



**Politecnico  
di Torino**

# A Digital Twin to Support the Development of Advanced Thermal Management Solutions for Battery Electric Vehicles

Federico Millo, Luciano Rolando, Afanasie Vinogradov

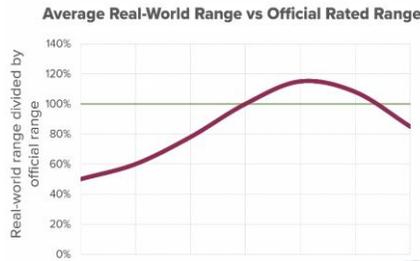
# Introduction



**Electric Vehicles** shows several **peculiarities related to the Thermal Management of the powertrain** that may require an optimization of the energy flows of the powertrain.



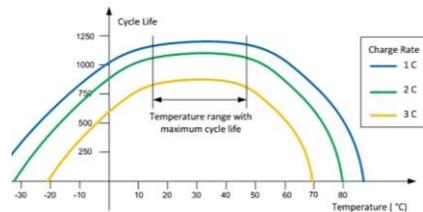
**Range**



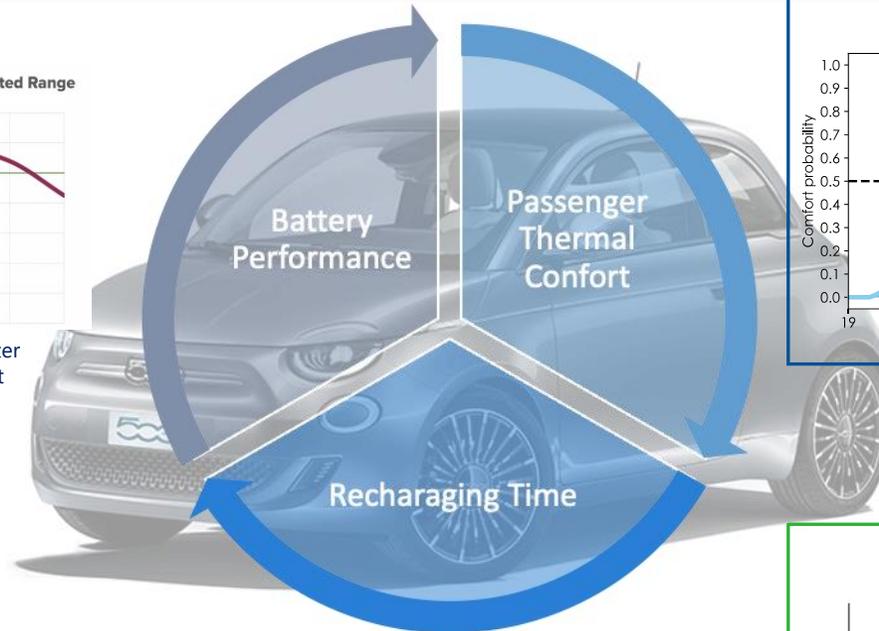
Electric Vehicles in Winter  
Drive Electric Vermont  
(driveelectricvt.com)



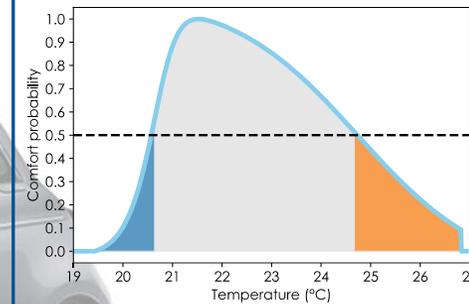
**Aging**



Review and recent advances in battery health monitoring and prognostics technologies for electric vehicle (EV) safety and mobility, **S. Rezvanizani, Z. Liu**

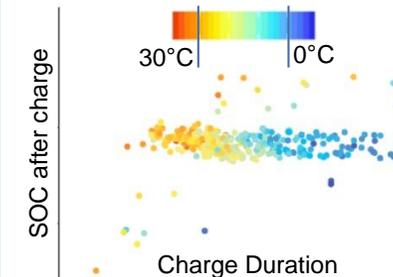


## Passenger Thermal Comfort



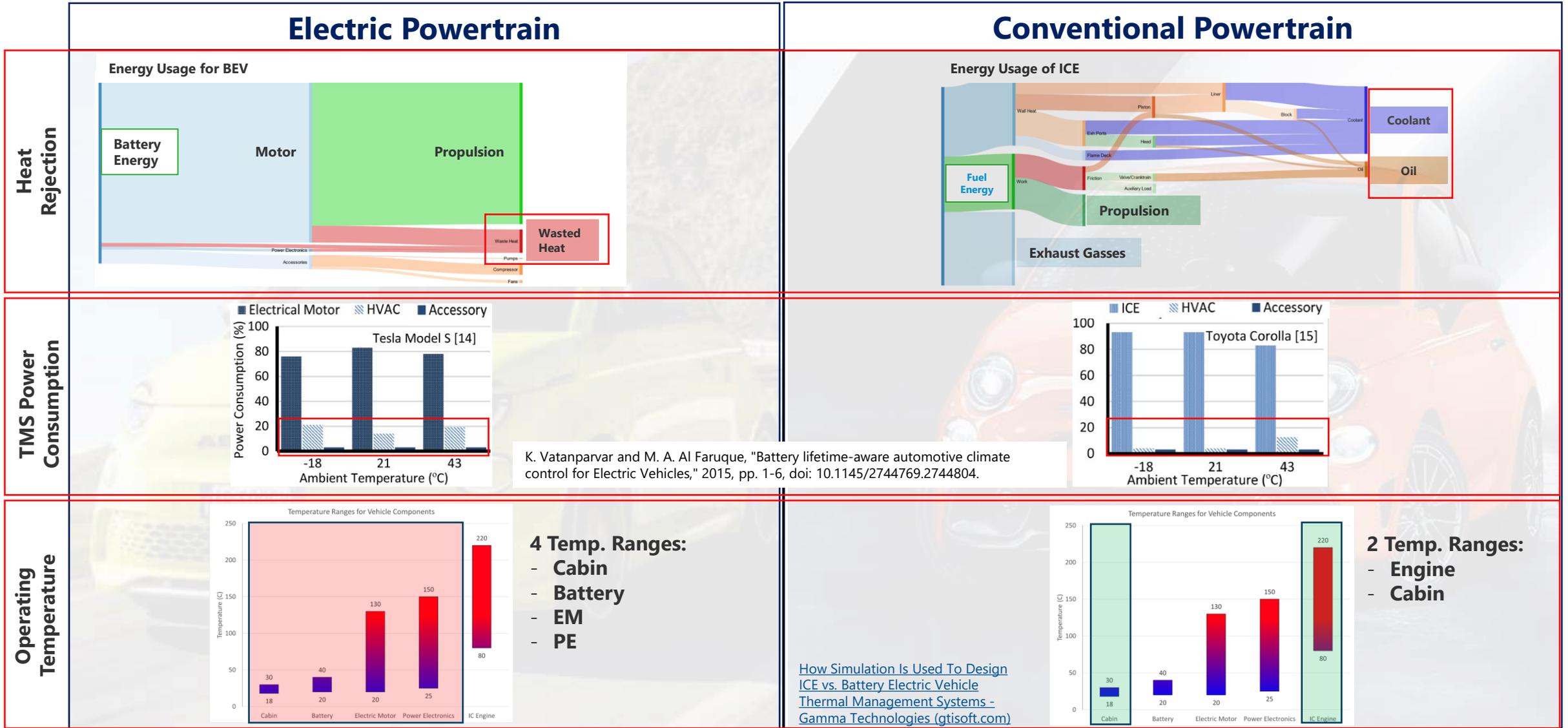
Meimand, M., Jazizadeh, F., A personal touch to demand response: An occupant-centric control strategy for HVAC systems using personalized comfort models, *Energy and Buildings*, Vol. 303, 2024, <https://doi.org/10.1016/j.enbuild.2023.113769>

## Recharging Time



Empirical analysis of electric vehicle fast charging under cold temperatures. **Y. Motoaki, W. Yi**

# Introduction



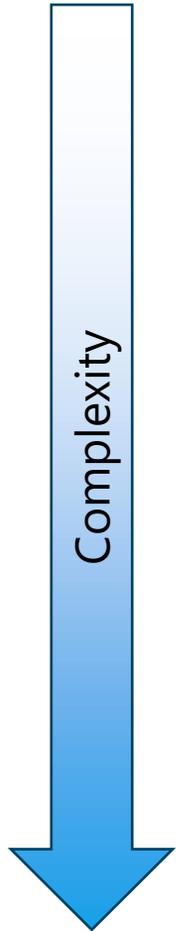
K. Vatanparvar and M. A. Al Faruque, "Battery lifetime-aware automotive climate control for Electric Vehicles," 2015, pp. 1-6, doi: 10.1145/2744769.2744804.

[How Simulation Is Used To Design ICE vs. Battery Electric Vehicle Thermal Management Systems - Gamma Technologies \(gtisoft.com\)](#)

# Introduction



These challenges lead to a wide range of possible **TMS architectures** and **Operating Fluids**



**500e – Electric PTC + Conventional Air Conditioning System**

AC CONDENSER  
POWERTRAIN RADIATOR  
PTC  
BATTERY CHILLER  
PTC

HVAC Heater  
HVAC Compressor  
Thermal Systems  
• Power electronics  
• HV Battery  
Battery Coolant Heater

**Optemus Process – Indirect heat Pump**

CONDENSER  
CHILLER  
RADIATOR  
Compact Refrigeration Unit

238  
429  
257

**Direct Heat Pump Architecture**

R1234YF  
R744 CO2

**Possible Operating Fluids**

Properties	R134A	R1234YF	R290 PROPANE	R744 CO2
GWP	1430	4	3	1
Flammability	Low	Medium	High	Low
Enthalpy difference @ 0 °C [kJ/kg]	197.2	163.2	373.4	231.1
Pressure level @80 °C [bar]	26.3	25.2	31.3	73.6
Refrigeration Cycle	Subcritical	Subcritical	Subcritical	Trans critical

**Aim of the Work:**



Development of a **comprehensive and fully physical digital twin** of a BEV capable of supporting the design of its thermal management system.



# Agenda

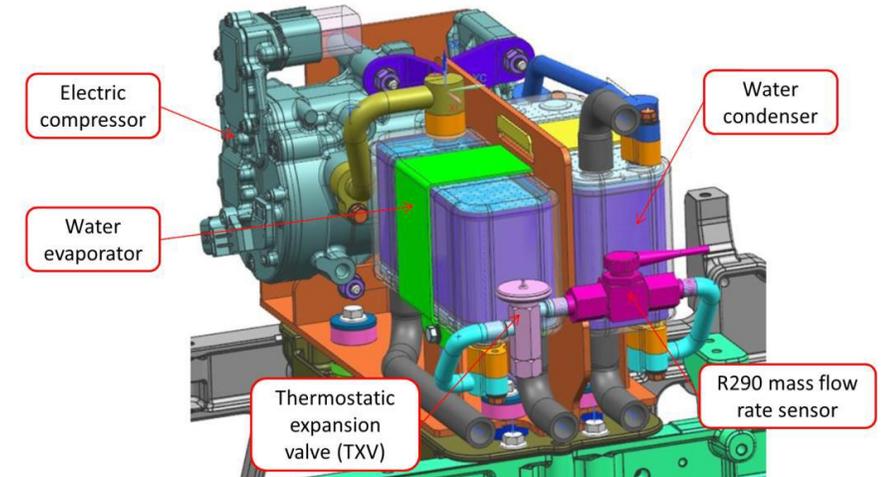
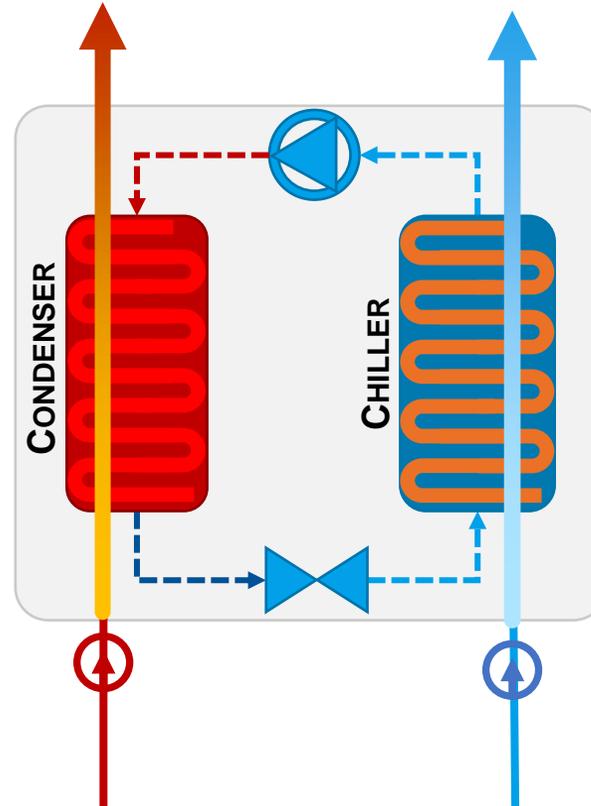
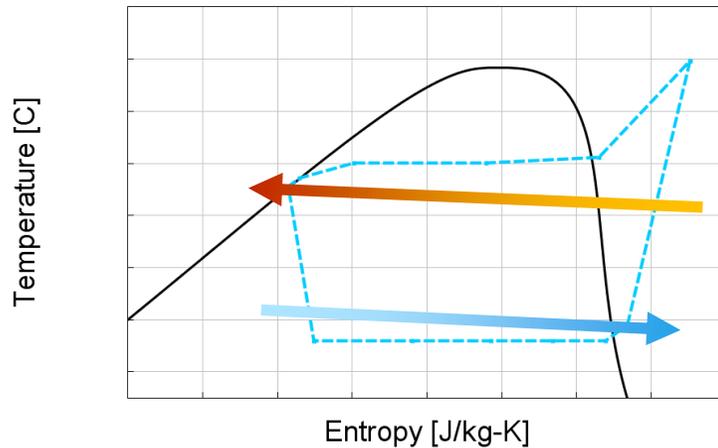
- Introduction
- **Thermal Management Systems**
  - **Indirect Heat Pump**
  - Direct Heat Pump
- Modelling
  - Indirect Heat Pump
  - Direct Heat Pump
- Conclusions

# Integrated Heat Pump Layout

At the core of the heat pump system, there is a device, the **compact refrigeration unit**, capable to generate **heat** and **cold**.

Main elements of the **compact refrigeration unit** are:

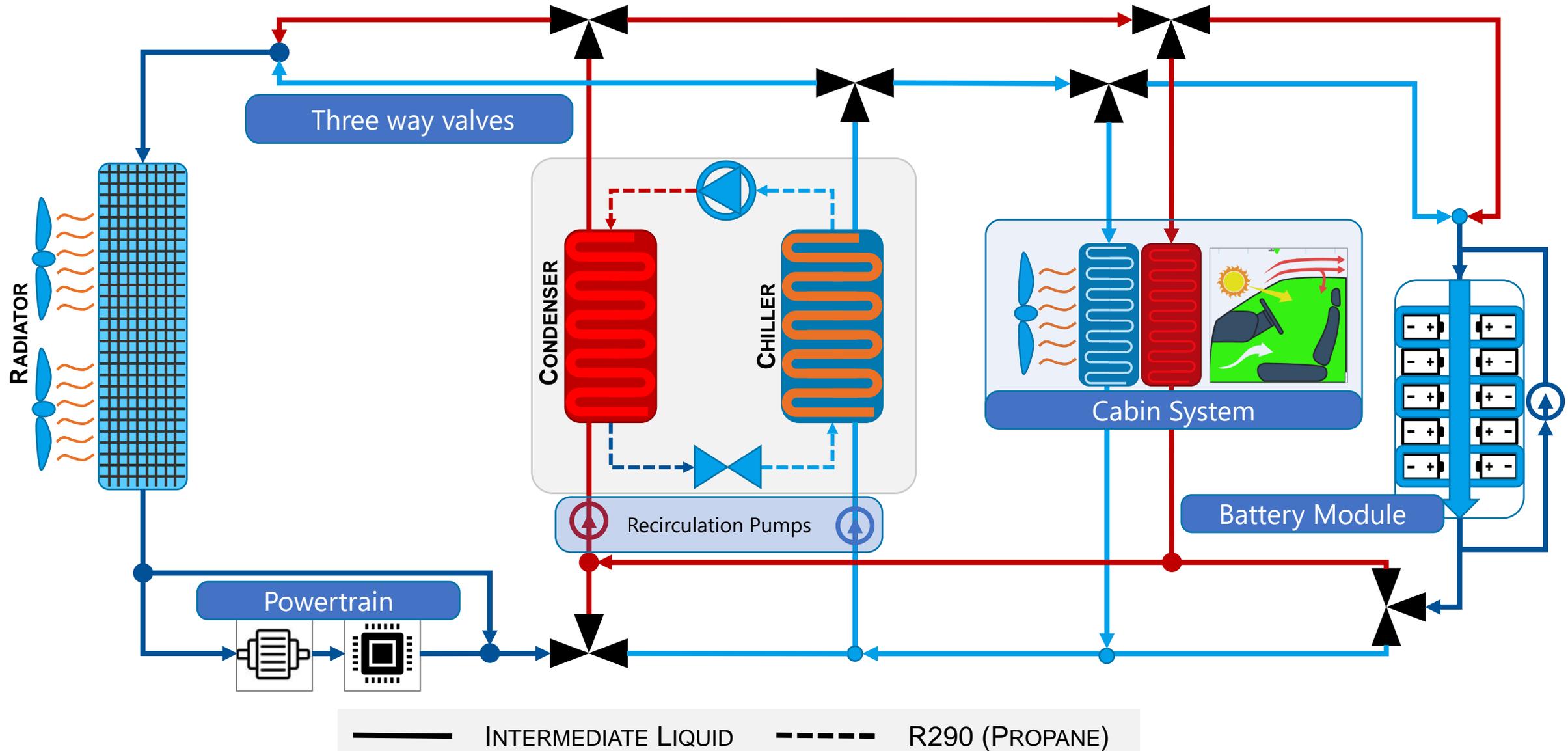
- Compressor
- Water-refrigerant heat exchangers for condenser and evaporator
- Thermostatic expansion valve (TXV)



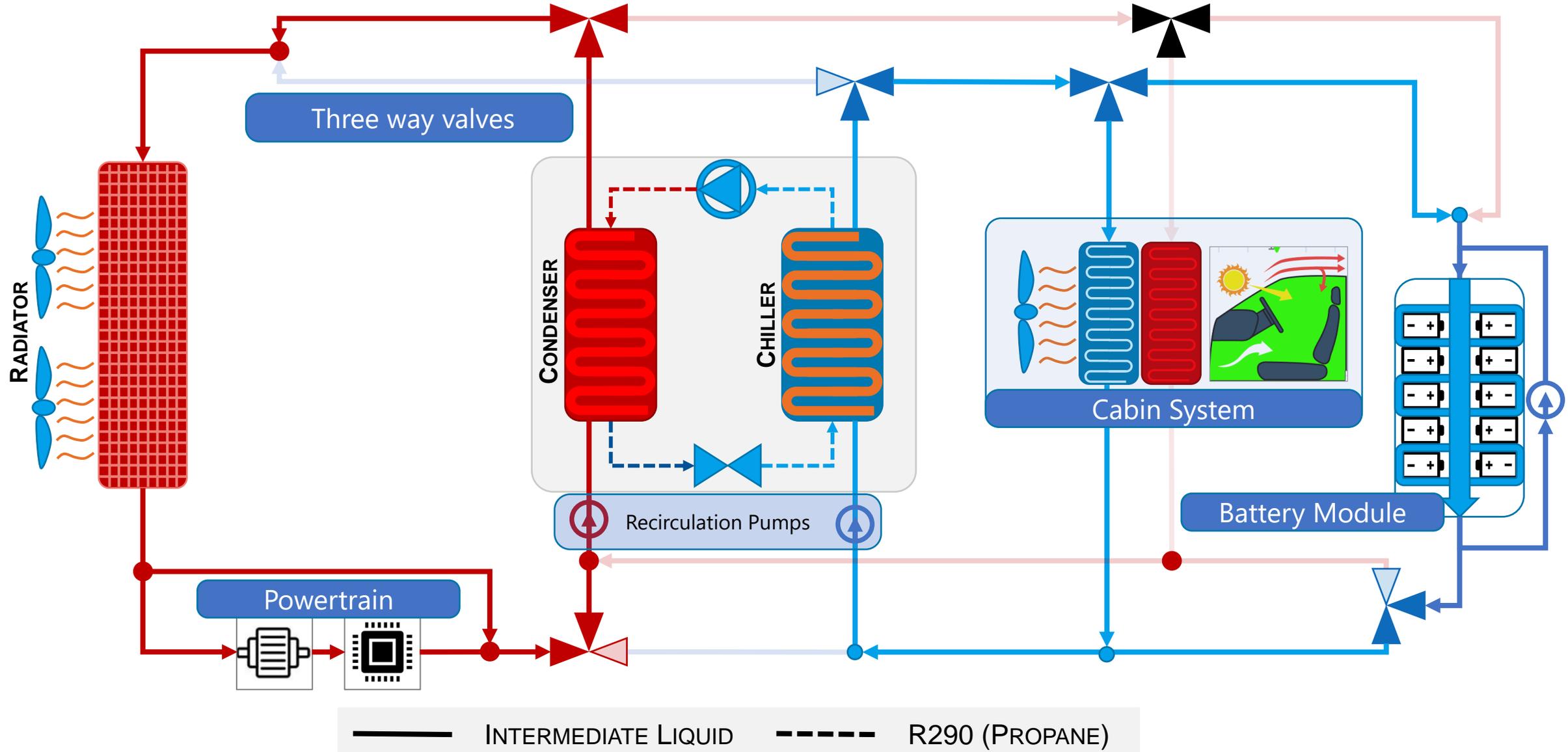
OPTEMUS Newsletter, Issue 2 (2017)

— INTERMEDIATE LIQUID      - - - - R290 (PROPANE)

# Indirect Heat Pump Layout



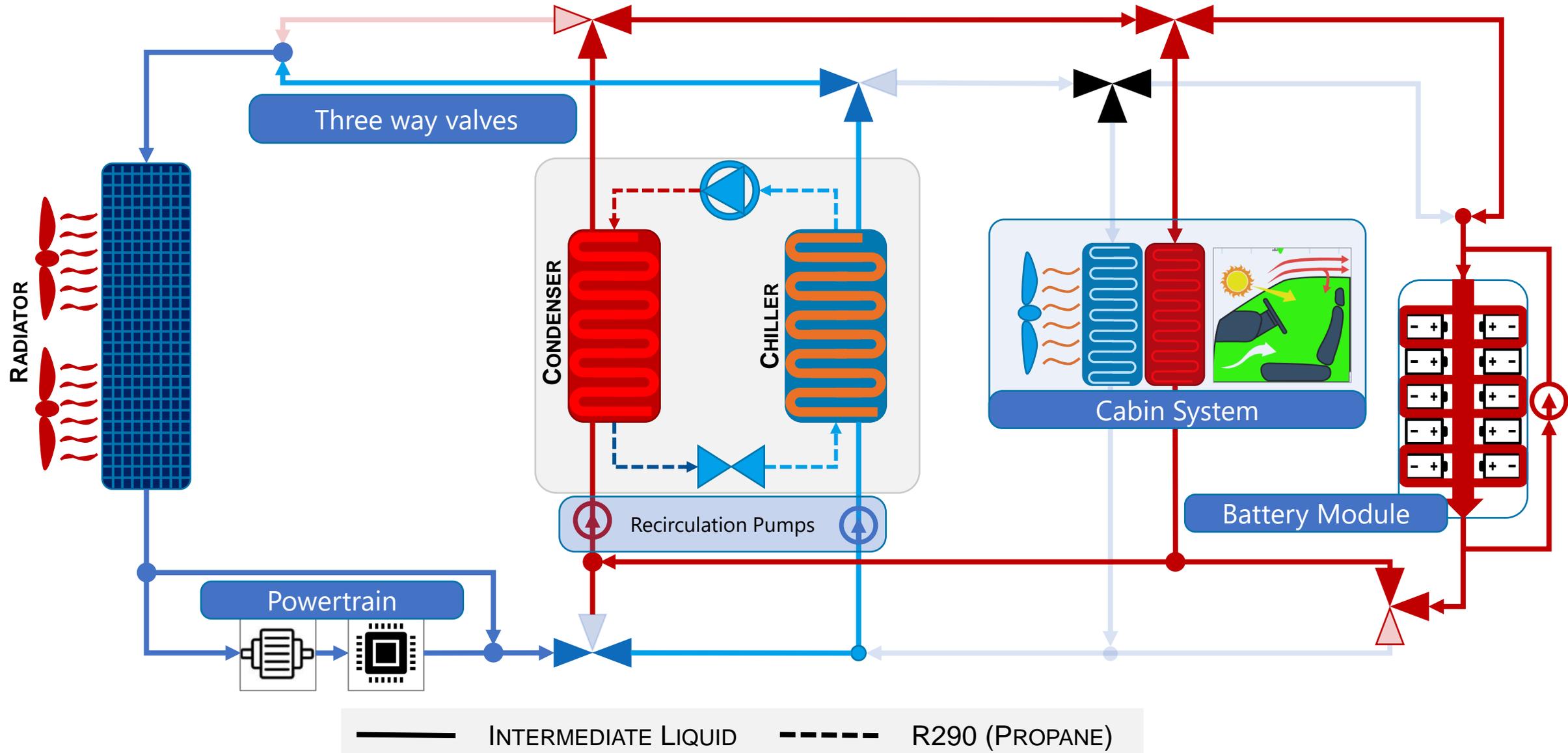
# Indirect Heat Pump Layout



# Indirect Heat Pump Layout



Cabin and Battery Heating

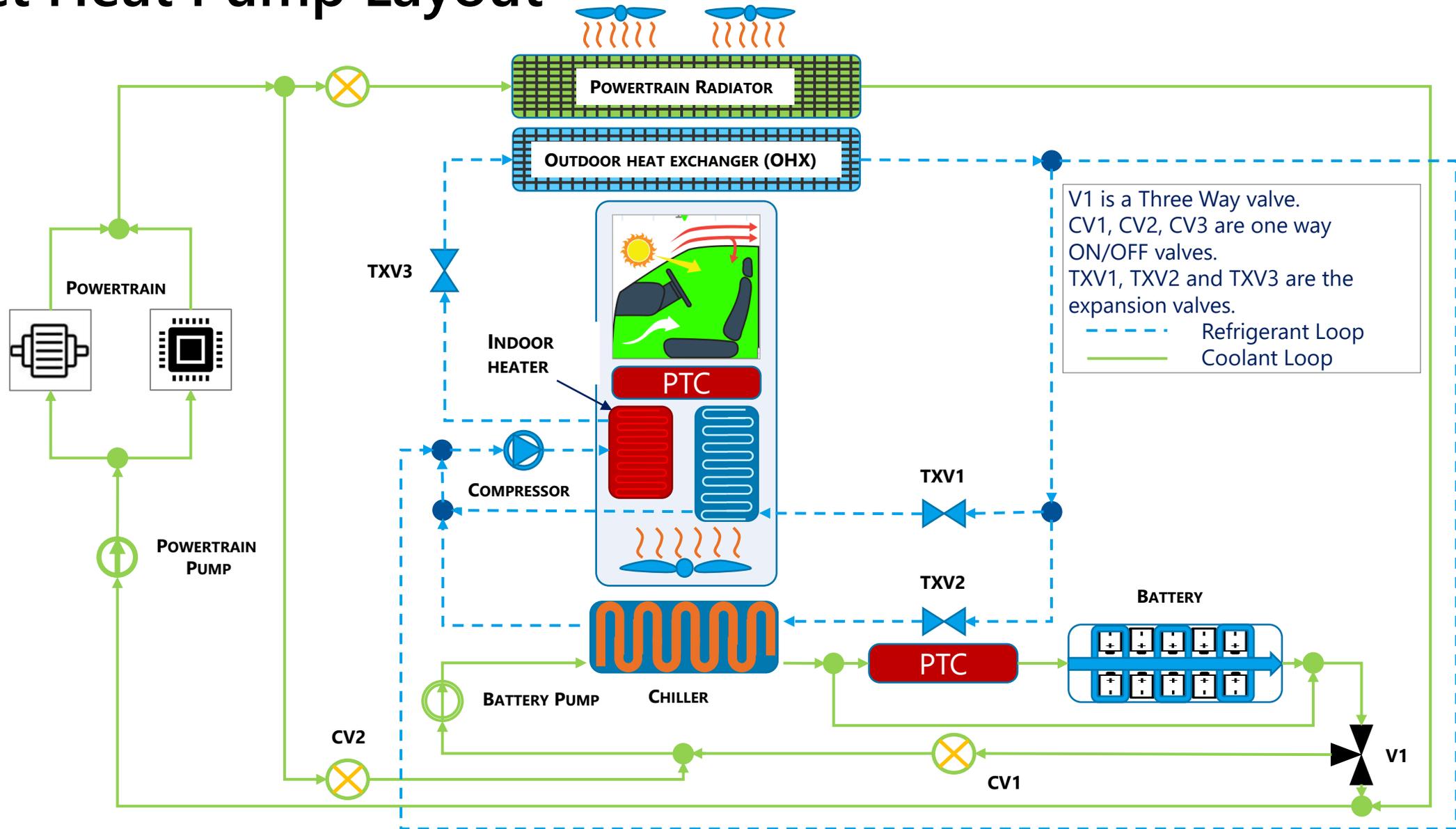




# Agenda

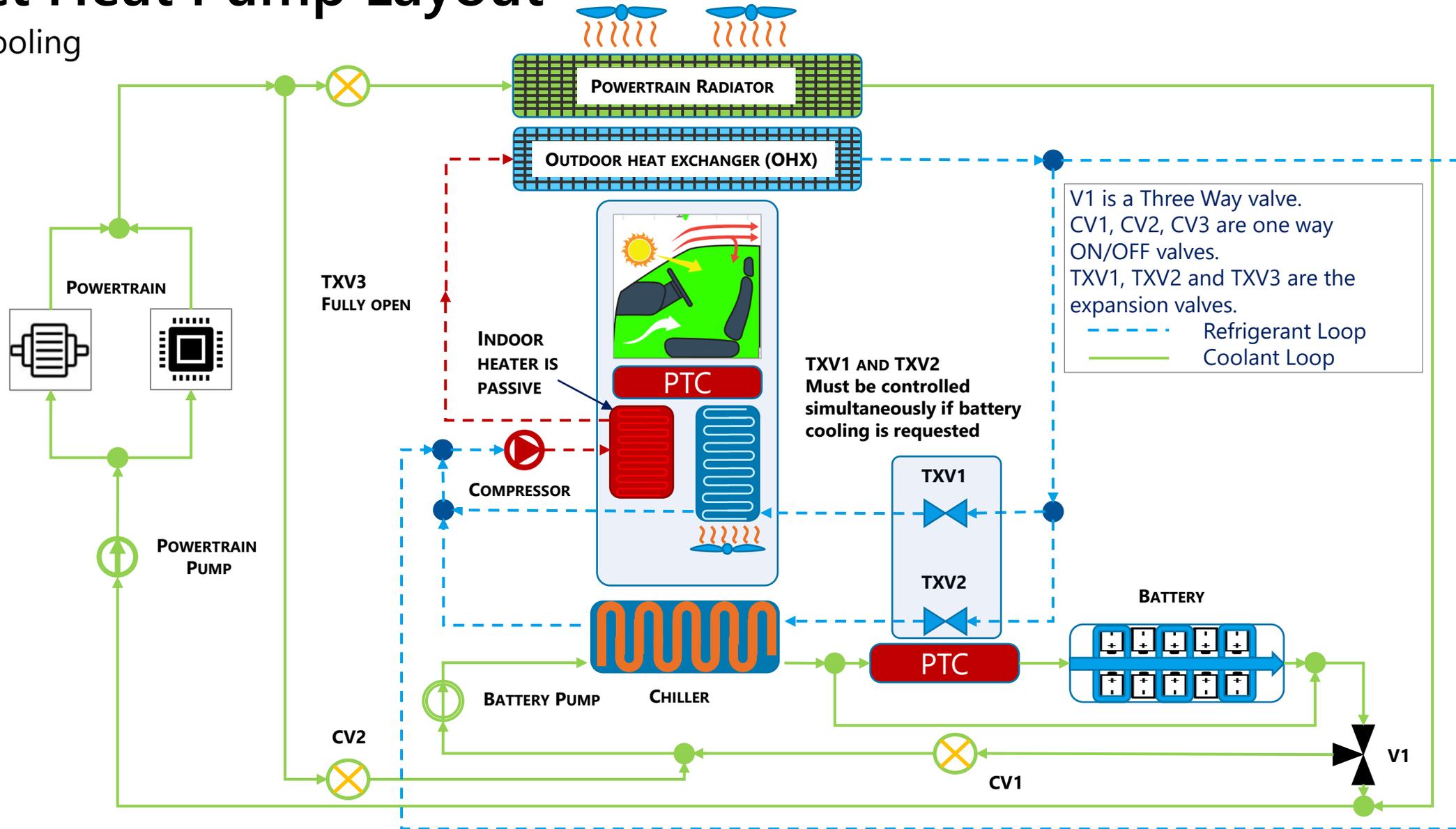
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# Direct Heat Pump Layout



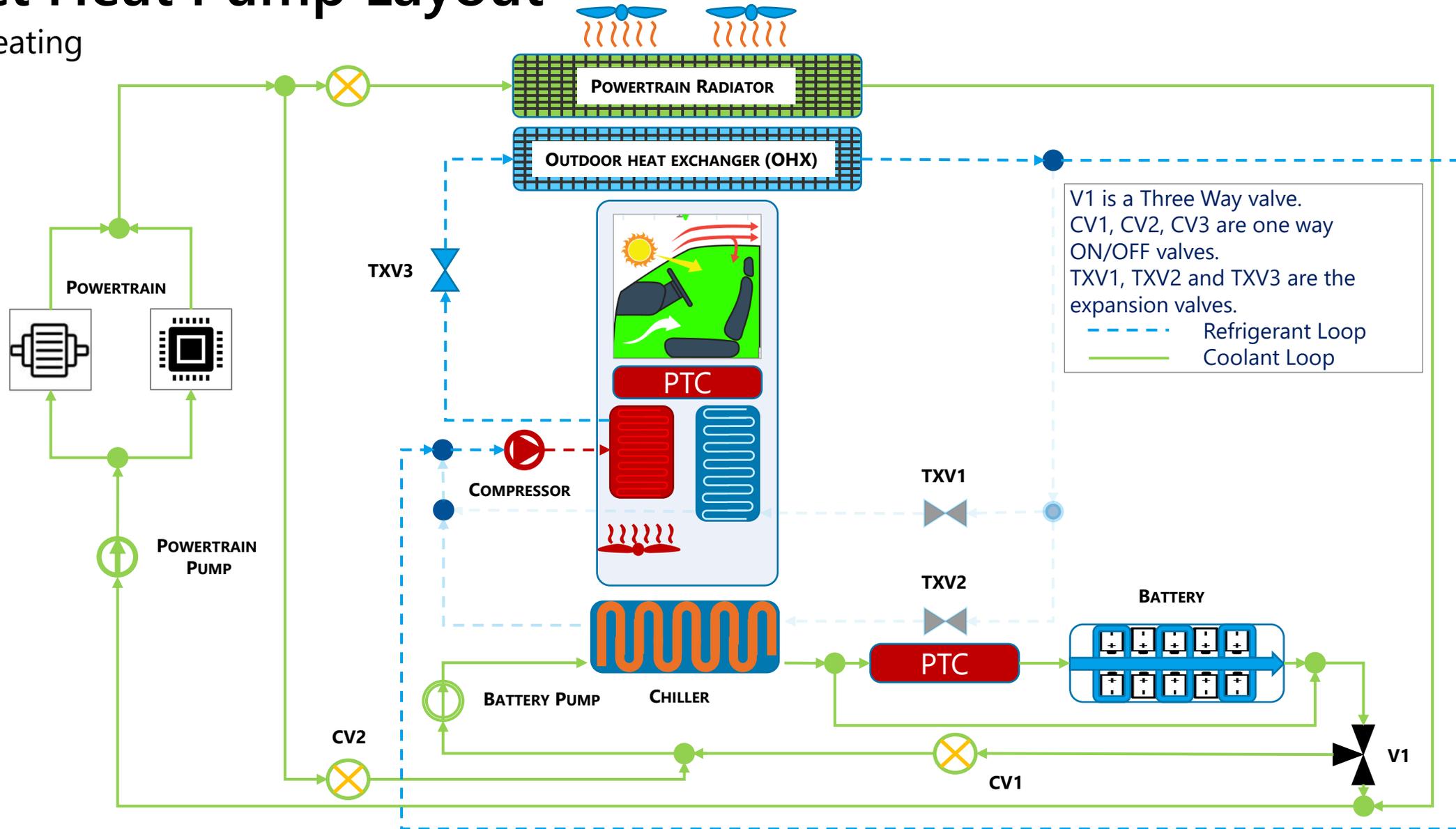
# Direct Heat Pump Layout

## Cabin Cooling



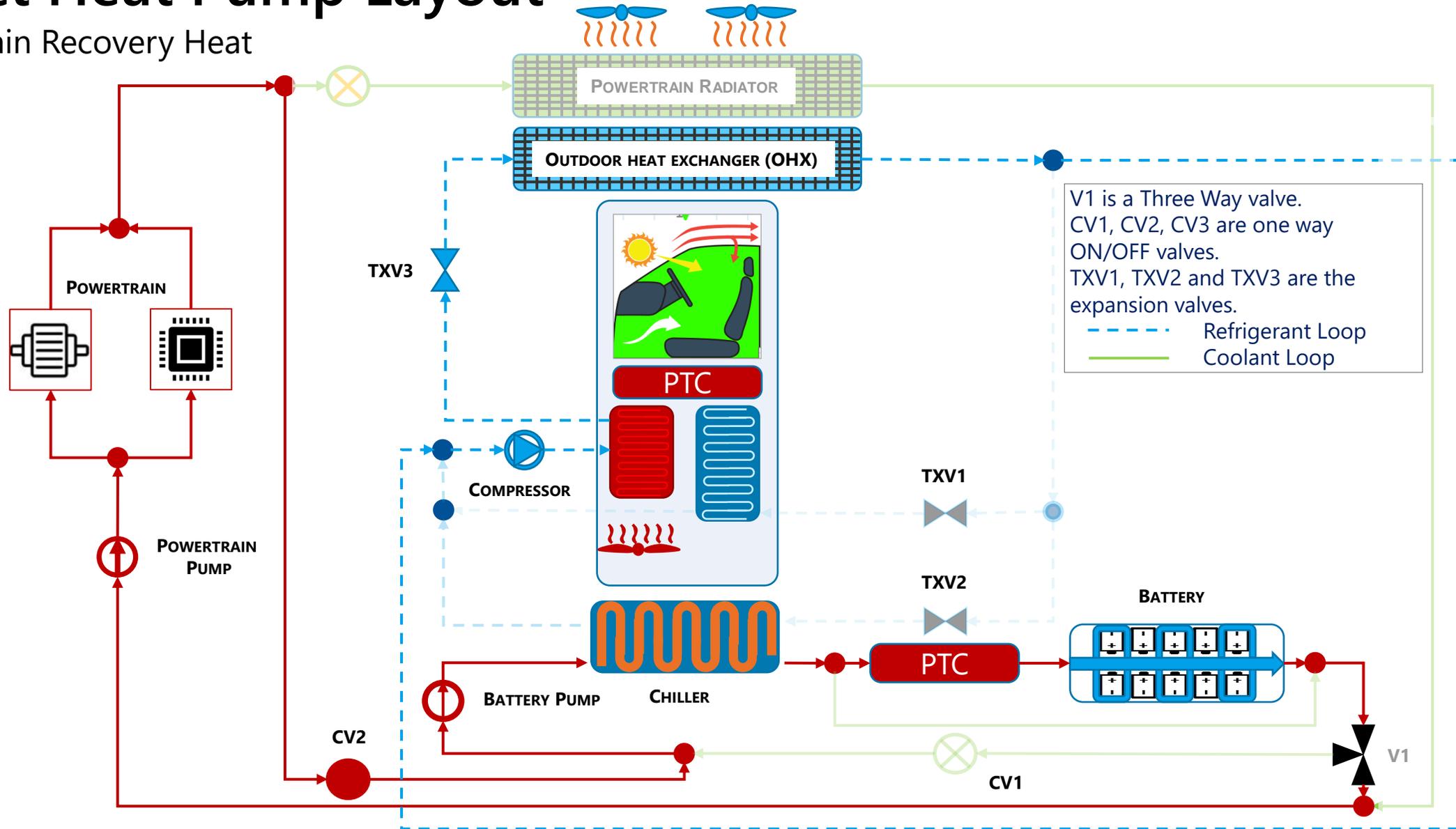
# Direct Heat Pump Layout

## Cabin Heating

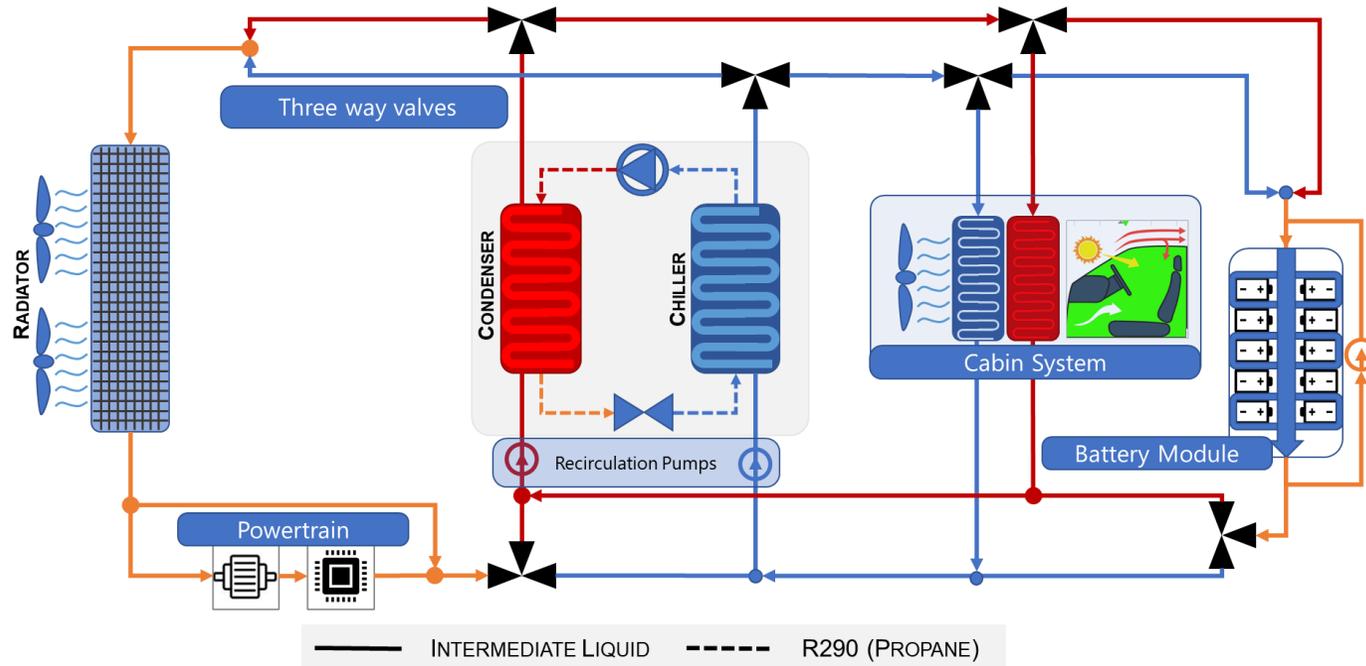


# Direct Heat Pump Layout

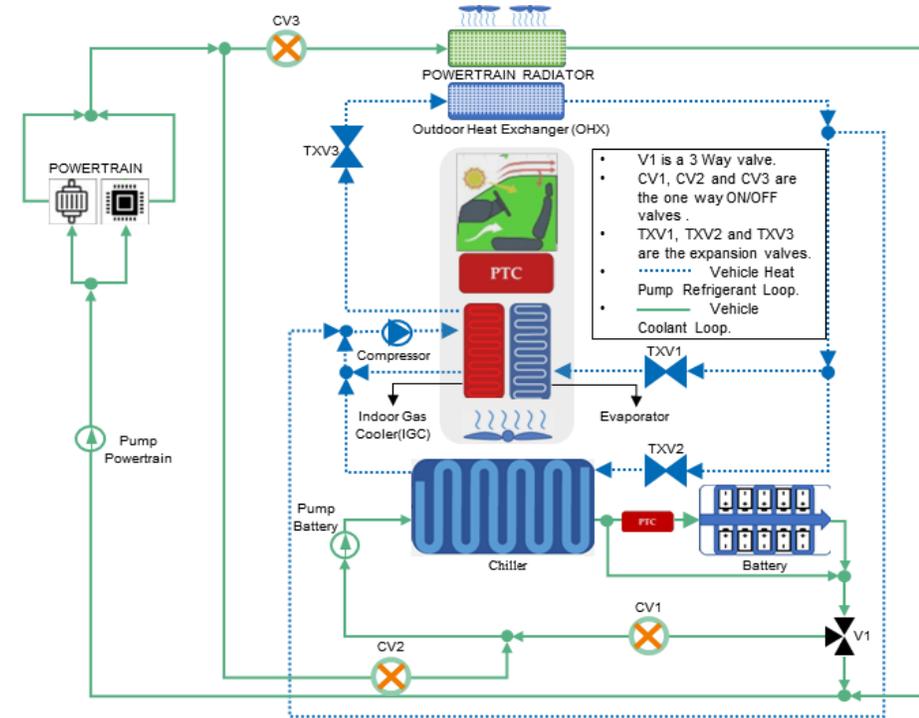
Powertrain Recovery Heat



# System Overviews



- Modular concept
- Refrigerant enclosed in a single loop
  - Simplified superheat control
  - Limited volume resulting in lower refrigerant charge
- Intermediate fluid → lower efficiency (partially compensated by the superior properties of propane)



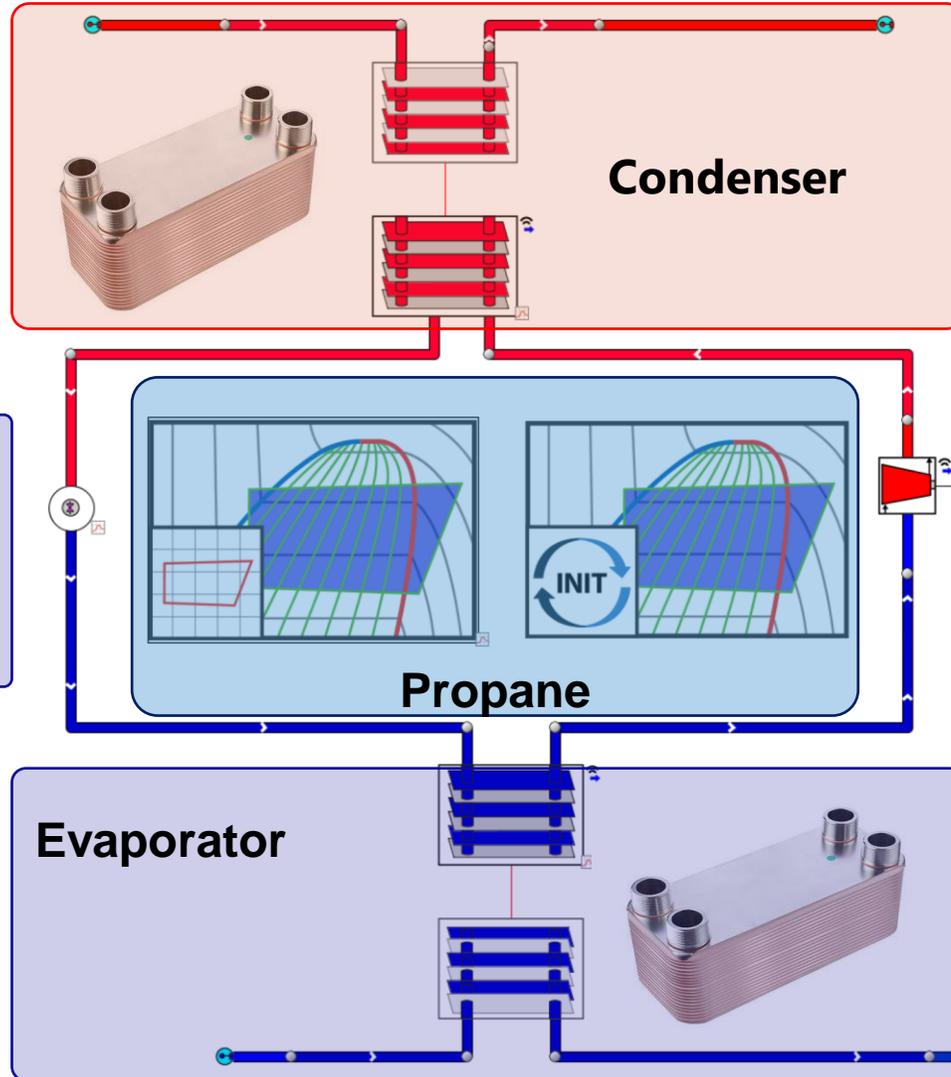
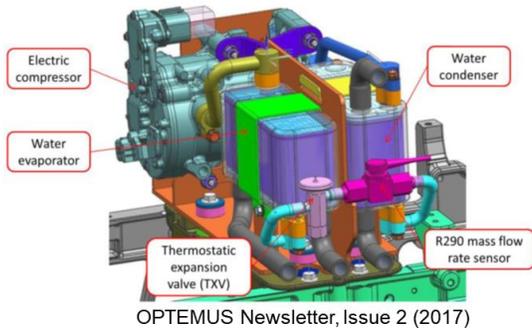
- Integrated concept
- Efficiency ensured by the direct system
- Increased complexity in the refrigerant loop
  - Control of the three TXVs is challenging
  - Different operating modes need to be clearly defined by operating on the TXVs



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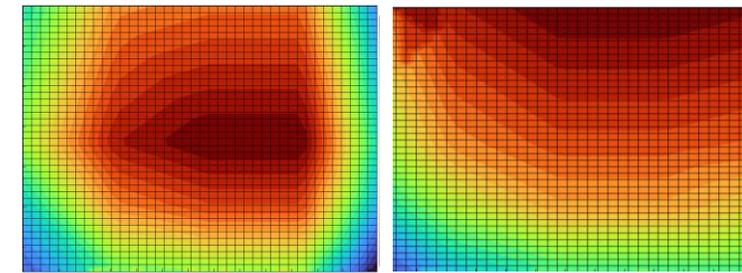
# Heat Pump: Compact Refrigeration Unit (CRU)



## Heat Exchangers

- Physical model with 1D discretization along fluid flow
- Calibrated and validated with experimental data

## Volumetric Compressor

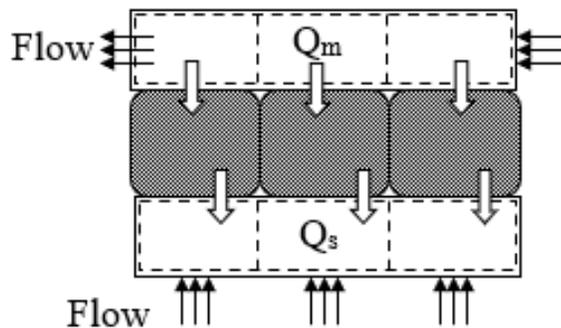


Isentropic Efficiency Map

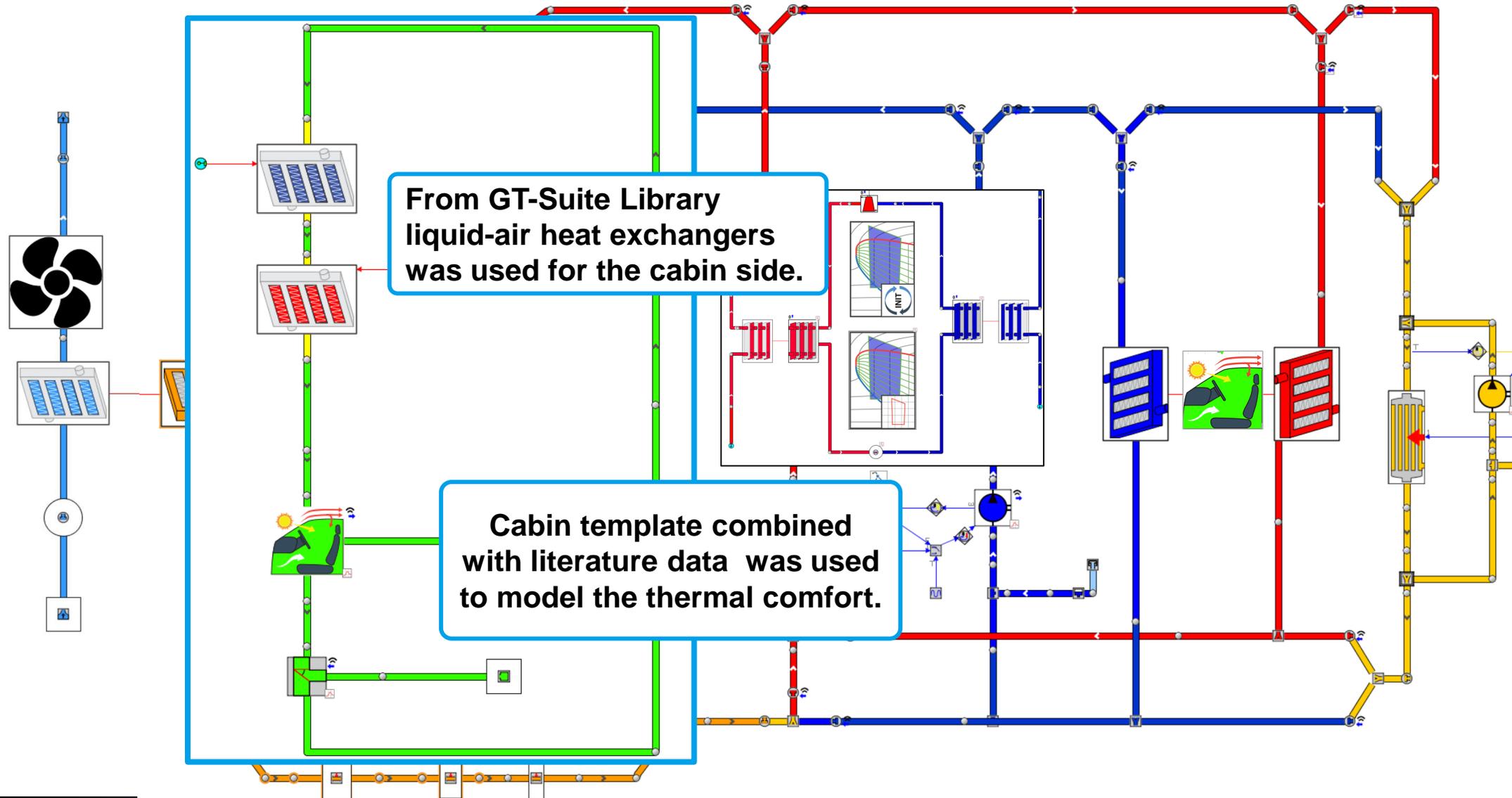
Volumetric Efficiency Map

## Thermal Expansion Valve (TXV):

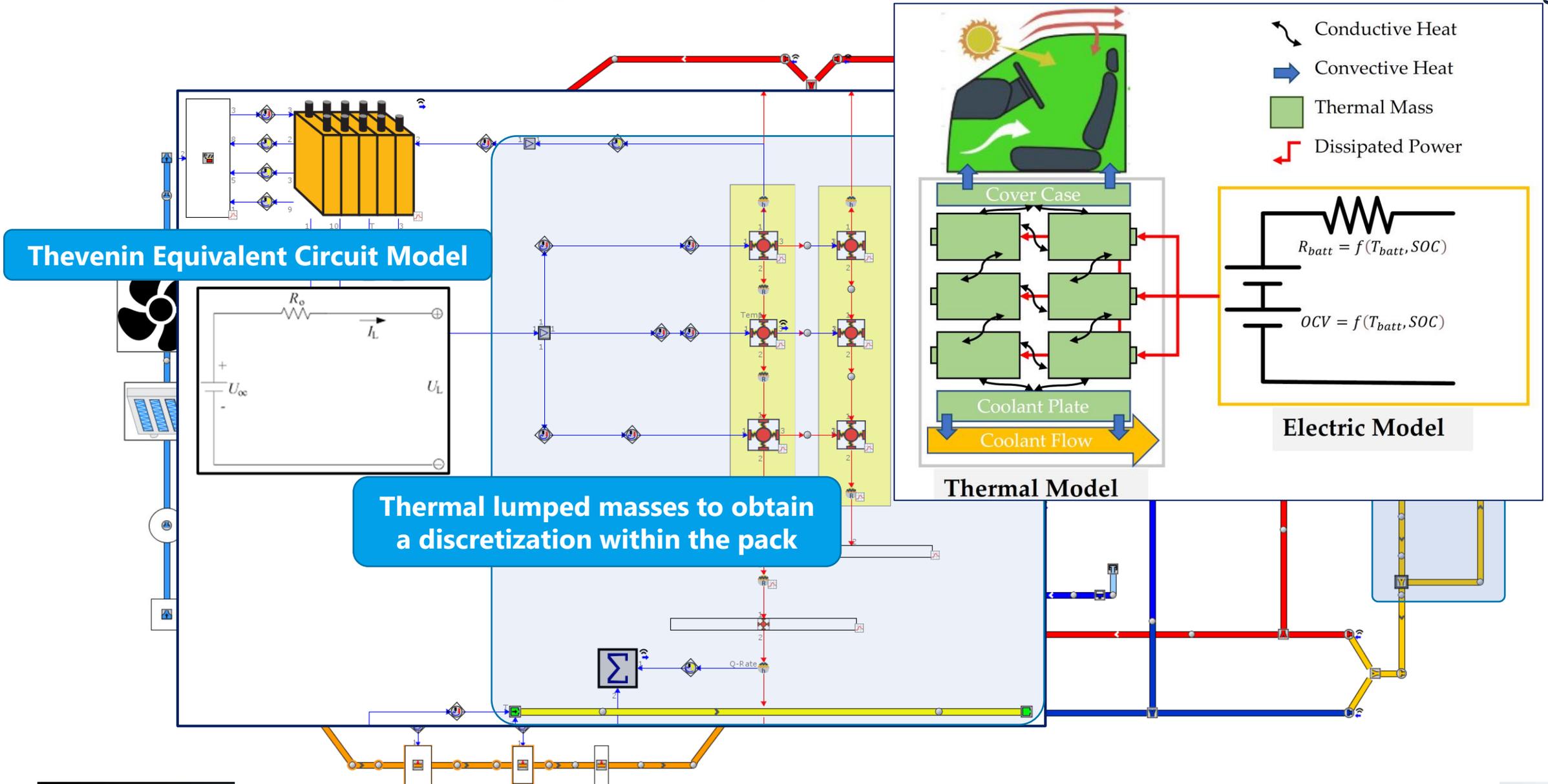
A simplified model based on **superheat** at the inlet of the compressor was used.



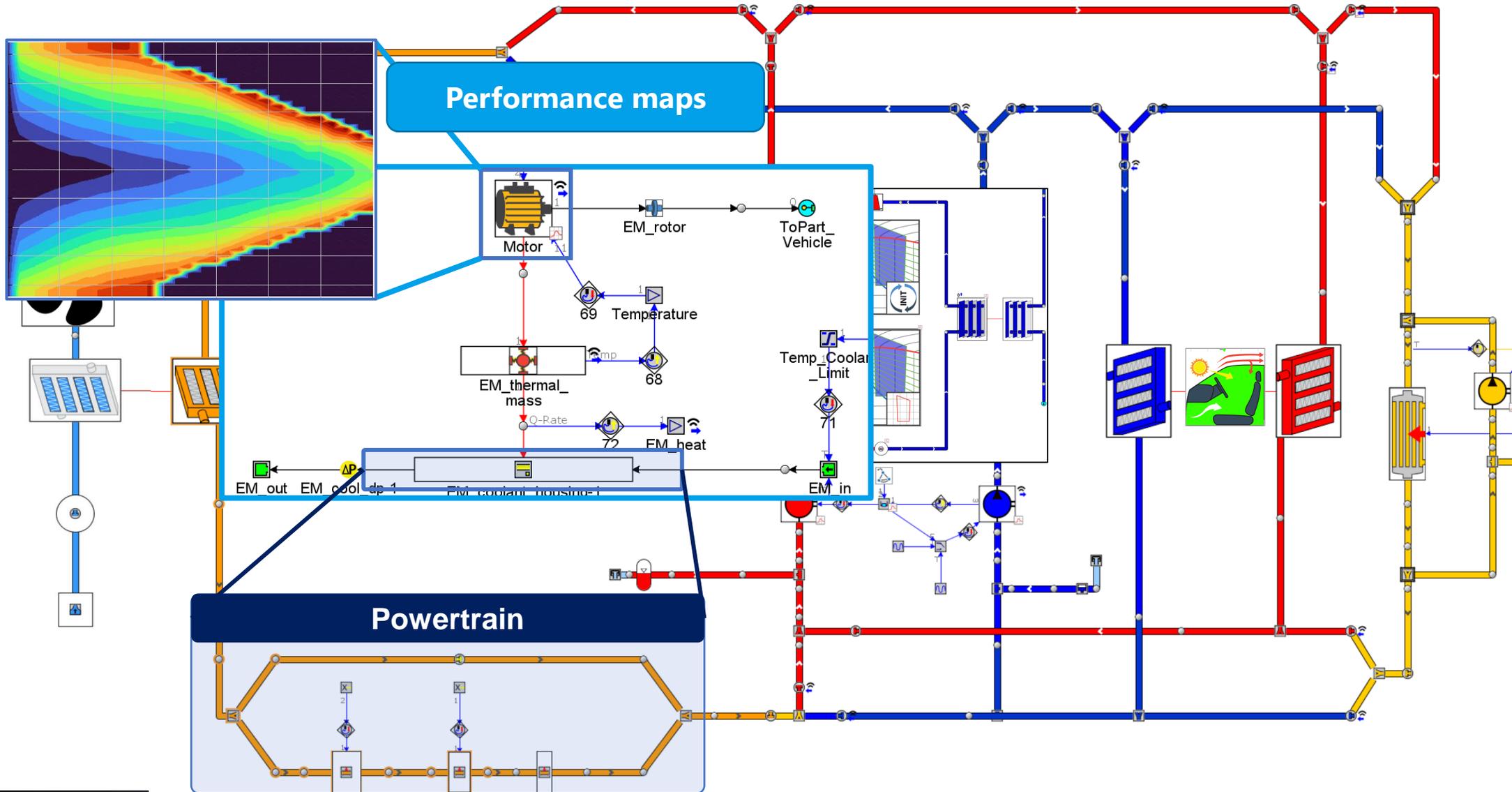
# Heat Pump Modelling: Cabin System



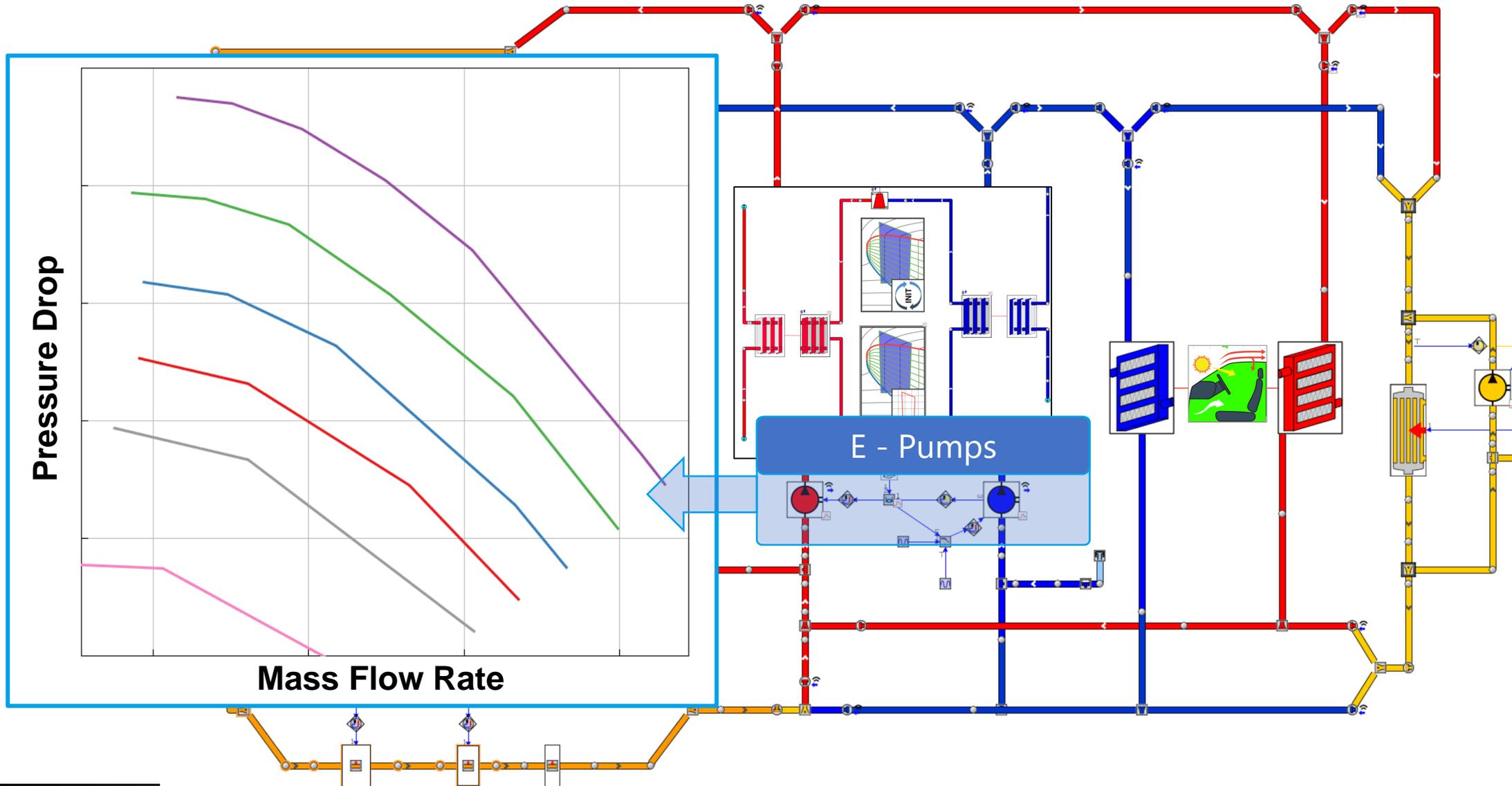
# Heat Pump Modelling: Battery



# Heat Pump Modelling



# Heat Pump Modelling





# Agenda

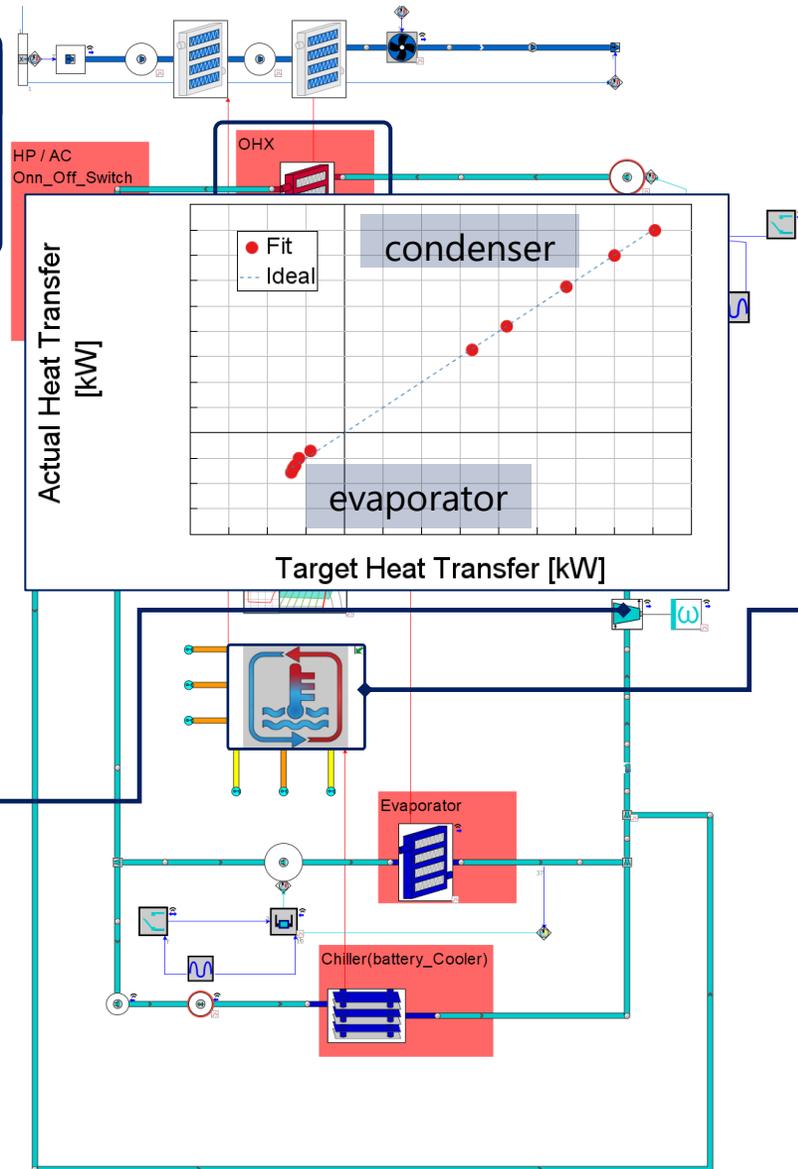
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# Direct Heat Pump Modelling

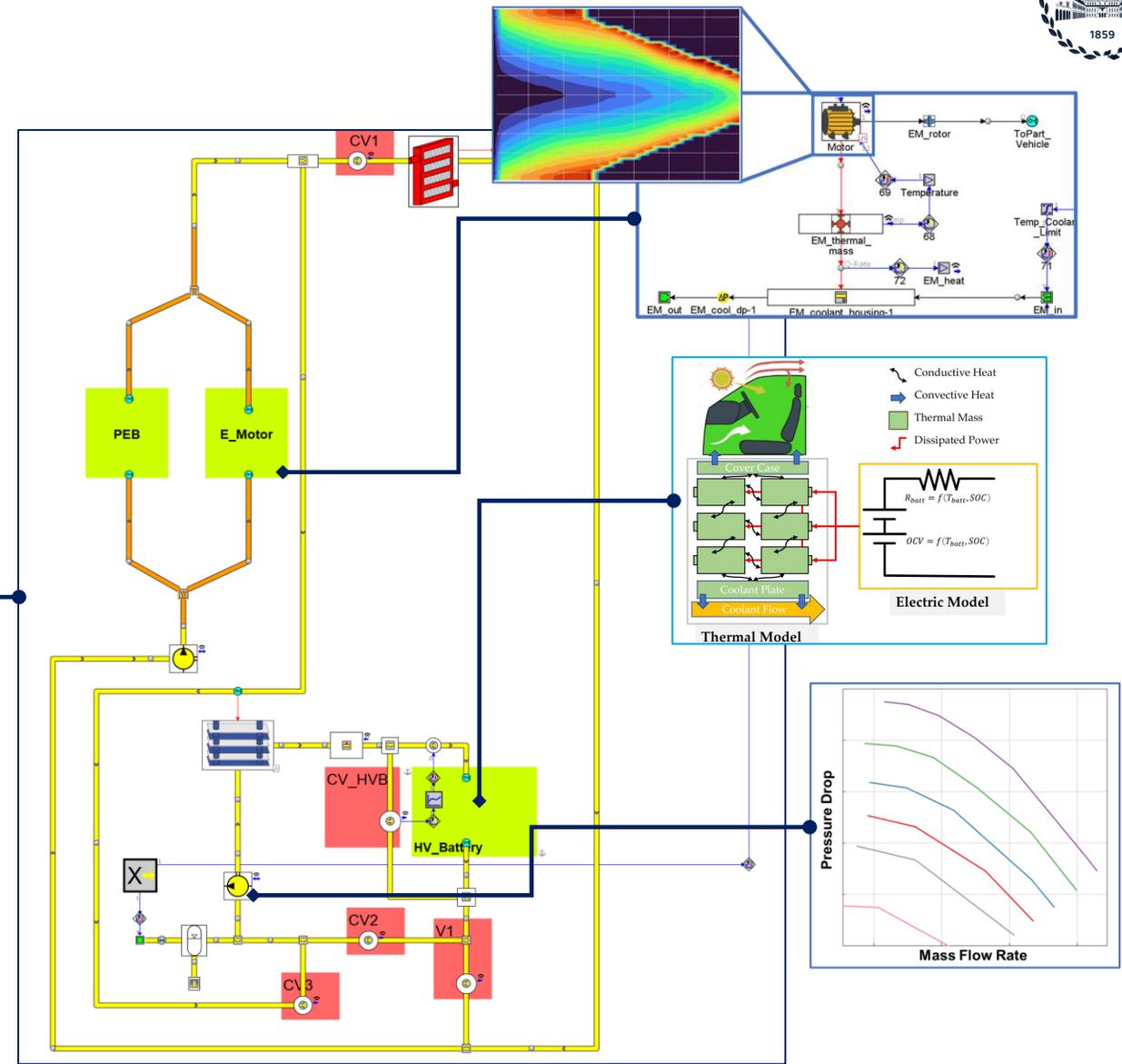
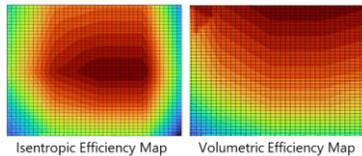


## Outdoor Heat Exchanger

- Evaporator
- Condenser



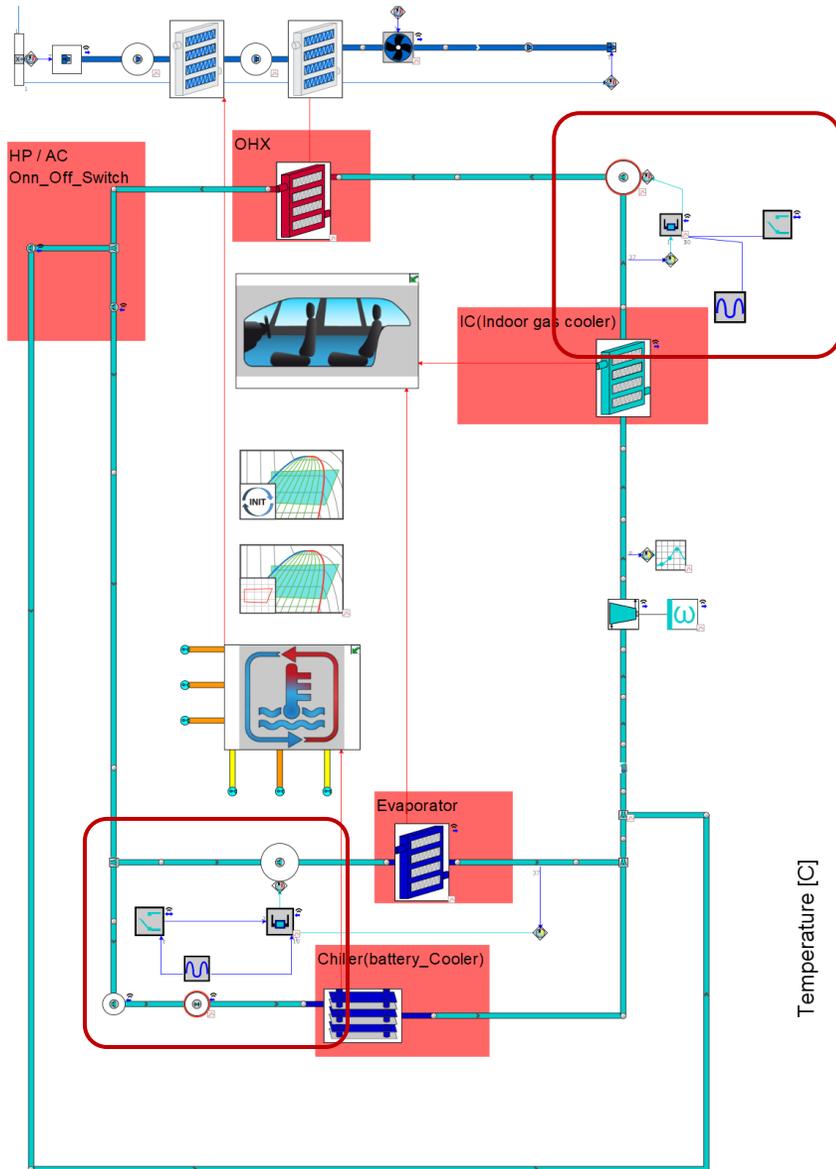
## Volumetric Compressor



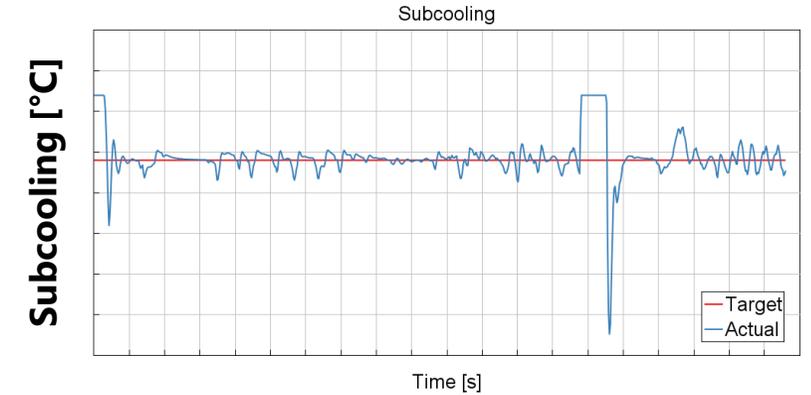
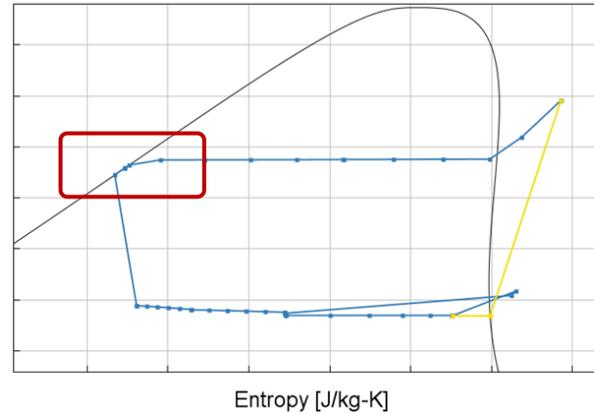
# Direct Heat Pump Modelling: TXV



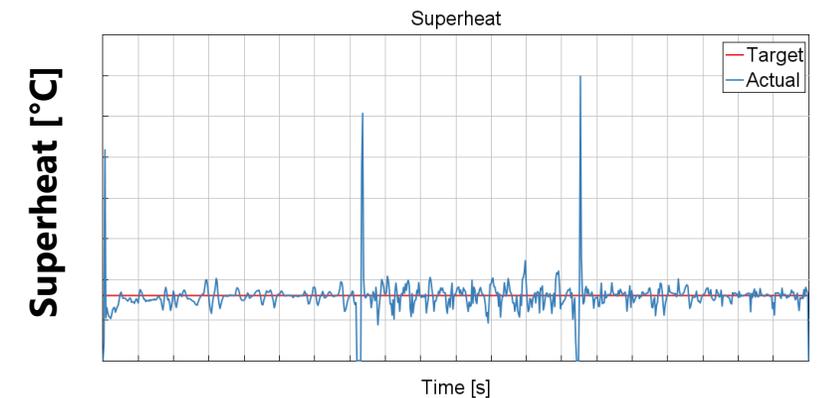
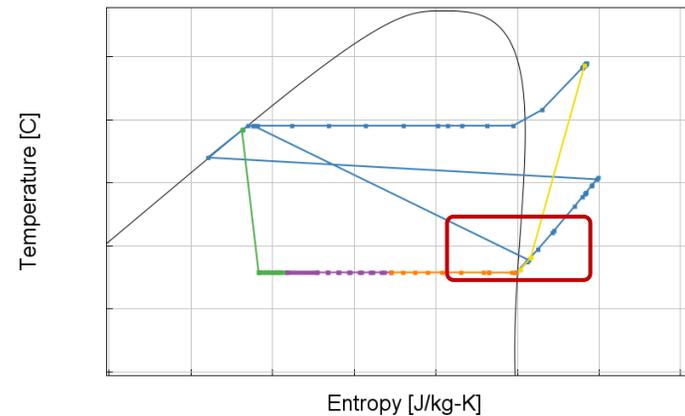
## Thermal Expansion Valve (TXV)



- **Sub Cooling** → **Cabin Heating**



- **Super Heat** → **Cabin and Battery Cooling**

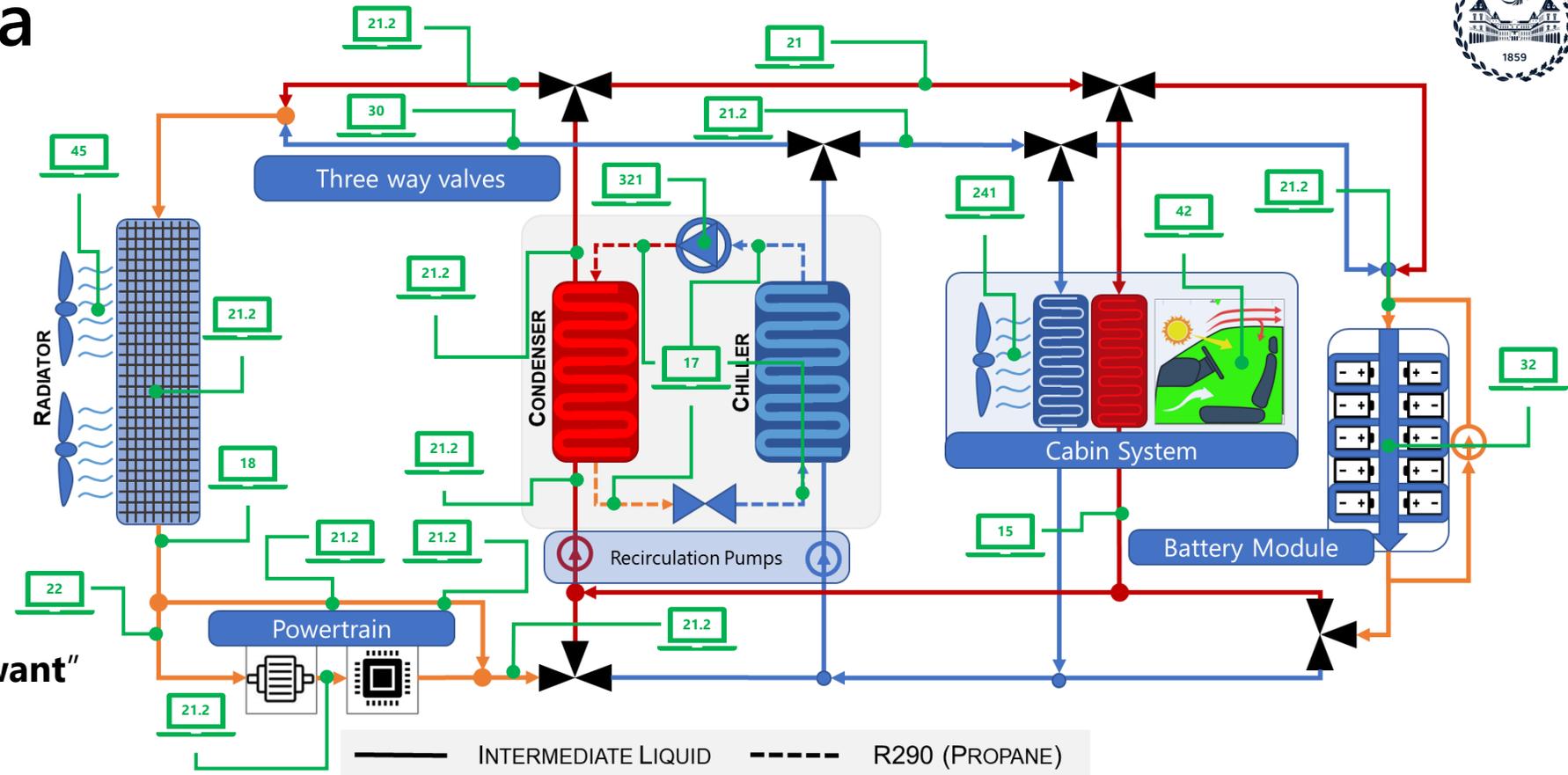


# Experimental Data

All quantities are ideally desired to be known:

- Mass flow rates
- Pressure
- Temperatures
- Cell Temperatures in the Battery Module

**"You can't always have what you want"**

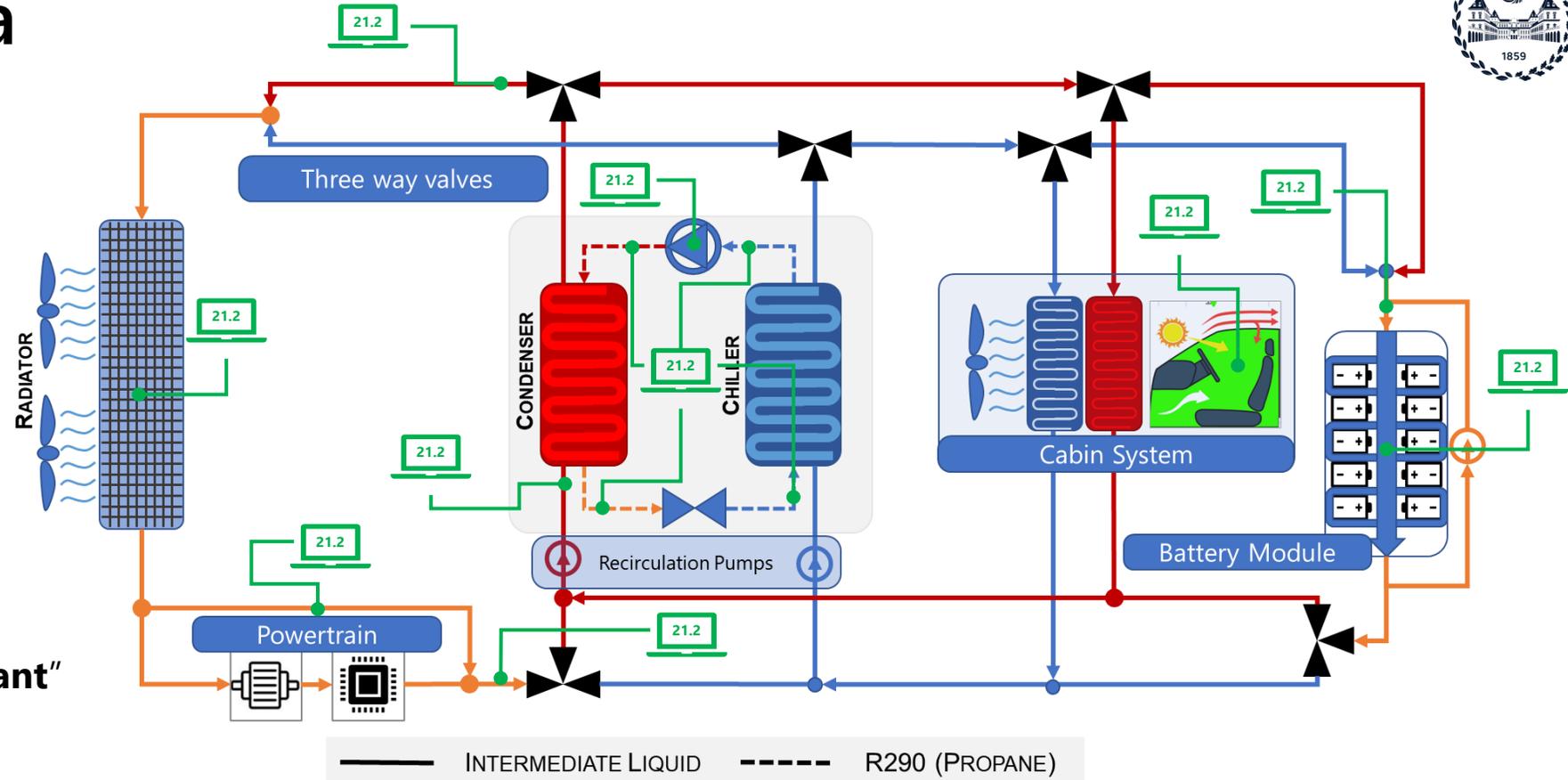


# Experimental Data



All quantities are ideally desired to be known:

- Mass flow rates
- Pressure
- Temperatures
- Cell Temperatures in the Battery Module



“You can't always have what you want”

But if you try sometimes, you can get what you need.

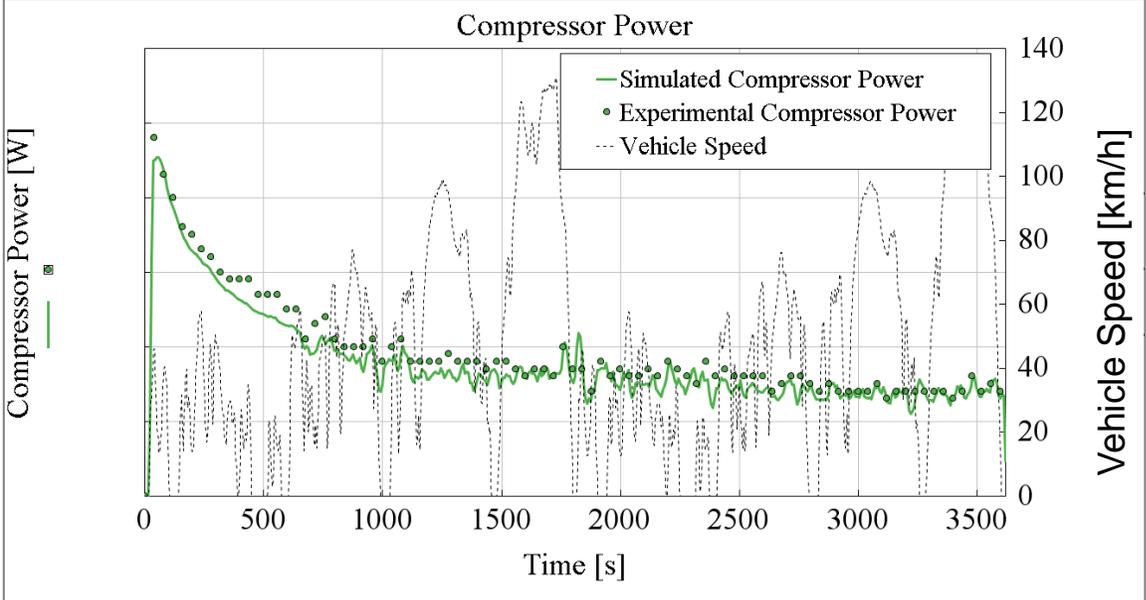
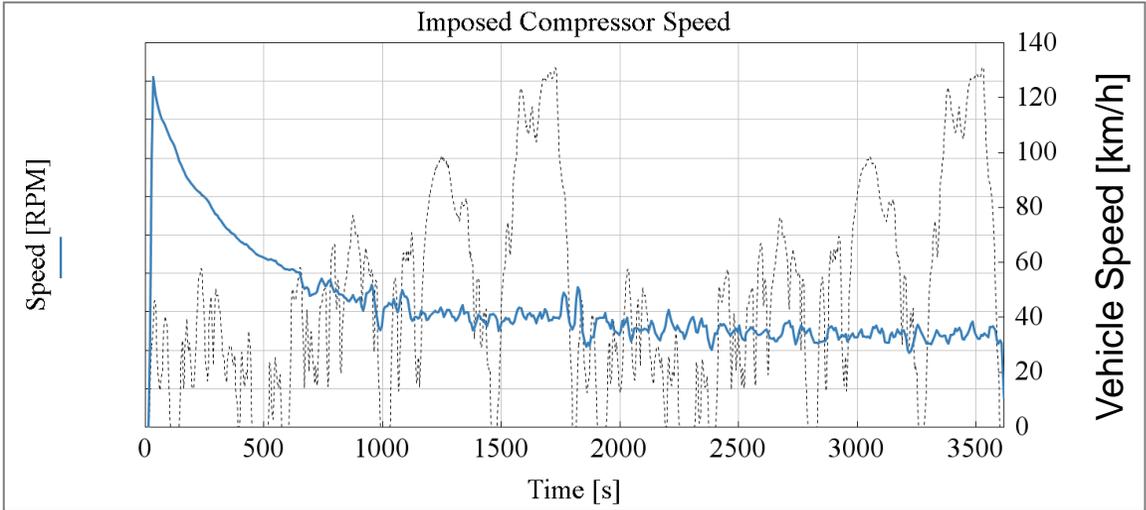
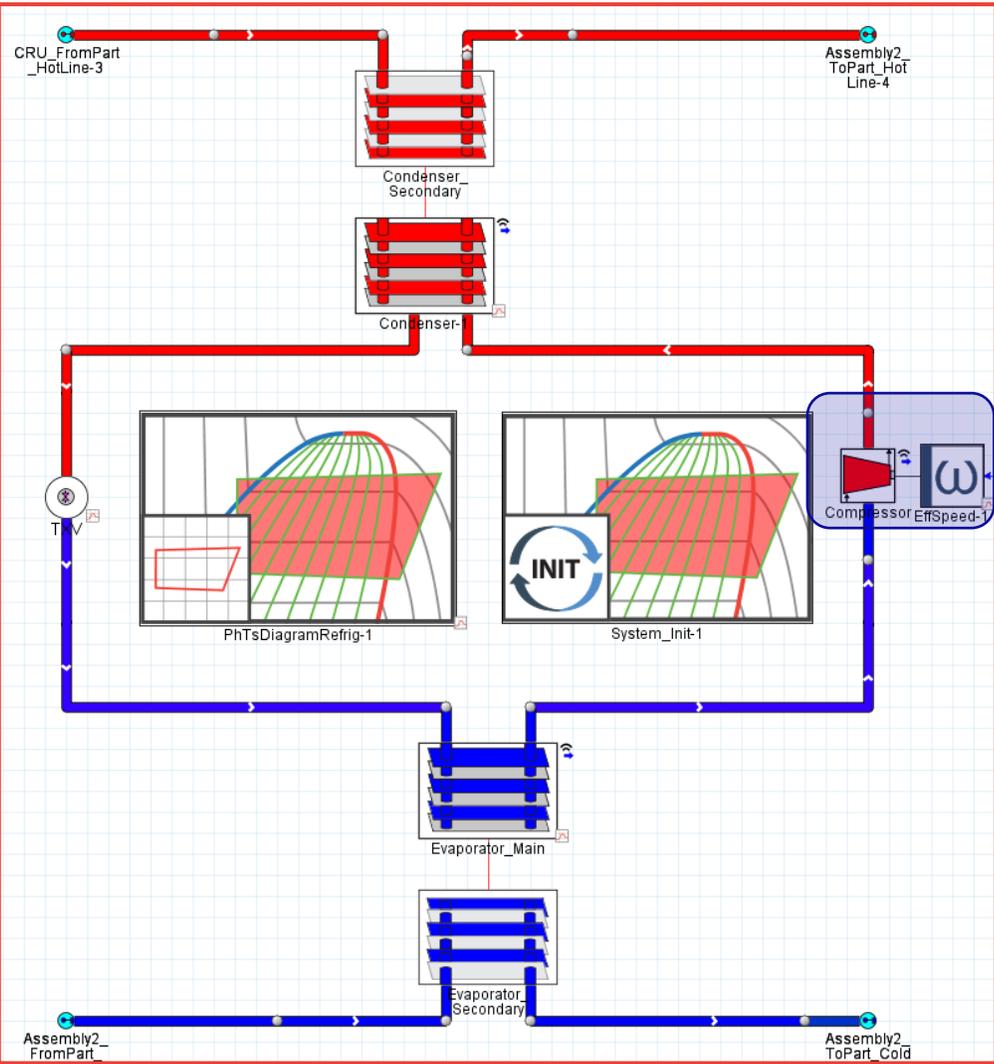
- Compressor Power
- Cabin temperature
- Battery Temperature

**Energetic quantities**

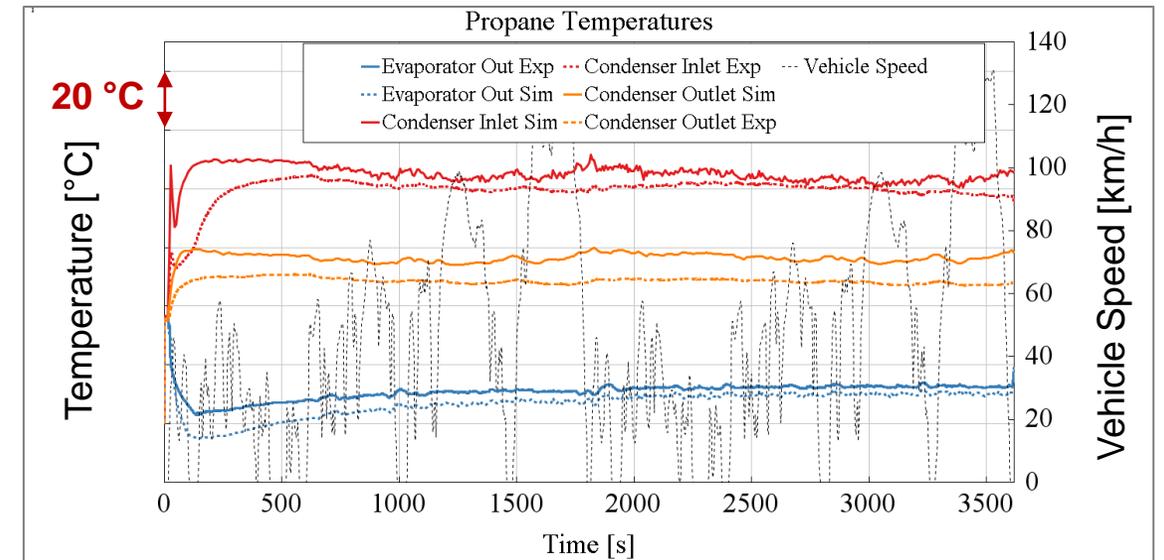
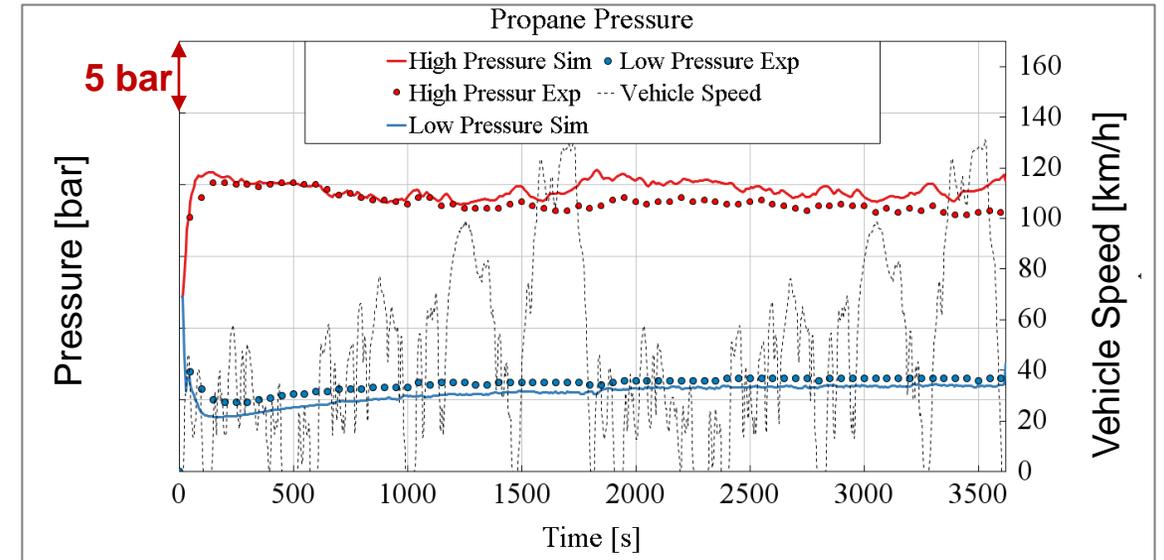
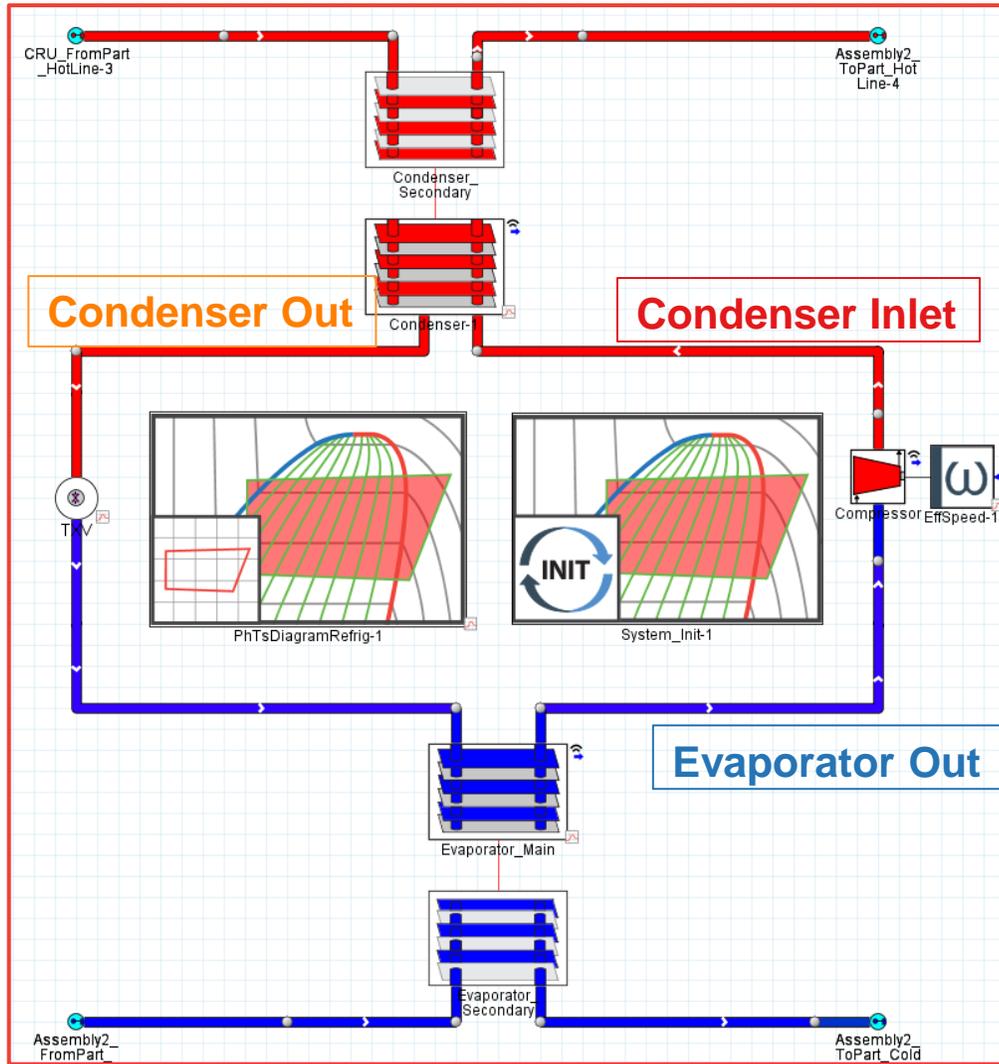
- Propane high temperature
- Propane high pressure line

**Control constrains**

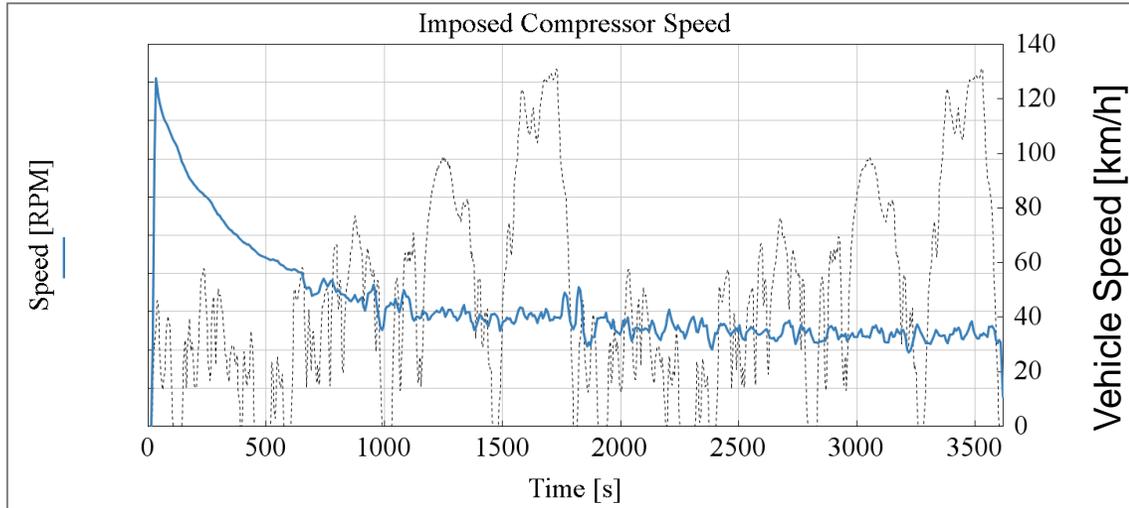
# CRU under Hot Environment



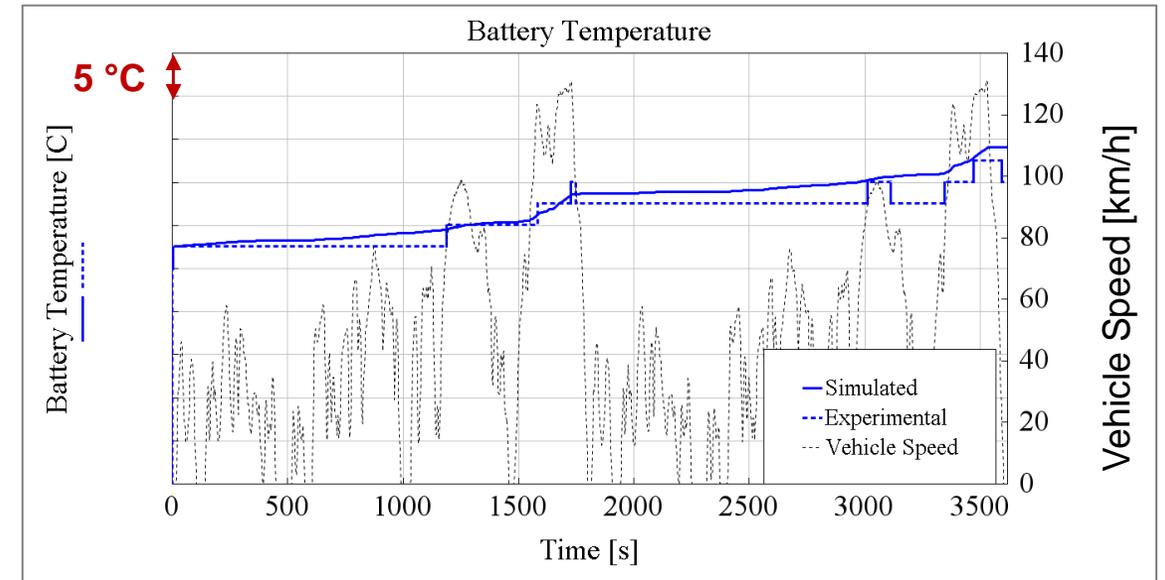
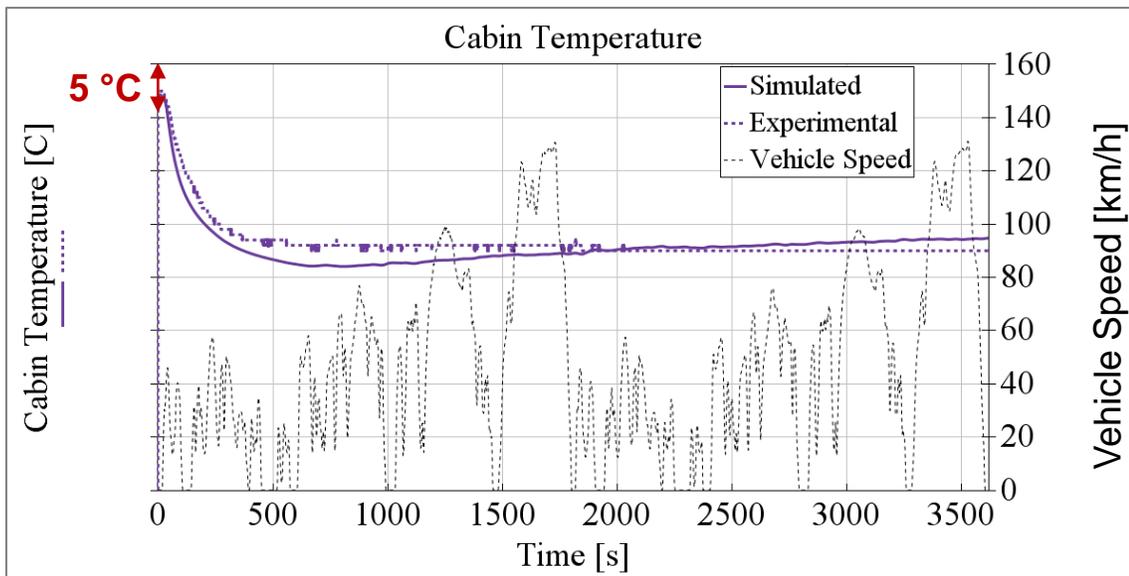
# CRU under Hot Environment



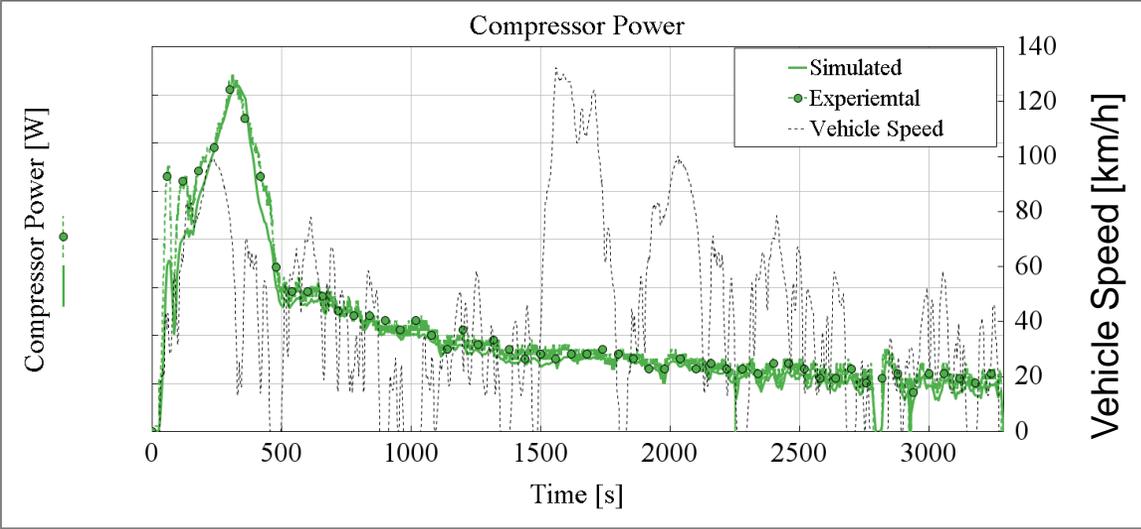
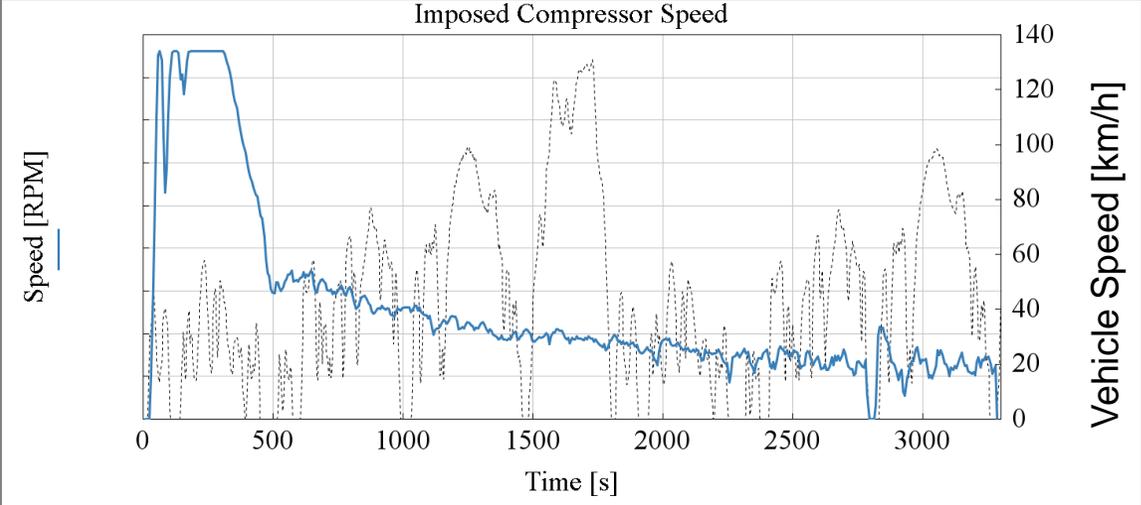
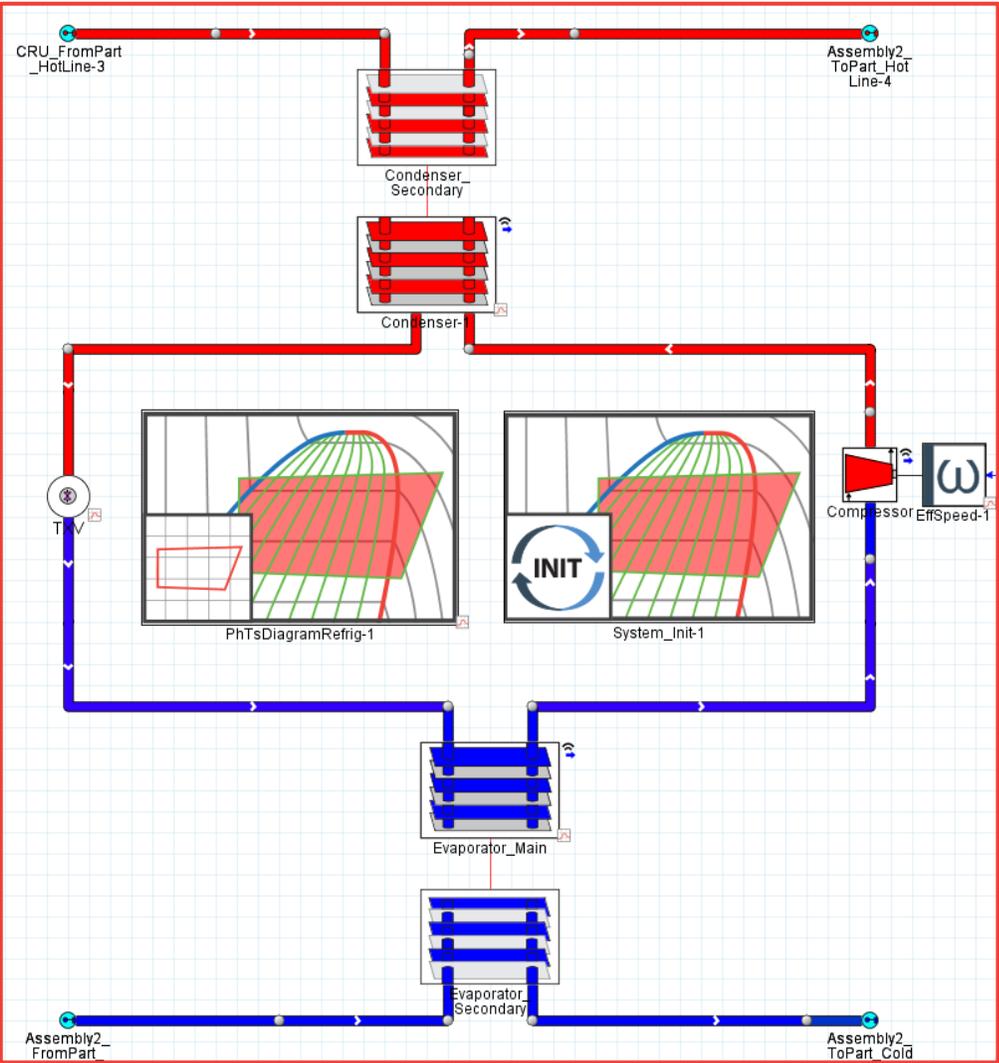
# CRU under Hot Environment



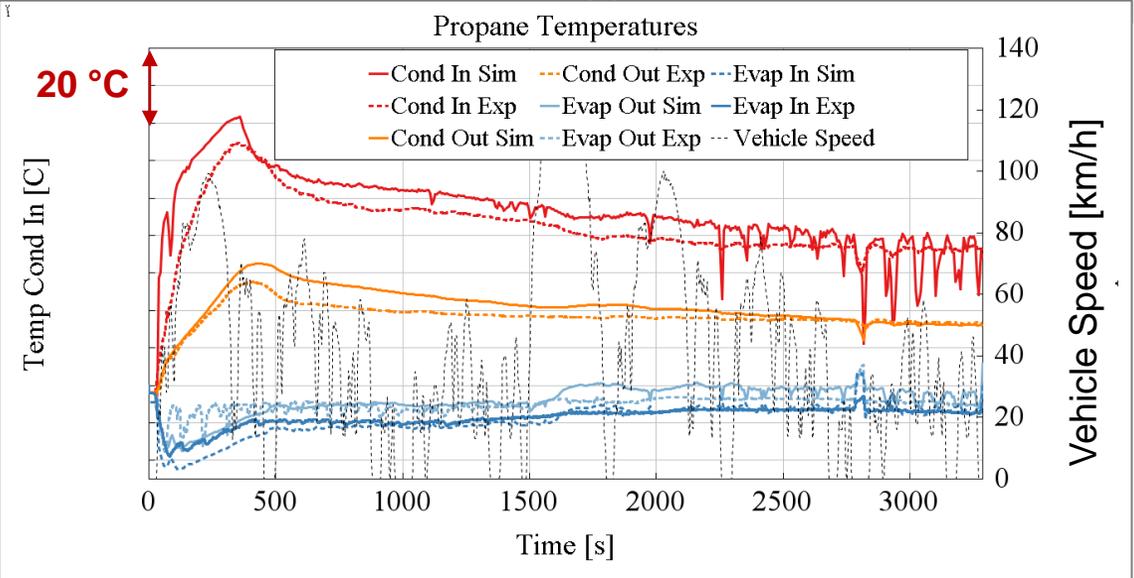
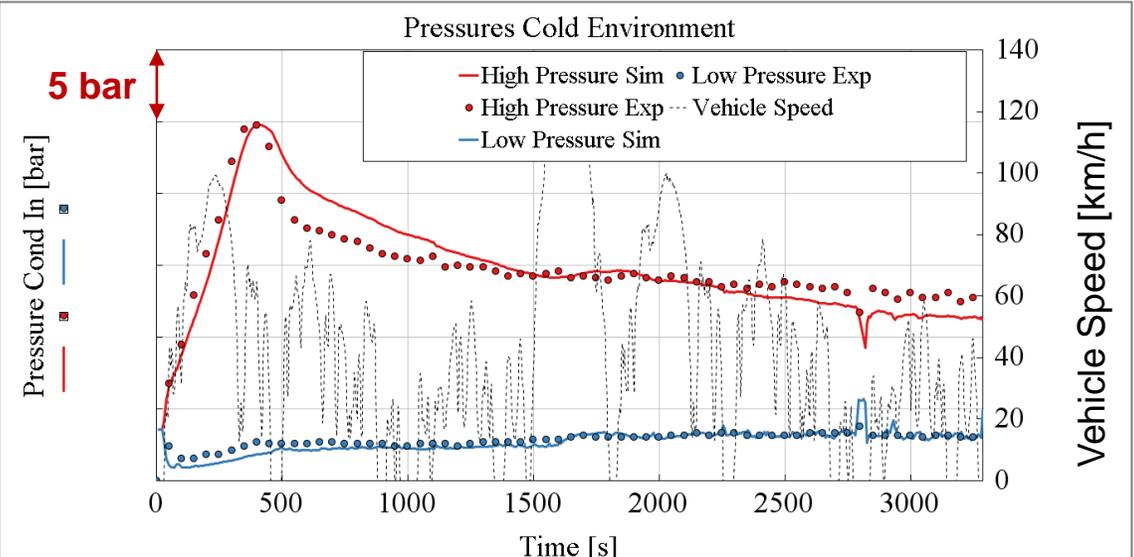
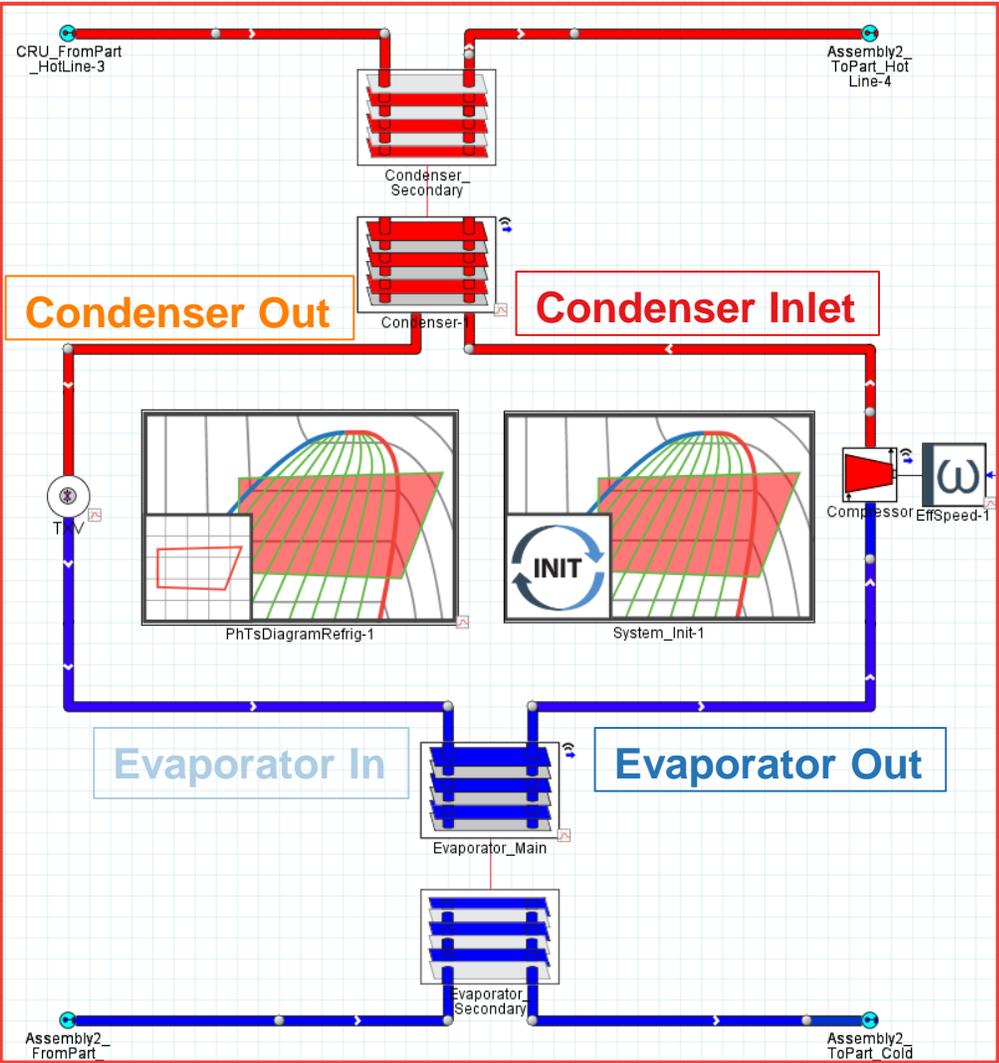
- **Cabin temperature** dynamic is well predicted, with the variation of compressor speed
- Slightly variation can be noticed at a constant speed, which can be attributed to external factors difficult to identify.
- **Battery temperature** increases when the cycle is more demanding with good accuracy.



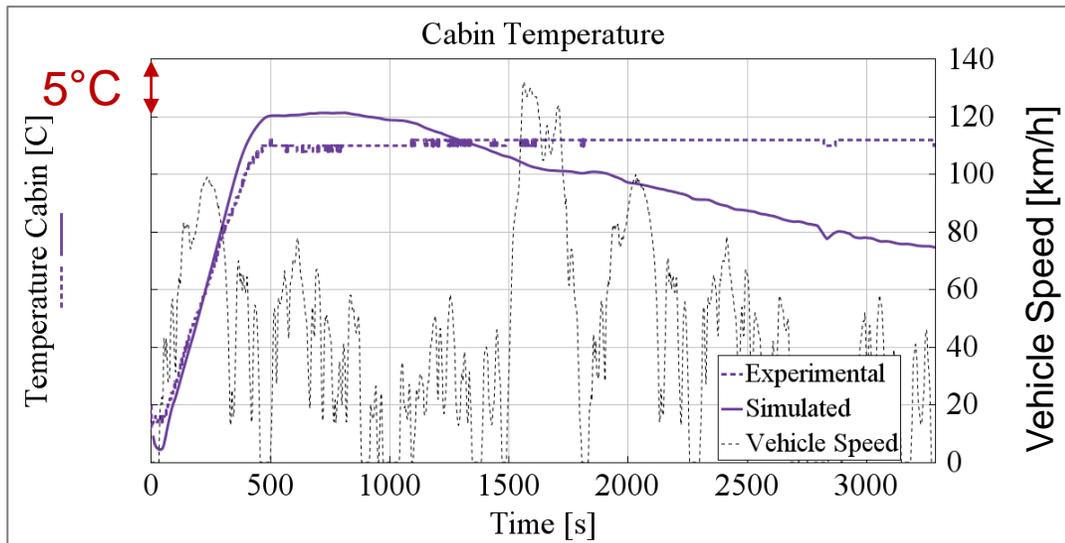
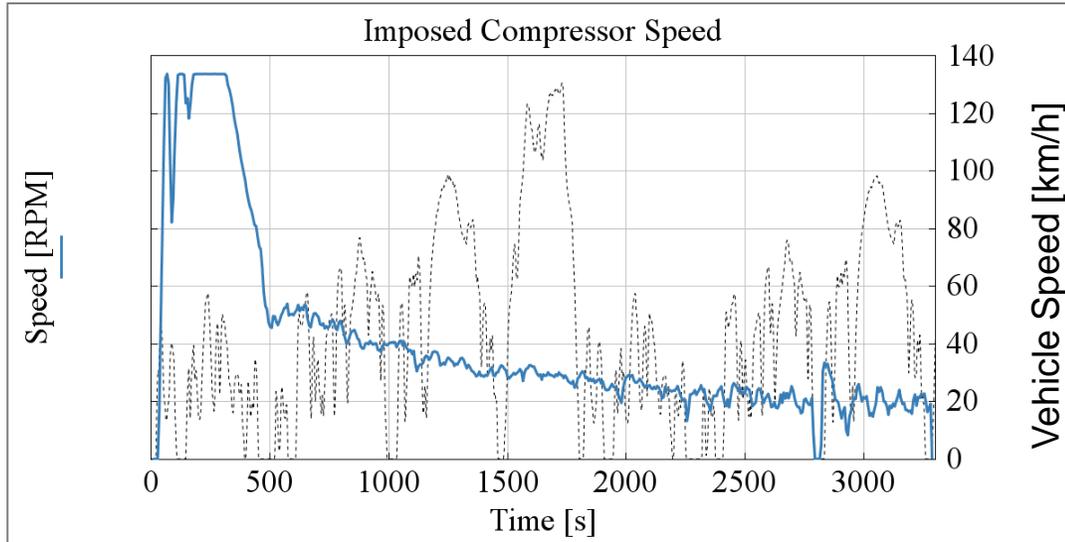
# CRU under Cold Environment



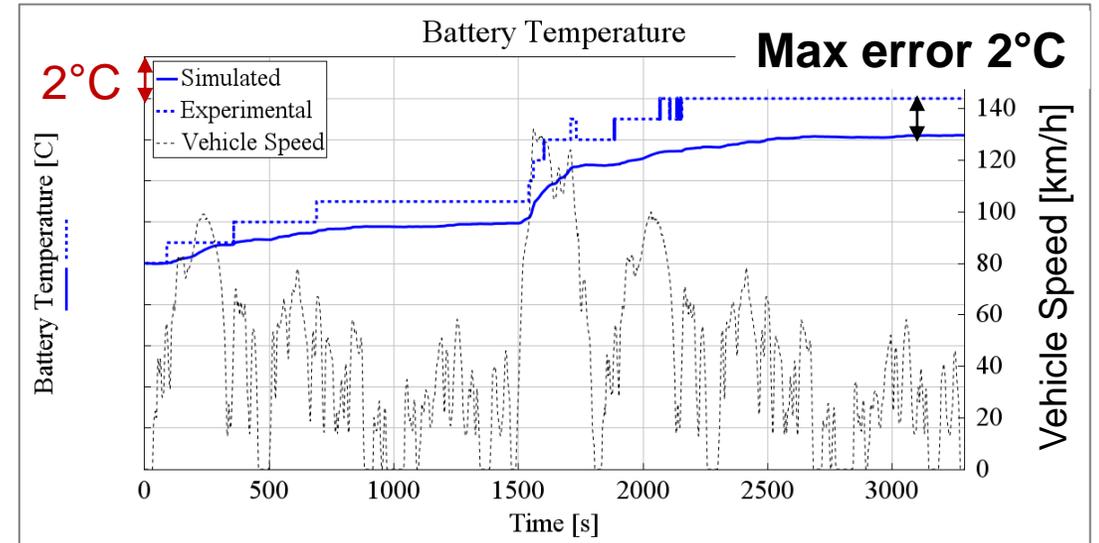
# CRU under Cold Environment



# CRU under Cold Environment



- **Cabin temperature** after 1000 seconds deviate from experimental data, possible explanation:
  - Cabin Blower actuation
- **Battery temperature** is underestimated during cold operation → Underestimate of battery losses at low temperatures.





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# Direct Heat Pump

## Higher complexity and effort:

- Refrigerant loop has a higher number of paths
- Three thermal expansion valve to be controlled according the different requests.
- Fewer experimental data points compared to the previous case.

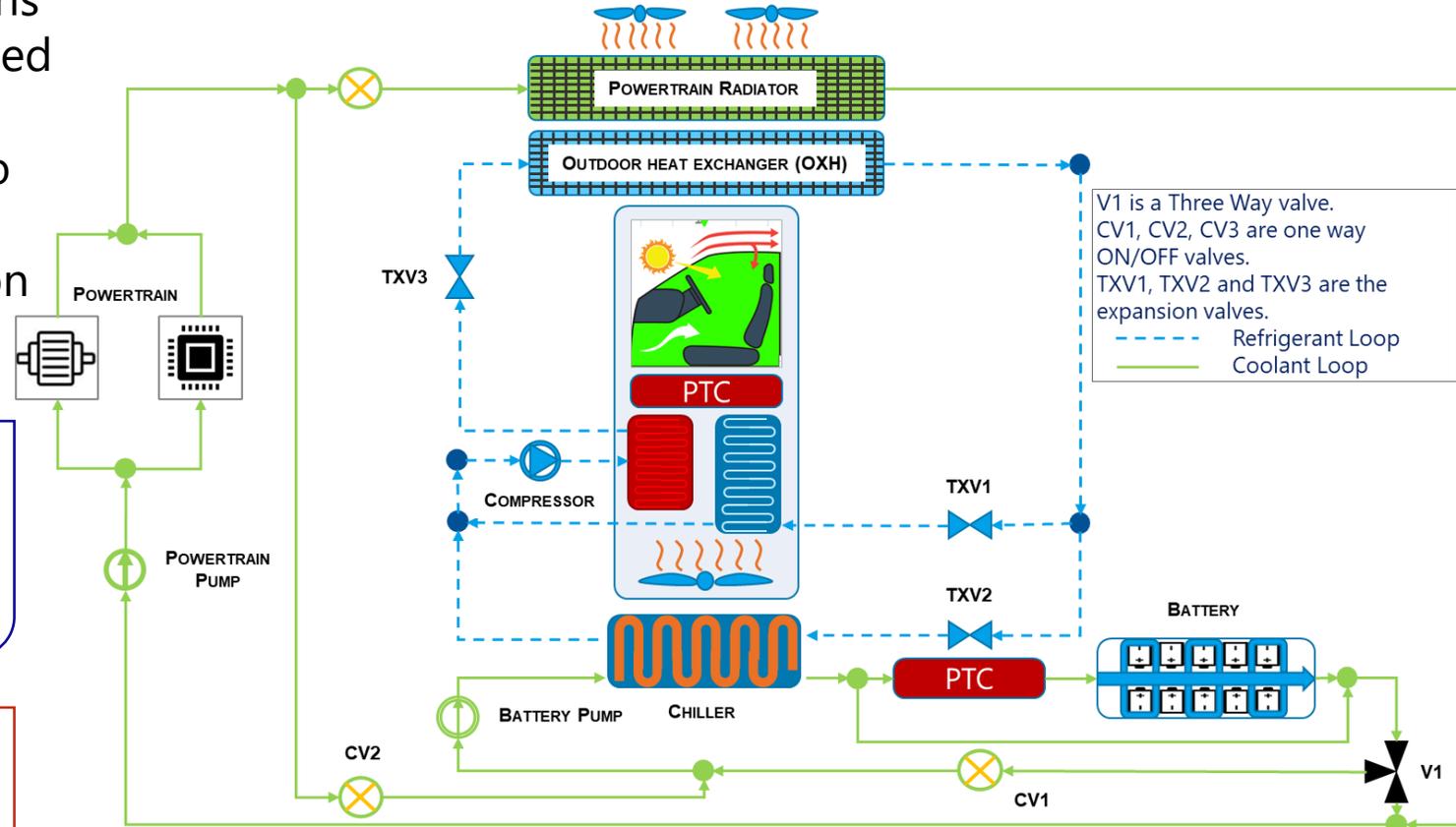
In this context, the focus was kept once again on some relevant physical quantities.

- Compressor Power
- Cabin temperature
- Battery Temperature

**Energetic quantities**

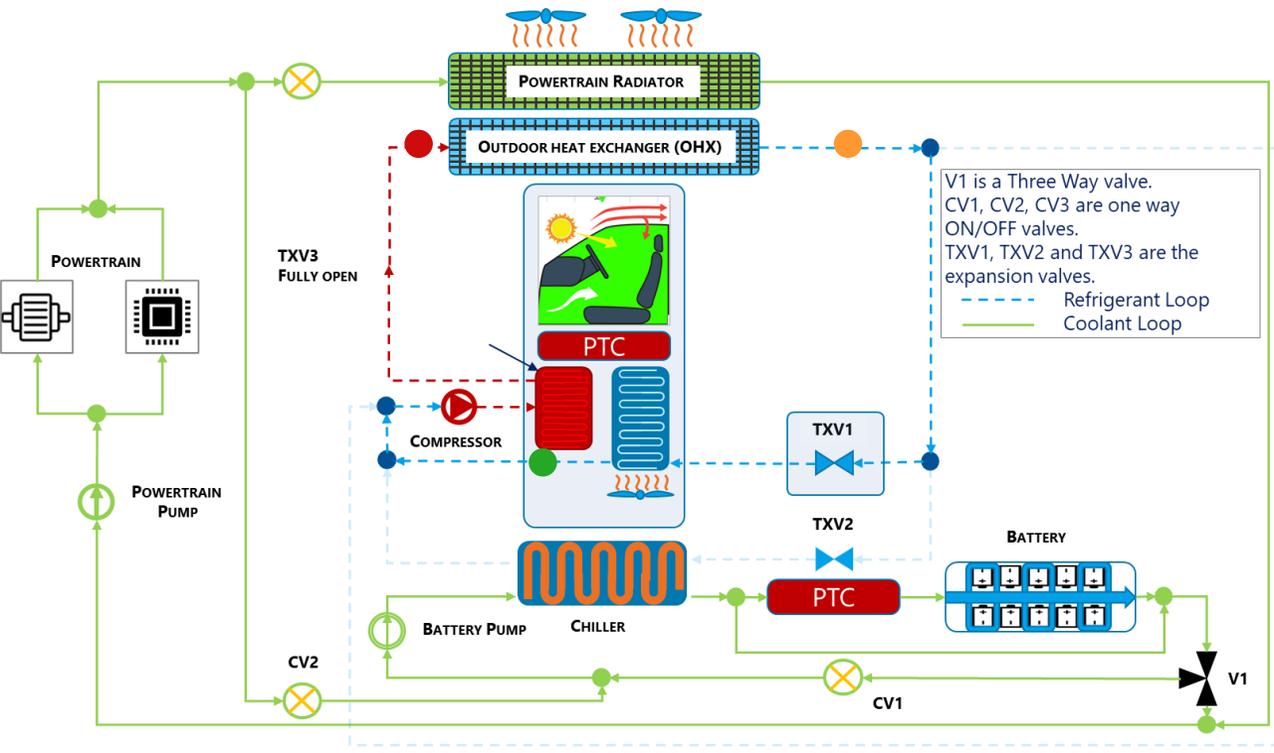
- R123yf temperature
- R123yf pressure

**Control constrains**

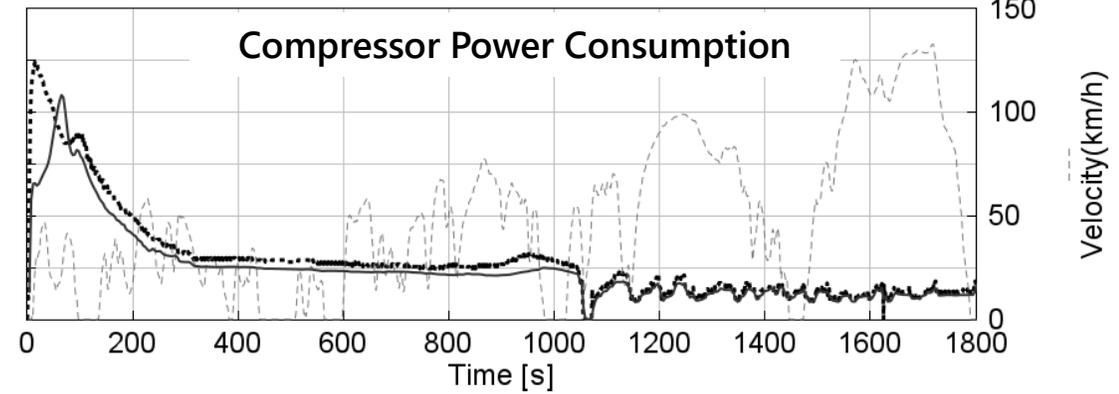


# Direct Heat Pump

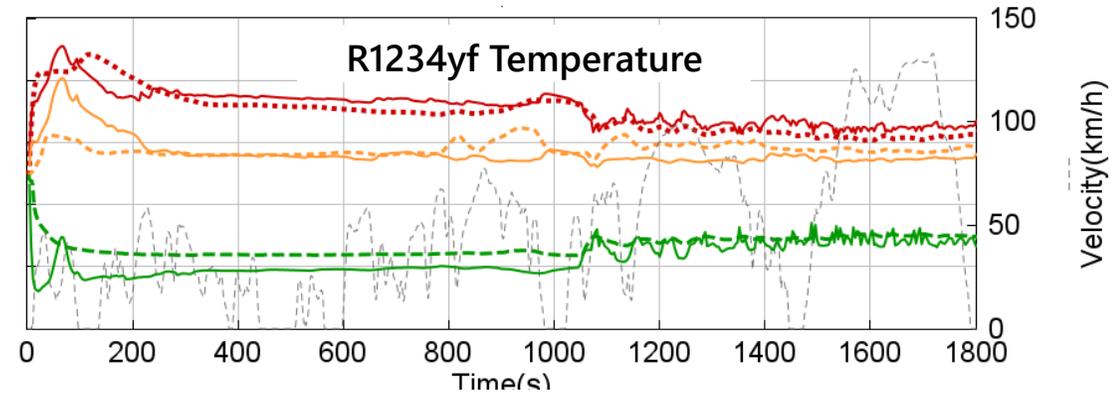
Environment 35 °C



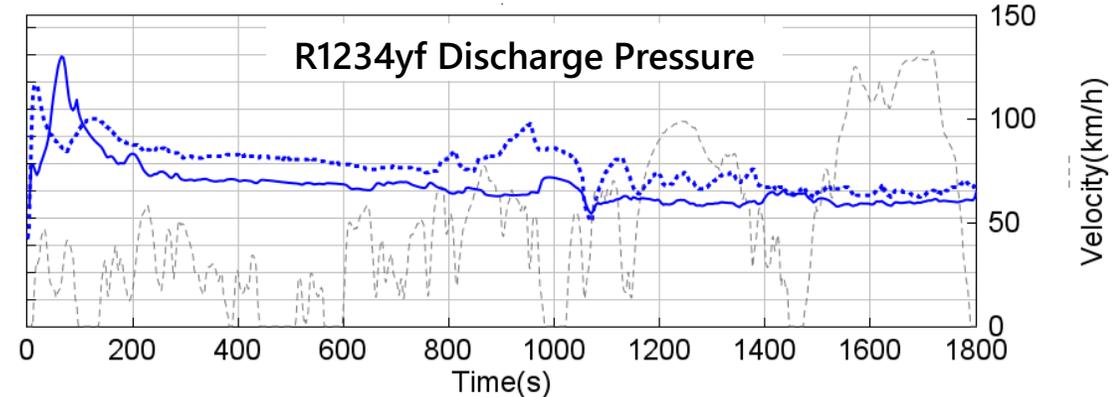
Compressor Power [kW]



Temperature [C]



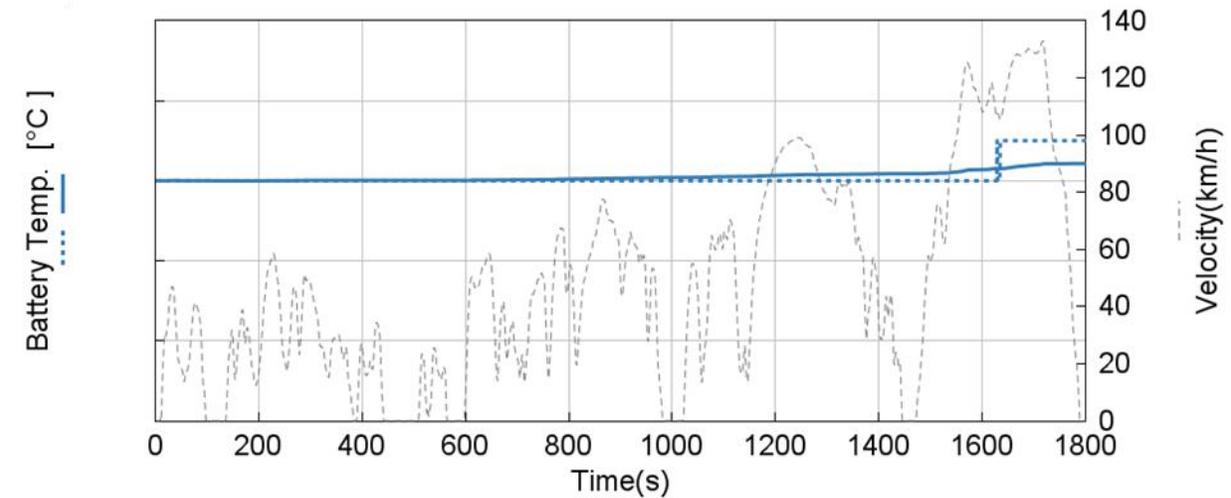
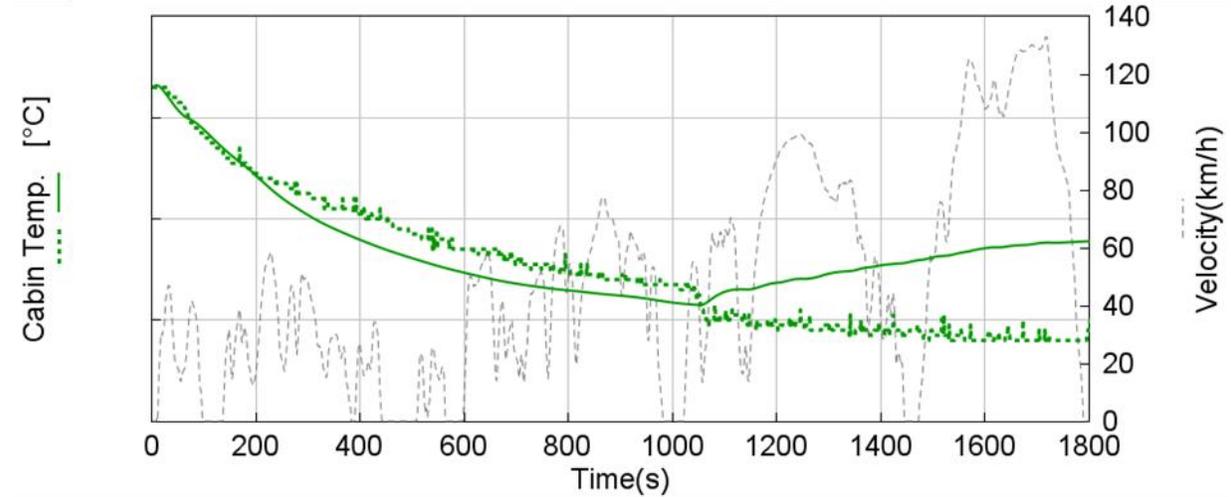
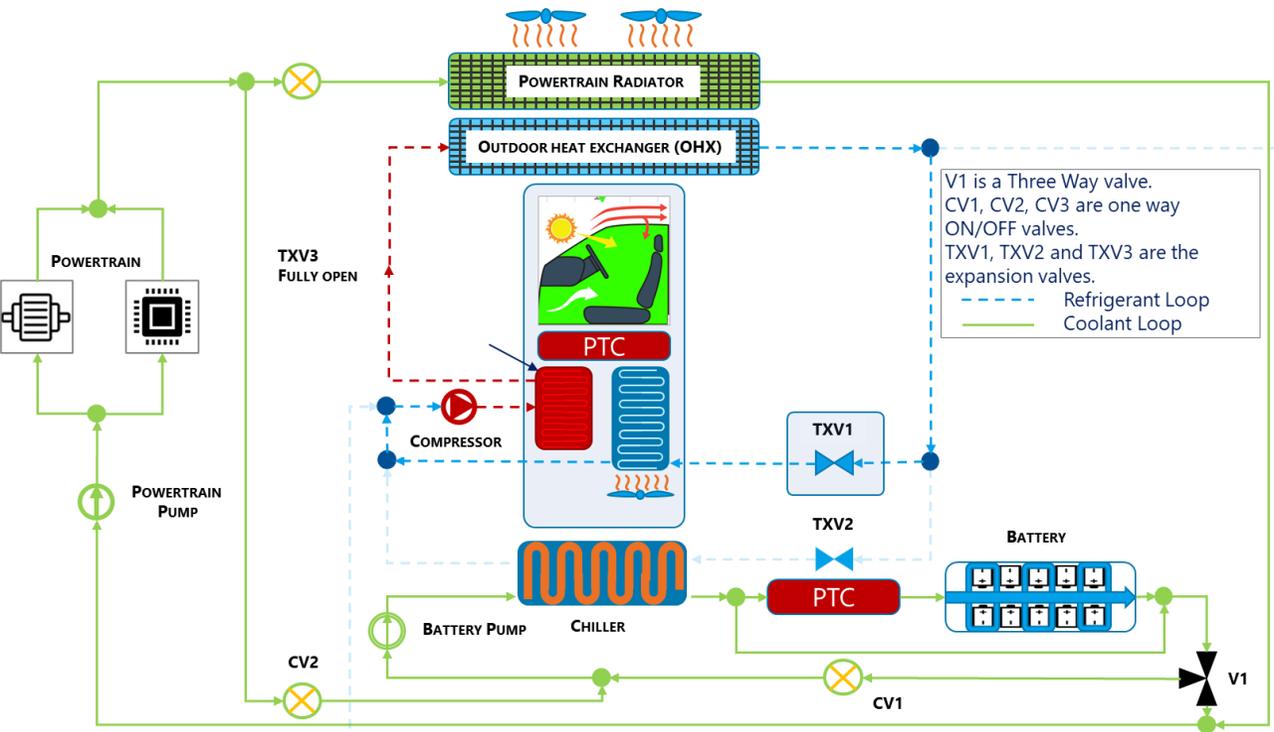
Dis. Pressure(bar)



# Direct Heat Pump



Environment 35 °C





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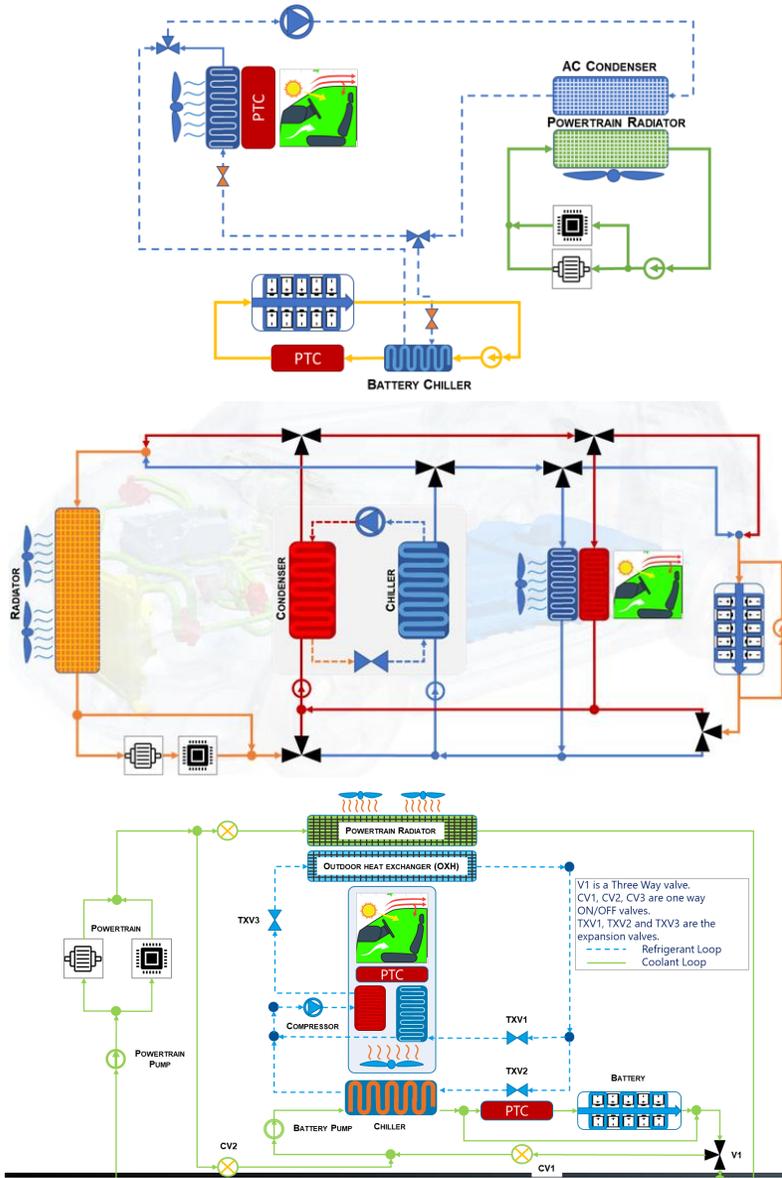
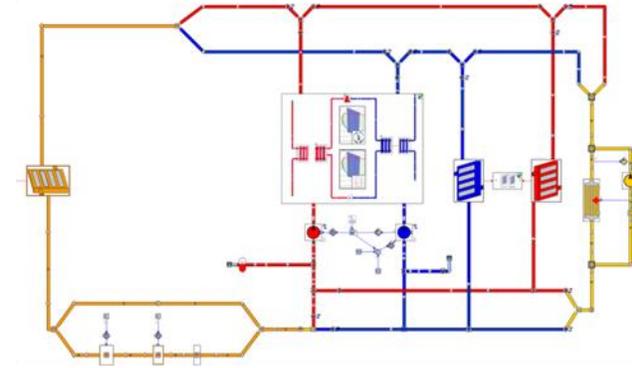
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# Conclusion

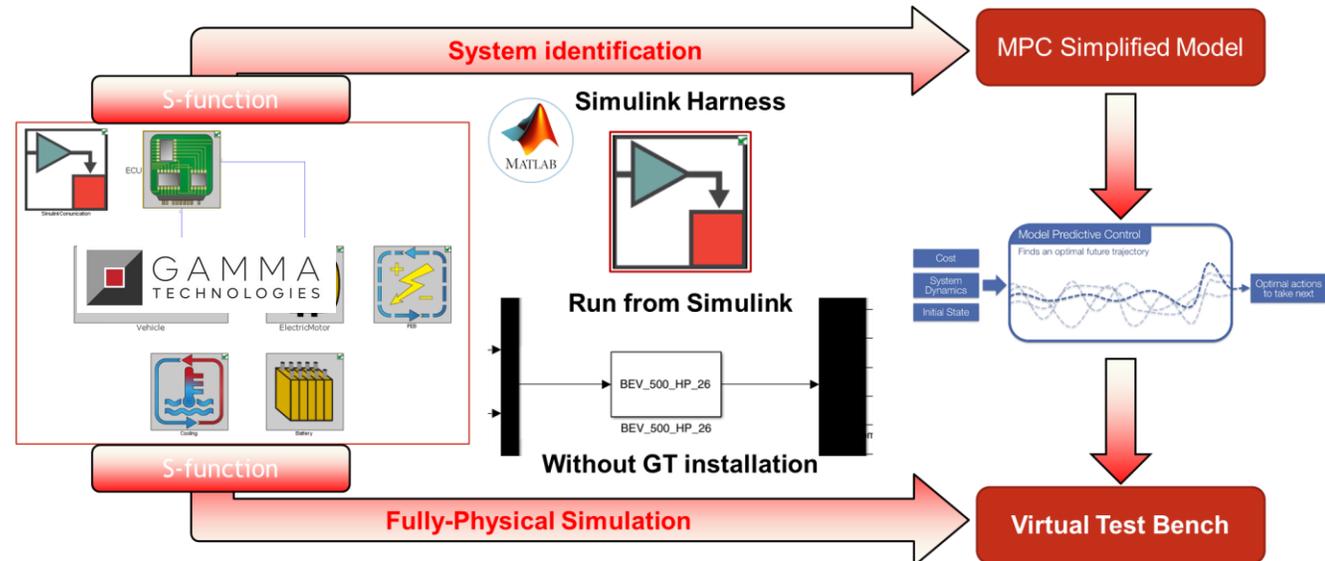
During this activity the multiphysics approach provided by GT-Suite proved to be fundamental to the design, understanding and development of the system.

## Model Development

- Layout investigation and troubleshooting
- Components modelling
- Refrigerant exploration (CO2)
- Investigation on battery management strategies: precondition/fast charging.



## Control Development



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