Battery Electric Vehicle Thermal Management System Graph-Based Modeling

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OVERVIEW

Heat loads in Battery Electric Vehicles (BEV) are known to be **highly transient** during operation. However, traditional TMS design approaches rely on evolving known pre-existing design with **no up-front consideration of controls and transient operations**.

The objective is to **develop novel modeling methods to be used for closed-loop transient system analysis that enable up-front definition of optimal TMS design concepts for BEV**.

1. Capture of **transient and steady state dynamics** of the TMS accurately at the component, cycle and system level.
2. Evaluation of **closed-loop performance.**

Graph-based modeling is used due to its ability to facilitate both dynamical analysis, as well as control synthesis. It is also computationally efficient for more complex systems.

Literature Review

BEV TMS Modeling [1]:

- Modeling commonly done with preset thermodynamic libraries.
- Compares different TMS, such as Heat Pump-based and Waste Heat Reduction- based architectures.
- Lack of component and topology optimization.
- Control design has been limited to General Integrated Loop (GIL).

Graph-based modeling [2]:

Model a general vapor compression system (VCS) of a BEV.

- Optimized performance metrics to cool the cabin.
- Geometry and topology of components were not considered.
- Cabin cycle, electronics cooling cycle and battery cooling cycle were not considered.

REFERENCES

[1] S. Singh, M. Jennings, S. Katragadda, J. Che, and N. Miljkovic, "System design and analysis methods for optimal electric vehicle thermal management," Applied Thermal Engineering, vol. 232, Sep. 2023

[2] K. M. Russell, "Modeling and control of thermal management systems on electric vehicles," Thesis, University of Illinois at Urbana-Champaign, 2023.

[3] T. J. Shelly, "PARAMETRIC ANALYSIS AND OPTIMIZATION OF LONG-RANGE BATTERY ELECTRIC VEHICLE THERMAL MANAGEMENT SYSTEMS," thesis, Purdue University Graduate School, 2020.

[4] A. Bolander, T. Bird, W. A. Malatesta, K. McCarthy, and N. Jain, "A Multi-state Graph-based Framework for Dynamic Modeling of Turbomachinery Components," in AIAA SCITECH 2024 Forum, in AIAA SciTech Forum. , American Institute of Aeronautics and Astronautics, 2024.

[5] TLK-Thermo GmbH, "TLK-Thermo – Engineering Services and Software for Thermal Systems," TLK-Thermo GmbH, [Online]. Available: https://www.tlk-thermo.com/en/.

TMS Architecture

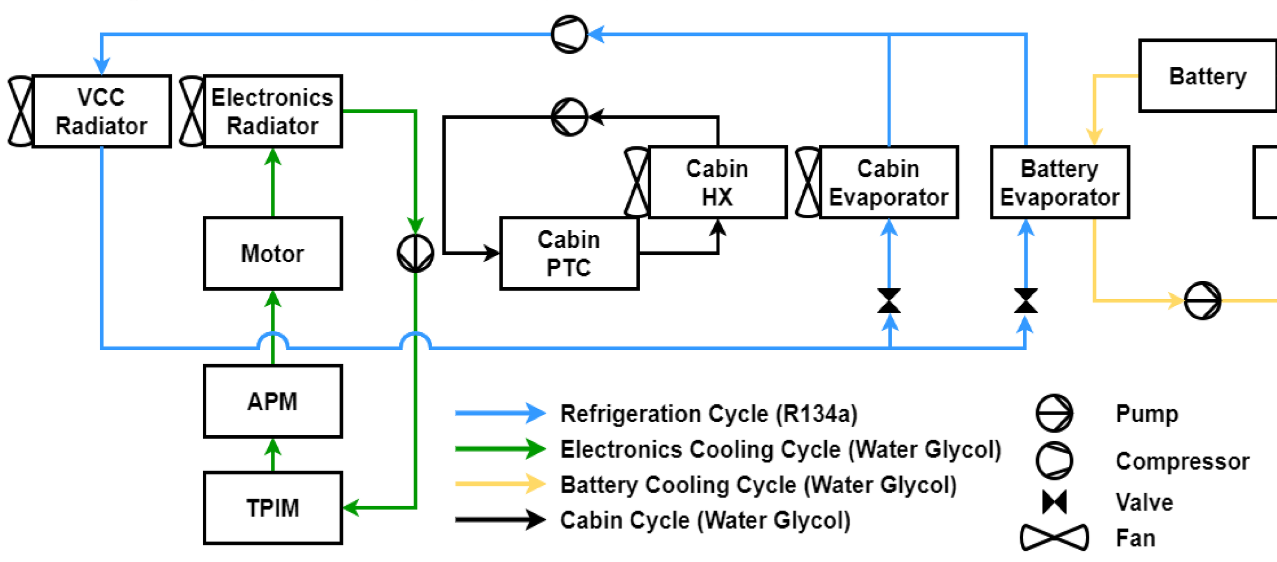


Figure 1: Base TMS architecture [3]. Consists of four loops: Refrigeration cycle, electronics cooling cycle, battery cooling cycle and cabin cycle.

Table 1: *List of graph-based model components*

BEV Component	Model	Description
Battery Evaporator	Two-Phase HX	Counter-flow plate HX
Cabin Evaporator		Cross-flow MPET HX
VCC Radiator		Cross-flow MPET HX
Electronics Radiator	Single-Phase HX	Cross-flow MPET HX
Cabin HX		Cross-flow MPET HX
Compressor	Efficiency-based	Isentropic compressor
Valve	Expansion Valve	Isenthalpic valve
Battery	RC-network equivalent	Second-order Thevenin model.
Pump	Simple Pump	Efficiency-based pump
Heater	Cold Plate	PTC Heater

Component Modeling

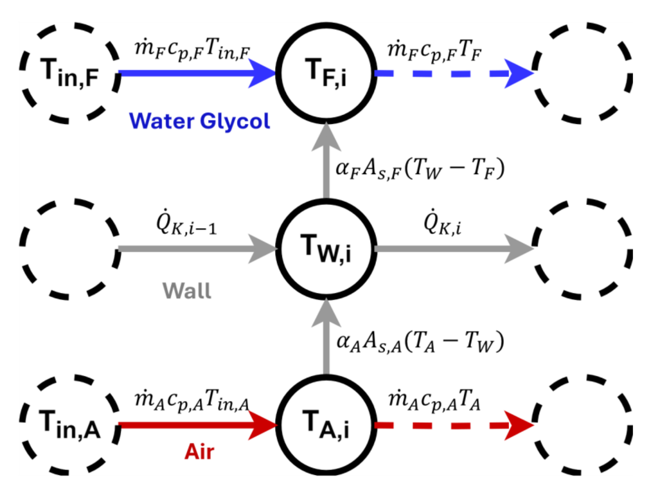


Figure 2: Single-phase HX graph-based modeling for one control volume.

Single-state graph-model representation, $\boldsymbol{C\dot{x}} = -\boldsymbol{\bar{M}\Gamma}$:

$$\begin{bmatrix} m_F c_{p,F} & 0 & 0 \\ 0 & m_W c_{p,W} & 0 \\ 0 & 0 & m_A c_{p,A} \end{bmatrix} \begin{bmatrix} \dot{T}_F \\ \dot{T}_W \\ \dot{T}_A \end{bmatrix} = -\begin{bmatrix} 1 & -1 & 0 & -1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & -1 & 0 & 1 \\ 0 & 0 & 1 & 0 & 1 & -1 & 0 \end{bmatrix} \begin{bmatrix} \dot{m}_F c_{p,F} T_F \\ \alpha_F A_{s,F}(T_W - T_F) \\ \dot{m}_A c_{p,A} T_A \\ \dot{m}_F c_{p,F} T_{in,F} \\ \alpha_A A_{s,A}(T_A - T_W) \\ \dot{m}_A c_{p,A} T_{in,A} \\ \dot{Q}_{K,i} - \dot{Q}_{K,i-1} \end{bmatrix}$$

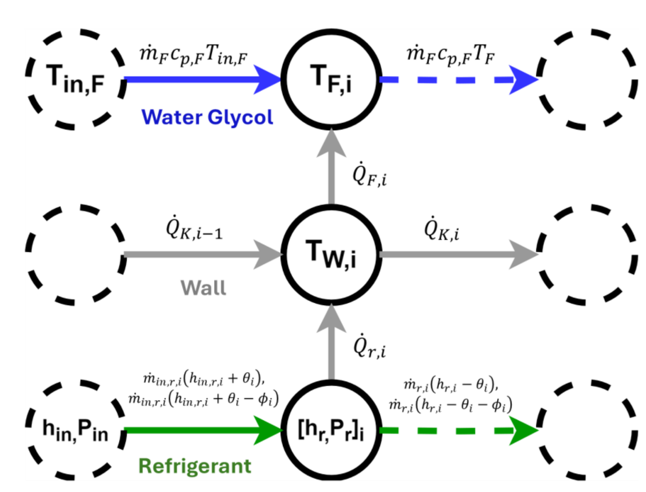


Figure 3: Two-phase HX graph-based modeling for one control volume.

Multi-state graph-model representation [4], $\boldsymbol{C\dot{x}} = -(\boldsymbol{\bar{M}} * \boldsymbol{S})\boldsymbol{\Gamma}$:

$$\begin{bmatrix} \rho_h V_p & 0 & 0 & 0 \\ 0 & \kappa V_p & 0 & 0 \\ 0 & 0 & m_W c_{p,W} & 0 \\ 0 & 0 & 0 & m_F c_{p,F} \end{bmatrix} \begin{bmatrix} \dot{h}_r \\ \dot{P}_r \\ \dot{T}_w \\ \dot{T}_F \end{bmatrix} = -\begin{bmatrix} -1 & 1 & 1 & 0 & 0 & 0 & 0 & -1 & -1 & 0 & 0 \\ 1 & -1 & -1 & 1 & 0 & 0 & 0 & 1 & 1 & -1 & 0 \\ 1 & 0 & 0 & 0 & -1 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 1 & 0 & 0 & 0 & -1 \end{bmatrix} \begin{bmatrix} \dot{Q}_r \\ \dot{m}_r h_r \\ \dot{m}_r \theta_r \\ \dot{m}_r \phi_r \\ \dot{Q}_F \\ \dot{Q}_{K,i} - \dot{Q}_{K,i-1} \\ \dot{m}_F c_{p,F} T_F \\ \dot{m}_r h_{in,r} \\ \dot{m}_r \theta_{in,r} \\ \dot{m}_r \phi_{in,r} \\ \dot{m}_F c_{p,F} T_{in,F} \end{bmatrix}$$

Verification and Validation

High-Fidelity Model: Dymola with TIL 3.15.1 TLK Thermo GMBH Library [5].

- Model utilizes **finite volume method,** each containing a differential state.
- **Key Similarities**: Number of control volumes, state initial conditions, boundary conditions, effective geometries
- **Key Differences**: Heat transfer coefficient, geometry discretization, mass flow rate discretization, conduction model

Refrigeration Cycle:

Component-level validation of the two-phase HXs comparing Python graph-based model against high-fidelity Dymola model.

Dynamic simulation results shows:

- Outlet refrigerant enthalpy (h_r)
- Wall temperature (T_W)
- Outlet water glycol temperature (T_F)

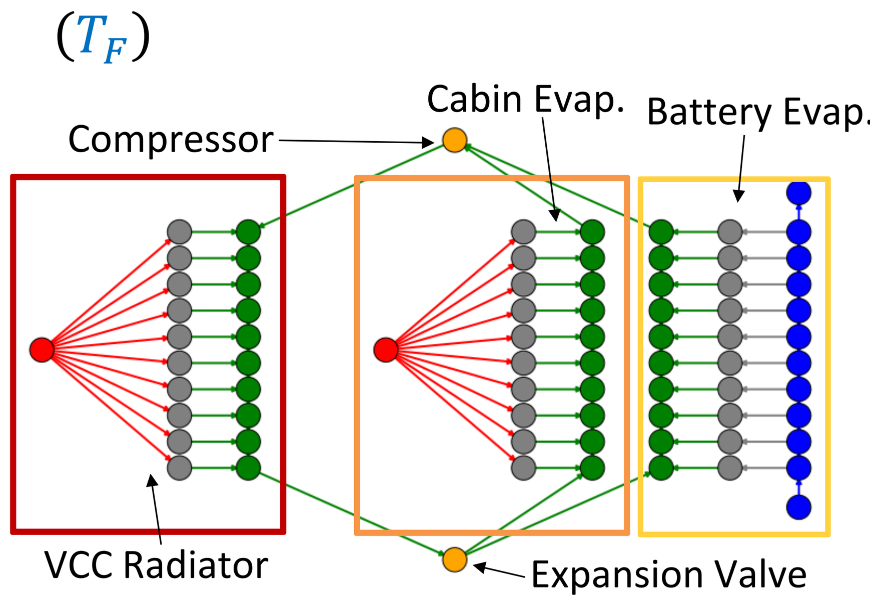


Figure 5: Python graph-based model representation of a Refrigeration Cycle.

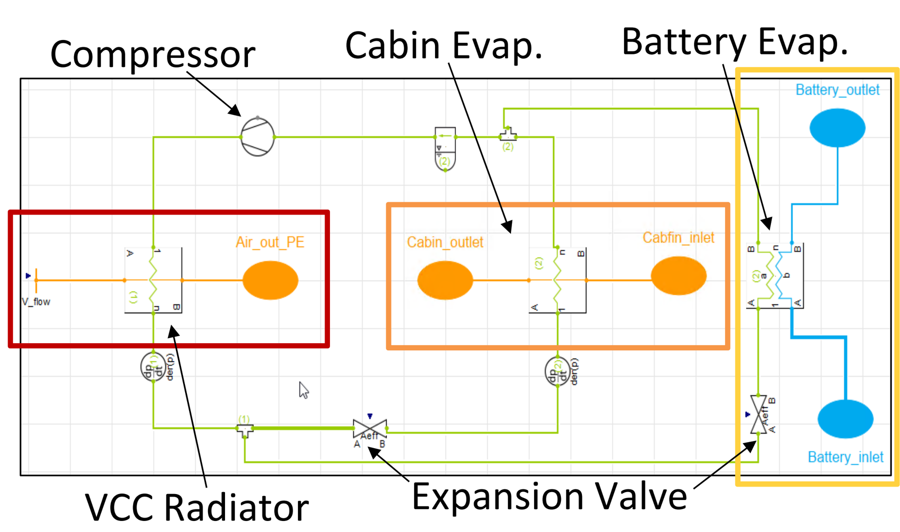
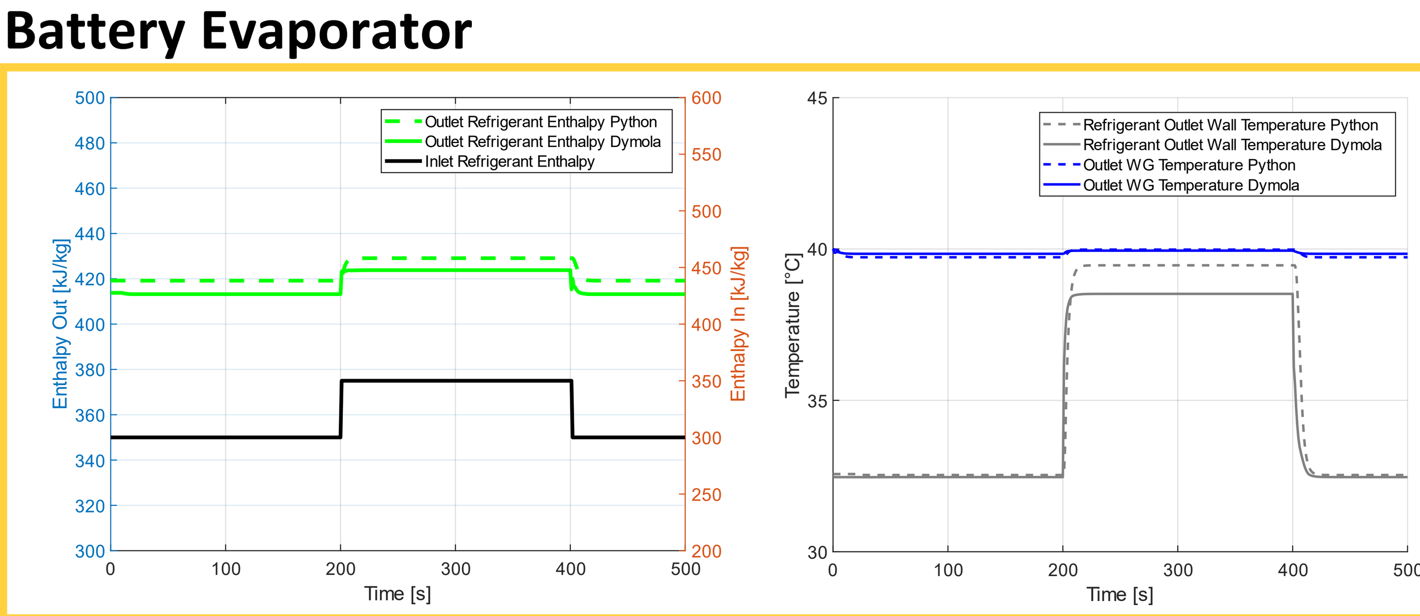


Figure 6: Dymola representation of a Refrigeration Cycle.

Battery Evaporator

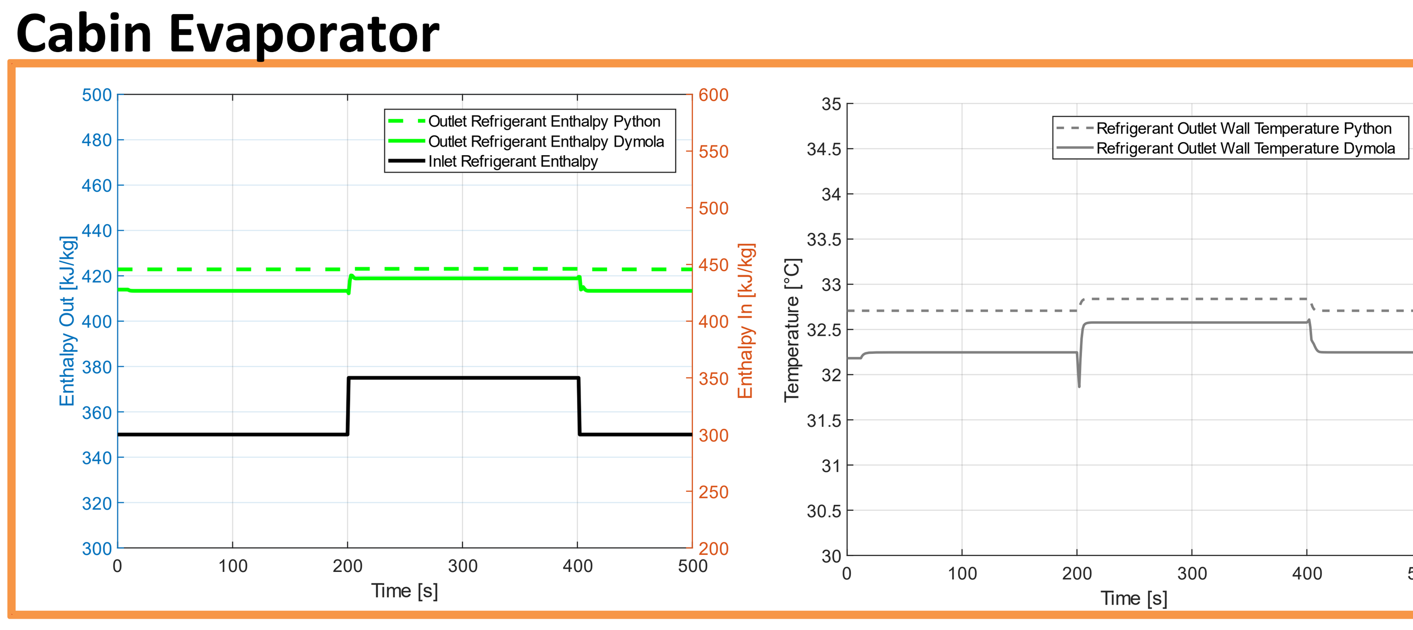


Left: Dynamic simulation of battery evaporator.

Maximum error (%):

- h_r: 3.32%
- T_W: 2.45%
- T_F: 0.35%

Cabin Evaporator

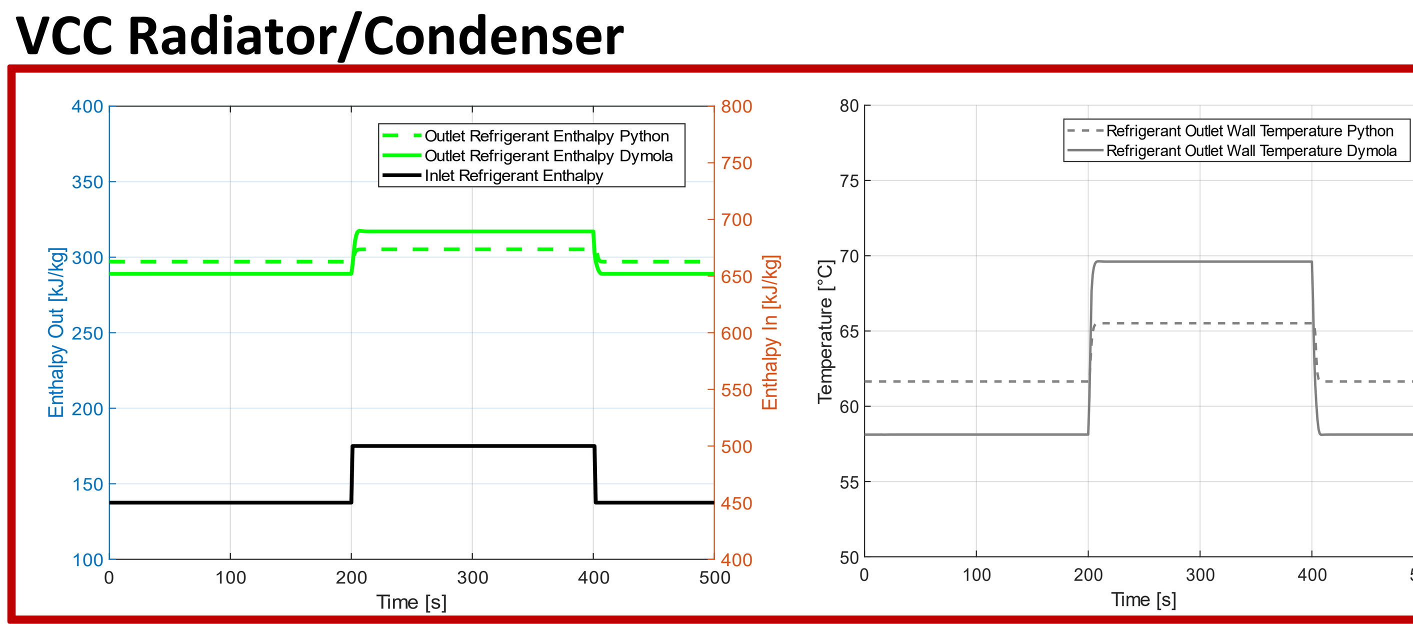


Left: Dynamic simulation of cabin evaporator.

Maximum error (%):

- h_r: 2.63%
- T_W: 3.08%

VCC Radiator/Condenser



Left: Dynamic simulation of VCC Radiator.

Maximum error (%):

- h_r: 3.87%
- T_W: 6.12%

Conclusions

The verification and validation shows that the graph-based model can accurately represent the high-fidelity model during transient and steady-state conditions at component level, with the maximum error calculated to be **6.12%.**

Future work:

- Conduct further verification and validation at cycle and system level to evaluate closed-loop performance.
- Apply an optimal feedback controller to enable up-front definition of the optimal TMS architecture.