ECCV Platform Thermal Management Systems

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Outline

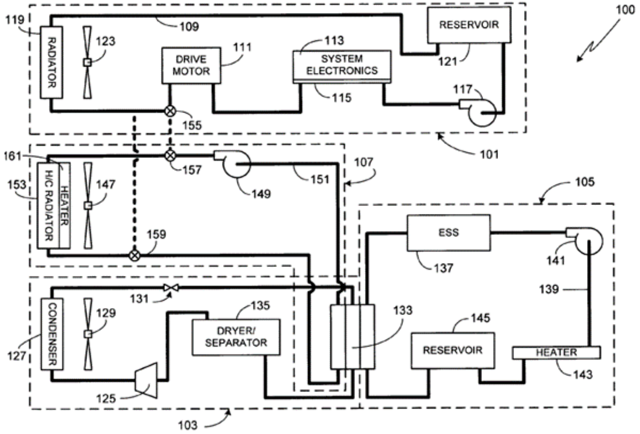
- Thermal Management (TM) thoughts and trends
- The ECCV Platform
- Latest Developments: Vapor-Compression Cycles (Refrigeration)
  - Why? How?
  - Thermodynamics of Refrigerants
  - Component Models
- Using the ECCV platform to evaluate the performance of a TMS

TMS Development over time

- TM systems are developed as an afterthought for conventional powertrains
  - ... according to thermal management engineers
  - TM *control* even more so
- Complexity of TM systems have increased significantly in a short timespan

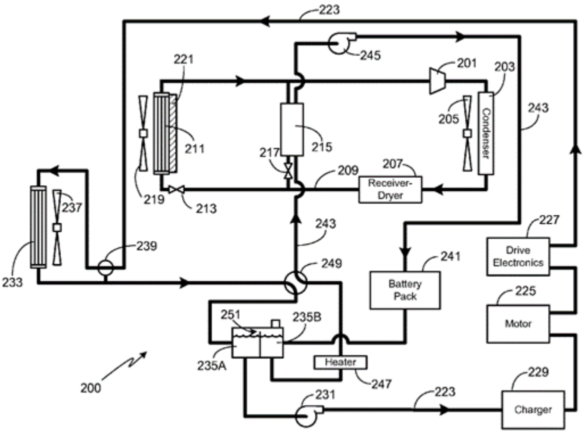
TMS Development over time

- Tesla patent, 2007 [1]



1 (Peng Zhou. *Electric vehicle thermal management system*. U.S. Patent US7789176B2, 2007)

- Tesla patent, 2012 [2]



[2] (Vincent Johnston. *Thermal management system with dual mode coolant loops.* U.S. Patent US8336319B2, 2012)

TMS Development over time

- Tesla patent, 2019[3]
- 16 modes (heating & cooling)
  - heating & cooling
  - specialized modes: charge conditioning, de-frosting etc.
  - special component operation, intentional losses etc.

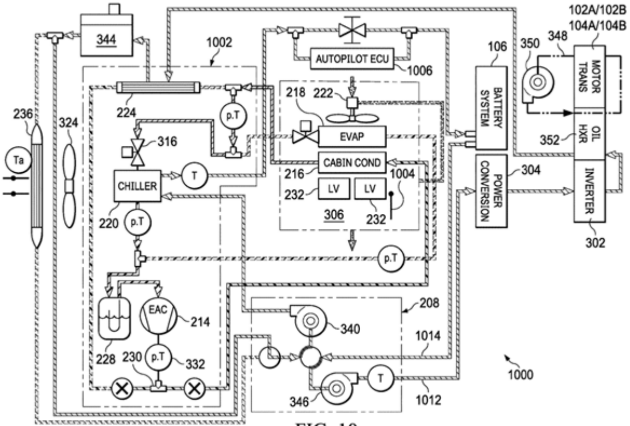
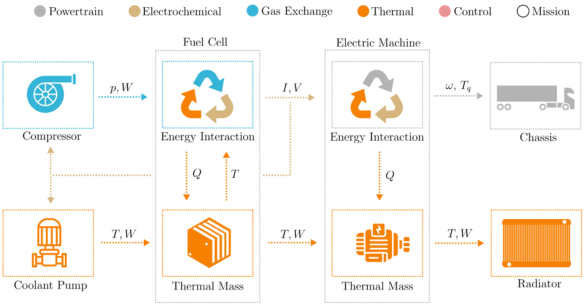


FIG. 10

[3] (Nicholas Mancini. *Optimal source electric vehicle heat pump with extreme temperature heating capability and efficient thermal preconditioning*. U.S. Patent US20190070924A1, 2018)

- A BEV and FCHEV simulator
- Three goals. A platform for ...
  - ... extracting realistic boundary conditions.
  - ... developing predictive energy management strategies.
  - ... model-based design of energy management systems
- A platform where industry and academia can collaborate without sharing IP.



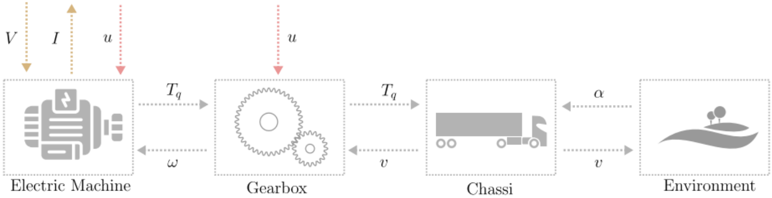
The ECCV Platform Overview

- Simple longitudinal vehicle dynamics.
- Missions are defined by the altitude profile and ambient conditions.
  - (or special circumstances, rest stops, refueling etc.)
- A driver (controller) is required.
  - Predictive speed control significantly impacts performance.

Longitudinal Vehicle Model

$$m\dot{v} = F_t - F_a - F_r - F_g(\alpha)$$

- F_g is *very* large ($m \approx 40$ ton). But recuperable.



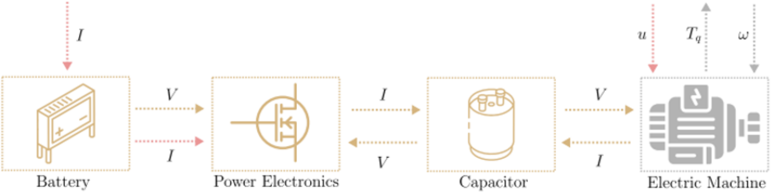
The ECCV Platform Overview

- The DC-bus voltage is a balance of suppliers and consumers.
- The battery current is controlled to maintain a bus voltage reference.
- DC/DC-converters are used to connect the battery and bus.
- The motor can be both a supplier and consumer from the bus.

Battery & DC-bus

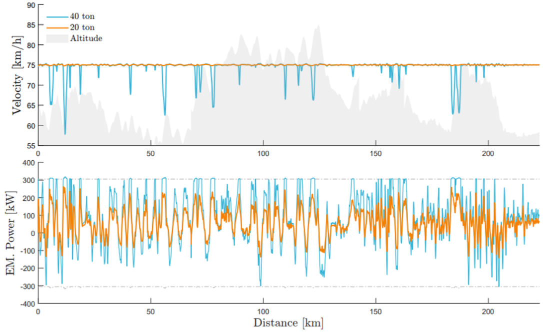
$$C\dot{V}_{bus} = I_{\text{supplier}} - I_{\text{consumer}}$$
$$\dot{V}_{bat} = f(I_{bat}, x, T)$$

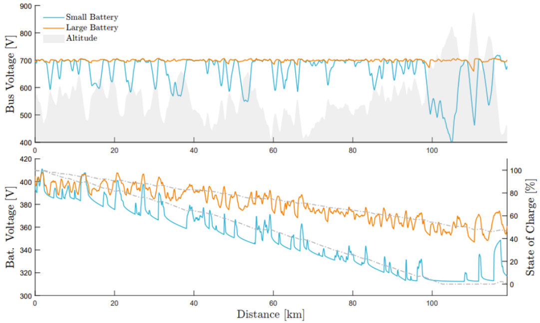
- x : State of charge.



The ECCV Platform Overview

- Some example simulation results using only the systems shown so far.





Model Validation

- Models and data from available literature.
- Varying degree of coverage.

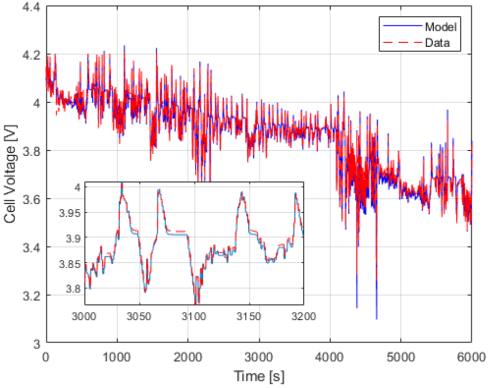


Figure: Battery cell voltage at $T = 25^\circ\ C$.

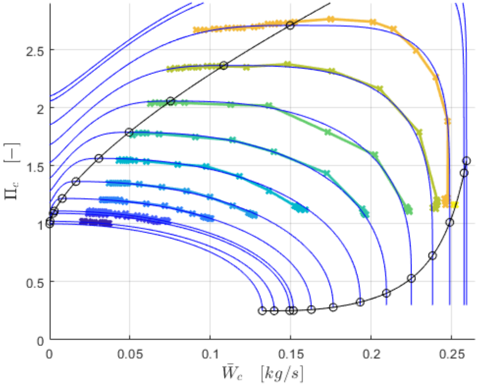
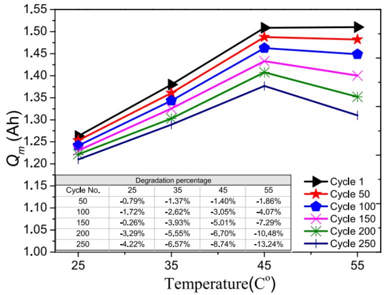


Figure: Compressor flow versus pressure ratio.

- Cell temperature has significant impact on cycle life.[4]
- No refrigeration $\implies$ Battery temperature > ambient temperature
- High battery temperature is a safety hazard



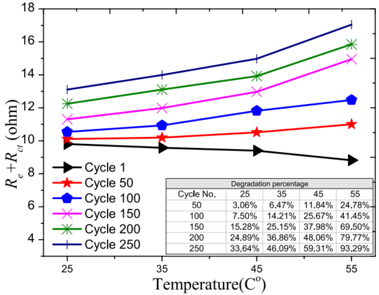


Figure: Resistance degradation vs. cycle & temperature

Figure: Capacity degradation vs. cycle & temperature

[4] (F. Leng, C. Tan, and M. Pecht. "Effect of Temperature on the Aging rate of Li Ion Battery Operating above Room Temperature". In: *Scientific Reports* [2015]. DOI: 10.1038/srep12967)

Refrigeration: How?

- Using compression and expansion, we can manipulate a medium to condense at high temperatures and evaporate at low temperatures.
- Steady-state calculation on this system is undergraduate thermodynamics.
    - ... transient modeling is not.

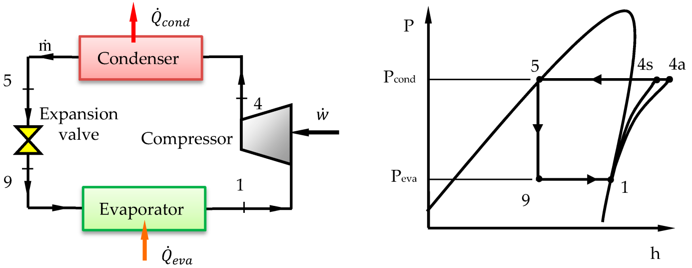


Figure: Standard vapor-compression cycle.[5]

[5] (Bahaa Saleh et al. "Performance Analysis and Working Fluid Selection for Single and Two Stages Vapor Compression Refrigeration Cycles". In: *Processes* 8.9 [2020]. ISSN: 2227-9717. DOI: 10.3390/pr8091017. URL: https://www.mdpi.com/2227-9717/8/9/1017)

Multiparameter Equations of State

- Most process modeling software rely on calls to REFPROP, CoolPROP, etc. for thermophysical fluid properties.
- The ECCV library is constrained to *only* standard Simulink.
- ... So what does REFPROP do?

State Equation Explicit in Helmholtz Energy

$$a(\rho, T) = a^0(\rho, T) + a^r(\rho, T)$$

- Density and Temperature are the natural variables.
- For *R1234yf*[6], the EOS has over 50 parameters (hence: multi).
- Extreme precision.
- With this equation, *all* thermodynamic properties can be calculated as partial derivatives.
- Applicable in the single-phase region.

[6] (Markus Richter, Mark O. McLinden, and Eric W. Lemmon. "Thermodynamic Properties of 2,3,3,3-Tetrafluoroprop-1-ene (R1234yf): Vapor Pressure and p-d-T Measurements and an Equation of State". In: *Journal of Chemical & Engineering Data* [2011]. DOI: 10.1021/je200369m)

Pressure-Enthalpy Maps

- We can generate maps by numerically solving the state equation

Step 1:

- Select T.
- Solve $g(\rho^v, T) = g(\rho^l, T)$ and $p(\rho^v.T) = p(\rho^l, T)$ for ρ^v, ρ^l.

Step 2:

- Select p^*, h^*.
- Solve $p^* = p(\rho, T)$ and $h^* = h(\rho, T)$ for ρ, T.

- For any new fluid, we only need the Helmholtz equation $\Longrightarrow$ All maps and functions can be generated.

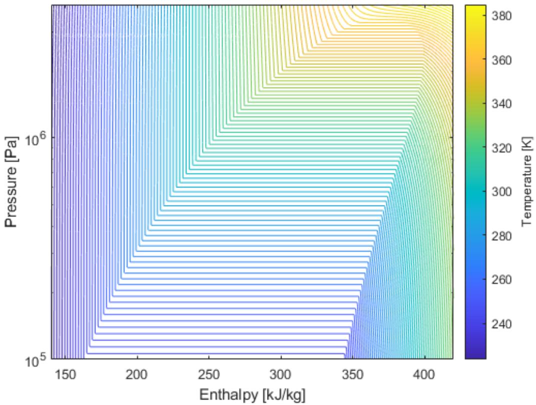
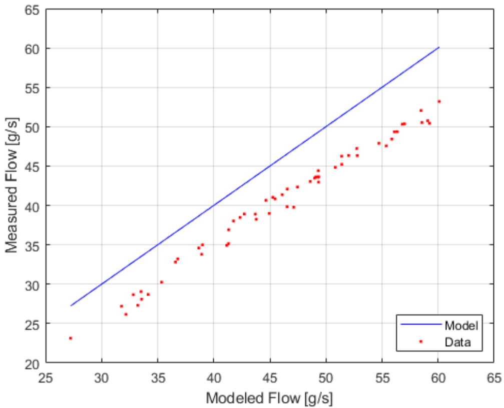


Figure: $p - h - T$ map of *R1234yf*.

- Data from automotive reciprocating compressor[7]
- Model by (Li, 2013)[8]
- Fluid in experiments was *R134a*.
- Model based on volumetric efficiency.



[8] (Joseph H. Darr. "Modeling of an Automotive Air Conditioning Compressor Based on Experimental Data". In: 1992. URL: https://api.semanticscholar.org/CorpusID:18119266)

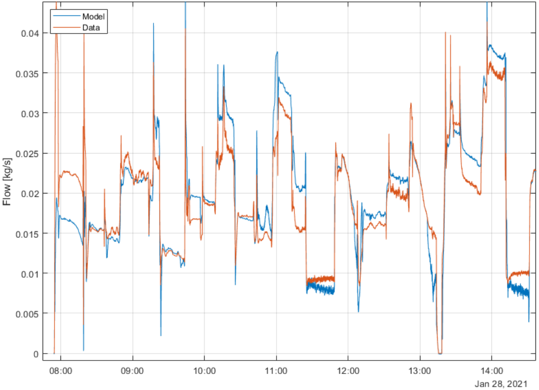
[8] (Wenhua Li. "Simplified steady-state modeling for variable speed compressor". In: *Applied Thermal Engineering* [2013]. DOI: https://doi.org/10.1016/j.applthermaleng.2012.08.041)

- Published flow-pressure-temperature data. [9]

Flow Model

$$\dot{m} = CA(\alpha)\sqrt{\rho\Delta p}$$
$$C = a_0 + a_1\alpha + a_2\alpha^2 + \dots$$

- α: Valve lift.
- A: Opening area.

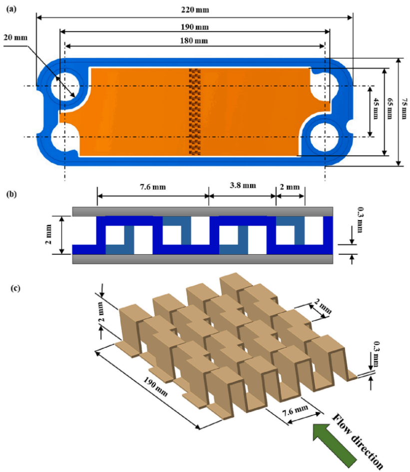


9 (Miles Walker. "Automotive R1234yf reversible heat pump system electronic expansion valve dataset and mass flow modelling". In: [June 2021])

Chiller: Plate Heat Exchanger with OSF Turbulator

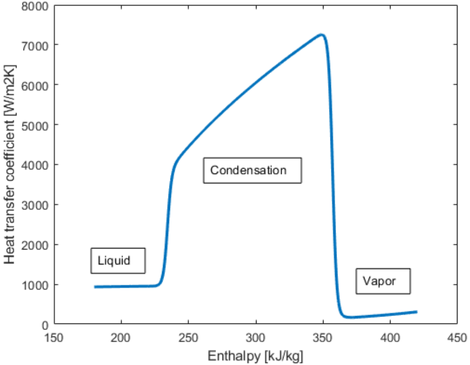
HTC Correlation

$$Nu = 3.918 Re_{eq}^{0.505} Re_l^{-0.1354} B_d^{0.213} Pr^{1/3}$$
$$Re_{eq} = G_{eq} D_h / \mu_l$$
$$G_{eq} = G(1-x) + G(\rho_l/\rho_g)^{0.5} x$$
$$Re_l = G D_h / \mu_l$$
$$B_d = g(\rho_l - \rho_g) D_h^2 / \sigma$$



[9] (Rajendran Prabakaran et al. "Condensation of R1234yf in a plate heat exchanger with an offset strip fin flow structure for electric vehicle heat pumps". In: *International Communications in Heat and Mass Transfer* [2023]. DOI: https://doi.org/10.1016/j.icheatmasstransfer.2023.106699)

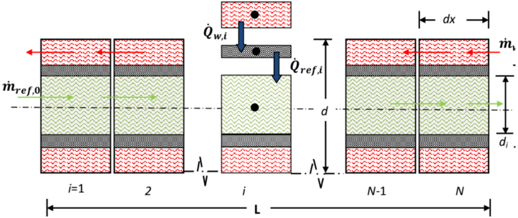
- The vapor fraction significantly influences the heat transfer coefficient.



Enthalpy balance for each volume

$$\dot{h}_i = \frac{W(h_{i-1} - h_i) + Q_w}{\rho V}$$

- Constant flow and pressure.



[9] (Musbaudeen O. Bamgbopa. "Modeling and performance evaluation of an organic Rankine cycle (ORC) with R245FA as working fluid". PhD thesis. May 2012)

Single-phase control volume

- How do we determine the system pressure levels?
- Two vapor-phase control volumes before & after the compressor.

General CV: Mass & Energy Balance

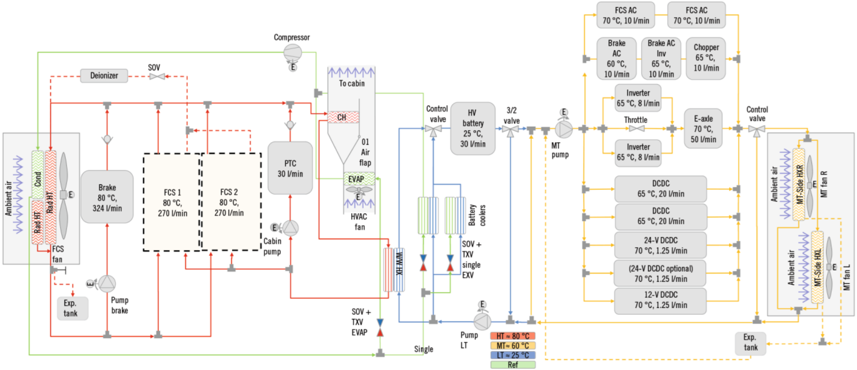
$$\dot{m} = W_{in} - W_{out}$$
$$\dot{U} = W_{in}h_{in} - W_{out}h(\rho, T)$$

- With ρ and T as state variables we can calculate any other properties using the Helmholtz-EOS.

Conversion to ρ, T

$$\dot{\rho} = \dot{m}/V$$
$$\dot{u} = \left(\frac{\partial u}{\partial T}\right)_{\rho}\dot{T} + \left(\frac{\partial u}{\partial \rho}\right)_{T}\dot{\rho}$$

- AVL Developed a TMS for a fuel cell truck.[10]
- Battery pack cooled by chillers
- Side-mounted radiators cool power electronics and traction motor.
- A liquid-to-liquid PHEX can siphon heat from the fuel cell circuit for extra cooling.



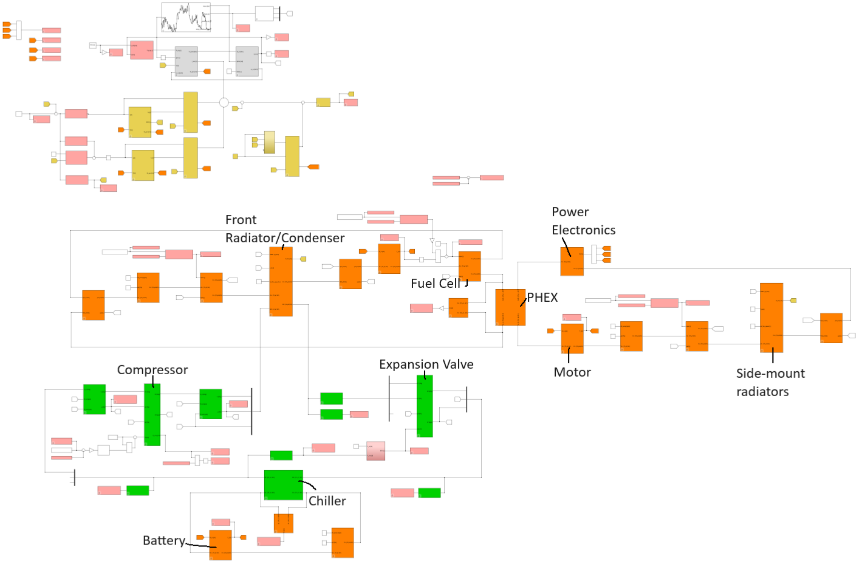
10 (J. Linderl, J. Mayr, and M Hutter. "Optimized Fuel Cell Drive for Long-haul Trucks". In: *ATZ Heavy Duty Worldwide* [2021]. DOI: 10.1007/s41321-021-0407-5)

Side-mounted Radiators

- Mercedes-Benz GenH2 Truck prototype[11]
- Side mounted radiator & fan assemblies

[11] (*Mercedes-Benz GenH2 Truck prototype*. https://media.daimlertruck.com/. Accessed: 2023-11-13)

ECCV Implementation

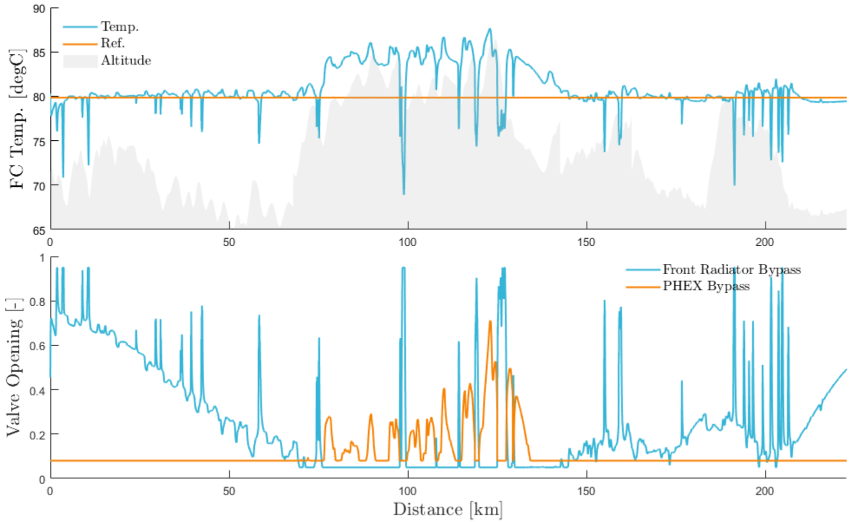


ECCV Implementation: Control objectives

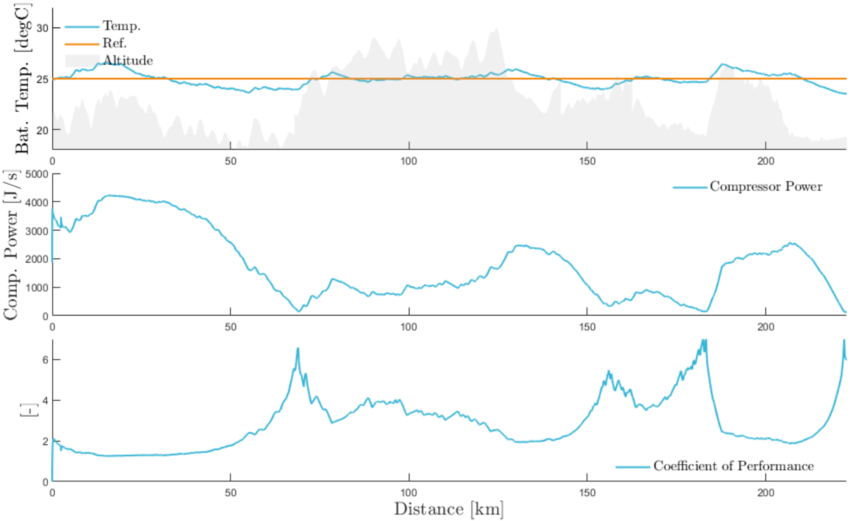
- A difficult mission: München altitude profile at $T_{amb} = 40$ °C and $m = 40$ ton.
- Simple control using P/PI regulators.

Objective	Reference		1st	2nd	3rd
Speed	75	km/h	Motor torque		
DC-bus	700	V	Battery Current	Fuel Cell Current	Burn-off Current
SOC	50	%	Fuel Cell Current		
Battery Temp.	25	°C	Compressor Speed		
Fuel Cell Temp.	80/85	°C	Radiator Bypass Valve	PHEX Bypass Valve	
Motor Temp.	70	°C	Side-Radiator Bypass Valve	PHEX Bypass Valve	
Chiller Superheat	5	°C	Expansion Valve		
Condenser Subcooling	>5	°C	Refrigerant Charge		

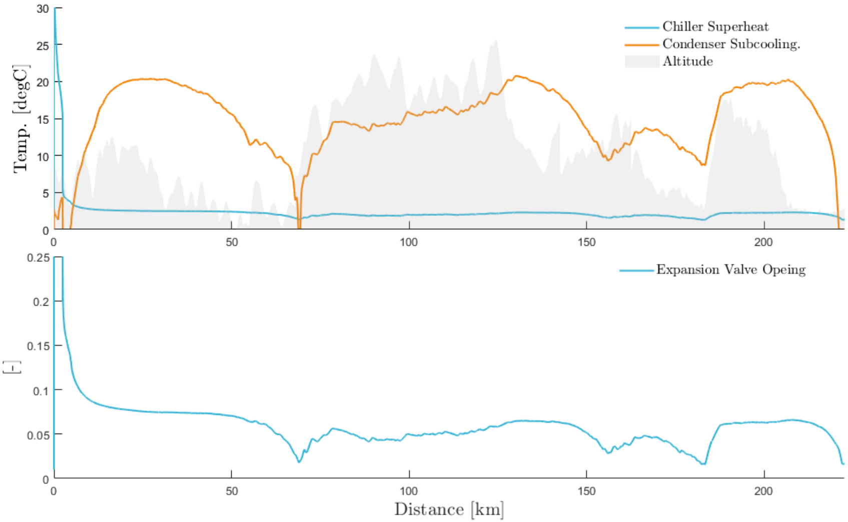
Simulation Results



Simulation Results

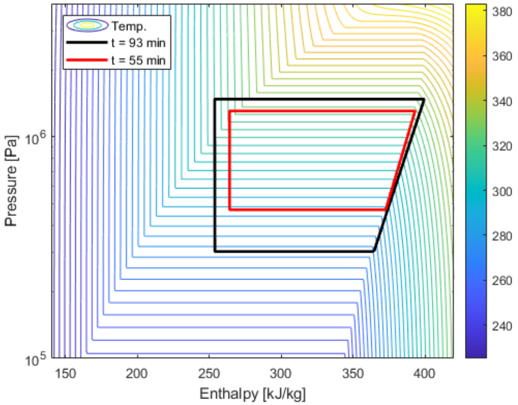


Simulation Results



Conclusions & Future Work

- The system performs well considering the difficult conditions.
- The liquid-to-liquid heat exchanger connecting the fuel cell coolant circuit to the motor circuit is able to save the fuel cell from overheating.
  - $\implies$ Side-mounted radiators are great.
- A condenser/chiller pair is able to maintain battery temperature at 25 °C.
- Superheat and subcooling temperatures are within acceptable limits, and good COOP-values were achieved.



Conclusions & Future Work

- Incusion of cabin air-conditioning.
- Extensive model validation in cooperation with Volvo Trucks.
- Development of predictive energy management strategies.
- Increased collaboration with other universities.