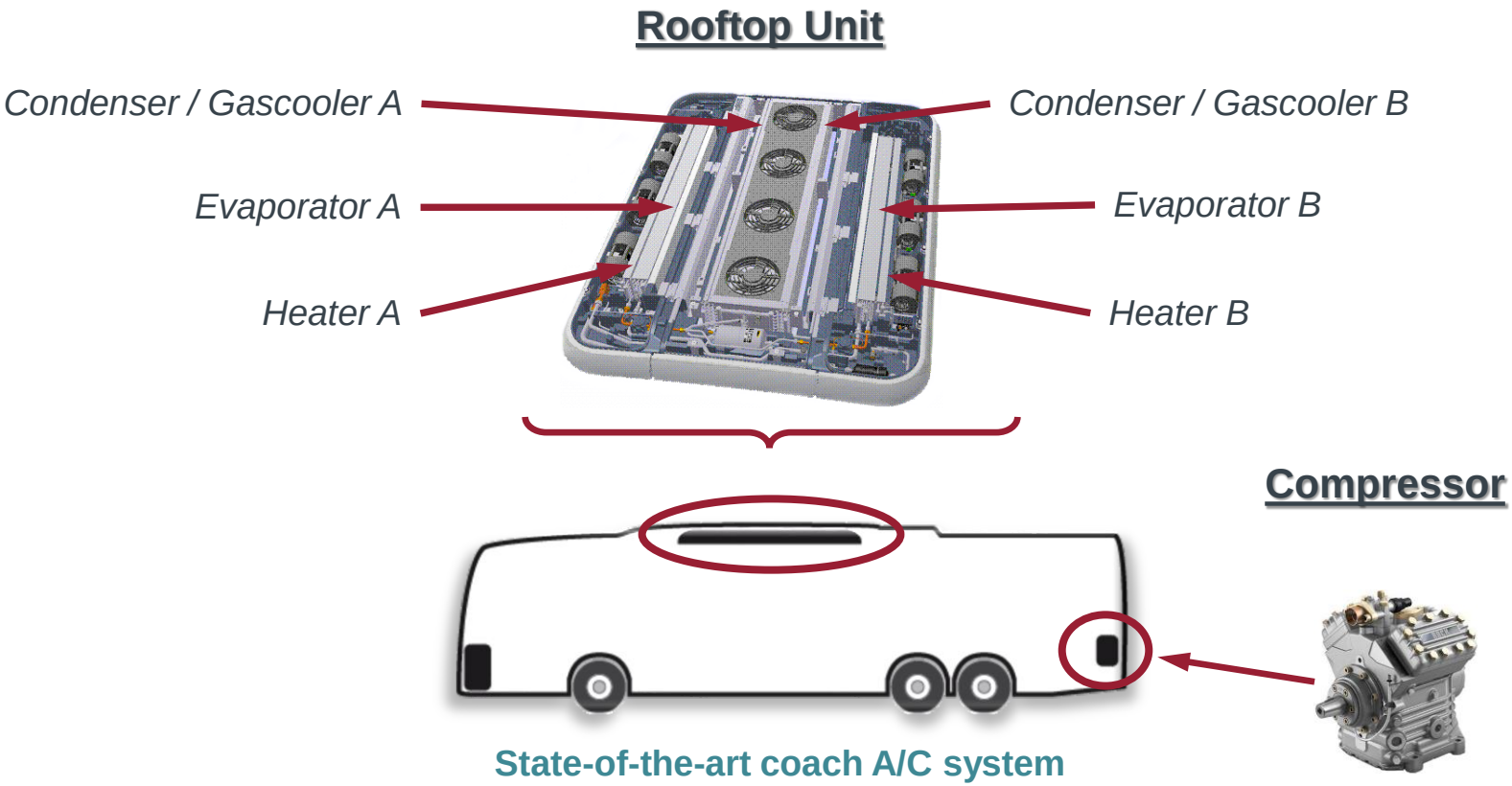

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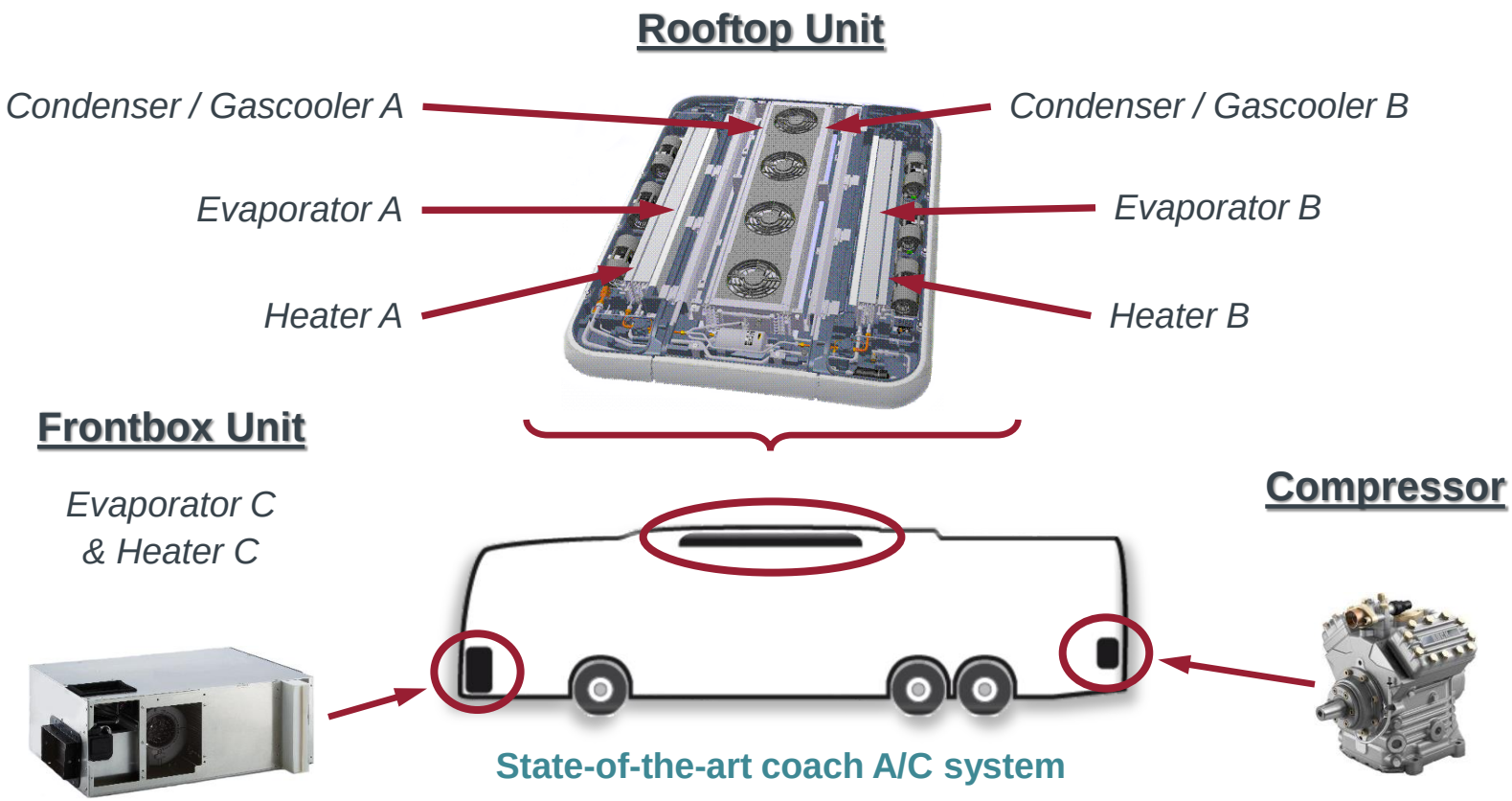

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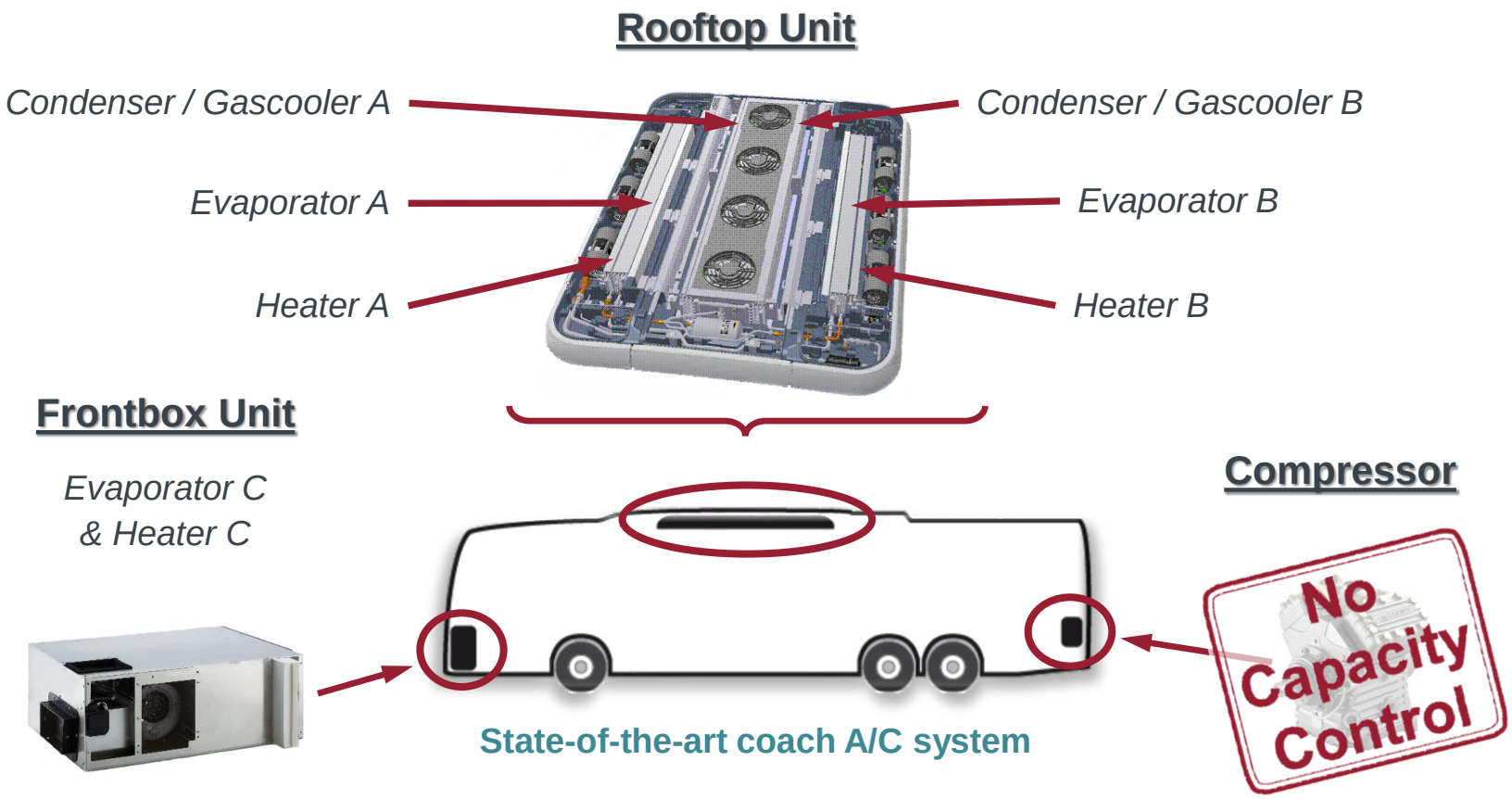
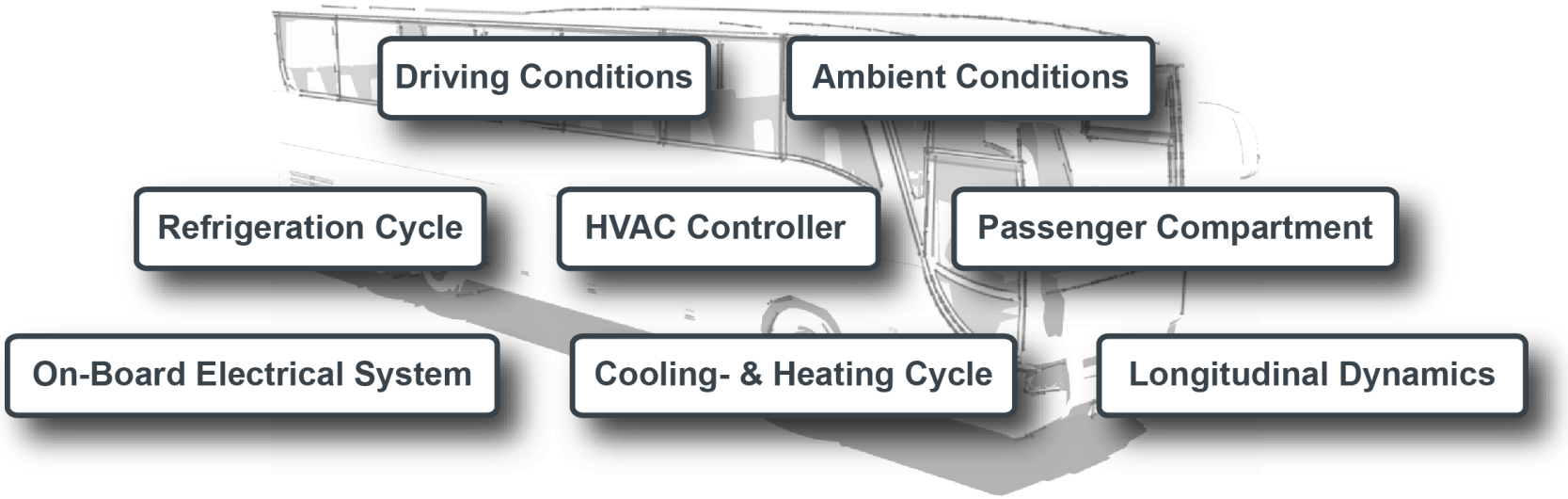


Controlling air-side cooling capacity by reheat of the cooled air!

Modelica Model

Subsystem of complete physical vehicle model of a coach

(developed and validated for research issues in the realm of air conditioning systems in buses)

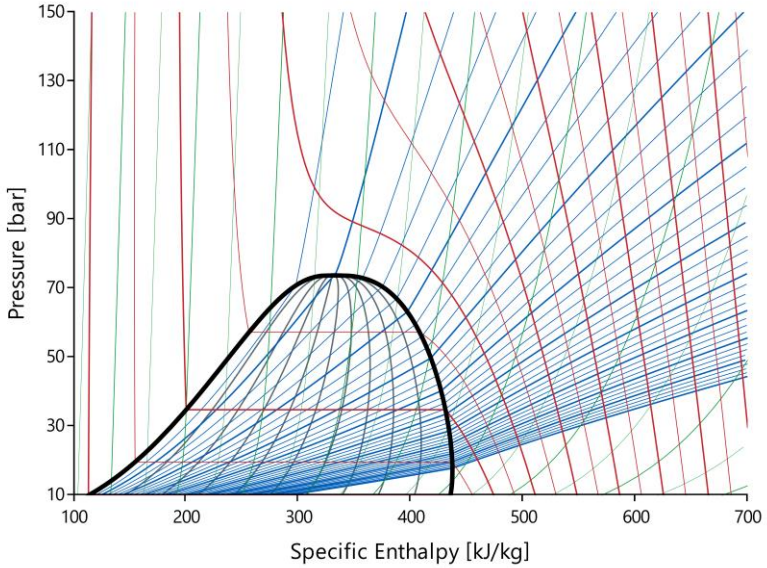


(all subsystems modeled using Modelica and solved using one integrator)

Modelica Model

Multiparameter Fundamental Equation of State by Span & Wagner 1996

Spline Based Table Lookup Method

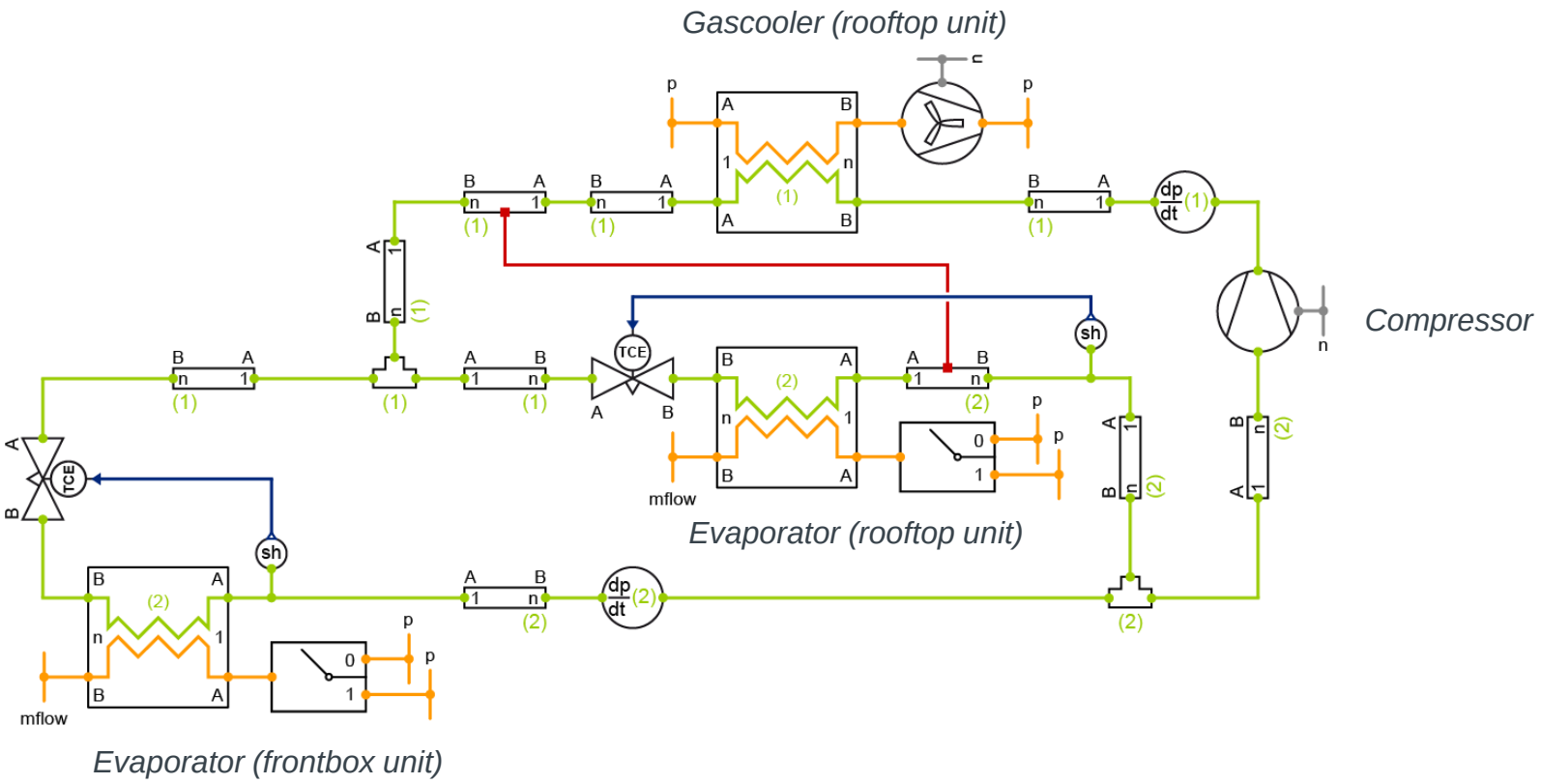


Bicubic Spline Interpolation

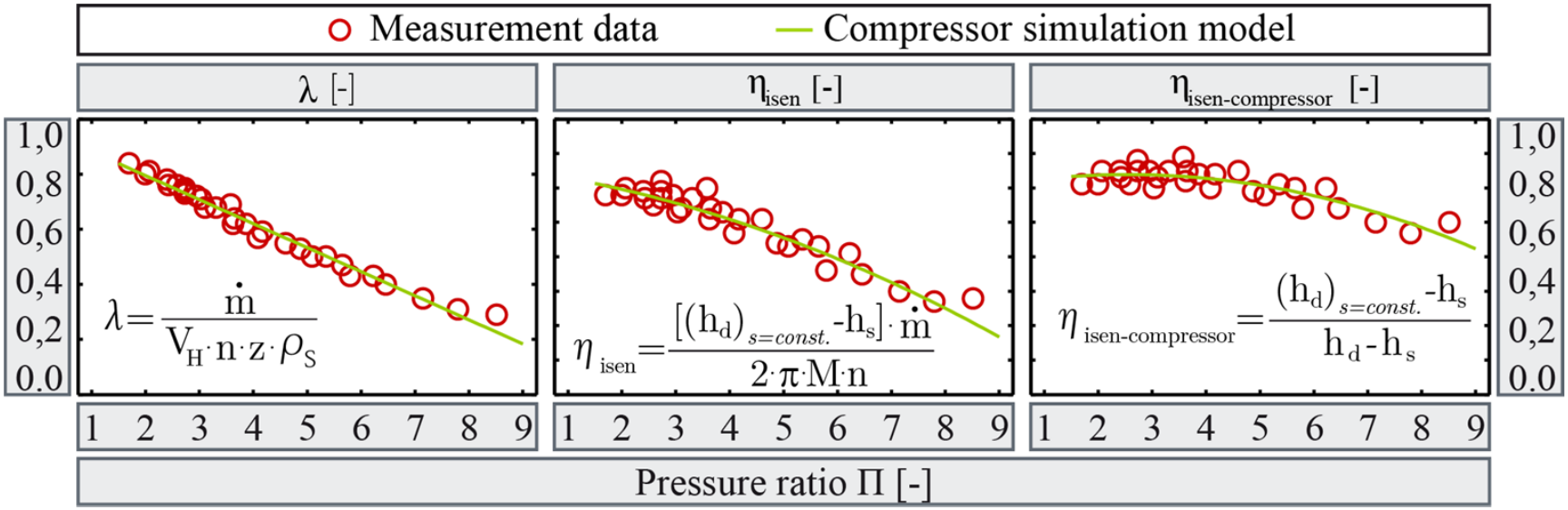
similar to IAPWS Guideline / Kunick 2015

Modelica Model

Detailed model of R-744 refriegrant cycle with modelling of all fundamentally relevant heat transfer and pressure losses



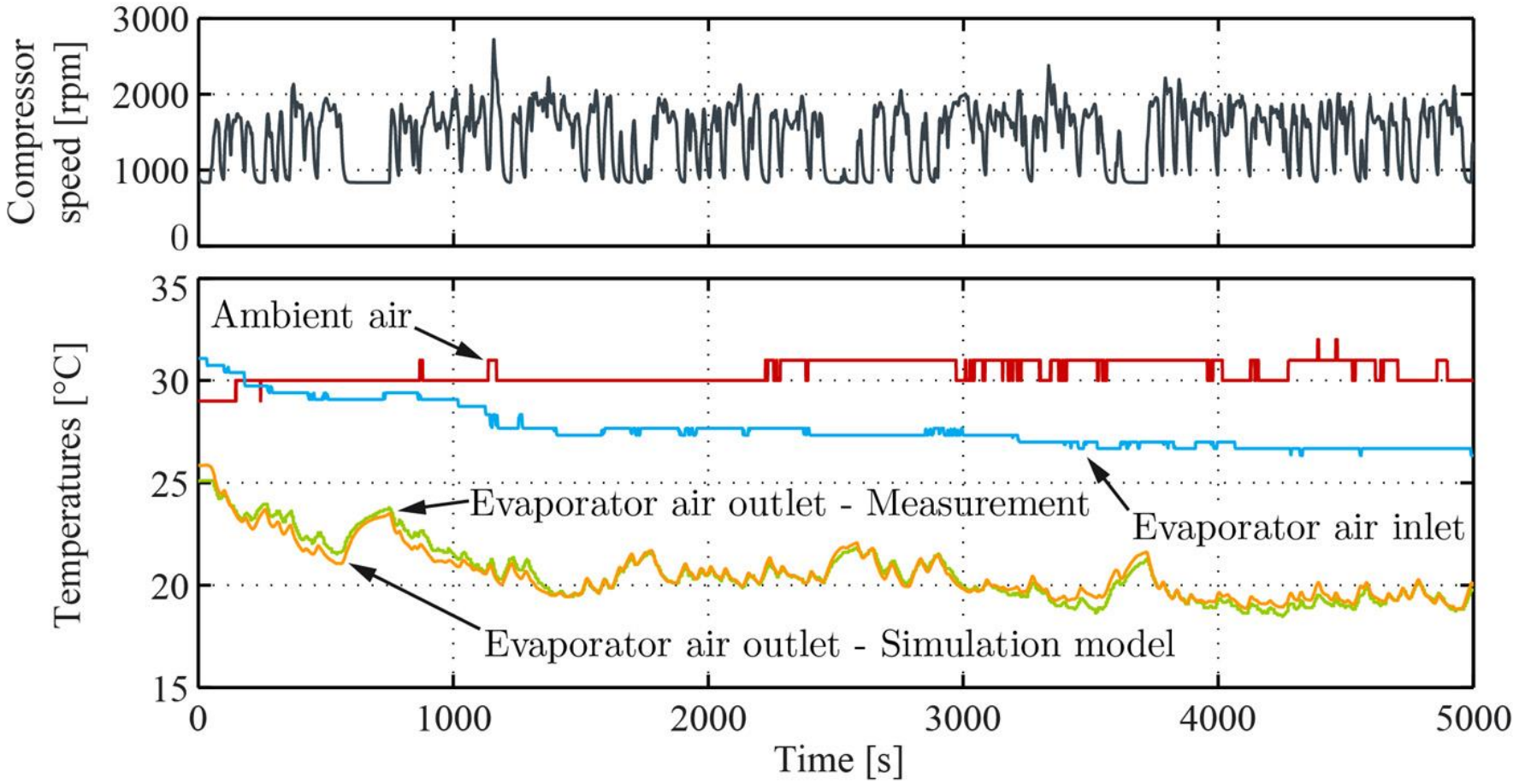
Compressor Validation



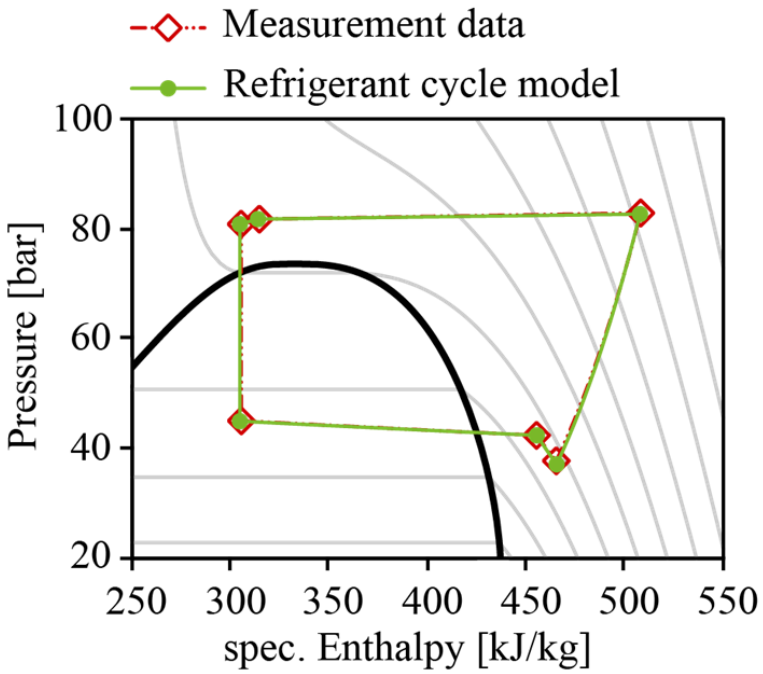
Heat Transfer and Pressure Drop

- Air side heat transfer and pressure drop correlation by Haaf 1988
- Refrigerant side heat transfer:
  - One phase:
    - Re < 2300: Nusselt := 3.657
    - 2300 < Re < 10^4: Nusselt by Gnielinski 1975
    - 10^4 < Re: Nusselt by Dittus and Boelter 1930
  - Two phase:
    - Condensation by Cavallini et al 2006 and Kondou and Hrnjak 2011
    - Evaporation by Gungor and Winterton 1987
- Refrigerant side pressure drop:
  - Re > 2300: Swamee and Jain 1976 (Colebook-White)
  - Re < 2300: ξ=64/Re

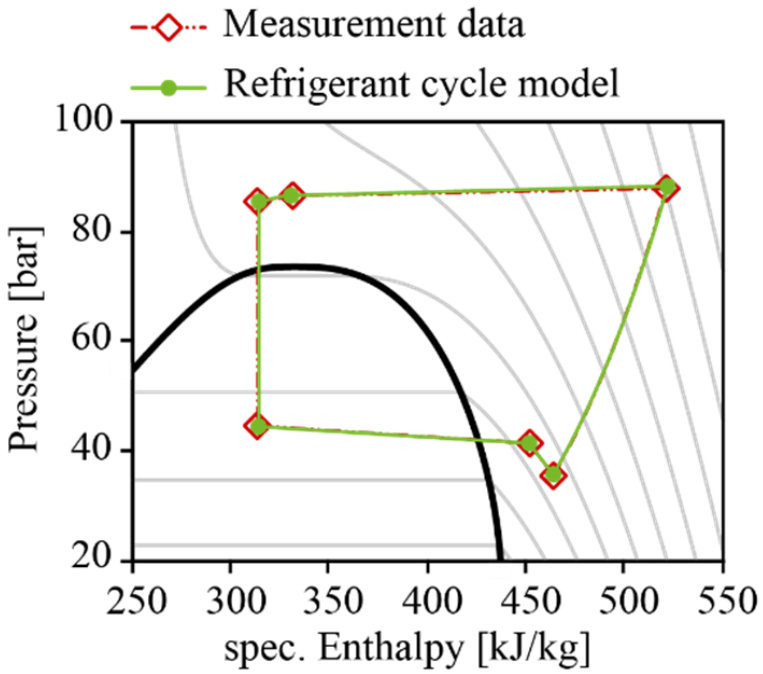
AC System Validation



AC System Validation



After 2000s



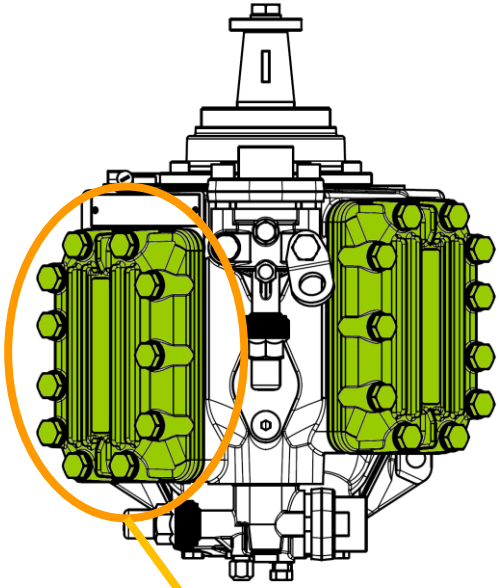
After 3500s

Compressor capacity control methods

- State-of-the-art: constant displacement, coupled to engine
- Cooling capacity is controlled with heating
- Possible measures to control the compressor capacity
  - Continuously variable transmission
  - Separate drive with electric machine
  - Cycling clutch operation
  - Cylinderbank shutdown
  - Two-speed pulley gearbox

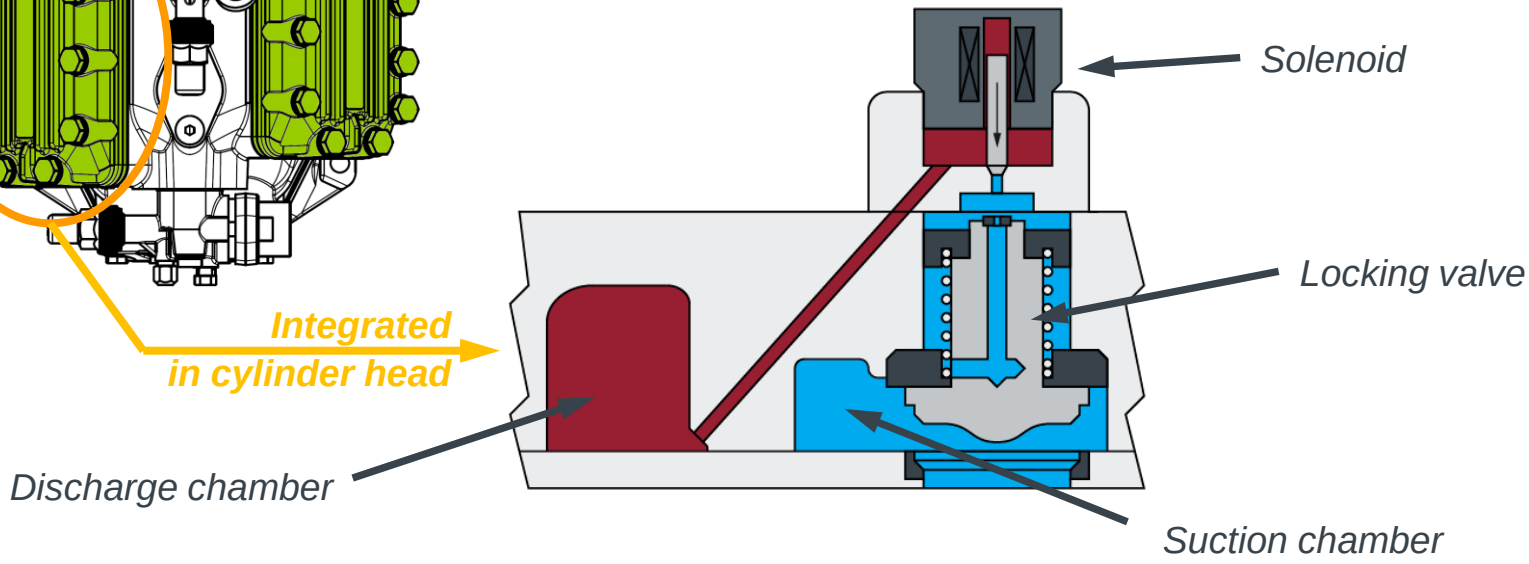
Compressor capacity control methods

Cylinder bank shutdown by suction gas interlock



Solenoid not energized, suction inlet is open

Full load operation



Compressor capacity control methods

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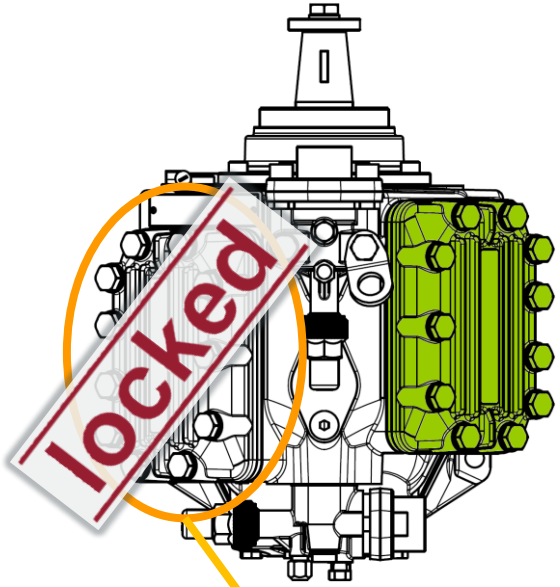
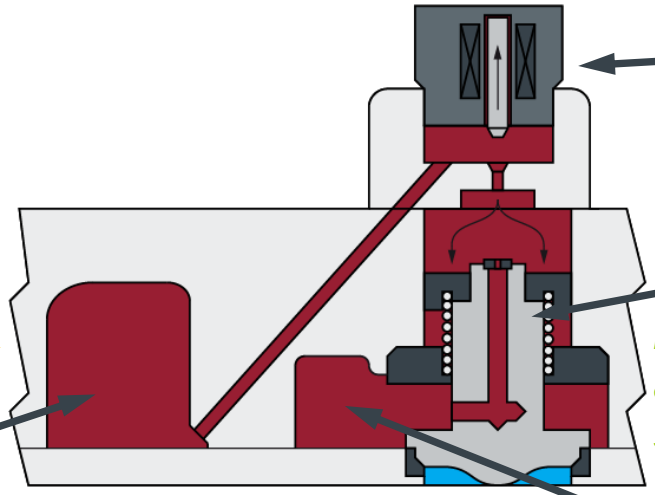


Solenoid energized, suction inlet is closed

Part load operation



Solenoid ***energized***

Locking valve

moves downwards
&
shuts off suction chamber

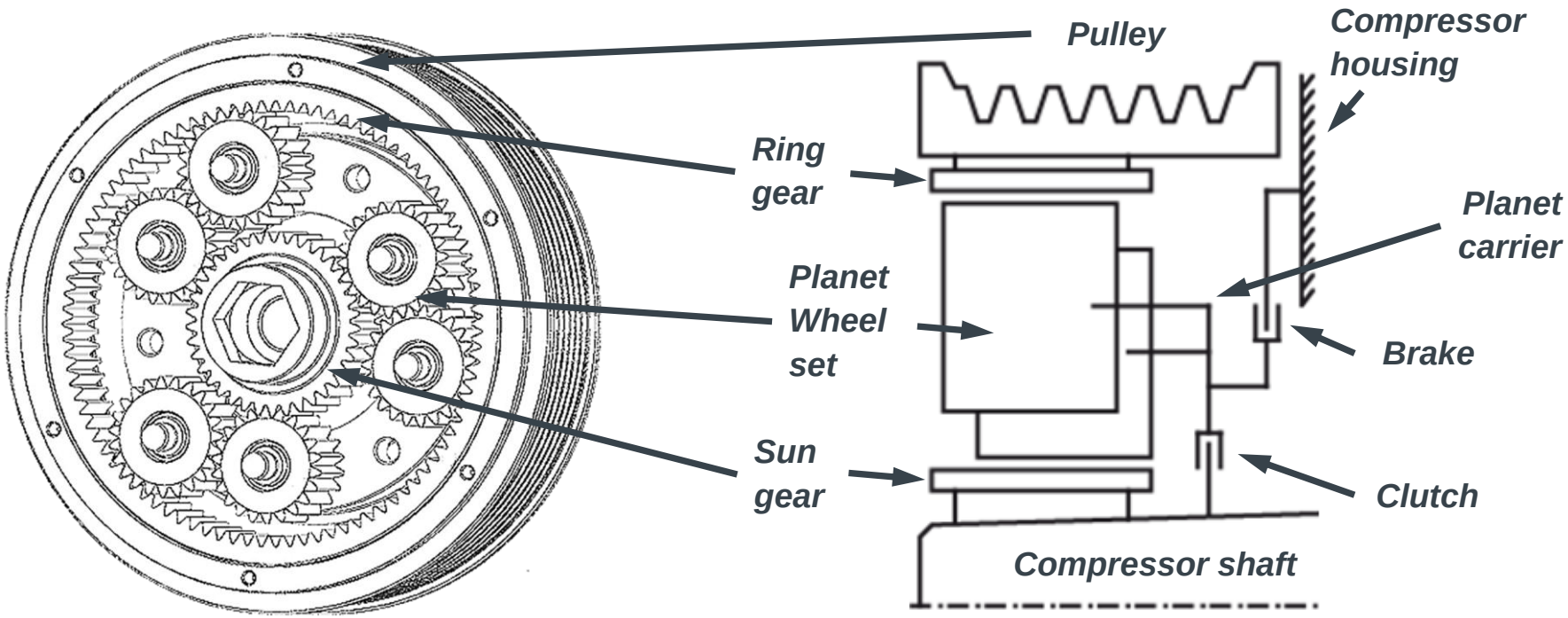
Integrated
in cylinder head

Discharge chamber

Suction chamber

Compressor capacity control methods

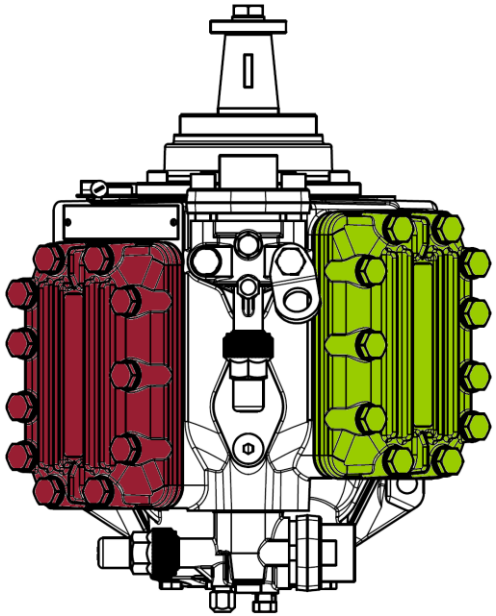
Speed control by pulley integrated planetary gearbox



Energy Saving Concepts

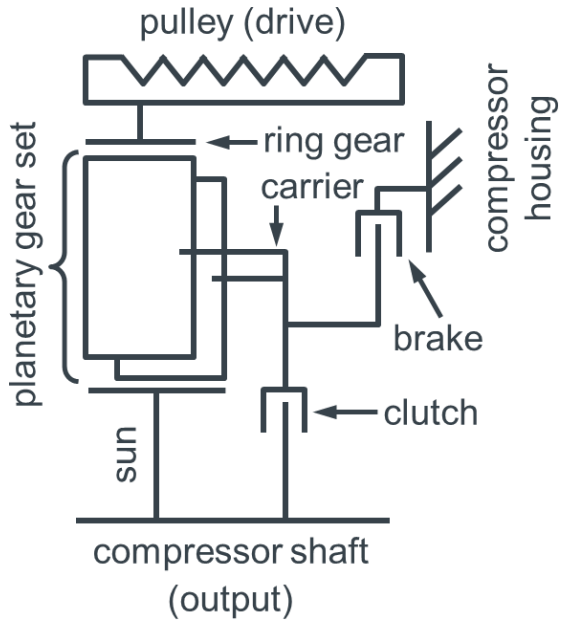
Cylinder-Bank Shutdown

Suction gas shut-off via pilot-controlled solenoid valve

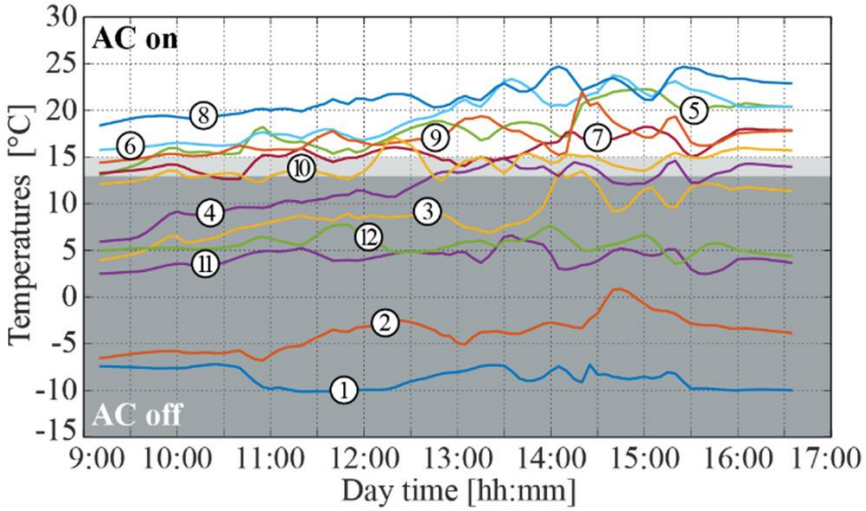


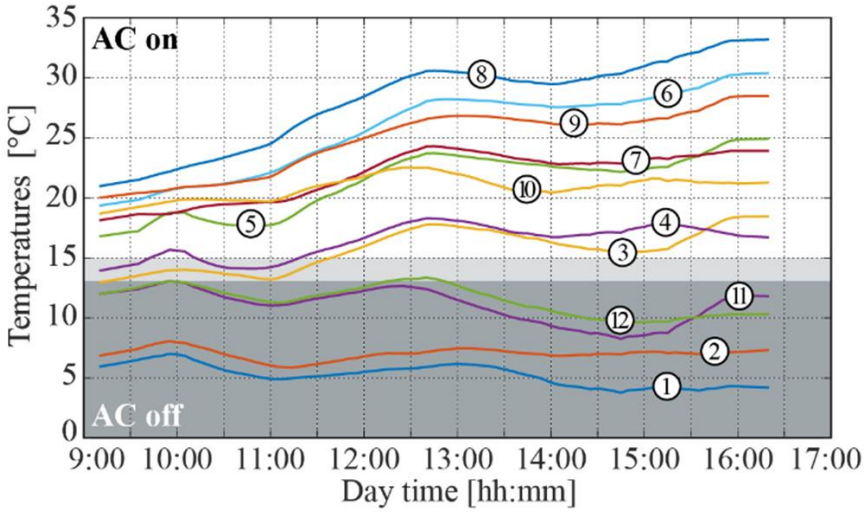
Modified Gearbox

Pulley Integrated Two Speed Gearbox

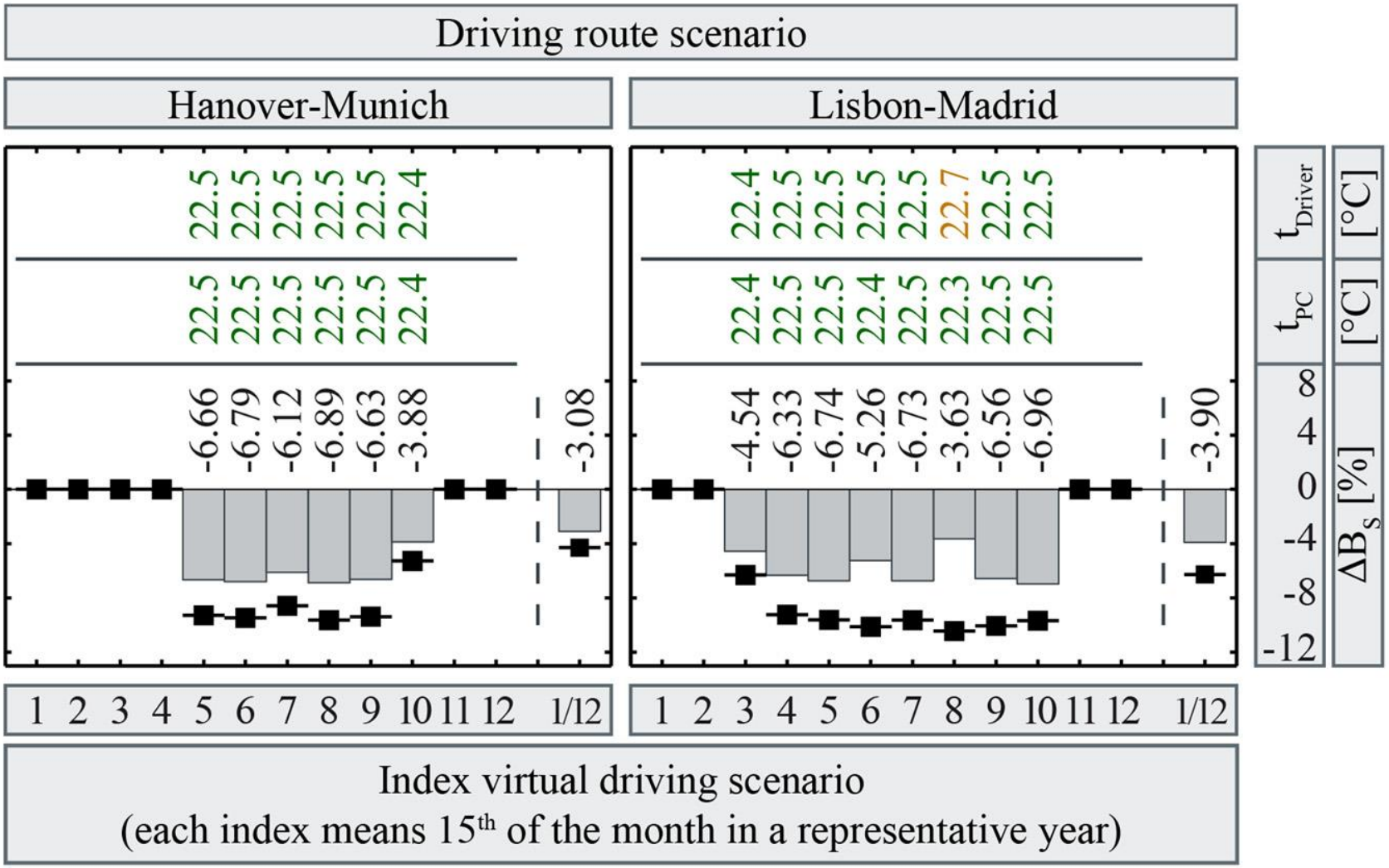


Highly Dynamic Boundary Conditions

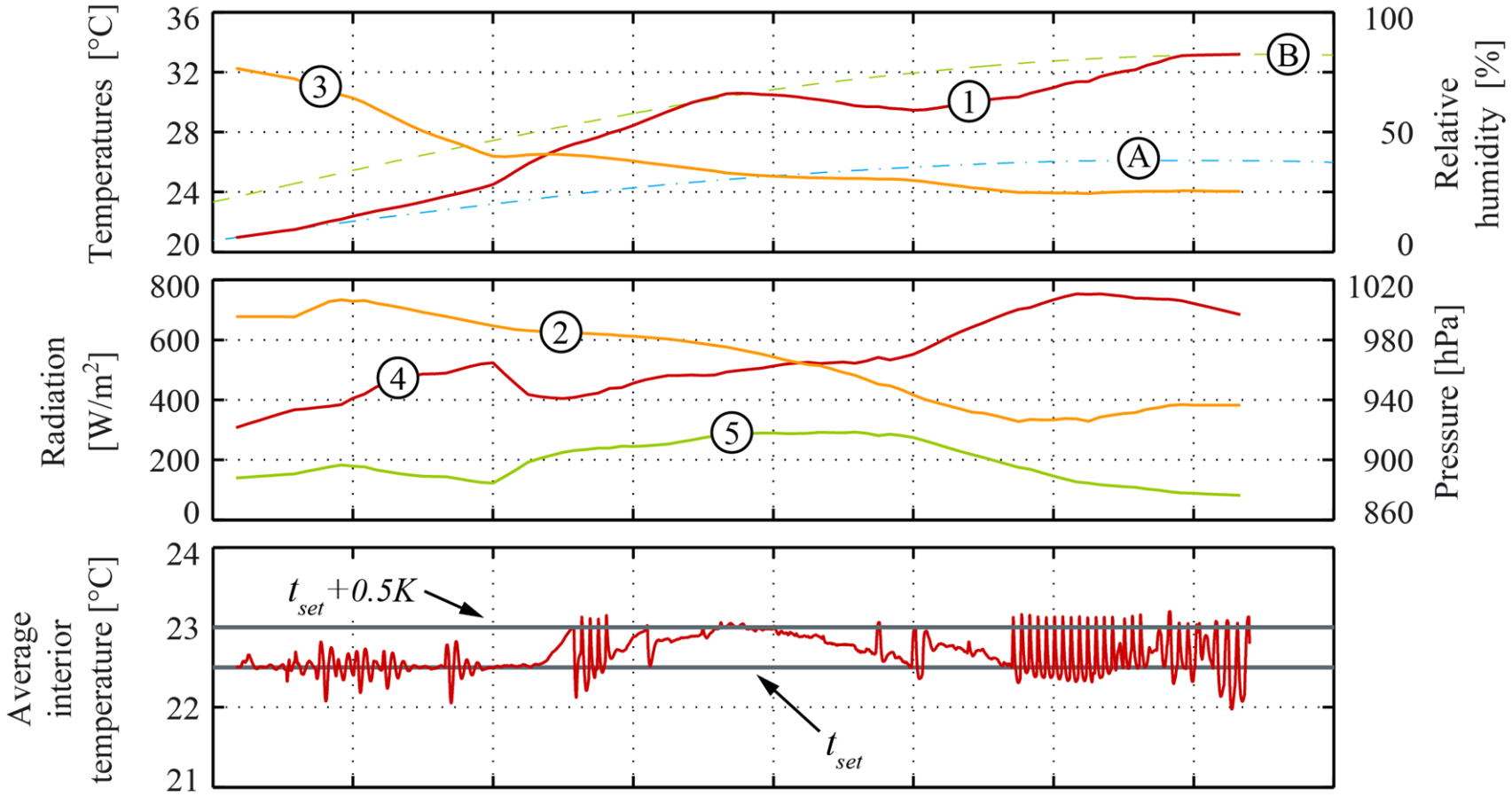




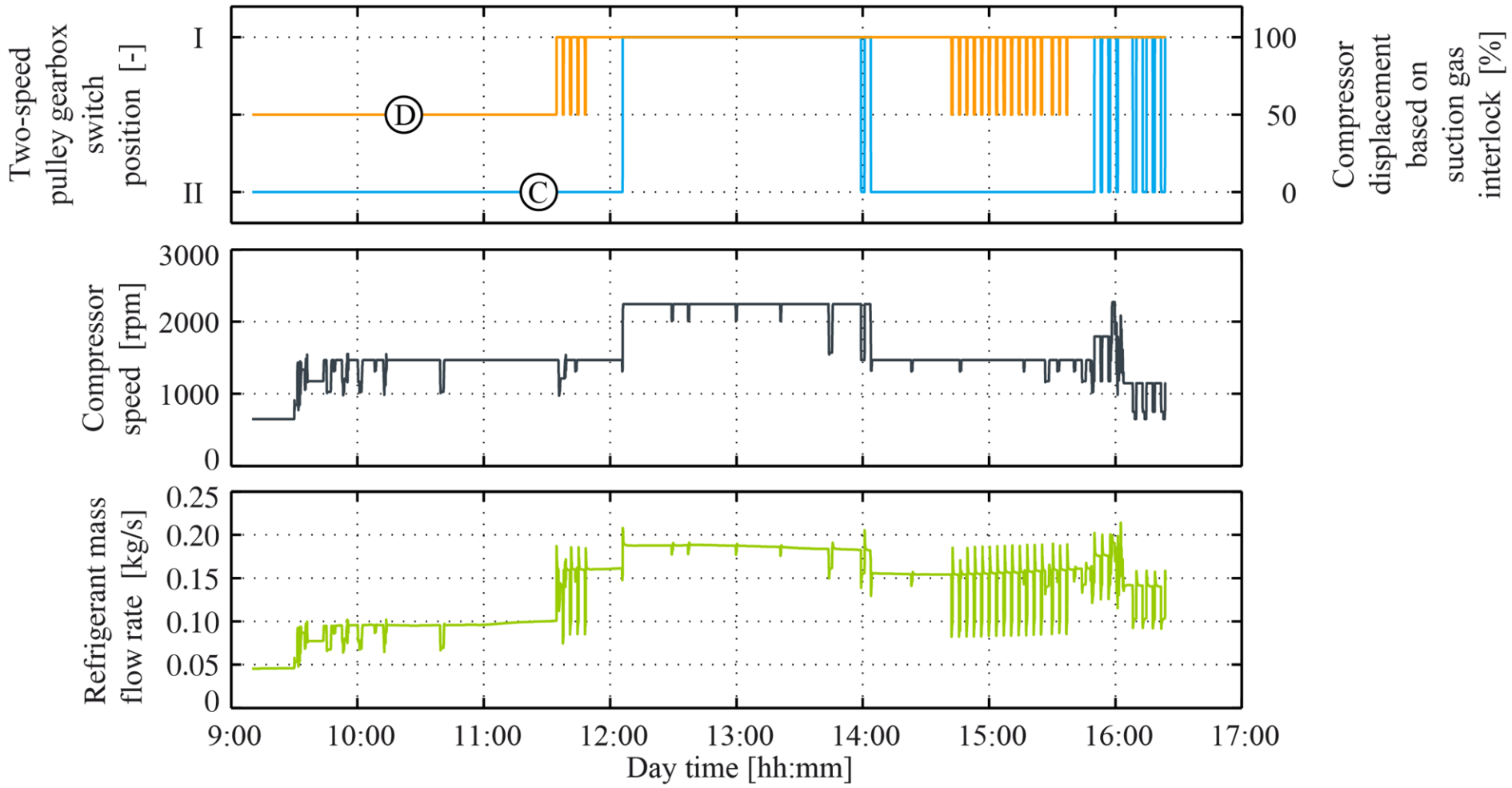
Results


Driving route scenario
Hanover-Munich
Lisbon-Madrid
22.5 22.5 22.5 22.5 22.5 22.4
22.5 22.5 22.5 22.5 22.5 22.4
-6.66 -6.79 -6.12 -6.89 -6.63 -3.88 -3.08
22.4 22.5 22.5 22.5 22.5 22.7 22.5 22.5
22.4 22.5 22.5 22.4 22.5 22.3 22.5 22.5
-4.54 -6.33 -6.74 -5.26 -6.73 -3.63 -6.56 -6.96 -3.90
1 2 3 4 5 6 7 8 9 10 11 12 1/12
1 2 3 4 5 6 7 8 9 10 11 12 1/12
Index virtual driving scenario
(each index means 15th of the month in a representative year)
t_Driver [°C]
t_PC [°C]
ΔB_S [%]
8
4
0
-4
-8
-12

Results


Temperatures [°C]
36
32
28
24
20
3
1
B
A
100
50
0
Relative humidity [%]
Radiation [W/m²]
800
600
400
200
0
2
4
5
1020
980
940
900
860
Pressure [hPa]
Average interior temperature [°C]
24
23
22
21
$t_{set}+0.5K$
t_{set}

Results


Two-speed pulley gearbox switch position [-]
I
II
D
C
100
50
0
Compressor displacement based on suction gas interlock [%]
Compressor speed [rpm]
3000
2000
1000
0
Refrigerant mass flow rate [kg/s]
0.25
0.20
0.15
0.10
0.05
0
9:00
10:00
11:00
12:00
13:00
14:00
15:00
16:00
17:00
Day time [hh:mm]

Statistics

Refrigeration Cycle – AC System Validation

19740	time-varying variables
391	continuous time states
2	linear equation systems (2,3)
20	nonlinear equation systems (1,1,1…)
8	Time faster than real time (laptop i7)

Total Vehicle Model – Virtual Test Drive

28012	time-varying variables
830	continuous time states
8	linear equation systems (largest: 8)
53	nonlinear equation systems (largest: 3)
2	Time faster than real time (laptop i7)

Conclusion

- Refrigeration cycle model for R-744 AC system
- Total vehicle model
- Two-speed pulley gearbox and compressor capacity control
- Virtual test drive with realistic boundary conditions
- Total average fuel consumption reduced by 6%
- Robust and fast refrigerant cycle and total vehicle model

Thank you for your attention.

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