Vehicle Thermal System Modeling in Simulink®



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Overview – New Project

Timeline

Project Start Date: FY14
Project End Date: FY15
Percent Complete: 25%

Budget

Total Project Funding:

- DOE Share: $225K
- Contractor Share: $0K

Funding Received in FY13: $0K

Funding for FY14: $225K

Barriers

- Cost – *Timely evaluation of vehicle thermal systems to assist with R&D*
- Computational models, design and simulation methodologies – *Develop tool to help with optimization of future vehicle thermal system designs and prediction of impacts on fuel economy*
- Constant advances in technology – *Help industry to advance technology with improved tools*

Partners

- Collaborations
  - Halla Visteon Climate Control
  - Delphi
  - Daimler Trucks
  - VTO Advanced Power Electronics and Electric Motors (APEEM) Team
  - In discussion with others
- Project lead: NREL

Relevance

THE CHALLENGE

- Heating has a large impact on electric vehicle range, larger than air conditioning (A/C) systems
- Electrified heavy-duty A/C systems may provide necessary infrastructure to add heating at limited additional cost
- With increasing electrification, vehicle thermal systems are increasingly important for effective and efficient light- and heavy-duty vehicle design
- Autonomie lacks tools for vehicle thermal systems modeling based on 1st principles

THE OPPORTUNITY

- Tools will assist with evaluation of advanced thermal management and heating solutions using flexible, freely available tools for the MATLAB®/ Simulink environment that can co-simulate with Autonomie
- Leverage NREL's vehicle thermal management expertise
  - Energy storage thermal management
  - APEEM thermal management
  - Integrated vehicle thermal management project
  - Heating, ventilating, and air conditioning (HVAC) expertise, building on the A/C system model developed previously

Relevance/Objectives

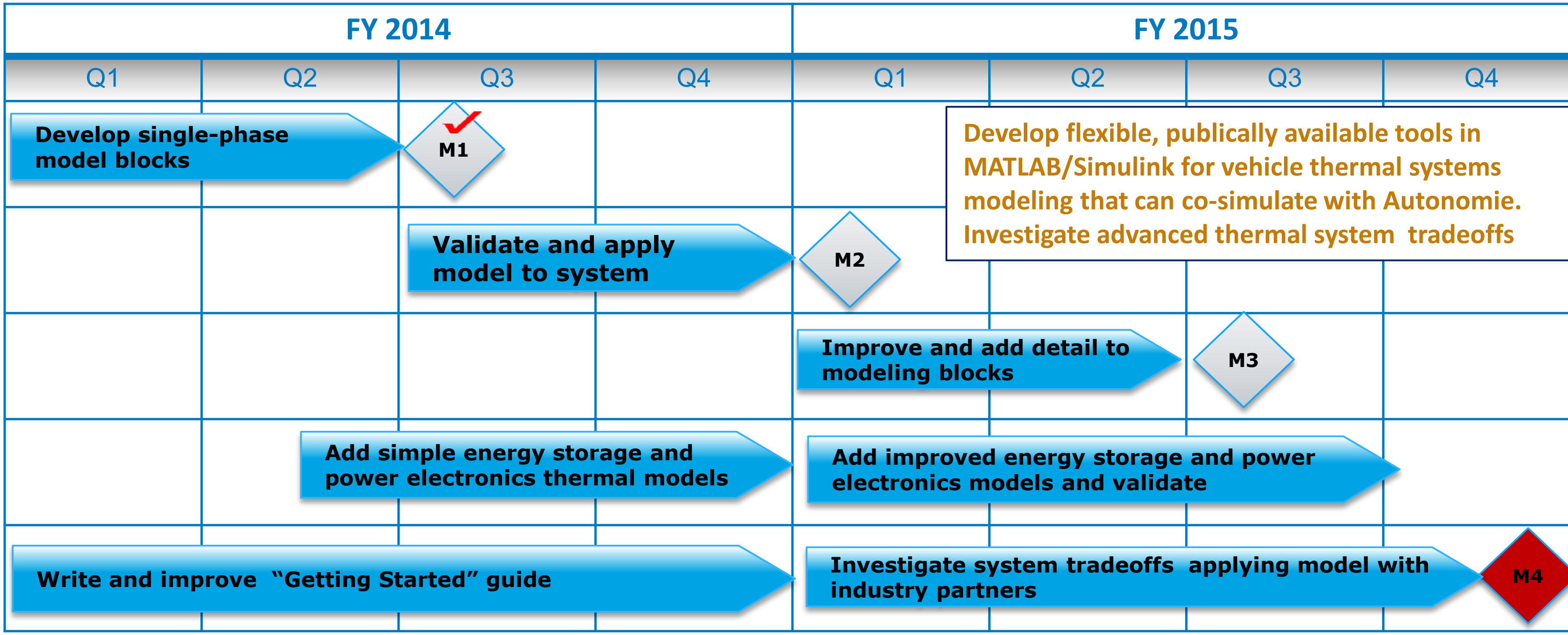
Goal

By 2015, develop flexible, publically available tools in MATLAB/Simulink for vehicle thermal systems modeling that can co-simulate with Autonomie and apply these tools with industry partners for R&D on advanced thermal systems.

Objectives

- Develop analysis tools to assess the impact of technologies that reduce thermal load, improve climate control efficiency, and reduce vehicle fuel consumption
- Connect climate control, thermal systems, and vehicle-level models to assess the impacts of advanced thermal management technologies on fuel use and range
- Develop an open, accurate, and transient thermal system modeling framework using the MATLAB/Simulink environment for co-simulation with Autonomie

Approach – Milestones and Go/No-Go's



Milestones:

M1. Complete initial modeling framework. Run system simulation with basic cooling system components and demonstrate feasibility. **Go/No-Go**: Model of concept demonstration system predicts reasonable trends. ✓

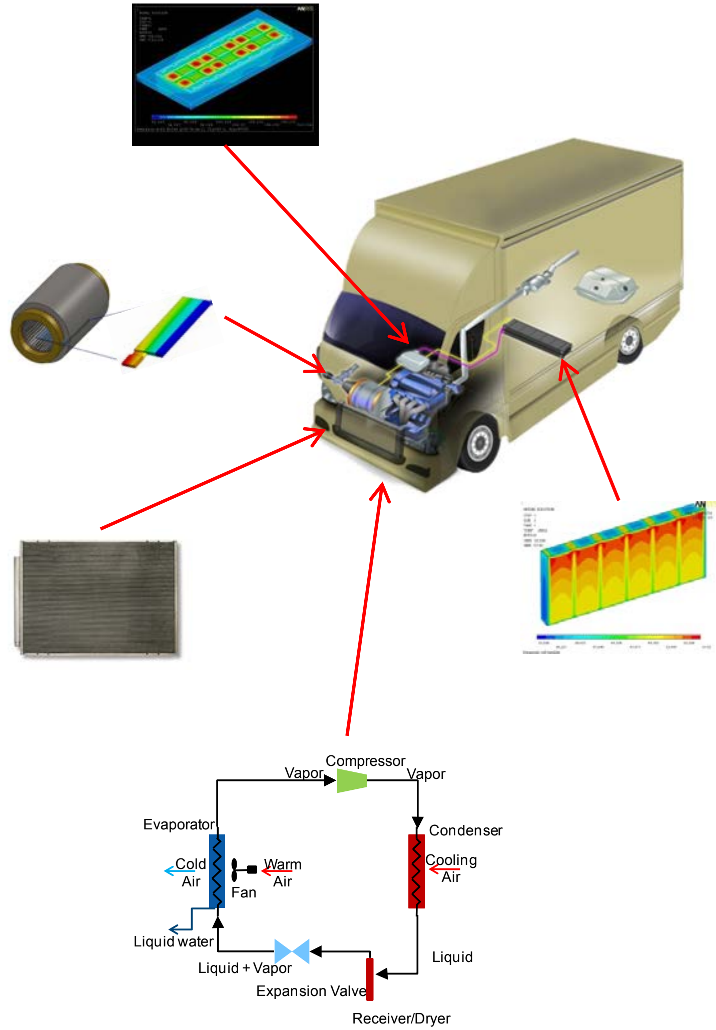
M2. Validated single-phase model built from building blocks, allowing for easy modification. Release beta version of model. **Go/No-Go:** Confirm that model can be successfully validated and is predicting performance with acceptable accuracy (20%)

M3. Improve component models, adding detail. Validate model to within 15% of available data.

M4. Improve model capabilities expanding on the single-phase, energy storage, and power electronics thermal models and validate. Apply developed Simulink tools with industry partners to look at system tradeoffs in co-simulation with Autonomie. Release updated code with expanded capabilities.

Approach/Strategy – MATLAB/Simulink-Based Tool

- 1-D simulation tool based on first principles; conservation of mass, momentum, and energy
- Leverage prior successful two-phase A/C system model development and thermal component expertise at NREL
- Develop a flexible software platform, capable of modeling the full range of vehicle thermal systems
- Include major components: heat exchangers, pumps, transport lines, fans, power electronics, battery chiller, engine, thermostat, A/C system (from prior development), etc.
- Develop models that run at least 10X real time to match well with the Mapped Component A/C system model previously developed



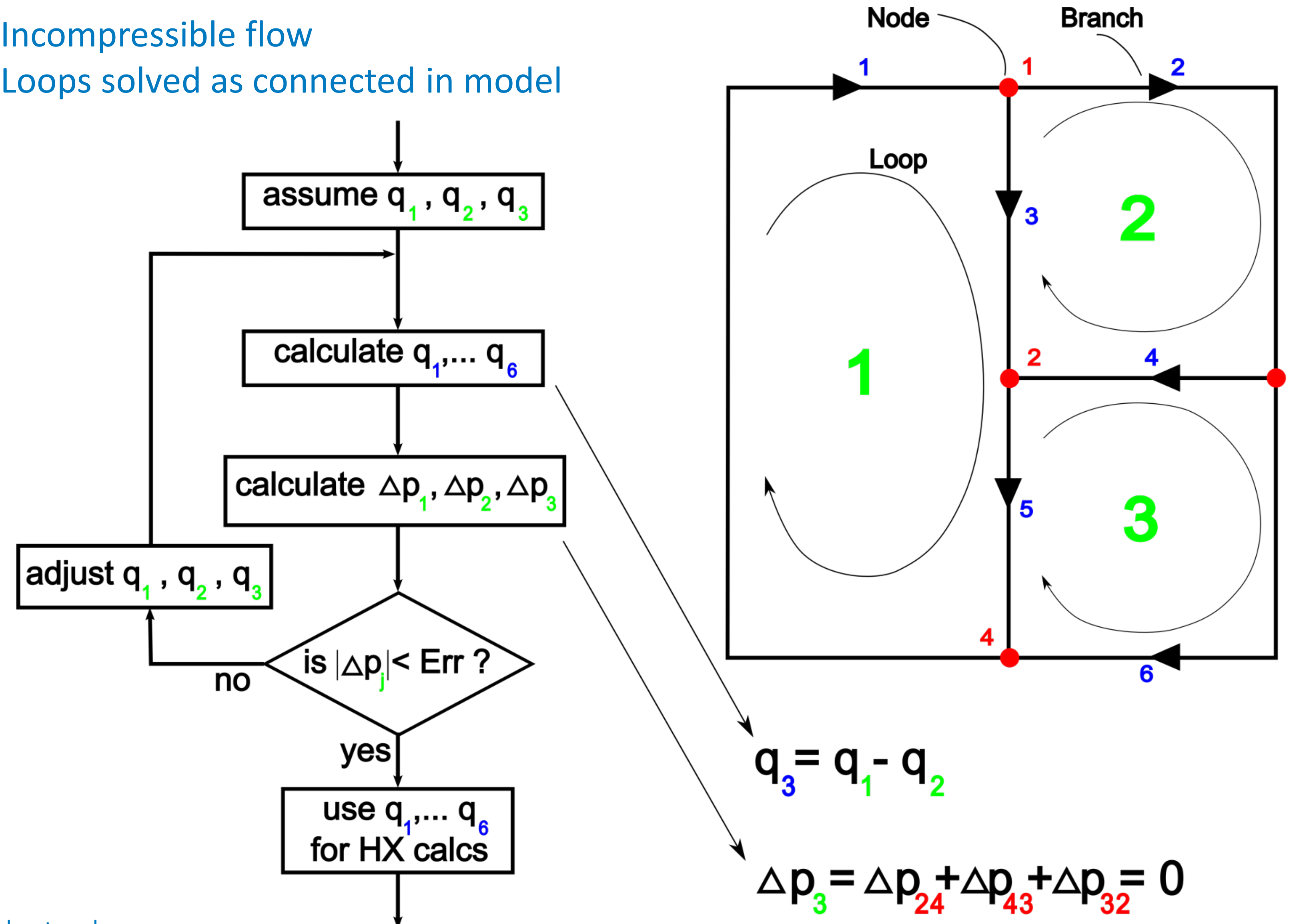
Approach/Strategy – Key Features

- **The model will be flexible and capable of modeling a wide range of system configurations and components**
- **The model will be switchable between varying levels of accuracy an execution speed, e.g., useful for predicting both short (pump RPM) and long (engine warmup) transients**
- **For fast execution of the model, a method that works with relatively high simulation time step is needed therefore,**
  - Incompressible flow for coolant is assumed
  - Solid thermal masses will have a limited level of spatial distribution
  - Coolant thermal mass will have varying levels of spatial distribution
  - Heat transfer calculations will have varying levels of speed and accuracy by using the Effectiveness-NTU method, Distributed Parameter component models, and Mapped Performance component models as appropriate
- **For accuracy, temperature-dependent coolant viscosity and specific heat are needed**

Technical Accomplishments – Coolant Flow Calculations

Solves general flow loops as connected in model

- Incompressible flow
- Loops solved as connected in model



HX = heat exchange

Technical Accomplishments and Progress

Completed initial representative component models

Component	Status
Coolant	50/50 ethylene glycol/water temperature-dependent properties
Water pump	2-D lookup table for flow rate vs. pressure rise and RPM
Plenum model	Enthalpy in plenum is the integral of incoming minus outgoing enthalpy flow rates
Thermostat	1-D lookup table for position vs. coolant temperature, and 2-D lookup table for flow rate vs. position and pressure differential
Radiator	Switchable between Mapped Performance sub-model and Distributed Parameter sub-model
Low-temperature heat exchanger, space heater, transport lines	Use assumed effectiveness
Oil cooler	Use assumed effectiveness
Battery cooler	Simple 1-node model, Effectiveness-NTU method, use UA to calculate effectiveness
Engine	Simple 1-node model, Effectiveness-NTU method, use UA to calculate effectiveness
Non-capacitive junction	Mix out incoming coolant mass and enthalpy flow rates

Technical Accomplishments and Progress

Completed initial representative component models

Non-Capacitive Junction:

$$\dot{m}_{out} = \sum_i \dot{m}_{in}$$
$$\dot{H}_{out} = \sum_i \dot{H}_{in}$$

Plenum:

$$\frac{dH_{plenum}}{dt} = \dot{H}_{in} - \dot{H}_{out}$$

$$h_{plenum} = H_{plenum}/m$$

$$\dot{m}_{out} = \dot{m}_{in}$$

$$\dot{H}_{out} = \dot{m}_{out} \cdot h_{plenum}$$

For All:

$$h_{out} = \dot{H}_{out}/\dot{m}_{out}$$
$$T_{out} = T(h_{out})$$
$$p_{out} = p_{in} - \Delta p(\dot{m}_{out})$$

Low-temperature Radiator, Space Heater, and Transport Lines:

$$\dot{m}_{out} = \dot{m}_{in}$$
$$\dot{H}_{out} = \dot{H}_{in} - \varepsilon \cdot [\dot{H}_{in} - \dot{m}_{in} \cdot h(T_{air})]$$

Engine and Battery Cooler:

same as Low-temperature Radiator, except...

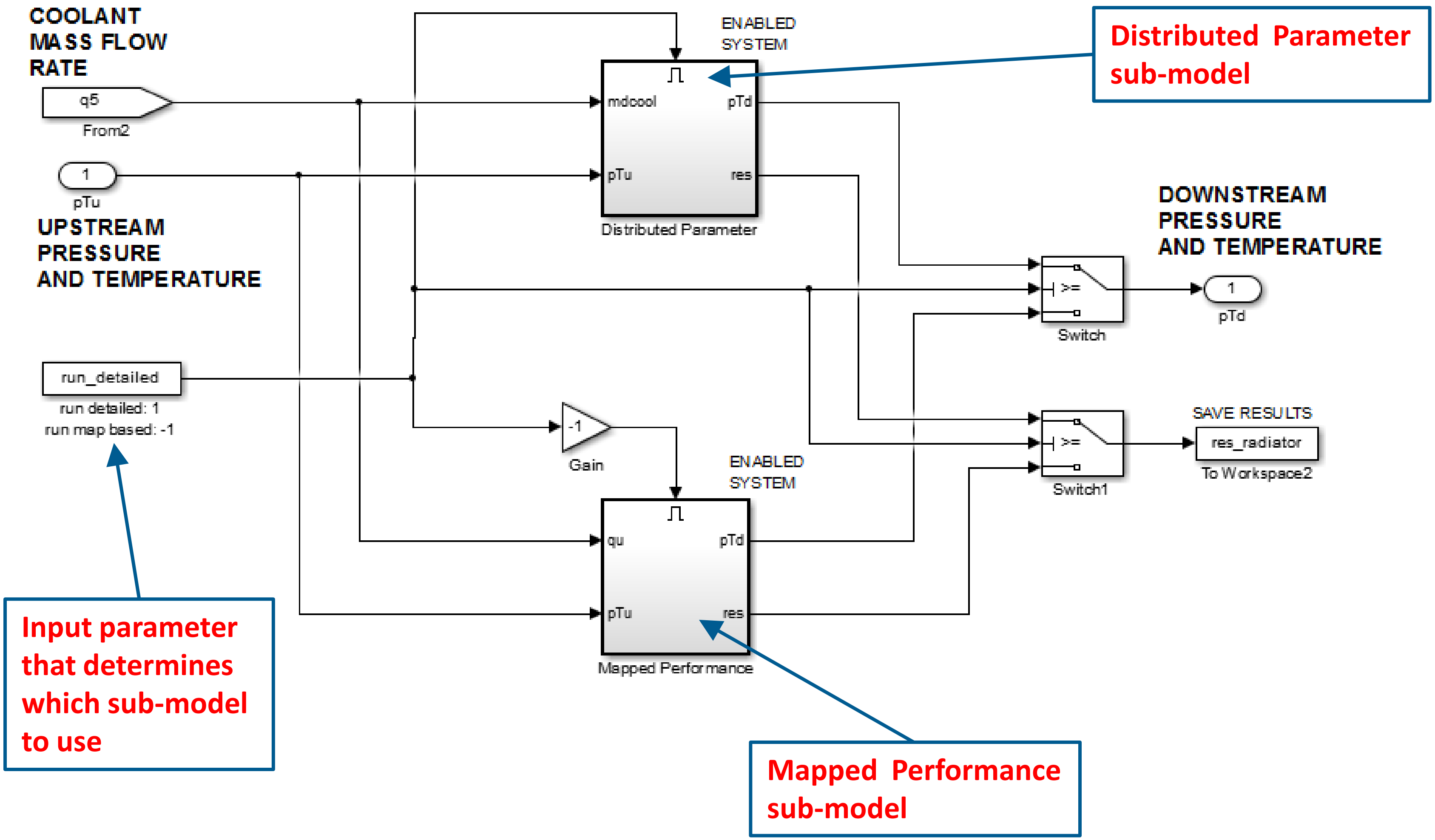
$$\varepsilon = \varepsilon(U \cdot A)$$

LT = low temperature

Technical Accomplishments and Progress

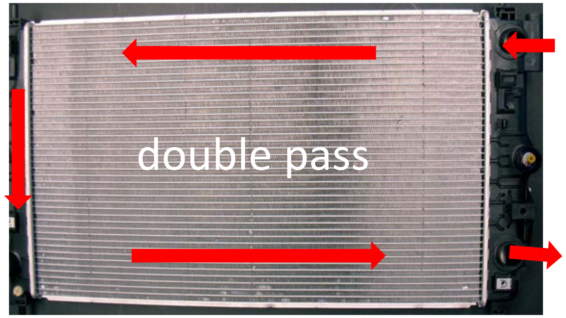
Radiator model: Distributed Parameter or Mapped Performance

Both Distributed Parameter and Mapped Performance sub-models available in the same model, user can set which is used

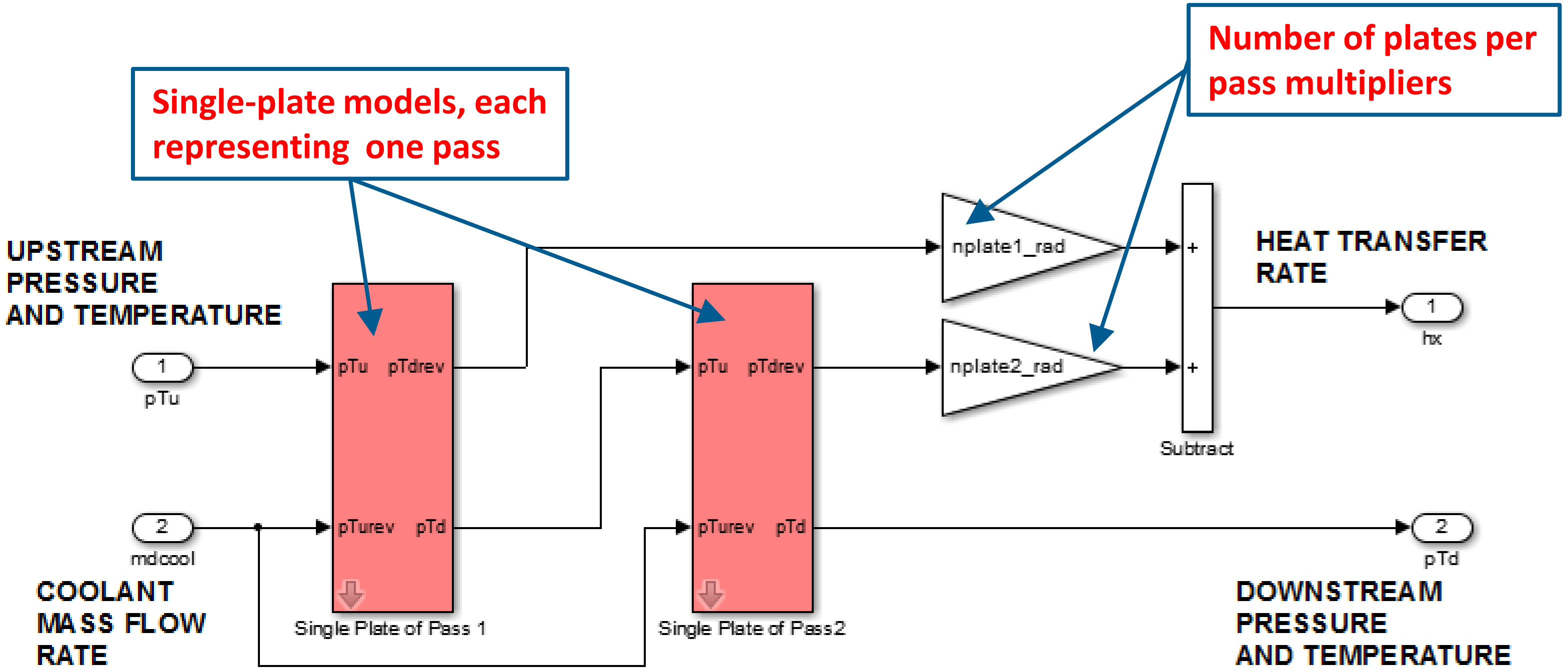


Technical Accomplishments and Progress

Radiator model: Distributed Parameter sub-model option

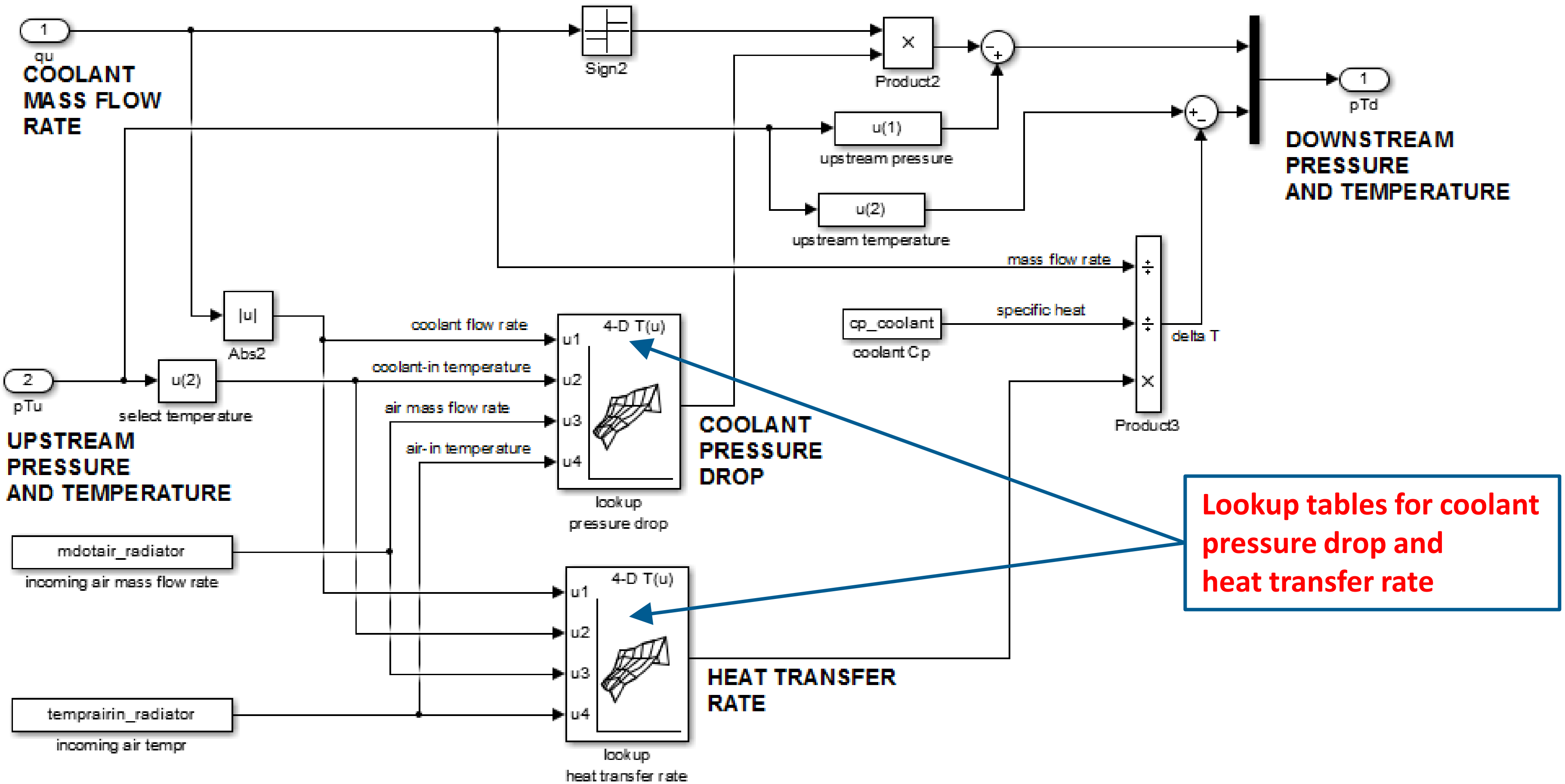


- **Allows user flexibility to define heat exchanger design**
- **Airside compact heat exchanger model from literature**



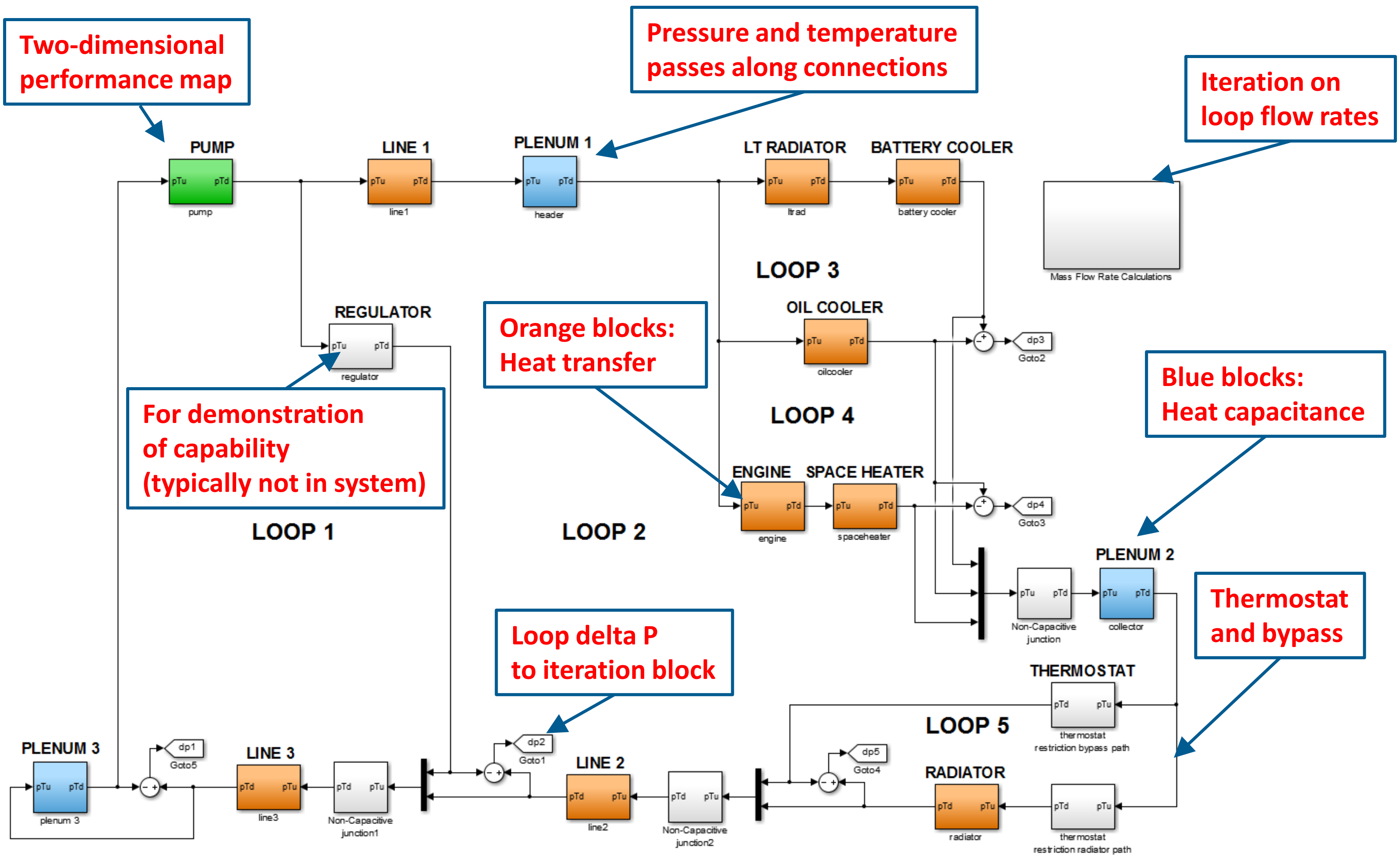
Technical Accomplishments and Progress

Radiator model: Mapped-Performance sub-model option



Technical Accomplishments and Progress

Top-level of the demonstration model in Simulink



Technical Accomplishments and Progress

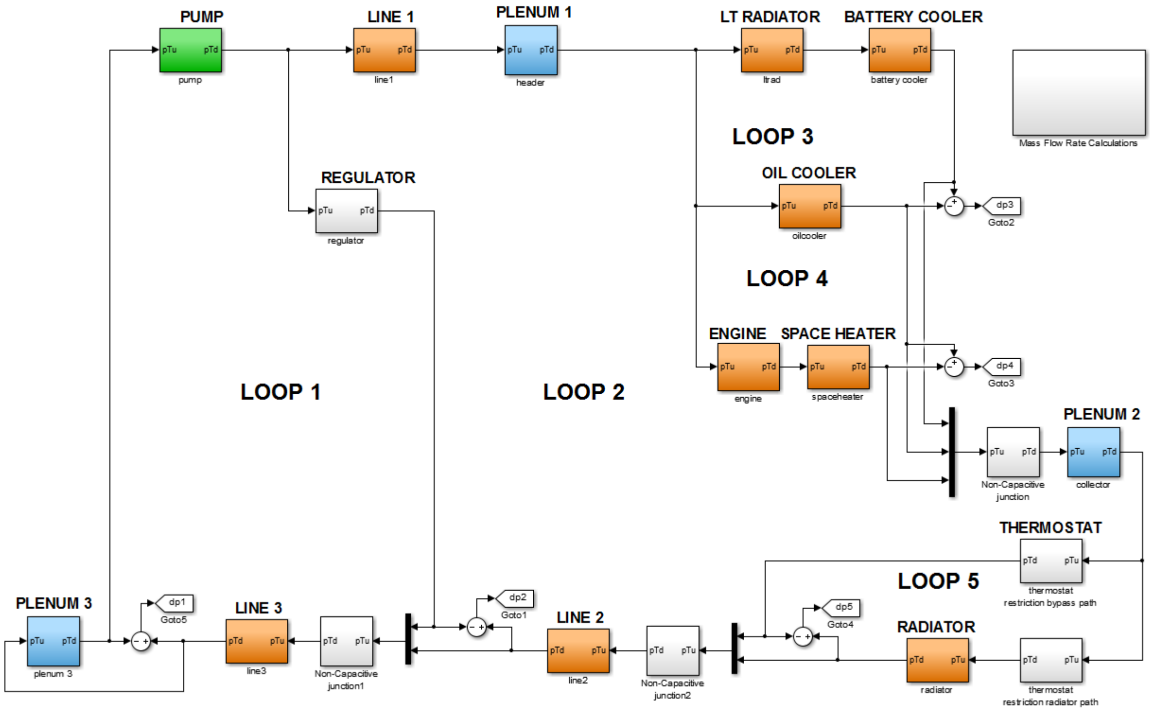
Results with demonstration model

Initial Simulation Conditions

- Start from cold soak
- Constant engine heat rejection
- Constant air flows
- Constant 1,500 pump RPM until it drops to 1,000 RPM at 1,000 sec

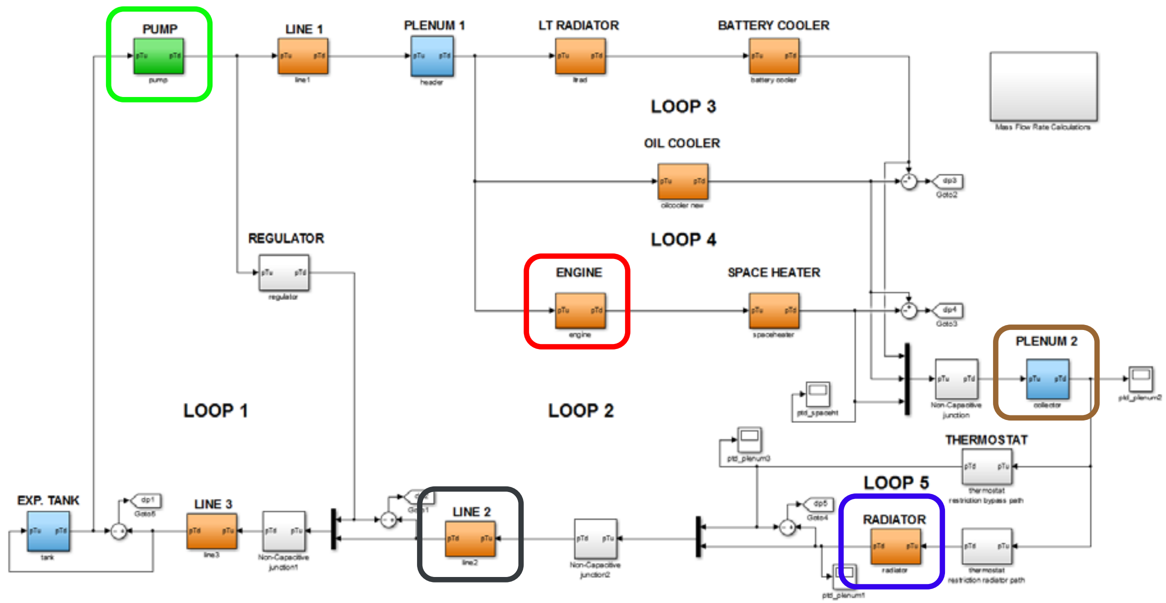
M1 Go-No-Go: Model of concept demonstration system predicts reasonable trends – Initial model shows expected reasonable trends

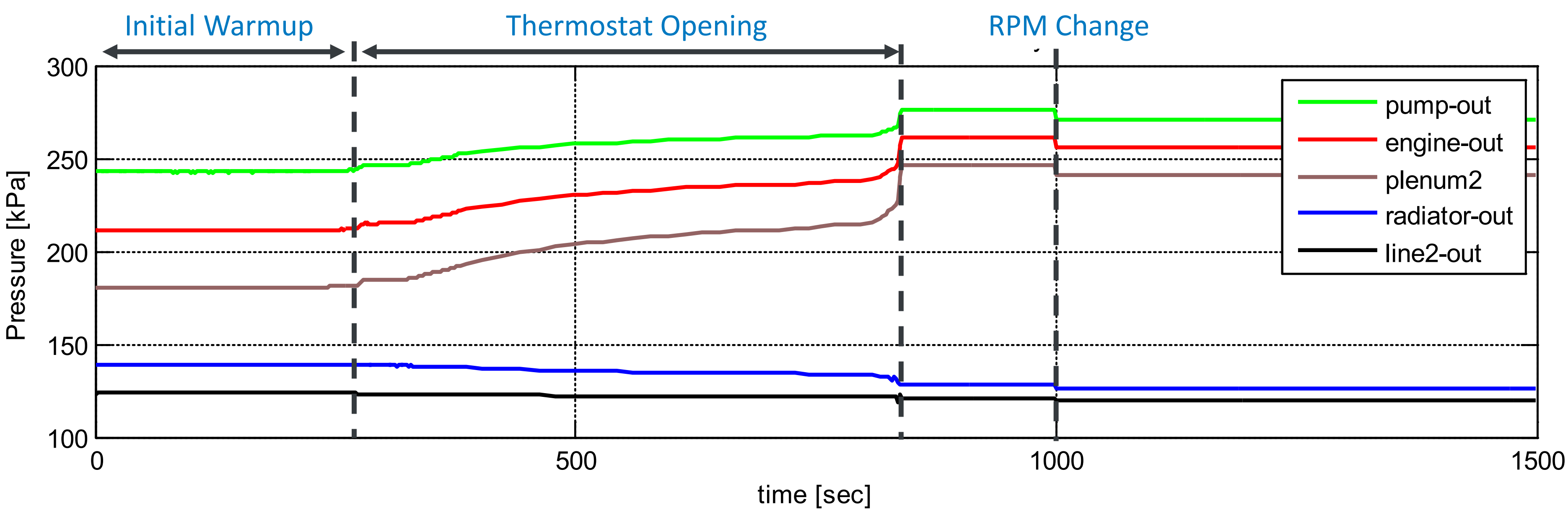
Demonstration model to test components, not intended to represent actual system



Technical Accomplishments and Progress

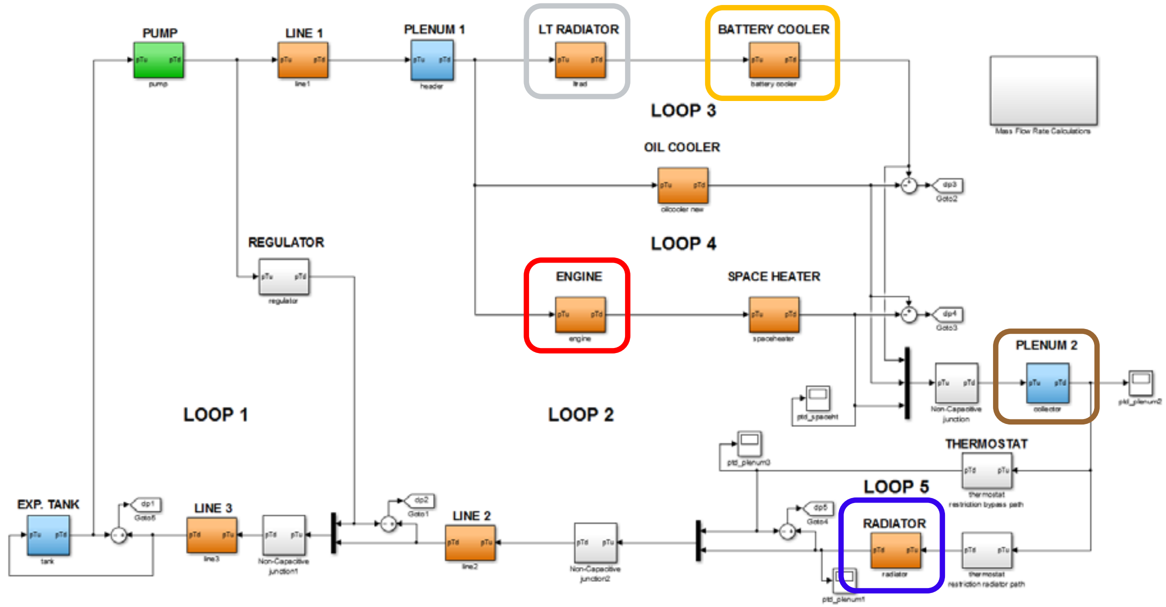
Coolant pressure

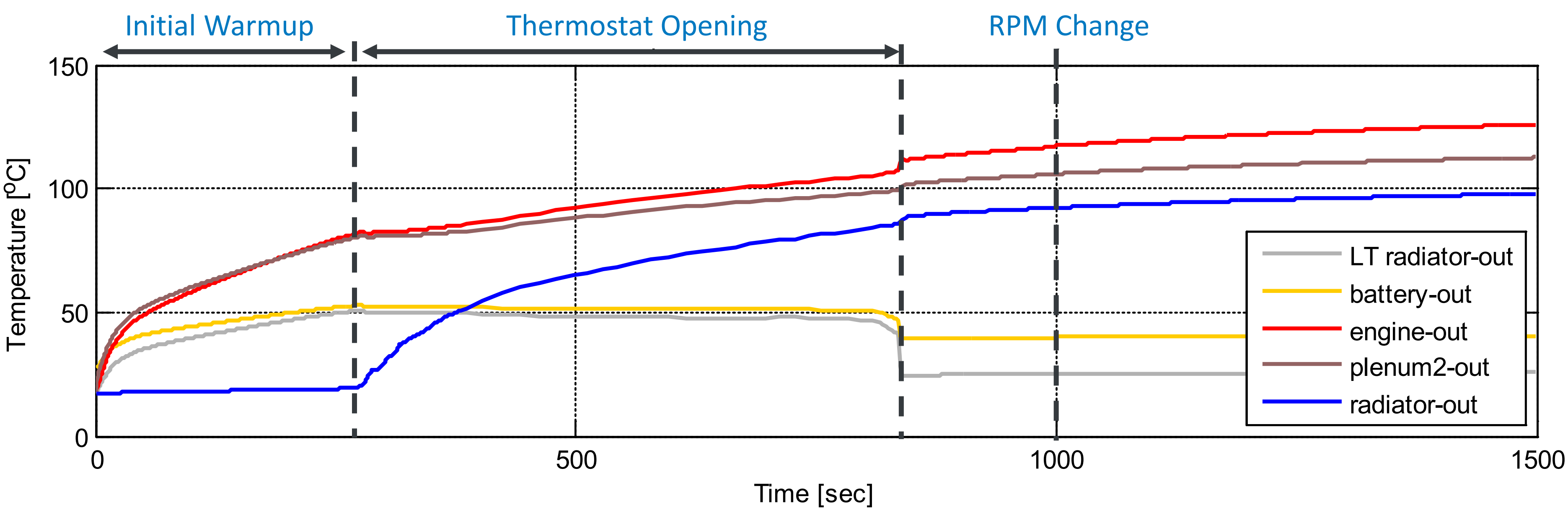




Technical Accomplishments and Progress

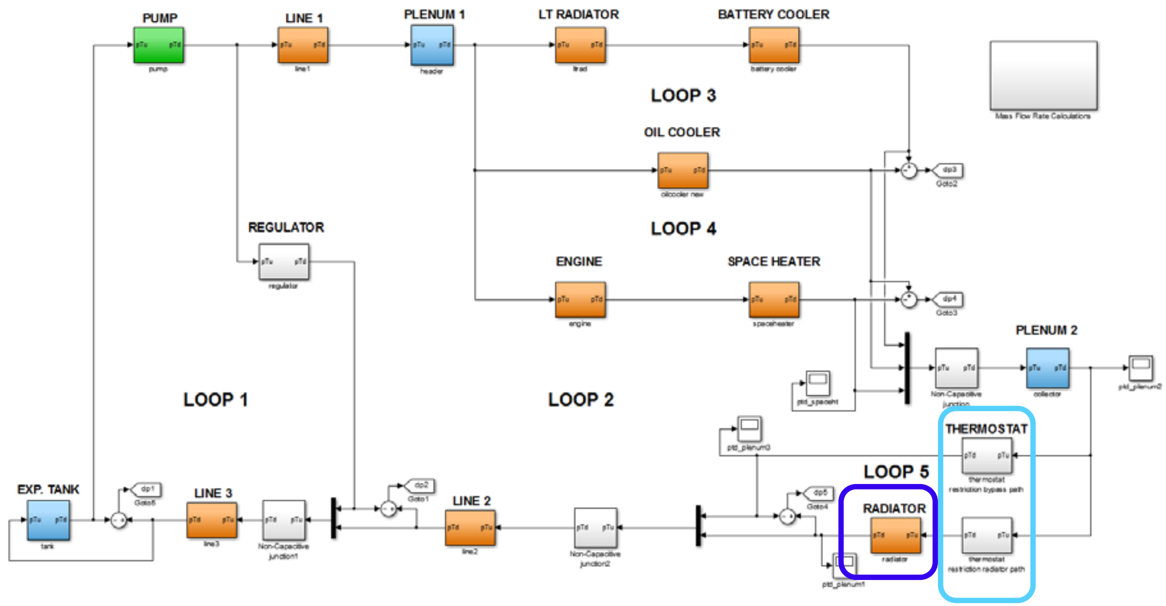
Coolant temperature

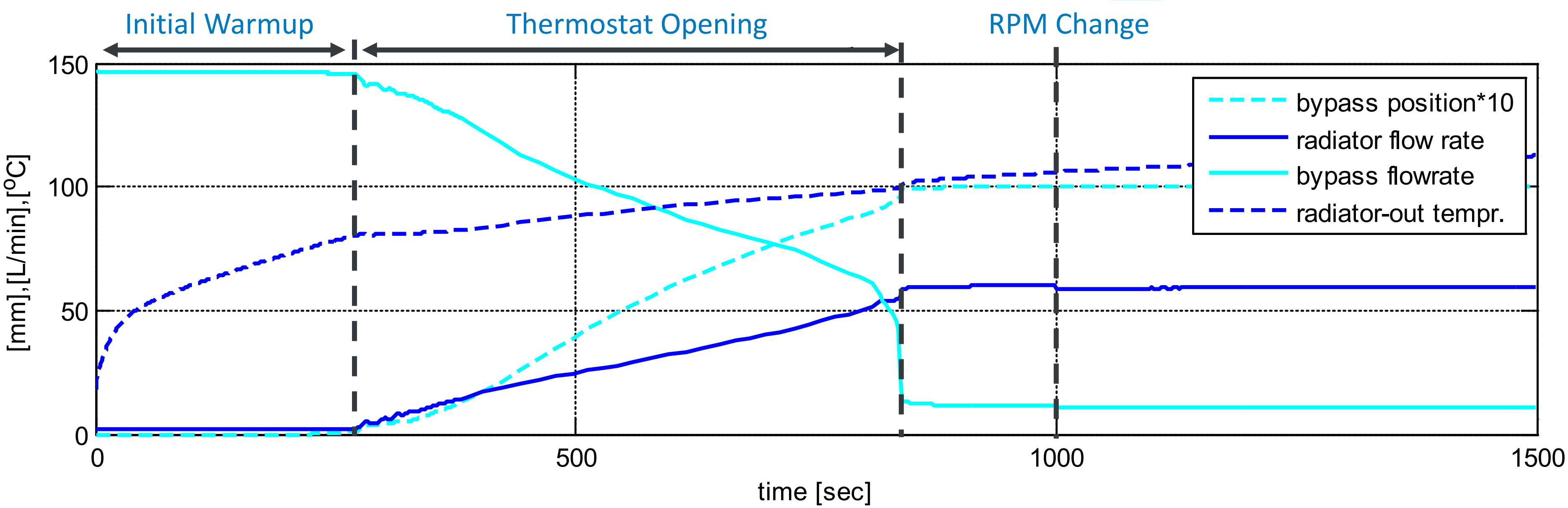




Technical Accomplishments and Progress

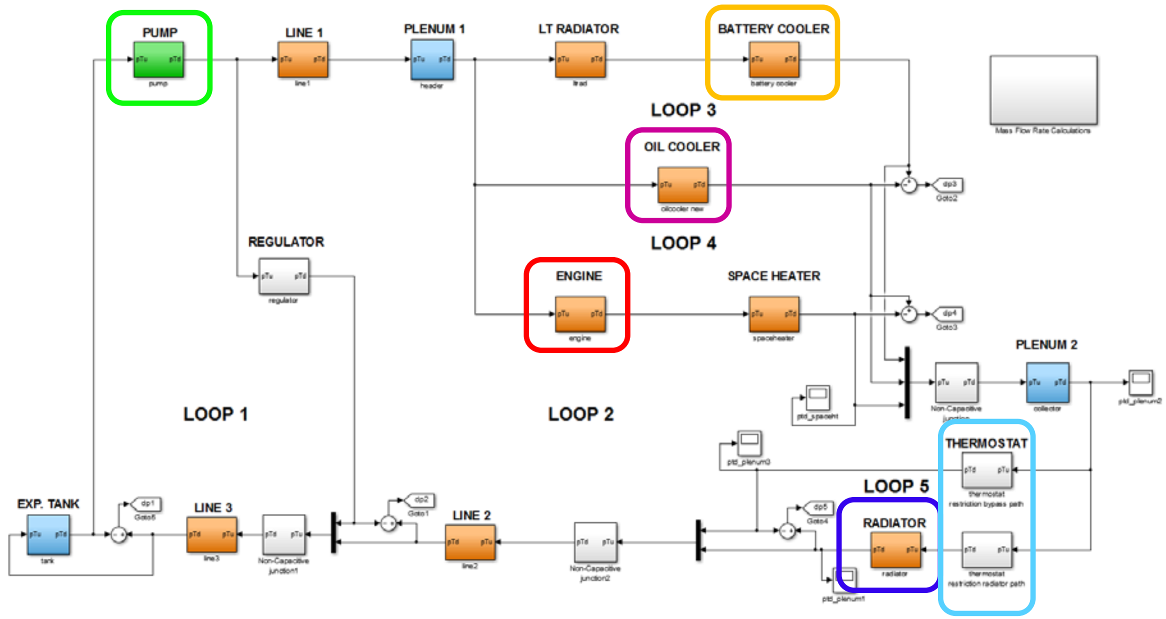
Thermostat bypass and resulting radiator behavior

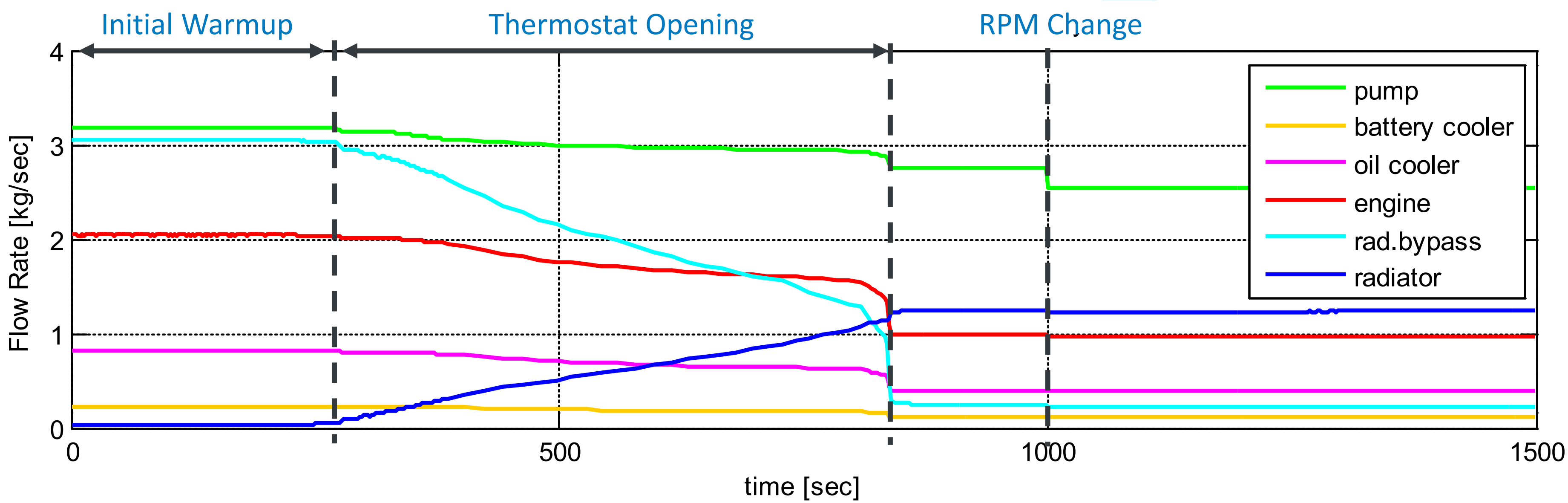




Technical Accomplishments and Progress

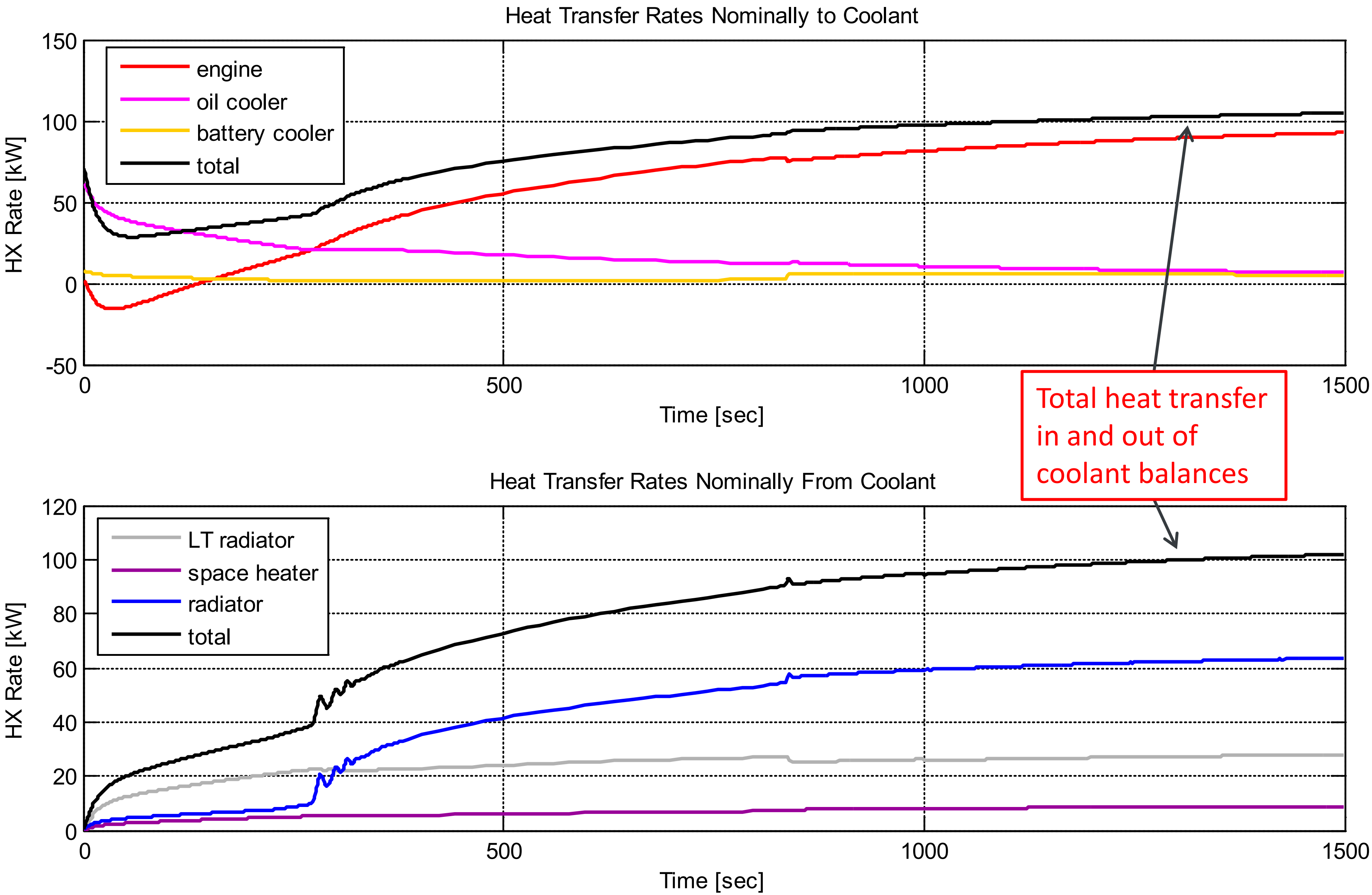
Coolant flow behavior at sample locations





Technical Accomplishments and Progress

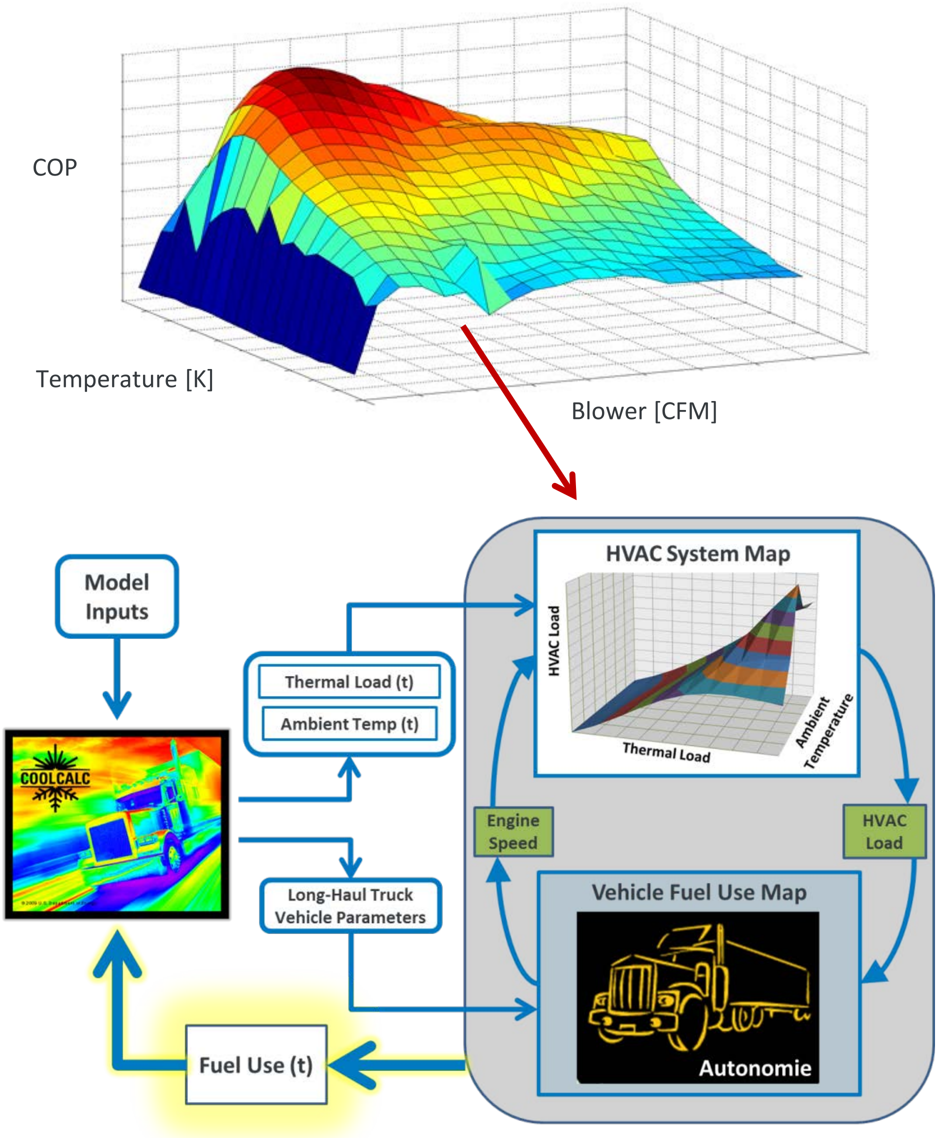
Heat transfer in and out of the system balances



Technical Accomplishments and Progress

Results are supporting other NREL thermal projects

- **Provides the link between HVAC, thermal system, and vehicle performance**
- **Provides capabilities to model advanced HVAC and thermal system concepts**



COP = coefficient of performance

Proposed Future Work

- **Continue model development**
  - Create Distributed Parameter sub-models for all components with heat exchange
  - Create Mapped Performance-based sub-models for all components with heat exchange
  - Make sub-models of components with heat exchange switchable between Distributed Parameter and Mapped Performance versions
  - Develop process of mapping the performance of all such components with the same model (eliminate the need for a suite of models)
  - Incorporate existing A/C system model
  - Collaborate with NREL Advanced Power Elections and Energy Storage groups to incorporate component thermal models
- **Build vehicle thermal system using component data and validate to system-level measured performance**
- **Model application with industry partners**
  - Model advanced light-duty vehicle thermal systems
    - Heat pump system
    - Advanced heat recovery concepts
  - Heavy-duty hybrid cooling systems
  - Build validated idle-off long-haul truck A/C system model
- **Leverage model results for the CoolCab project impact estimation**

Collaboration and Coordination with Other Institutions

- Halla Visteon Climate Control
  - Provided data for A/C system model and validation
  - Funding Opportunity Announcement award partner, assisting with models
  - Technical advice and discussion
- Delphi
  - Advanced concept modeling
- Daimler Trucks
  - Assisting with SuperTruck project
- NREL Advanced Power Electronics and Energy Storage Teams
  - Leveraging expertise and models
  - Enabling analysis of vehicle level impacts of power electronic thermal system changes
- Argonne National Laboratory
  - Autonomie integration
  - Vehicle-level system data
- Other collaboration discussion in progress

Summary

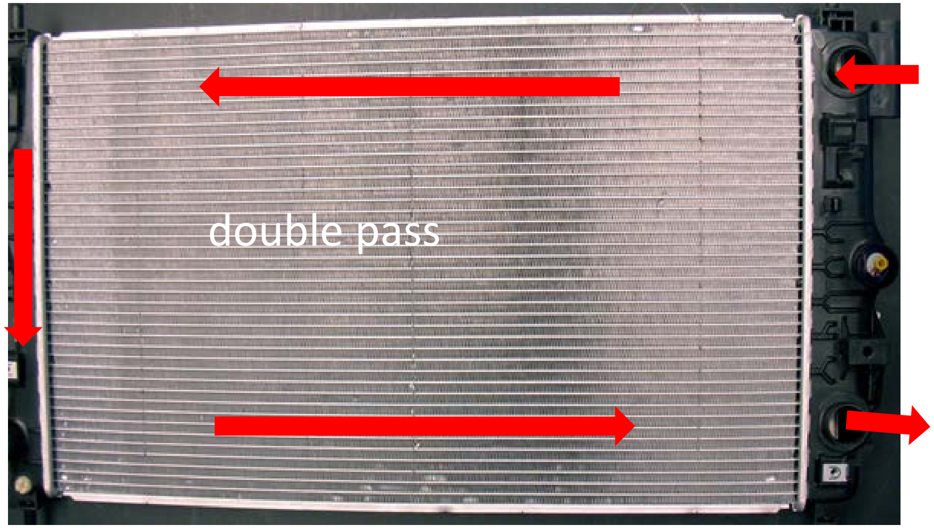
- With increasing electrification, vehicle thermal systems are increasingly important for effective and efficient light- and heavy-duty vehicle design
- Tools are being developed for evaluation of advanced thermal management and heating solutions using flexible, freely available tools for the MATLAB/Simulink environment that can co-simulate with Autonomie
- An initial thermal system modeling framework has been developed and the results are reasonable; the next step will be to model and validate models of specific vehicle thermal management systems
- Developed several initial partnerships and several other collaborations are being discussed

Technical Back-Up Slides

(Note: please include this “separator” slide if you are including back-up technical slides (maximum of five). These back-up technical slides will be available for your presentation and will be included in the DVD and Web PDF files released to the public.)

Distributed Parameter Model

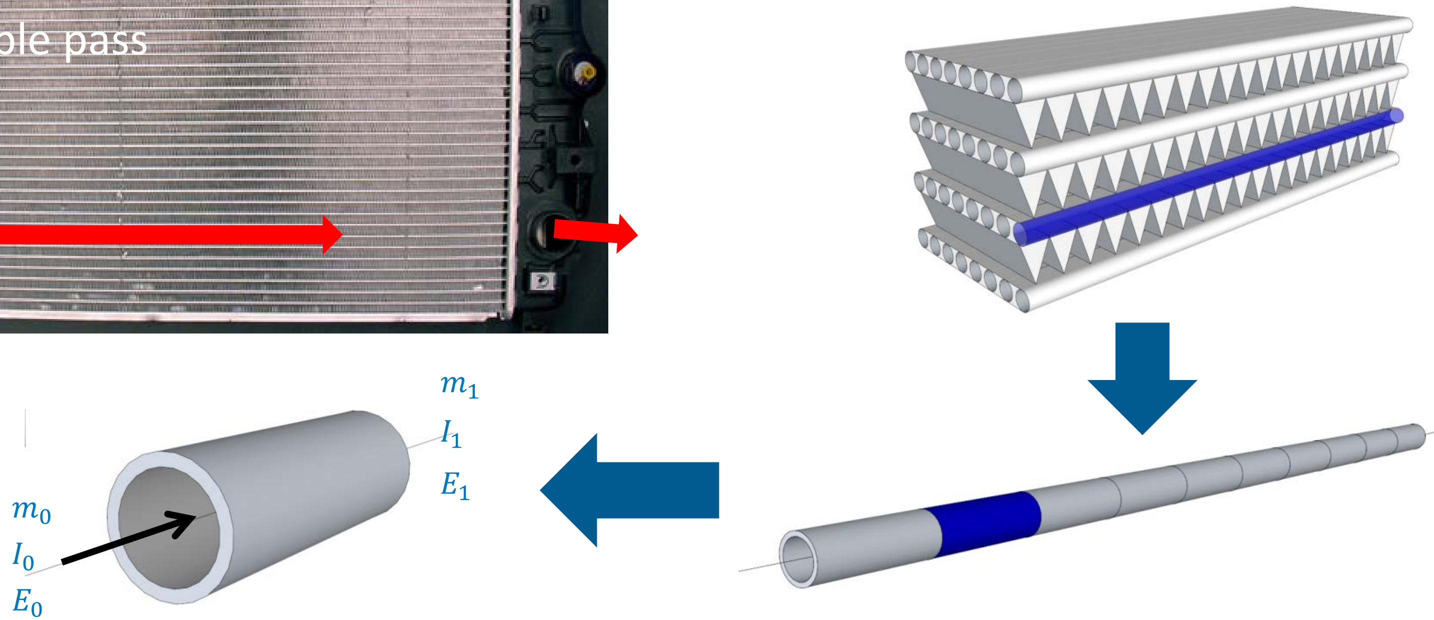
Two coolant passes in this example



Complex heat exchanger

- Multiple passes
- Multi-channel tubes
- Micro channels

Conservation equations solved in radiator plates



- A pass is a number of plates over which the coolant and airflow can be assumed identical
- A pass in this sense can be a traditional pass (serial pass) or some number of plates in a serial pass bundled together to create parallel passes (e.g., when airflow is very non-uniform)
- Only one plate in each pass is simulated, heat transfer and flow rates are multiplied by number of plates
- The steady state flow conditions are calculated using conservation of mass, momentum, and energy

Coolant to Wall Heat Transfer – Distributed Parameter Model

Condenser wall to refrigerant: $Q_{tr} = \bar{h} A_i (T_t - T)$

where the film coefficient is calculated with the Dittus-Boelter equation:

$$\left(\overline{Nu}_D \equiv\right) \frac{\bar{h} D}{k} = 0.023 Re_D^{4/5} Pr^n$$

The coefficient ***n*** can be modified for a particular geometry.

Wall to Air Heat Transfer – Distributed Parameter Model

Heat transfer from heat exchanger wall to air: $Q_{at} = \bar{h}_a A_o (T_a - T_t)$

j = 0.425 * $Re_{Lp}^{-0.496}$ where j is the Colburn factor

j = St * $Pr^{0.666}$ and $St = \frac{h_a}{c_p \rho V}$

and Re_{Lp} is the Reynolds number based on the louver pitch.

Or the more general correlation by Chang and Wang

$$j = Re_{Lp}^{-0.49} \left(\frac{\theta}{90}\right)^{0.27} \left(\frac{F_p}{L_p}\right)^{-0.14} \left(\frac{F_l}{L_p}\right)^{-0.29} \left(\frac{T_d}{T_p}\right)^{-0.23} \left(\frac{l}{L_p}\right)^{0.68} \left(\frac{T_p}{L_p}\right)^{-0.28} \left(\frac{\delta_f}{L_p}\right)^{-0.05}$$

Where Θ is the louver angle, F_p is the fin pitch, L_p is the louver pitch, F_l is the fin length, L_l is the louver length, T_d is the tube depth, T_p is the tube pitch, and δ_f is the fin thickness.

Chang, Y.J., and Wang, C.C., "A Generalized Heat Transfer Correlation for Louver Fin Geometry," *Int. J. Heat Mass Transfer,* Vol. 40, No. 3, pp. 533-544, 1997.