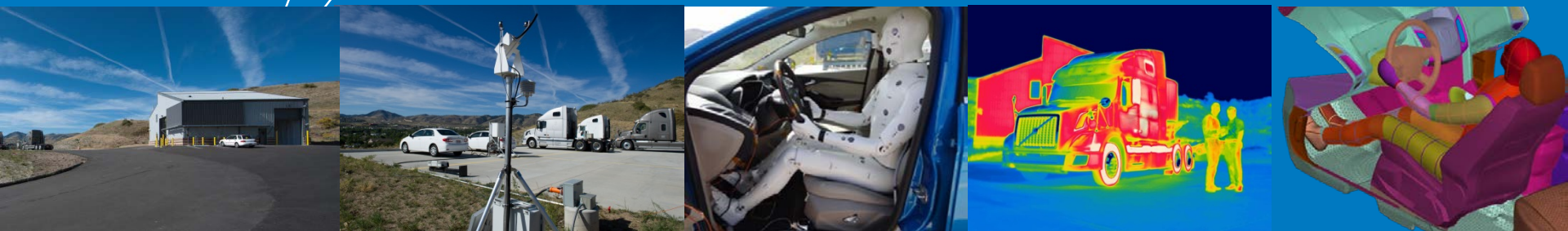


Vehicle Thermal System Modeling in Simulink



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**Team: Tibor Kiss, Gene Titov, and
Daniel Leighton**

National Renewable Energy Laboratory

June 9, 2015

Project ID #: VSS134

This presentation does not contain any proprietary, confidential, or otherwise restricted information.

Overview

Timeline

Project Start Date: FY14

Project End Date: FY16

Percent Complete: 50%

Budget

Total Project Funding:

- DOE Share: \$500K
- Partner contributions*: \$115K

Funding Received in FY14: \$225K

Funding for FY15: \$275K

**Direct funds and in-kind contributions
(not included in total).*

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
 - Oak Ridge National Laboratory (ORNL)-Cummins
 - VTO Advanced Power Electronics and Electric Motors (APEEM) Team
 - Argonne National Laboratory
- **Project lead: National Renewable Energy Laboratory (NREL)**

Relevance

THE CHALLENGE

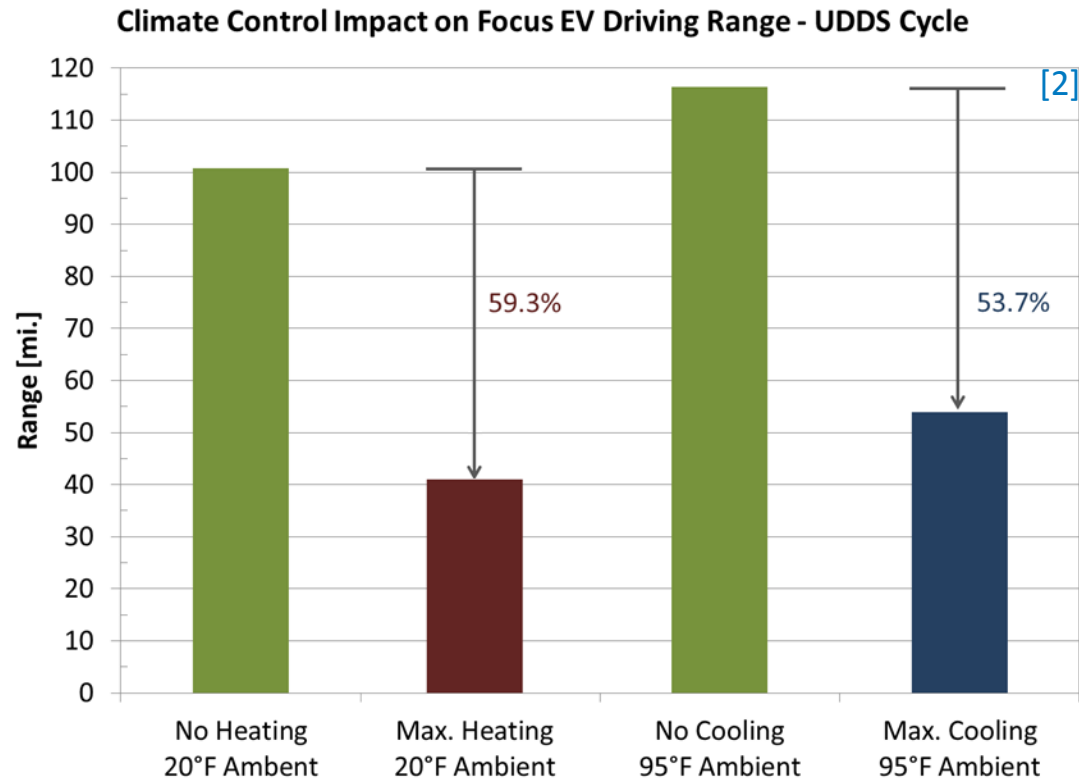
- Heating and air conditioning (A/C) have a large impact on electric vehicle (EV) range
- With increasing electrification, vehicle thermal systems are increasingly important for effective and efficient light- and heavy-duty vehicle design
- Electrified heavy-duty A/C systems may provide necessary infrastructure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

THE OPPORTUNITY

- Tools will assist with evaluation of advanced thermal management and heating solutions using a flexible, freely available framework developed for the MATLAB/Simulink 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

- A/C loads account for more than 5% of the fuel used annually for light-duty vehicles (LDVs) in the United States¹
- Climate control can reduce EV efficiency and range by more than 50%.
- Shortage of waste heat
- More efficient cooling methods allow for modes of operation based on driving and ambient conditions.



Advanced EV thermal management systems, however, can be more complex.

UDDS = Urban Dynamometer
Driving Schedule

1. *Rugh et al., 2004, Earth Technologies Forum/Mobile Air Conditioning Summit*
2. *Argonne National Laboratory's Advanced Powertrain Research Facility*

Relevance/Objectives

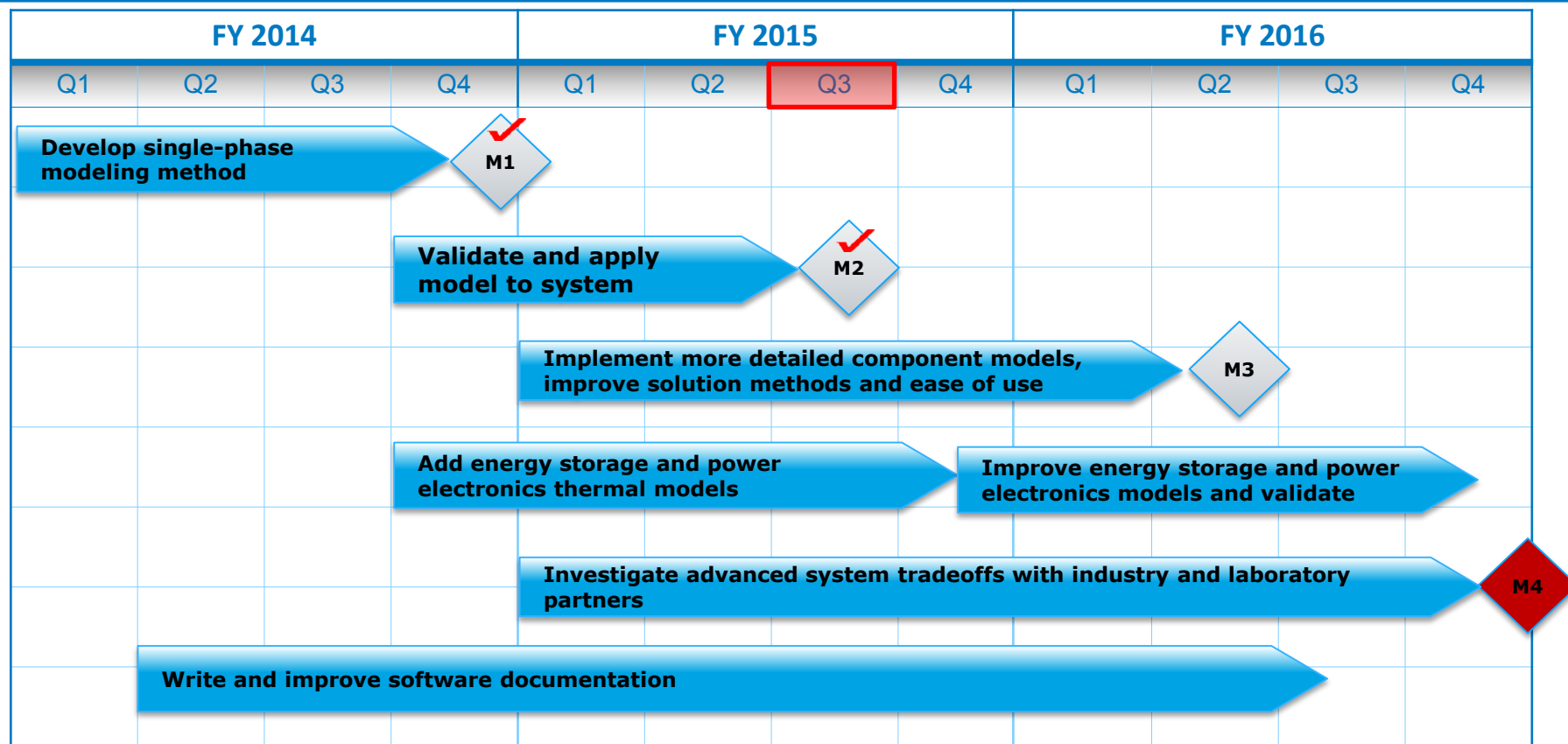
Goals

- **By 2016, develop a flexible, publically available framework in MATLAB/Simulink environment for modeling of vehicle thermal management systems capable of co-simulations with Autonomie.**
- **Use the framework to help the industry partners with R&D of advanced thermal management 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-simulations with Autonomie.

Approach: Milestones and Go/No-Go



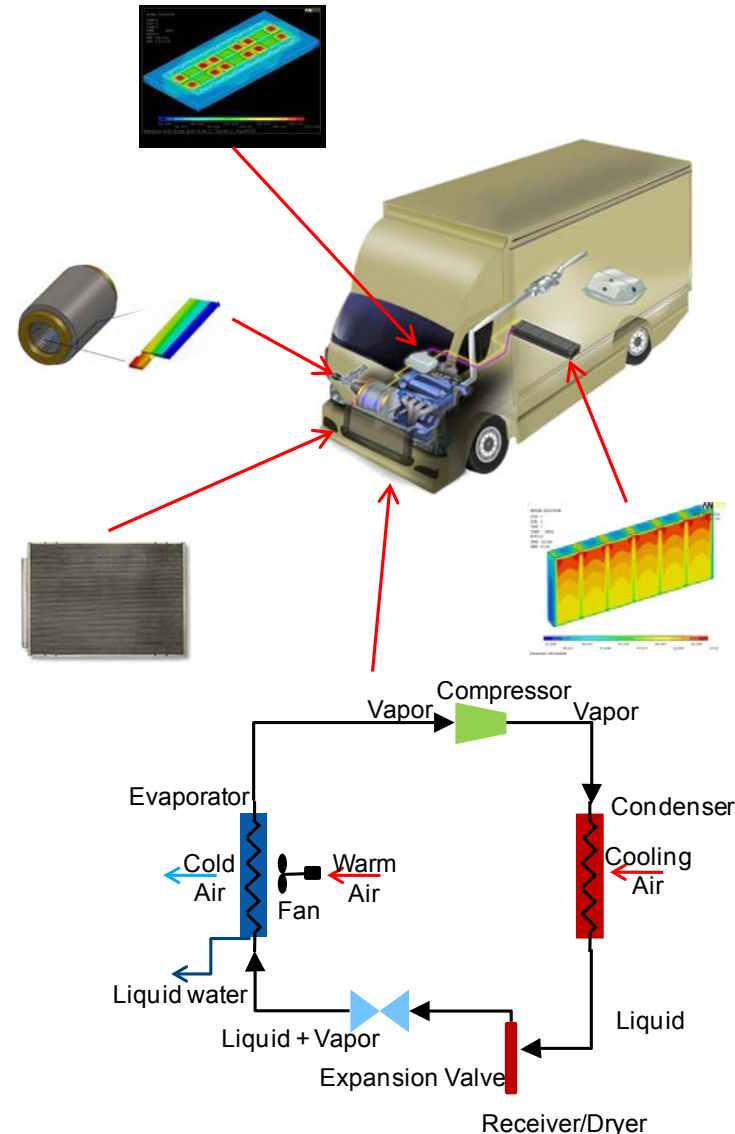
Milestones:

- 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. **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 10% 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: Advanced Thermal System Modeling Framework

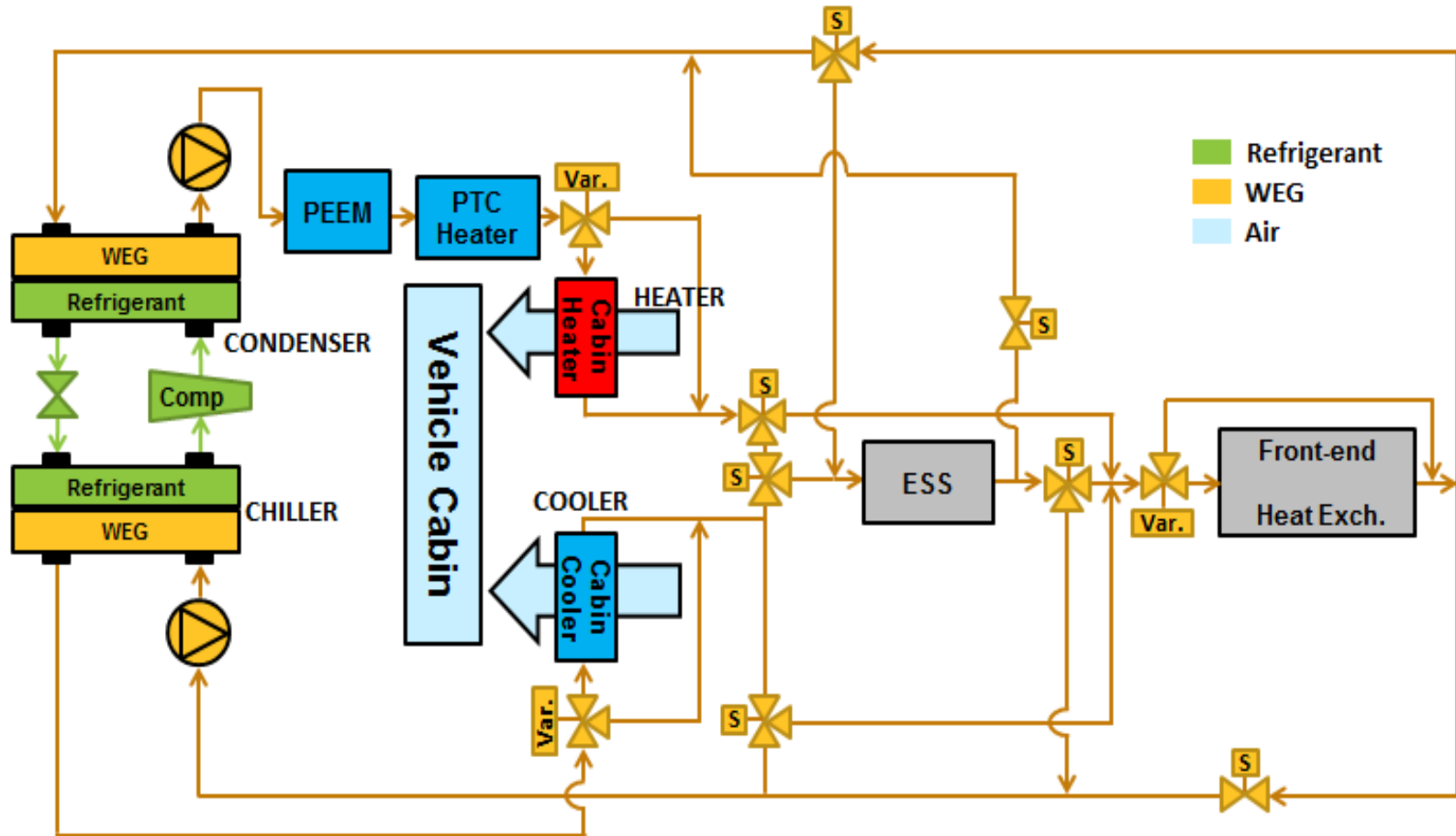
Develop MATLAB/Simulink-based model of the entire thermal system of a vehicle

- 1-D simulation tool based on first principles; conservation of mass, momentum, and energy
- 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, thermostat, etc.
- Build on prior successful two-phase A/C system model for a complete advanced vehicle thermal system modeling capability
- Develop models that run faster than real time
- Compatible with Autonomie for co-simulations.



Approach/Strategy:

Schematic of NREL's CFL EDV thermal management system

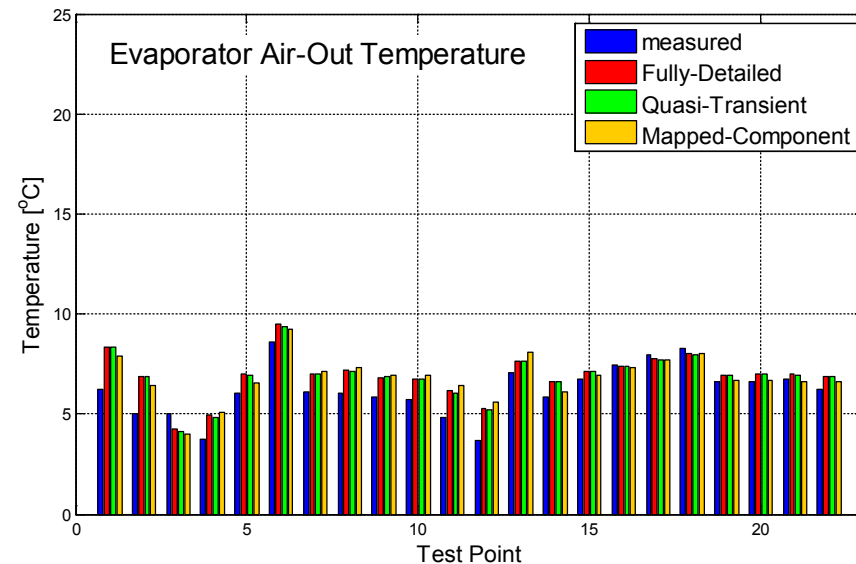
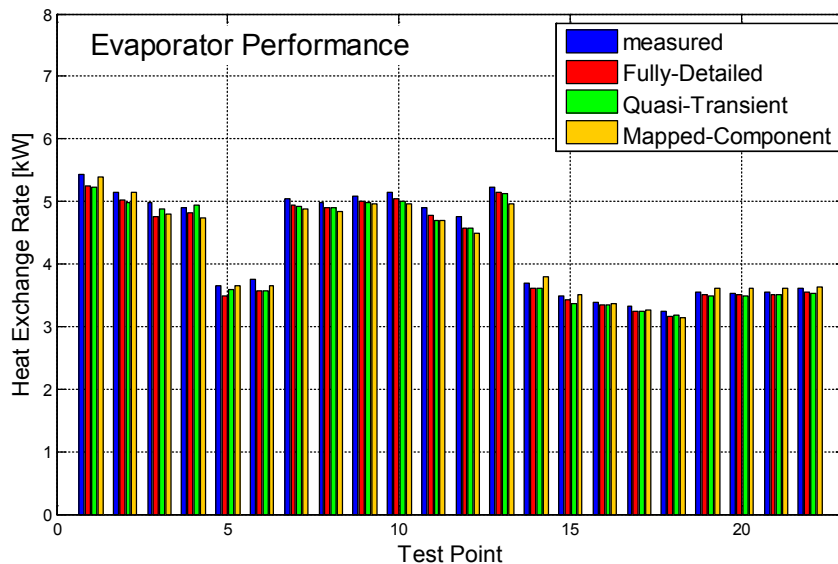
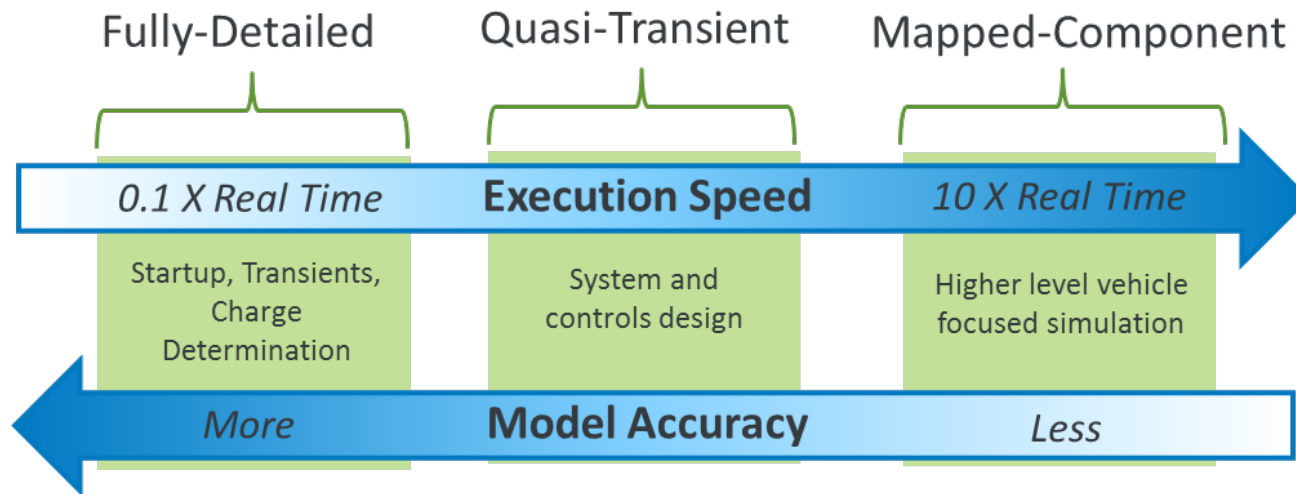


- Combined loop designs integrate all of the thermal sources and energy users into a single system
- System was used to validate the modeling framework.

WEG – water-ethylene glycol
CFL – combined fluid loops
EDV – electric drive vehicle

Previous Technical Accomplishments:

Two-phase refrigerant circuit simulation



Technical Accomplishments:

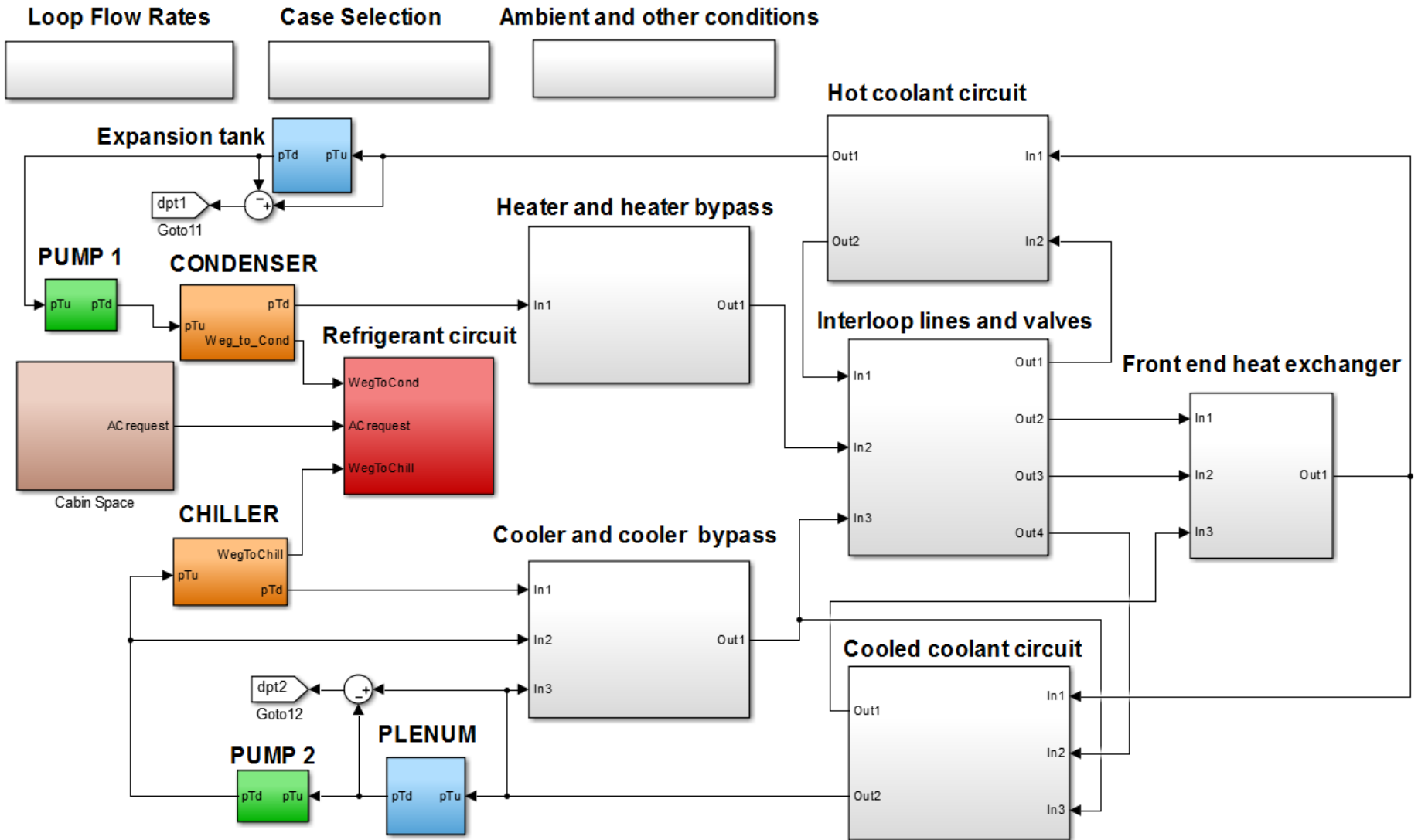
Coolant circuit simulation

- **General:**
 - Switchable between varying levels of accuracy and execution speed
 - Applicable for predicting both short (pump RPM) and long (engine warm-up) transients
 - Interface with vapor compression cycle simulations (two-phase simulations)
- **Coolant flow calculations:**
 - Incompressible flow for coolant, temperature dependent properties
 - Components represented by pressure drop vs. flow rate obtained from lookup tables, or distributed parameter component models
 - Coolant loop flow rates solved first, from which branch flow rates are calculated
- **Heat transfer calculations:**
 - Solid thermal masses accounted for in “Nodes”
 - Coolant thermal mass accounted for in “Plenum” simulation blocks
 - Varying levels of heat transfer calculation accuracy can be used:
 - Effectiveness-NTU (number of transfer units) method
 - Multi-dimensional lookup tables (tables from measurement or modeling)
 - Distributed parameter component models.

Technical Accomplishments:

Schematic of NREL's CFL EDV expressed in MATLAB/Simulink

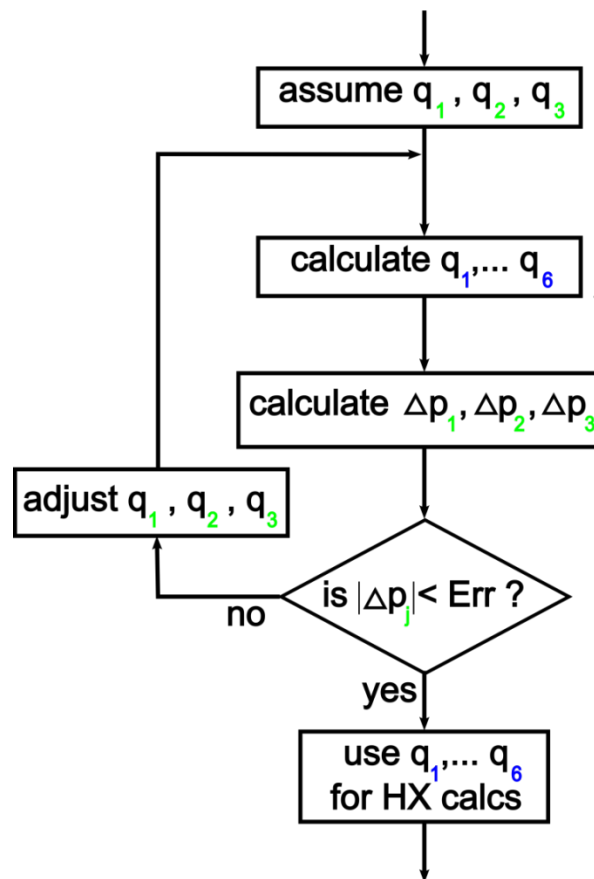
These three blocks have inner connections with blocks throughout the model



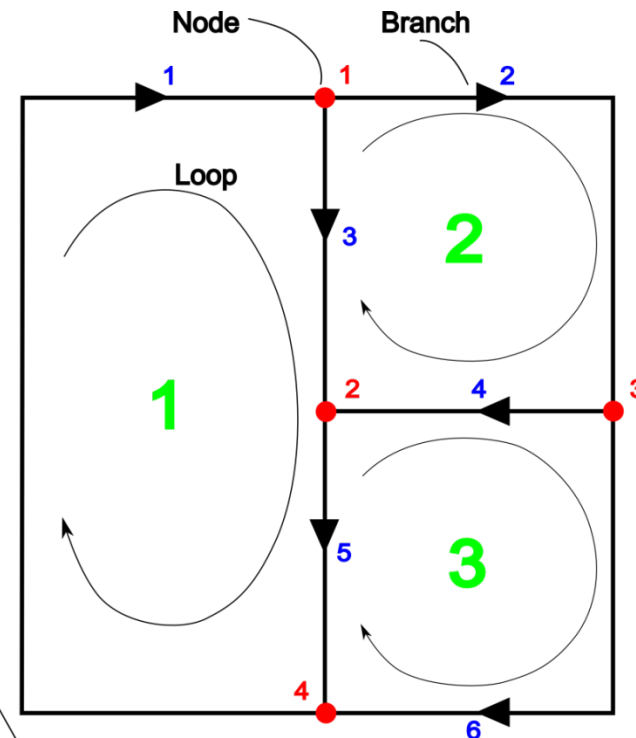
Technical Accomplishments:

Details of coolant circuit modeling

- Incompressible flow
- Complex rules apply for selecting loops.



Fluid network example. Green font “L”: loops; Red font “N”: nodes; Blue font “B”: branches



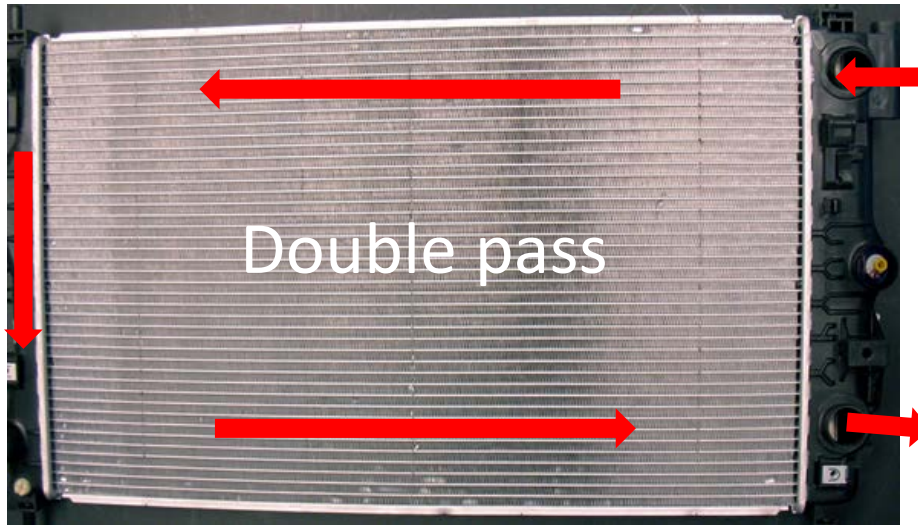
$$q_3 = q_1 - q_2$$

$$\Delta p_3 = \Delta p_{24} + \Delta p_{43} + \Delta p_{32} = 0$$

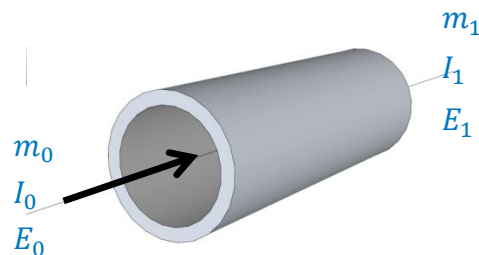
Technical Accomplishments:

Distributed parameter model

Two coolant passes in this example

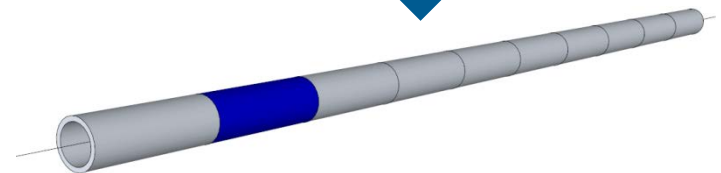
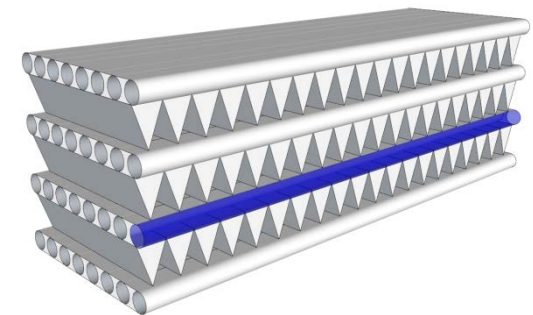


Conservation equations solved in radiator plates



Complex heat exchanger

- Multiple passes
- Multi-channel tubes
- Micro channels

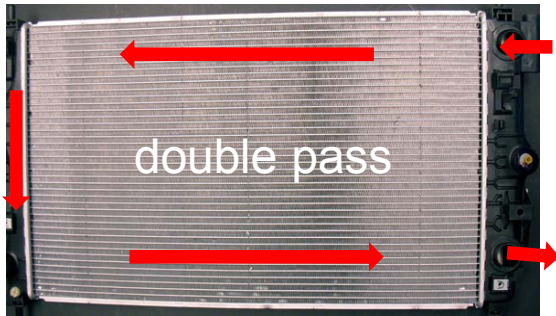


- A pass is a number of plates over which the coolant and airflow can be assumed identical
- A pass in this sense can be a traditional pass (serial pass) or some number of plates in a serial pass bundled together to create parallel passes (e.g., when airflow is very non-uniform)
- Only one plate in each 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.

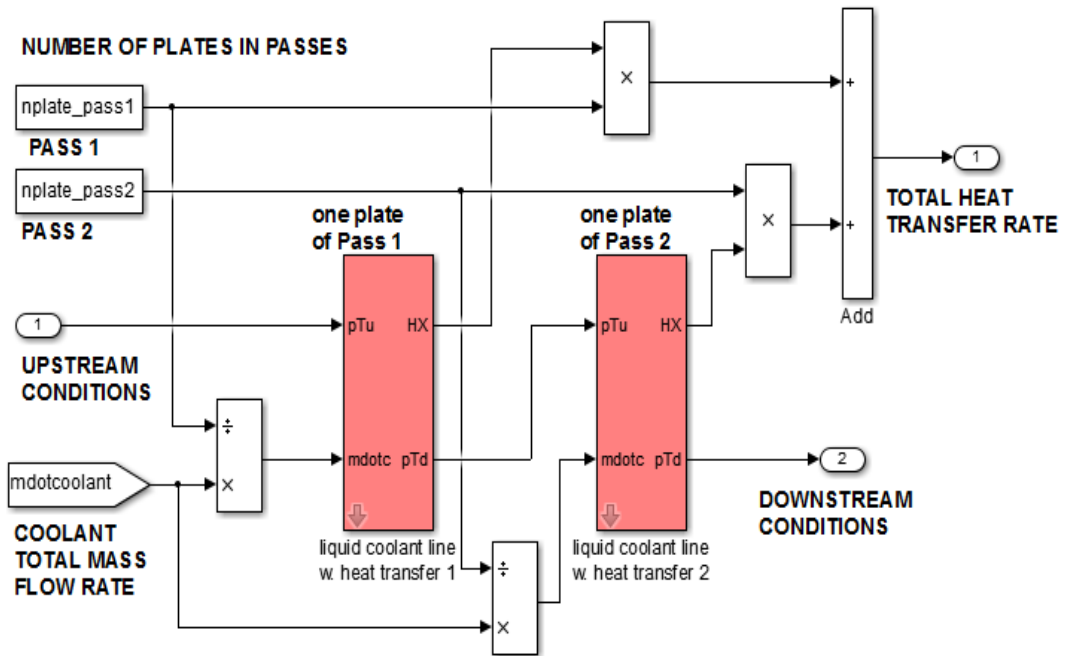
Technical Accomplishments:

Solving for component heat transfer rates in the liquid

The Distributed-Parameter model provides details and flexibility



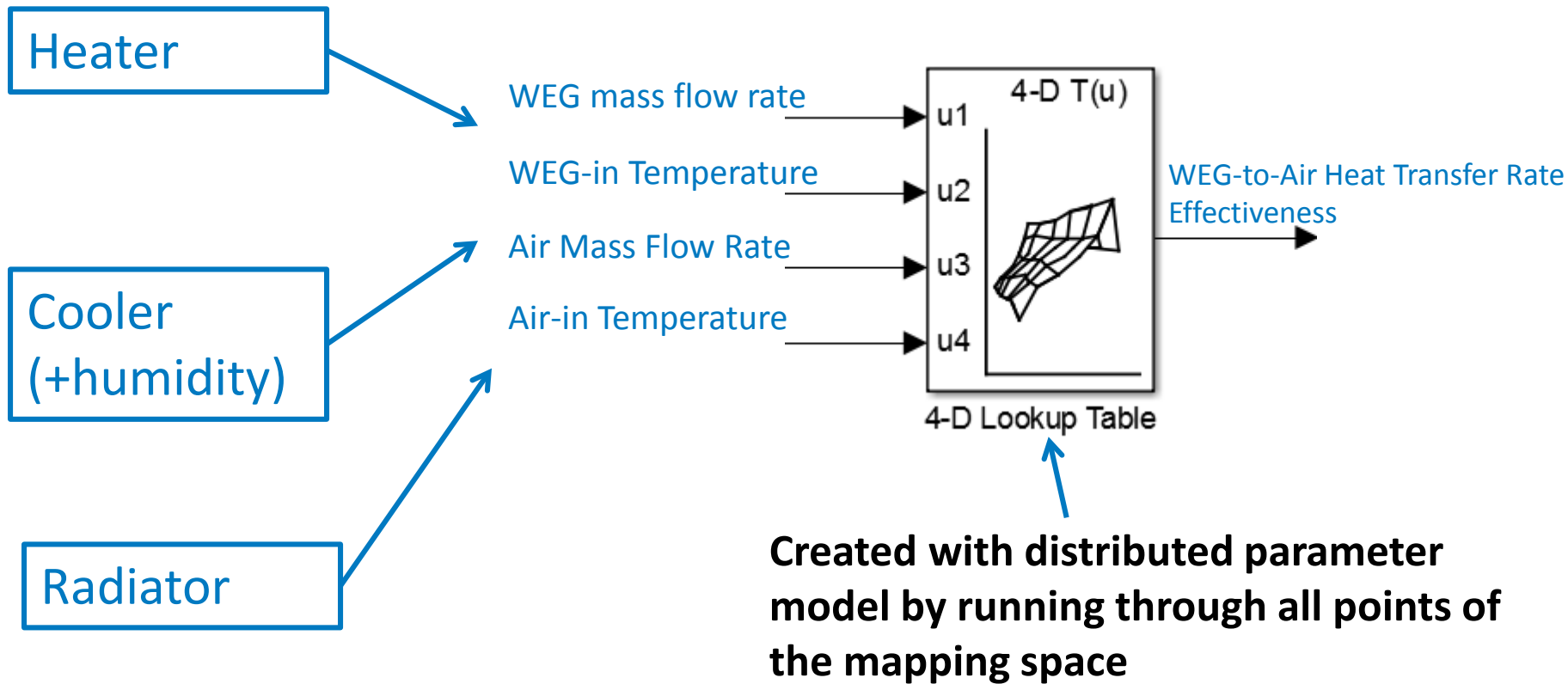
Two-pass radiator as an example



Technical Accomplishments: Coolant Circuit Simulation

Calculating heat transfer rates for mapped components

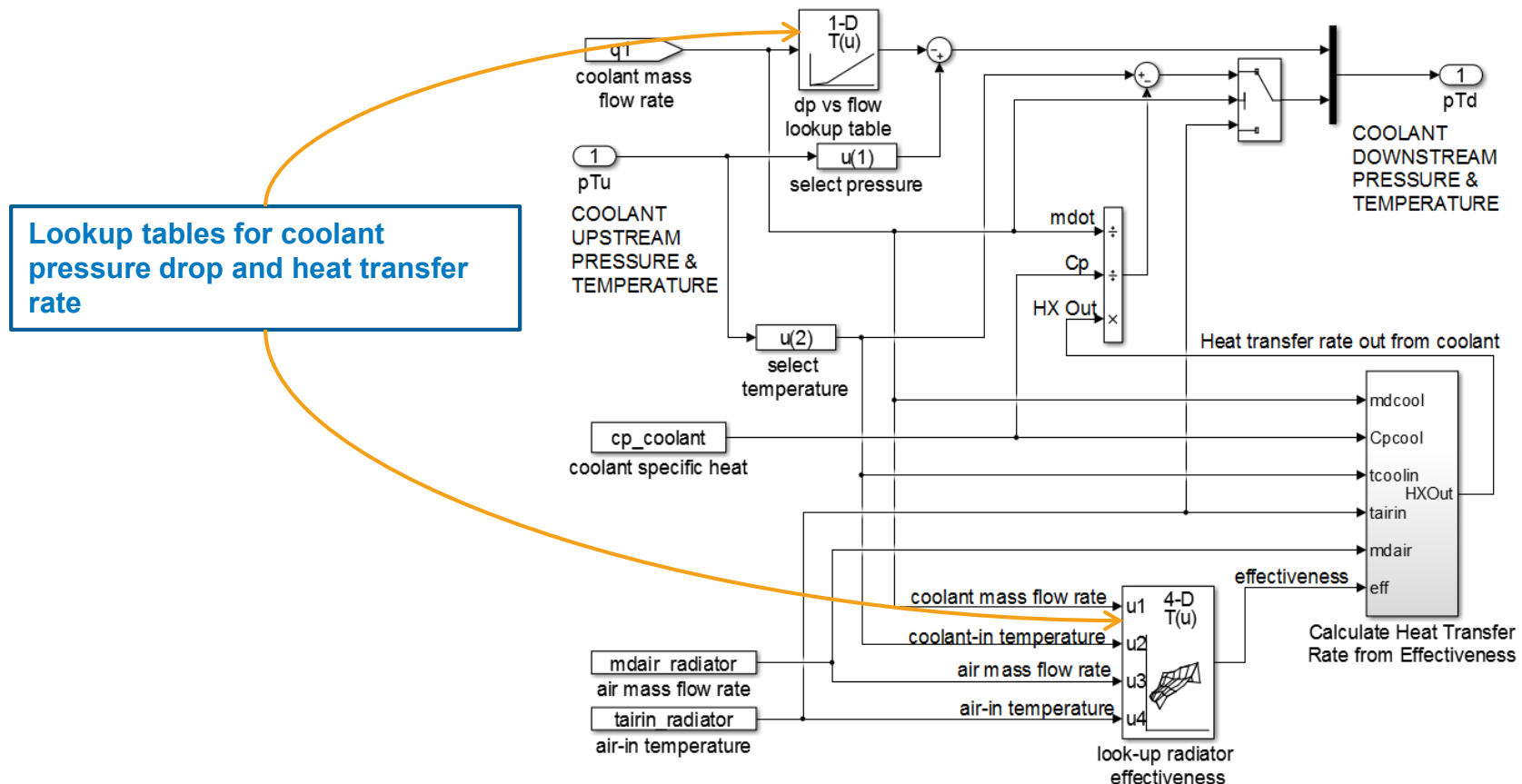
Use the distributed parameter component models to create performance lookup tables.



Technical Accomplishments: Coolant Circuit Simulation

Use performance lookup tables in the full system model

Front End Heat Exchanger (FEHX) Mapped-Component Model (simplified)



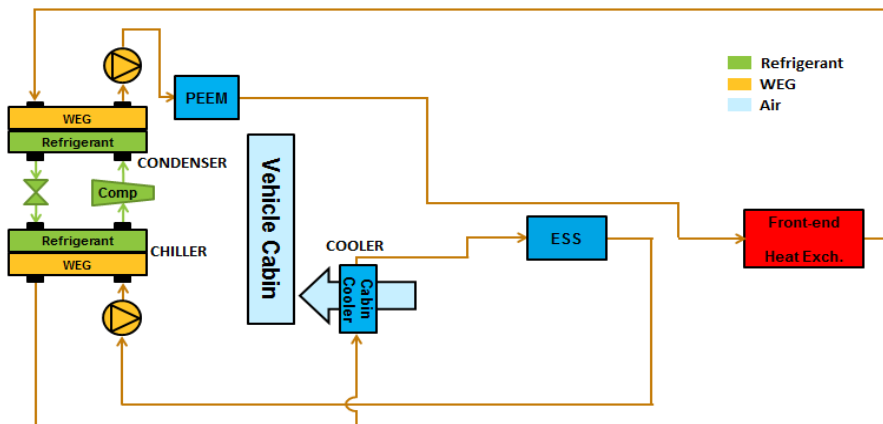
Calibrated liquid coolant heat exchangers were used to generate heat exchanger performance maps.

Technical Accomplishments:

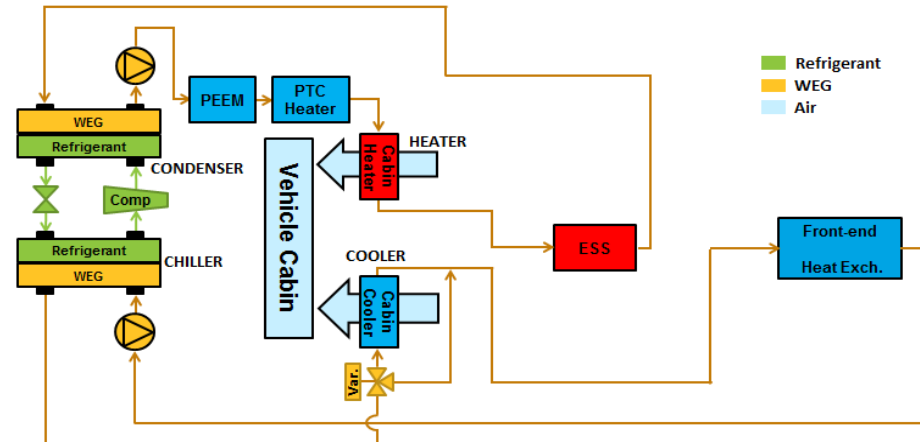
Combined loop thermal management system



A/C mode



Heat pump mode

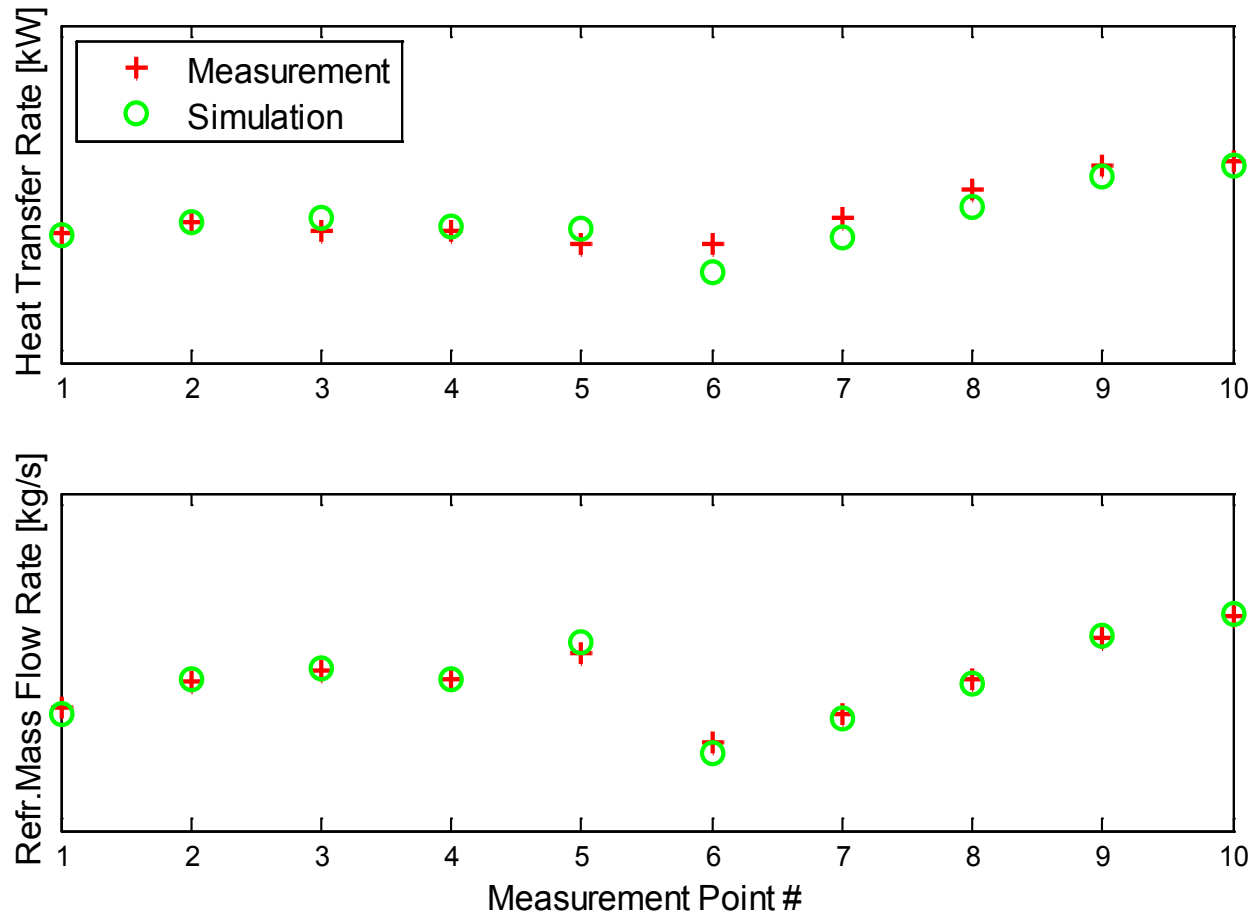


NREL's combined fluid loop EDV thermal management system test bench was selected for validation and demonstration of the modeling method.

1. Photo by Daniel Leighton

Technical Accomplishments:

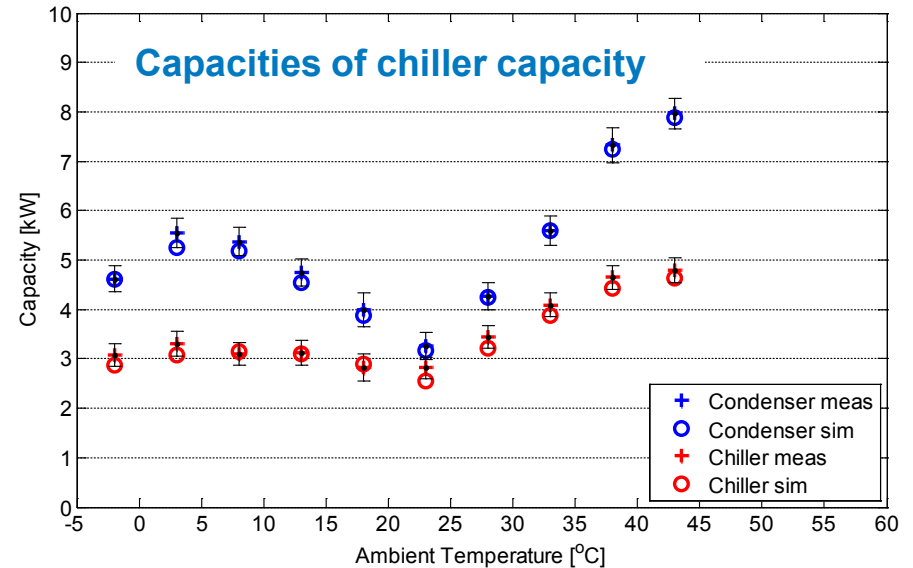
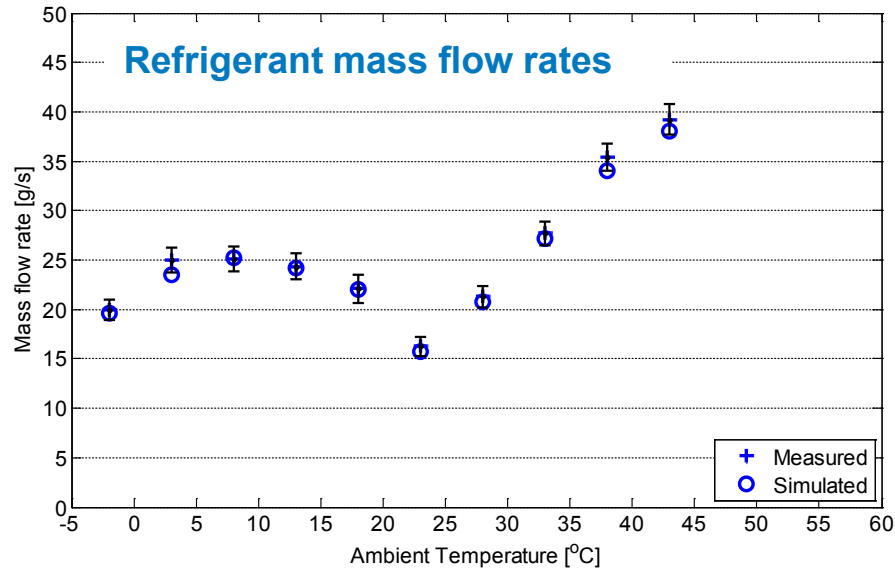
Chiller calibration using component data



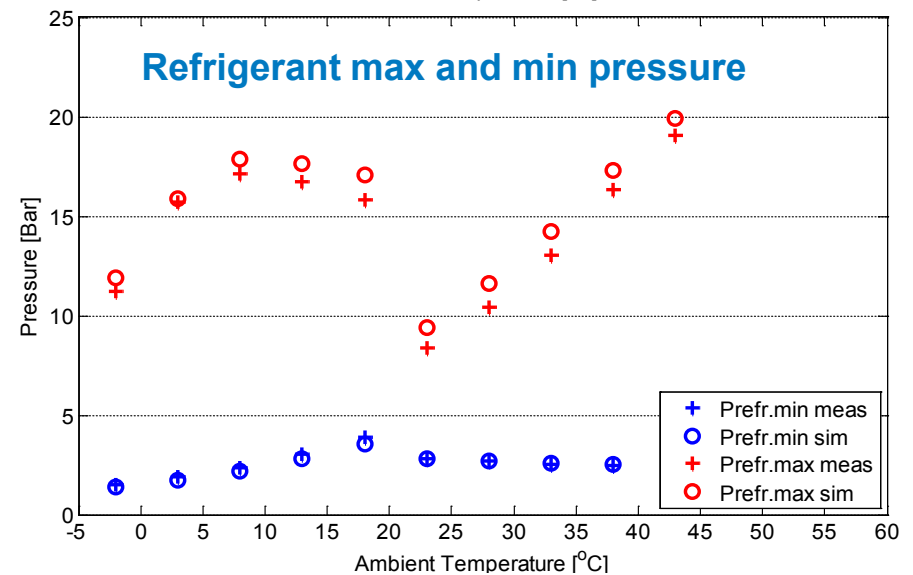
For calibration of the refrigerant-based heat exchangers, the Quasi-Transient A/C system sub-model was used

Technical Accomplishments:

Comparison to steady state measured data for the refrigerant side

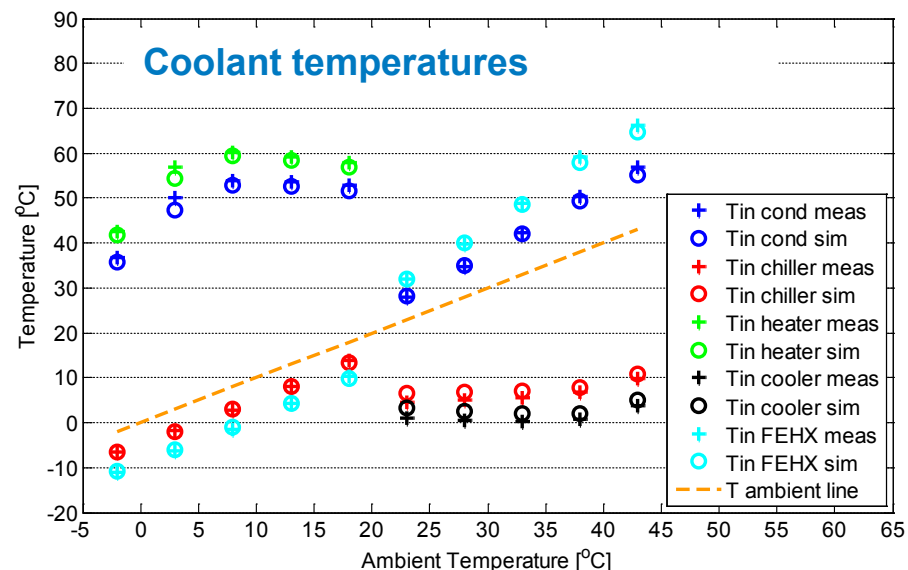
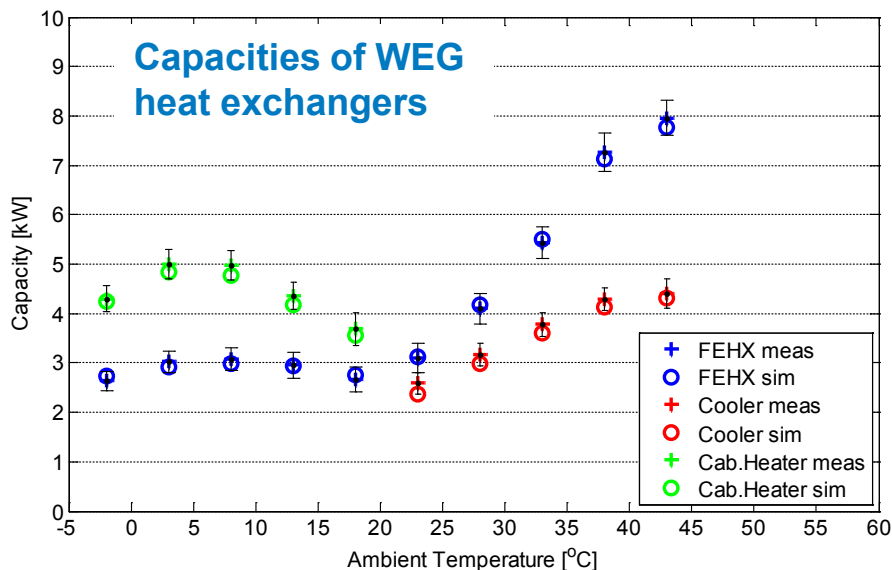


- The root mean square (RMS) error for capacities is 4.3%
- RMS error for pressure is 4.3%



Technical Accomplishments:

Comparison to steady state measured data for the coolant side



- **RMS capacity error for WEG heat exchanges is 3.6%**
- **RMS error for coolant temperatures is 1.20 K.**

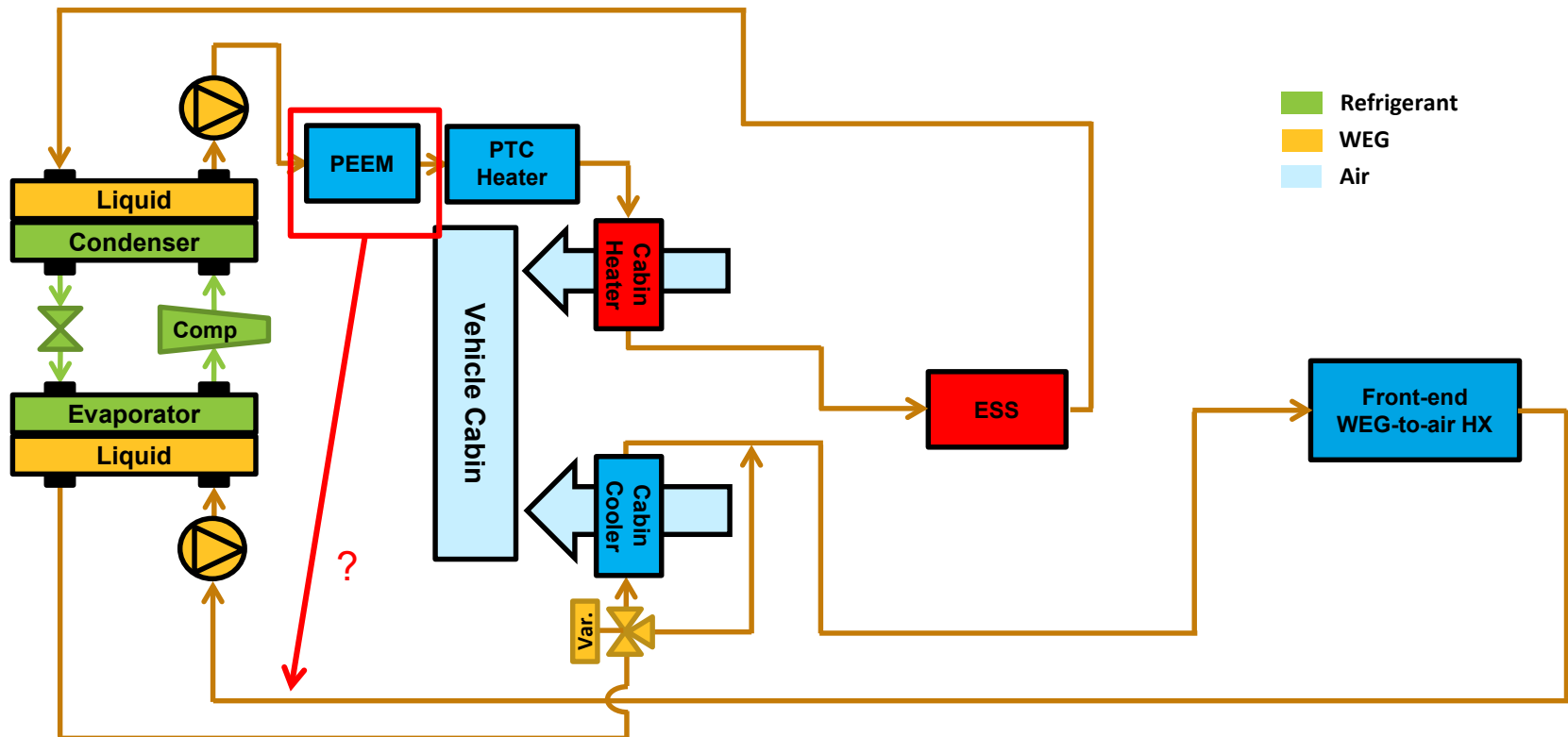
For these five comparison plots, 96% of the simulated points are within the 95% measurement uncertainty band.

Technical Accomplishments:

Determine optimal location of the power electronics and electric machine

Heating Mode: Would it be better to move PEEM into chiller loop for this system?

Argument: Higher compressor inlet temperature may cause higher compressor coefficient of performance (COP) and may reduce overall power consumption.

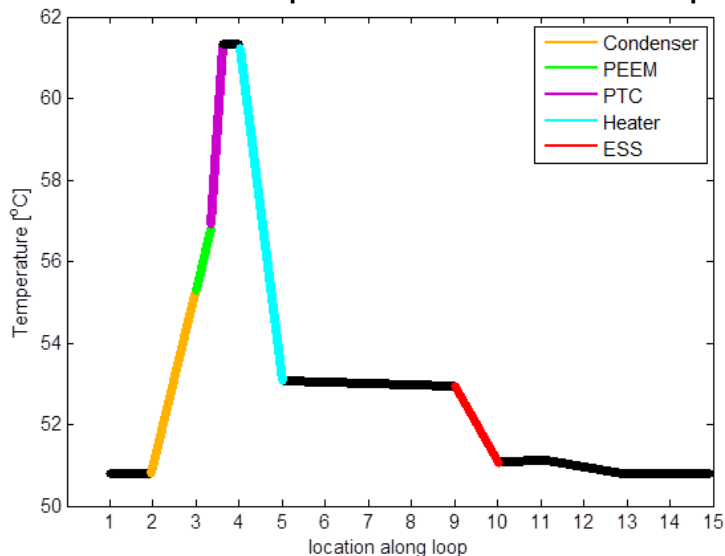


- A cold start of the system was selected for evaluation of the PEEM placement
- The comparison is done at a state after the initial fastest transients, quasi-steady

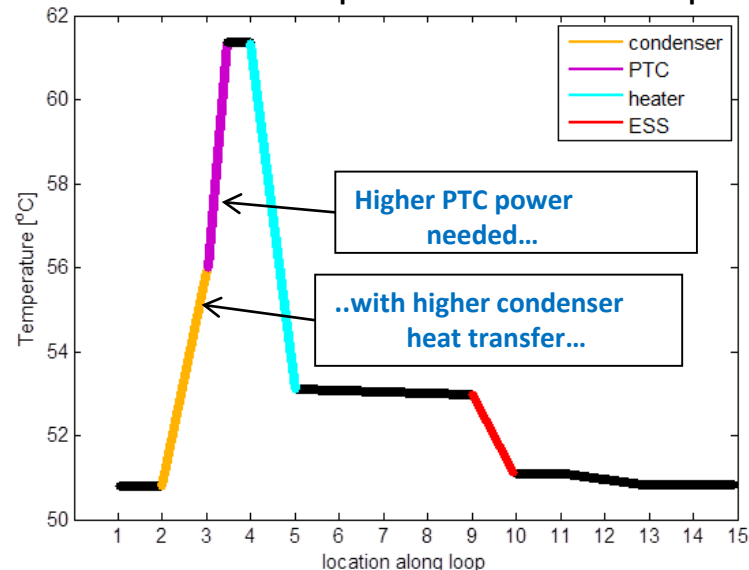
Technical Accomplishments:

Determine optimal location of the power electronics and electric machine

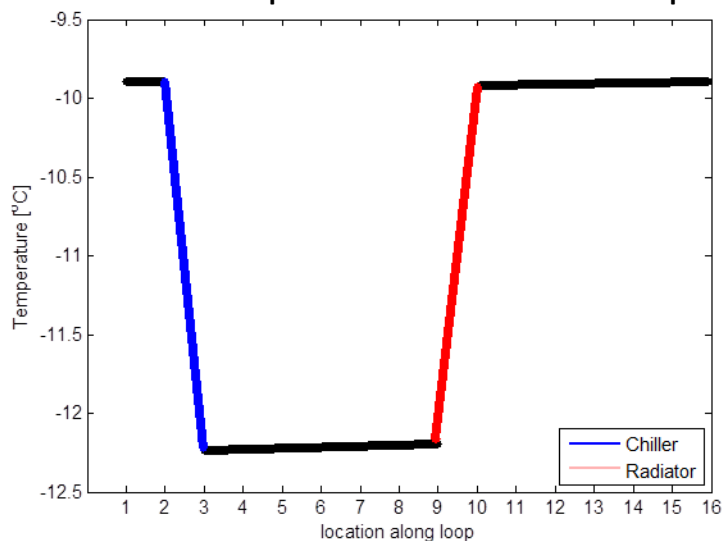
WEG in condenser loop when PEEM is in condenser loop



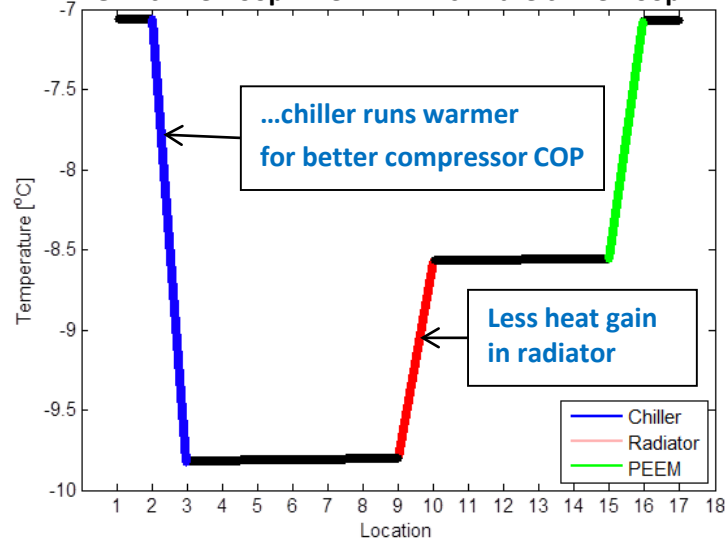
WEG in condenser loop when PEEM is in chiller loop



WEG in chiller loop when PEEM is in condenser loop



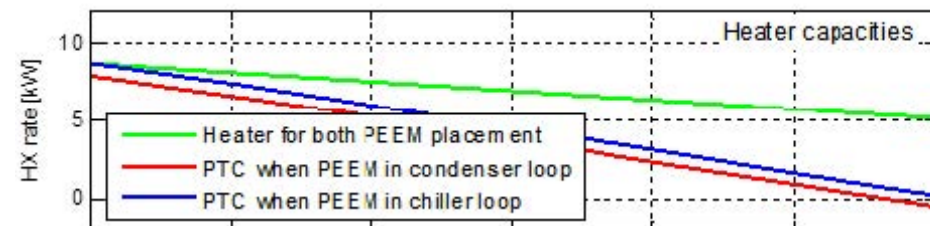
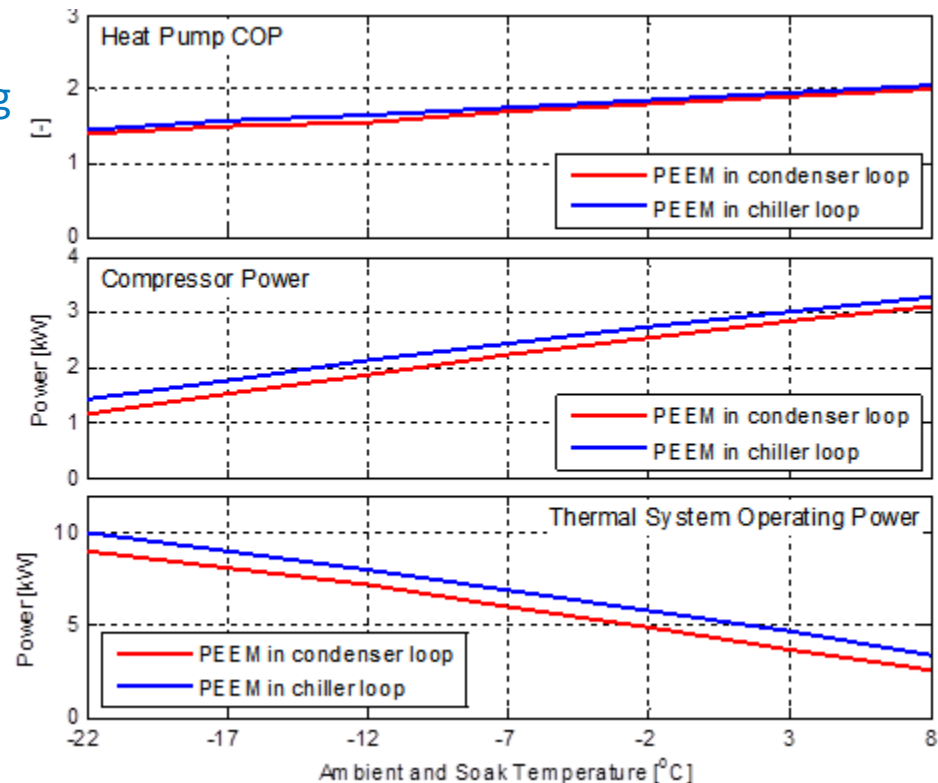
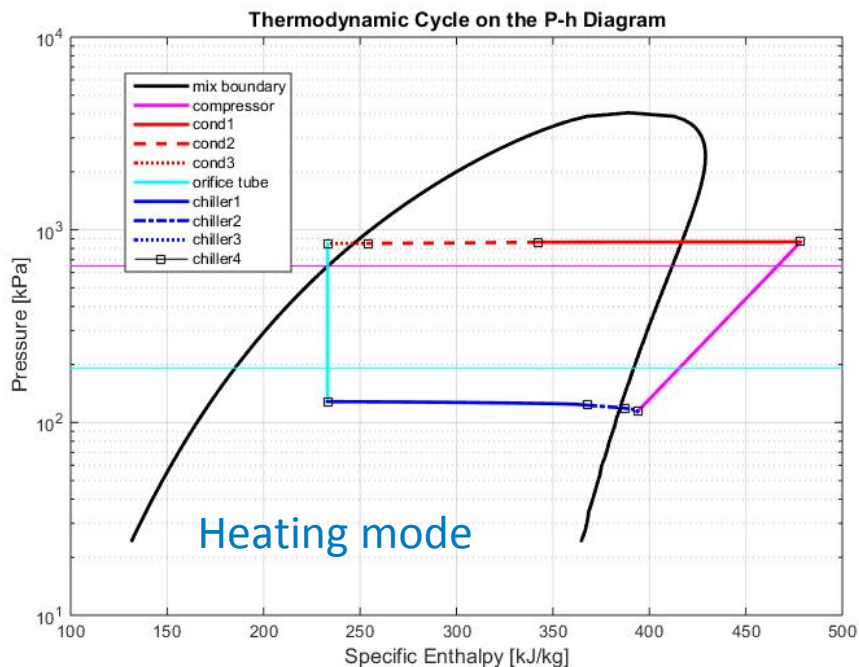
WEG in chiller loop when PEEM is in the chiller loop



Technical Accomplishments:

Determine optimal location of the power electronics and electric machine

- COP is higher for PEEM in chiller loop
- Condenser heat transfer is also higher, resulting in a net increase in compressor power
- PEEM in the chiller loop elevates FEHX coolant inlet temperature, reducing temperature difference and absorbed heat, resulting in additional PTC heat demand
- Increased PTC and compressor power increase total power.



Responses to FY14 AMR Reviewer Comments

Comment: ...the M1 milestone was completed and the results of the model are said to have "reasonable trend." This reviewer asserted that a discussion of how this was judged is warranted.

Response: Last year the statement "reasonable trend" was determined by comparing the framework build model responses to expected system behavior (from experience). The behavior was also verified to be physically correct, which included energy balances and responses to input signals such as thermostat opening. This year, a model was built using the framework for an advanced combined fluid loop system that included air conditioning, heat pump, and waste heat recovering modes. Agreement with test data is now quantified, with 96% of simulations points falling within a 95% confidence interval of the data.

Comment: The reviewer added that the objective was stated to develop models from the first principles, but several of the components were said to have lookup tables. The reviewer wanted to know if these tables were derived from the first principles or experimental data.

Response: Components were first modeled with a more accurate Distributed Parameter approach that used 1-D and 0-D modeling blocks to define the components by solving the mass, momentum, and energy equations. Distributed Component models could be used directly in the models; however, this level of detail would result in slower simulation speeds. In order to accelerate the simulations, Distributed Component models can and were used to generate the performance maps. In general, this approach allows the user to choose between the level of detail and simulation speed for each particular analysis.

Comment: The reviewer stated that with quantification of the loss of fidelity from the model being 1-D as opposed to 3-D would be useful here.

Response: The focus of this modeling framework is on the system behavior rather than component design. There certainly is a loss in the details of component behavior predictions any time 1-D models are used; however, with 1-D models there is a very large gain in speed and simplicity while the core component behavior is preserved. The comparisons with experimental data done this year showed that the model captured component and system behavior well.

Collaboration and Coordination with Other Institutions

- Halla Visteon Climate Control
 - Provided data for A/C system model and validation
 - Technical advice and discussion
 - *FOA award partner, leveraging tools assisting with models*
- Delphi Automotive
 - Provided data for combined fluid loop molding
 - Advanced concept modeling
 - *FOA award partner, leveraging tools to assist with models*
- Cummins and ORNL
 - A/C system modeling
- Daimler Trucks
 - Leveraged tools to assist on SuperTruck project
- Argonne National Laboratory
 - Autonomie integration
- Other collaboration discussion in progress.

Proposed Future Work and Remaining Challenges

- **Continue model development**
 - Complete improved single-phase solution method for larger, more complex systems
 - Add new refrigerant HFO-1234yf
 - Add more detailed energy storage and power electronics components
 - Add additional thermal components (heat exchangers, etc.)
 - Improve the cabin model
 - Improve ease of model development
- **Build and validate A/C system model for Cummins & ORNL project**
- **Model applications with industry partners and use to research advanced thermal systems**
 - Model advanced light-duty vehicle thermal systems
 - Heat pump system
 - Advanced heat recovery concepts
 - Build validated idle-off long-haul truck A/C system model
- **Improve Autonomie co-simulation**
- **Leverage model results for the CoolCab project impact estimation.**

Summary

- NREL's modeling toolset was extended to incorporate simulation of liquid coolant subsystems
- This new modeling methodology is especially useful for simulations of coupled refrigerant and liquid coolant-based thermal sub-systems
- Validation for ten steady-state system operating conditions of an advanced combined loop system was done against measured data showing 96% of the data within the 95% measurement uncertainty band
- Investigated optimal PEEM heat scavenging locations and determined that the high side coolant loop was the best location for the conditions of interest
- Increased industry partnerships and leveraged developed tools for advanced system projects.

Contacts and Acknowledgements

Contacts

- Jason Lustbader (Jason.lustbader@nrel.gov)
- Gene Titov (Eugene.Titov@nrel.gov)

Acknowledgements

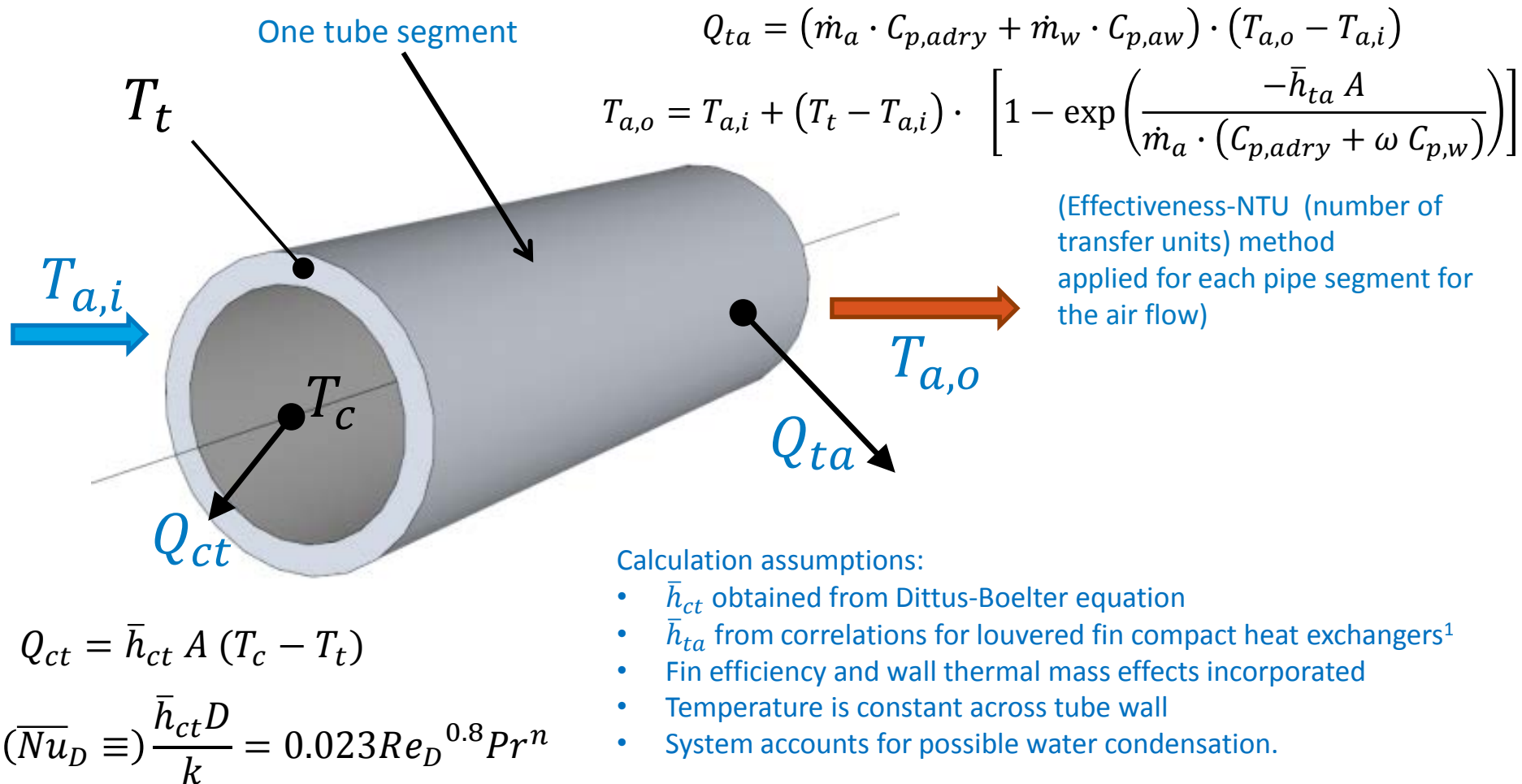
- The authors would like to thank
 - Delphi for components and component data
 - Halla Visteon Climate Control for component and system data
 - David Anderson and Lee Slezak, Technology Managers for the U.S. Department of Energy's Advanced Vehicle Technology Analysis and Evaluation for sponsoring this work

Technical Back-Up Slides

Coolant Circuit Simulation

Calculating heat transfer rates in line blocks

Methods used for distributed parameter component models



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