NREL
NATIONAL RENEWABLE ENERGY LABORATORY

# Vehicle Thermal System Modeling in Simulink


**P.I.: Jason A. Lustbader**
**Team: Gene Titov & Eric Miller**
**National Renewable Energy Laboratory**

**June 8, 2016**

Project ID #: VS134

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

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

# Overview

## Timeline

**Project Start Date: FY14**

**Project End Date: FY17**

**Percent Complete: 65%**

## Budget

**Total Project Funding:**

- DOE Share: $775K
- Partner contributions*: $200K

**Funding Received in FY15: $275K**

**Funding for FY16: $175K**

**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 assist with optimization of future vehicle thermal system designs and prediction of impacts on fuel economy and range
- ***Constant advances in technology*** – Help industry to advance technology with improved tools

## Partners

- Hanon Systems
- MAHLE
- Daimler Trucks
- Kenworth Trucks
- Cummins
- Oak Ridge National Laboratory (ORNL)
- VTO Advanced Power Electronics and Electric Motors (APEEM) Team
- Argonne National Laboratory (ANL)

**Project Lead: NREL**

# Relevance

## THE CHALLENGE

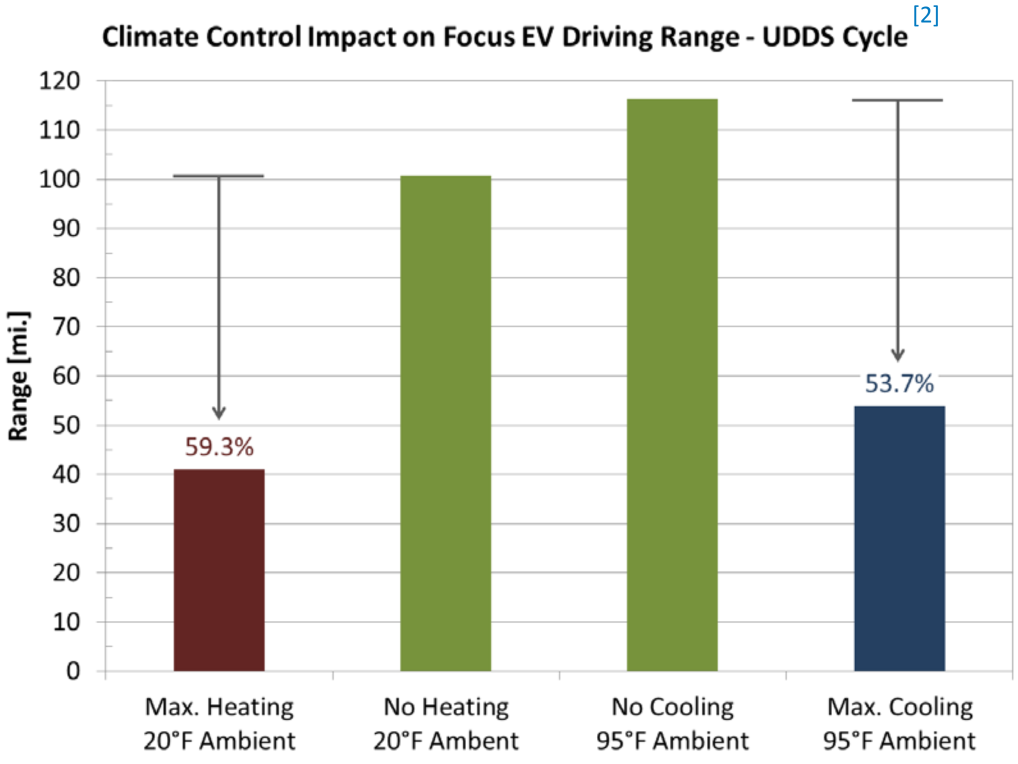
- Heating and air conditioning (A/C) have a large impact on electric vehicle (EV) range
- With increasing electrification, vehicle thermal systems are increasingly important for effective and efficient light- and heavy-duty vehicle design
- Electrified heavy-duty A/C systems may provide necessary infrastructure to add heating at limited additional cost
- Autonomie lacks thermal system models 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 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
  - Heating, ventilating, and air conditioning (HVAC) expertise, building on the A/C system model developed previously.

# Relevance

- **HVAC loads account for more than 5% of the fuel used annually for light-duty vehicles (LDVs) in the United States[1]**
- **Climate control can reduce EV efficiency and range by more than 50%**
- **Limited waste heat**
- **More efficient HVAC 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

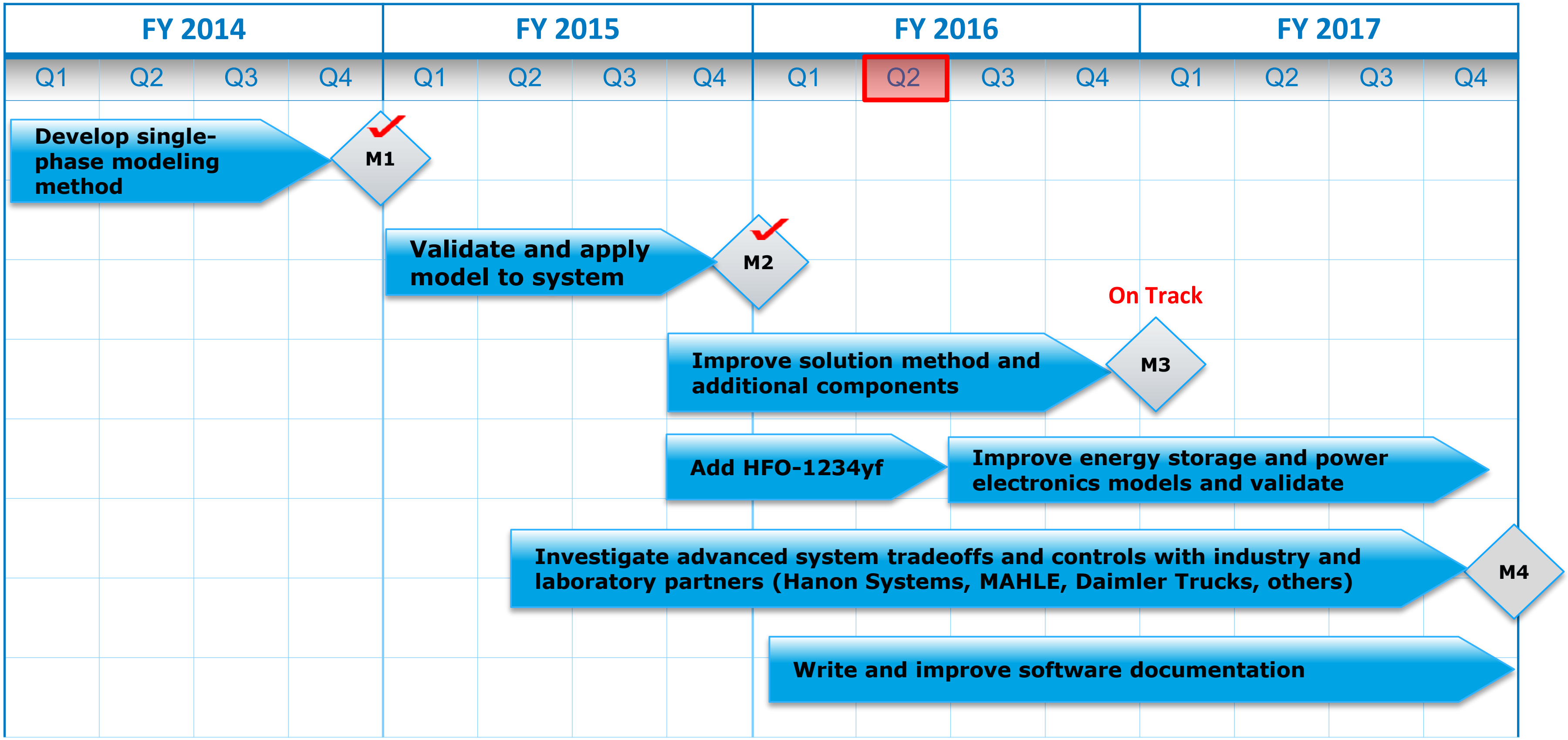
**Goals**

- **By 2017, develop a flexible, publically available framework in the MATLAB/Simulink environment for modeling of vehicle thermal management systems capable of co-simulations with vehicle level models.**
- **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 vehicle-level models such as 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**: Models of concept demonstration systems predict 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%).

**On Track**

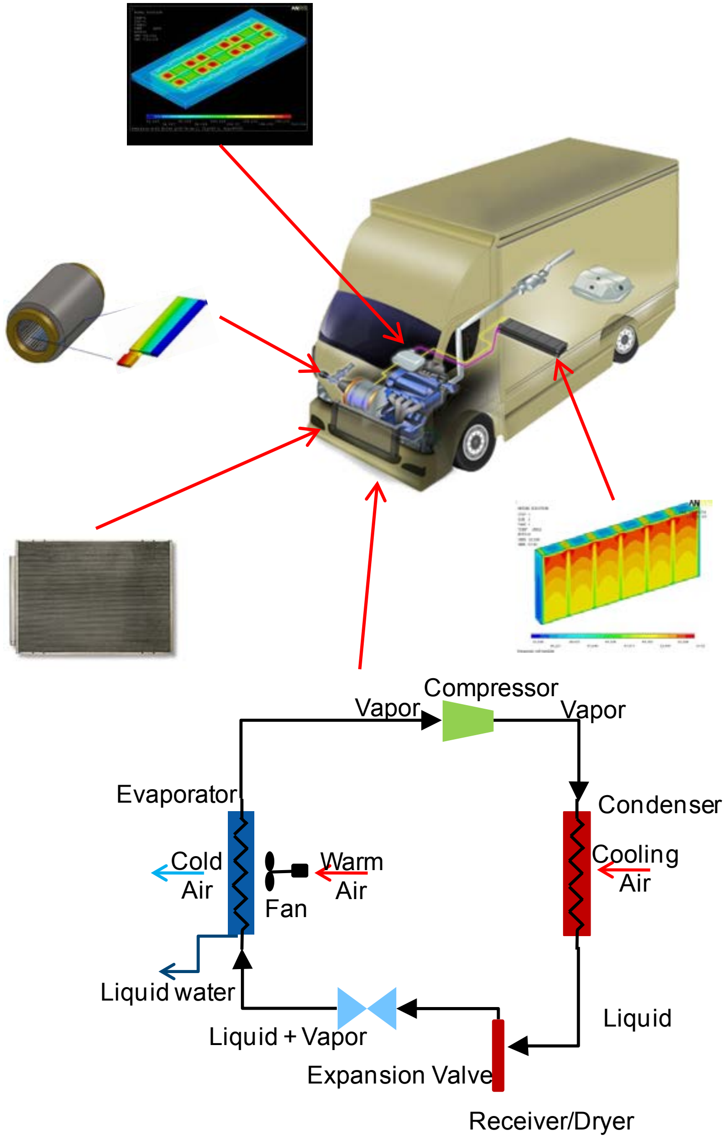
M3. Improve solution method, allowing for dynamic valves. Validate model to within 10% of available data.

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 vehicle model. Do initial thermal control investigations. Release updated code with expanded capabilities.

# Approach/Strategy: Advanced Thermal System Modeling Framework

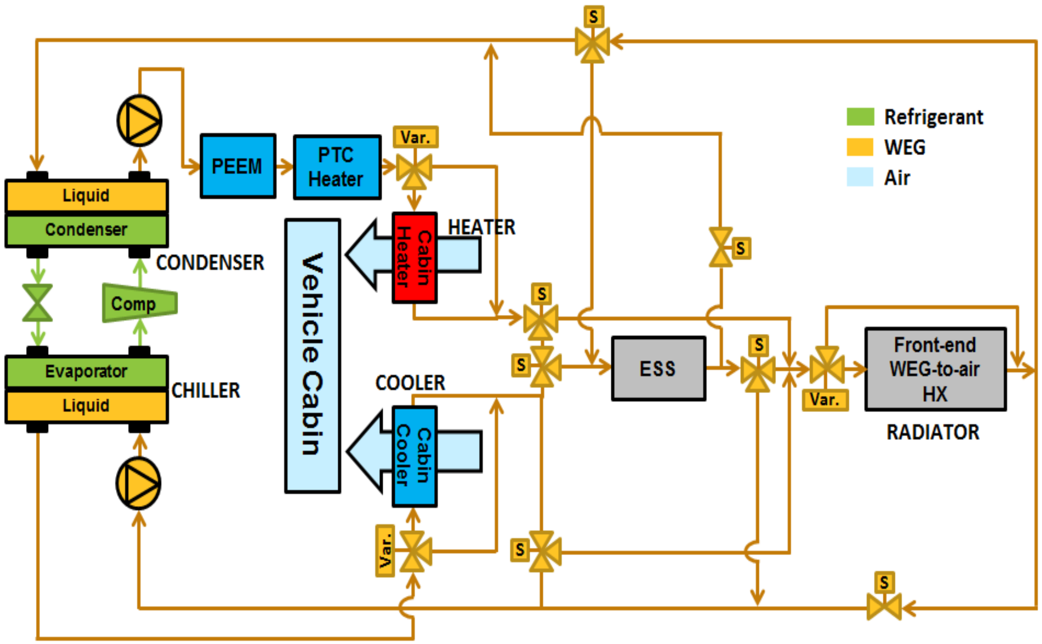
## Develop MATLAB/Simulink-based models of the entire thermal system of a vehicle

- 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 model, adding single-phase coolant loop models for advanced vehicle thermal system simulations
- Develop models that run faster than real time
- Compatible with vehicle-level models for co-simulations in Simulink



# Approach/Strategy: NREL's Advanced Combined Fluid Loop (CFL)

*Multiple modes of operation without reversing VCC* for greater efficiency*

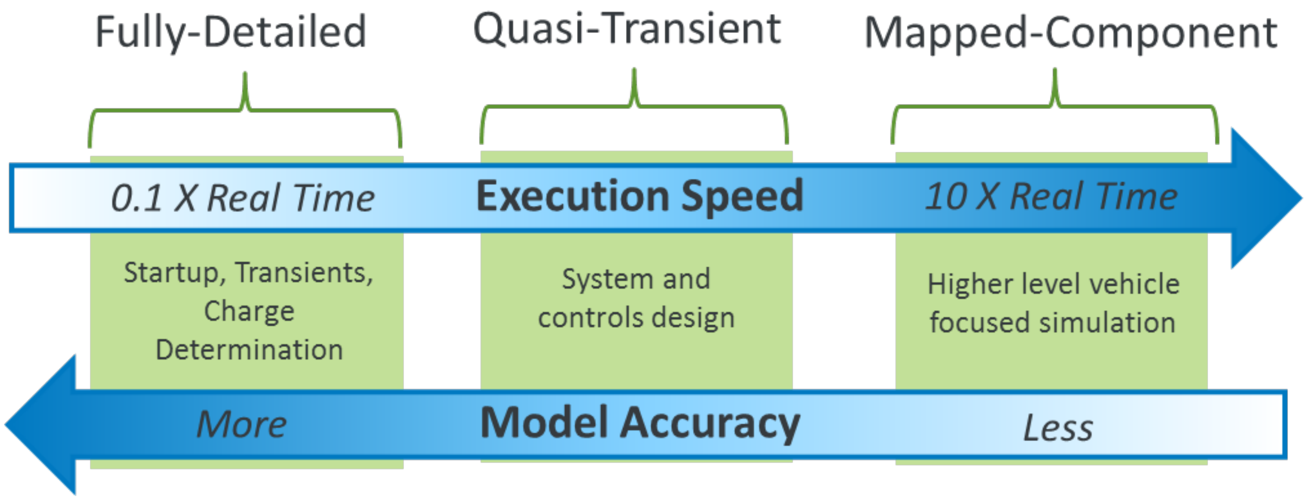



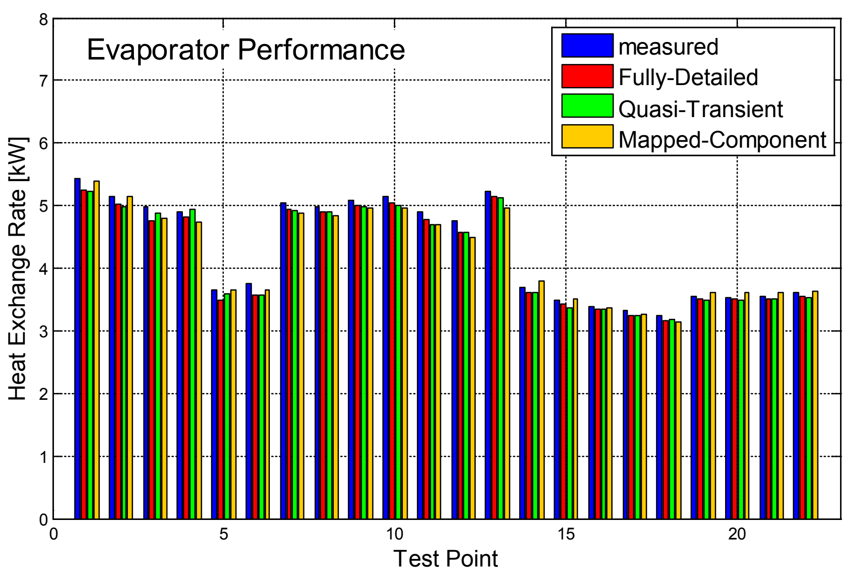

- Air conditioning
- Heat pump
- Free PEEM and battery cooling
- Free heating
- Battery heating
- Battery cooling
- PTC heating
- FEHX defrosting
- Cabin air dehumidifying

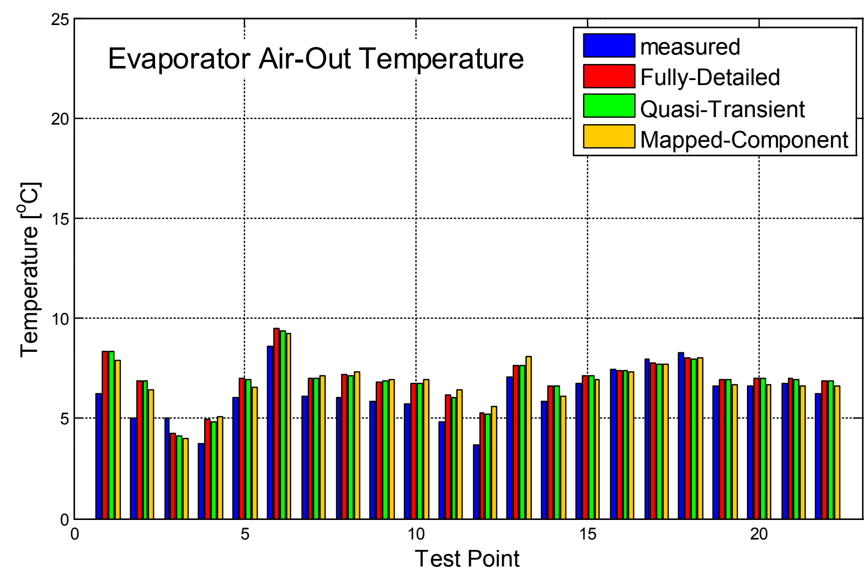
**VCC = Vapor Compression Circuit*
*FEHX = Front End Heat Exchanger*
*PTC = Positive Temperature Coefficient*

# Previous Technical Accomplishments

*Two-phase refrigerant circuit simulation*



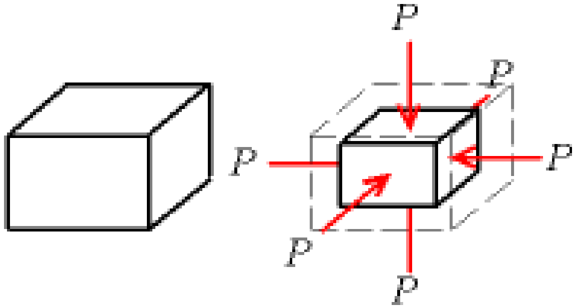



# Accomplishments: Quasi-Transient Approach for Coolant Loops

*Finite volume solution method*

Liquid/vapor networks modeled by 0-D volumes and 1-D pipes

- In finite volumes, “stiffness” is proportional to $\boldsymbol{dp/dm}$ and is large for liquids




**With the goal of reducing “stiffness”:**

- Use low artificial bulk modulus to make stiffness uniform across the network, allowing for larger time-steps

$$dp = \frac{B}{V}\frac{dm}{\rho_{ref}} \quad ; \quad \frac{B}{V} = \text{constant (and small)}$$

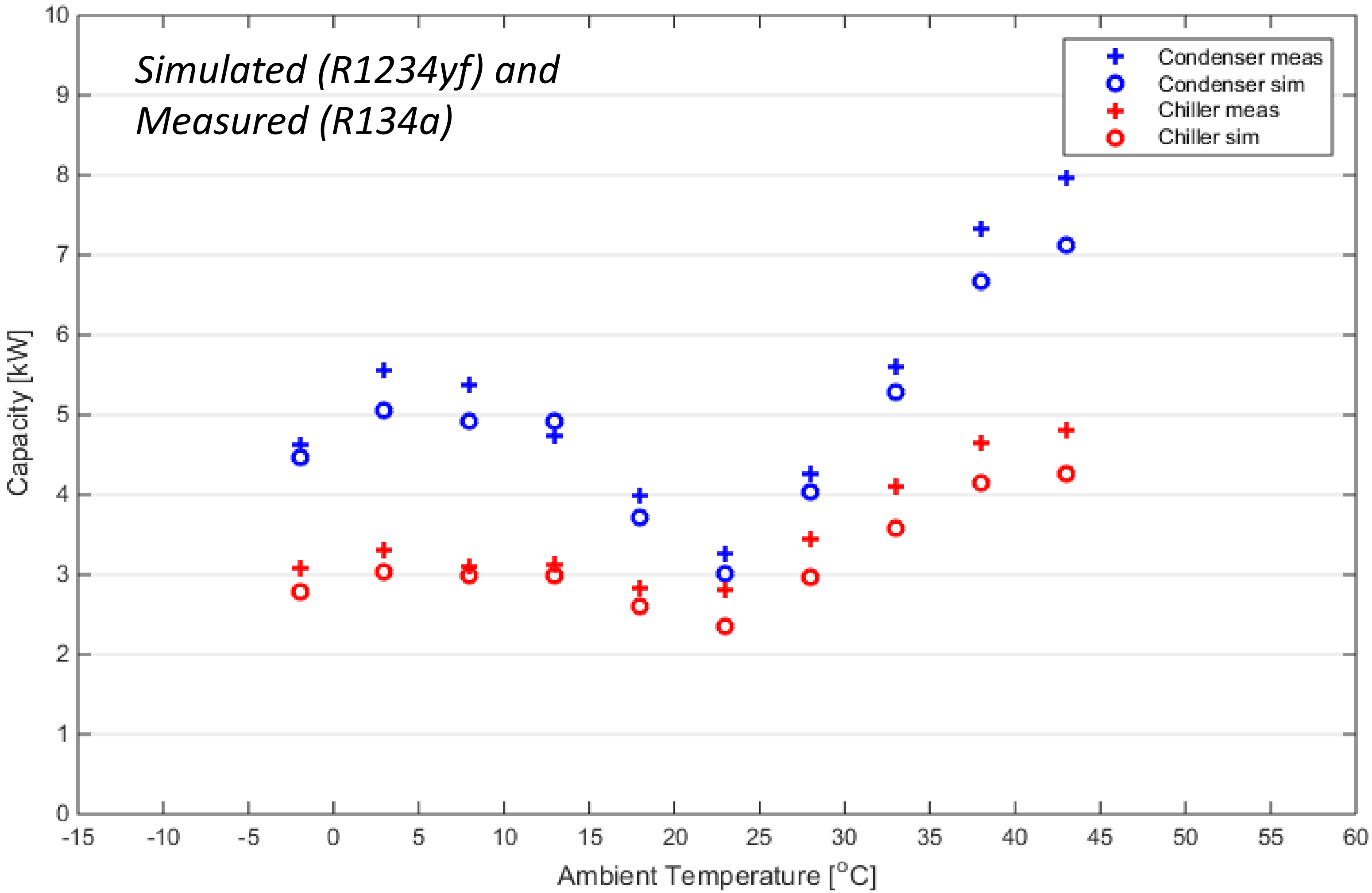
**Consequence:**

- Mass and energy imbalances with fast transients, accurate in steady state
- Solution at every time step tends to approach a steady state solution corresponding to the instantaneous values of boundary conditions
- Provides much faster simulations
- Does not require specification of flow direction

# Accomplishments: Added HFO-1234yf capability

*1234yf shows slightly lower performance as expected, providing qualitative agreement*

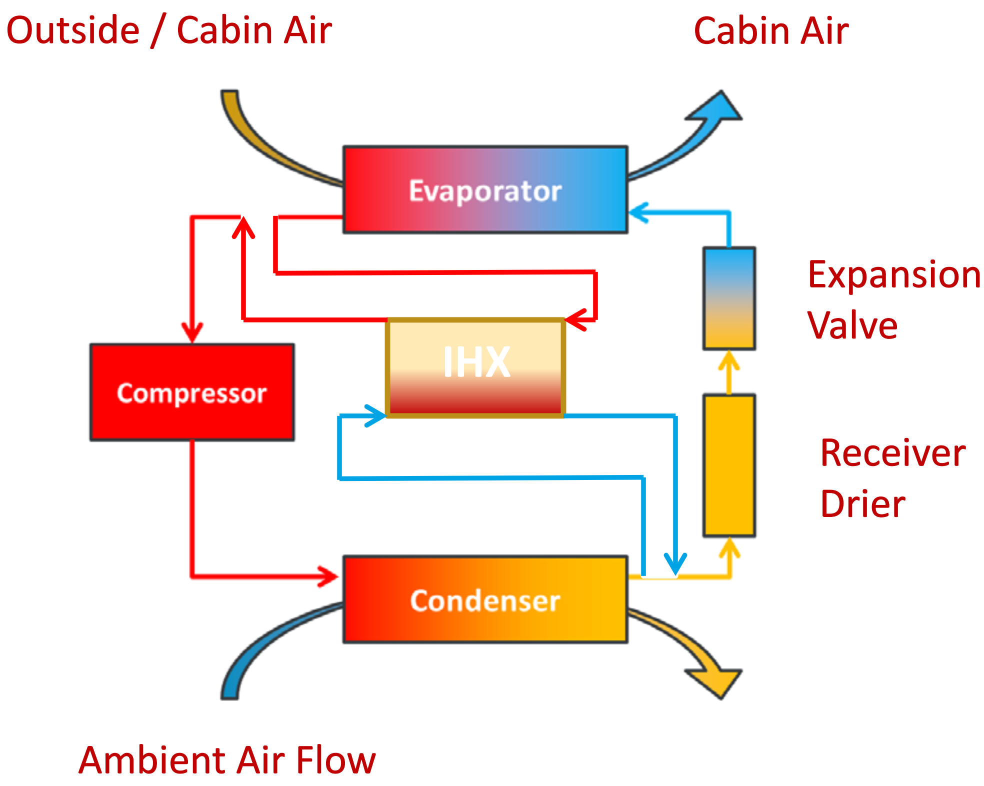
**Coolant-to-refrigerant heat-exchanger capacities**

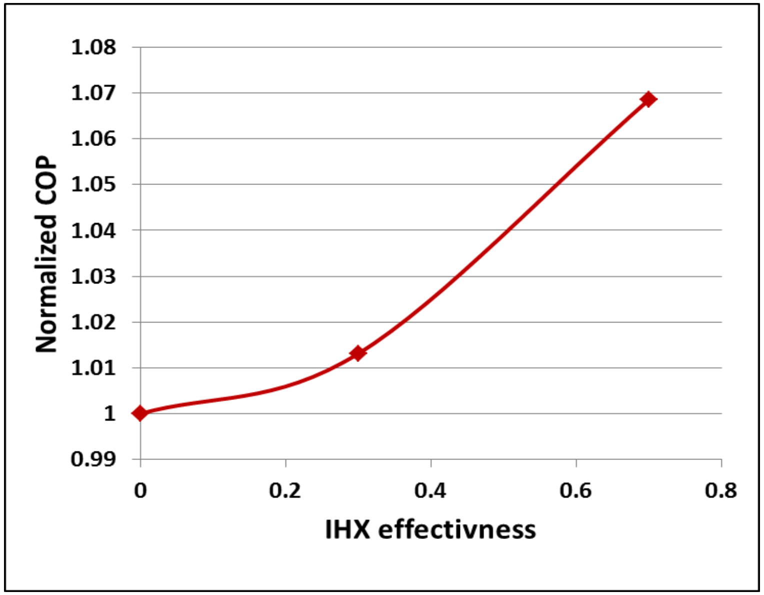


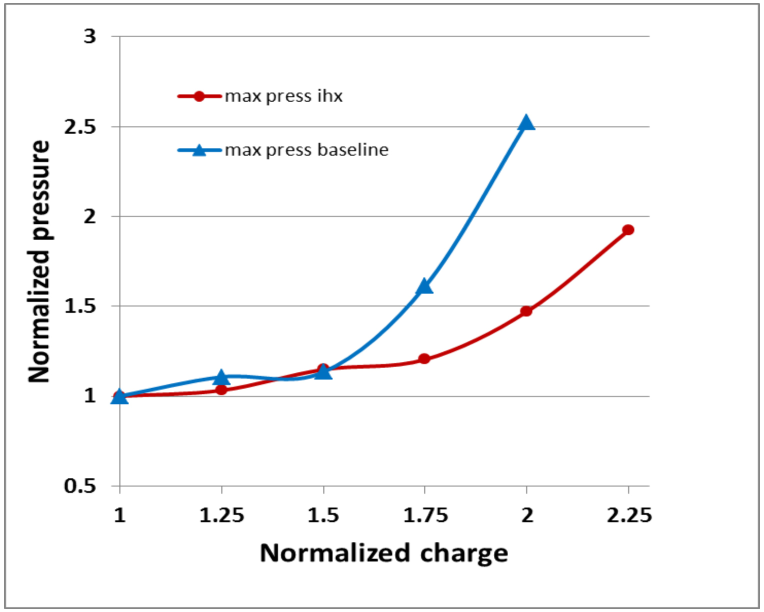
# Accomplishments: Added Internal Heat Exchanger

*Effectiveness based model*

6.5% increase in COP at IHX efficiency = 0.7 under example operating conditions



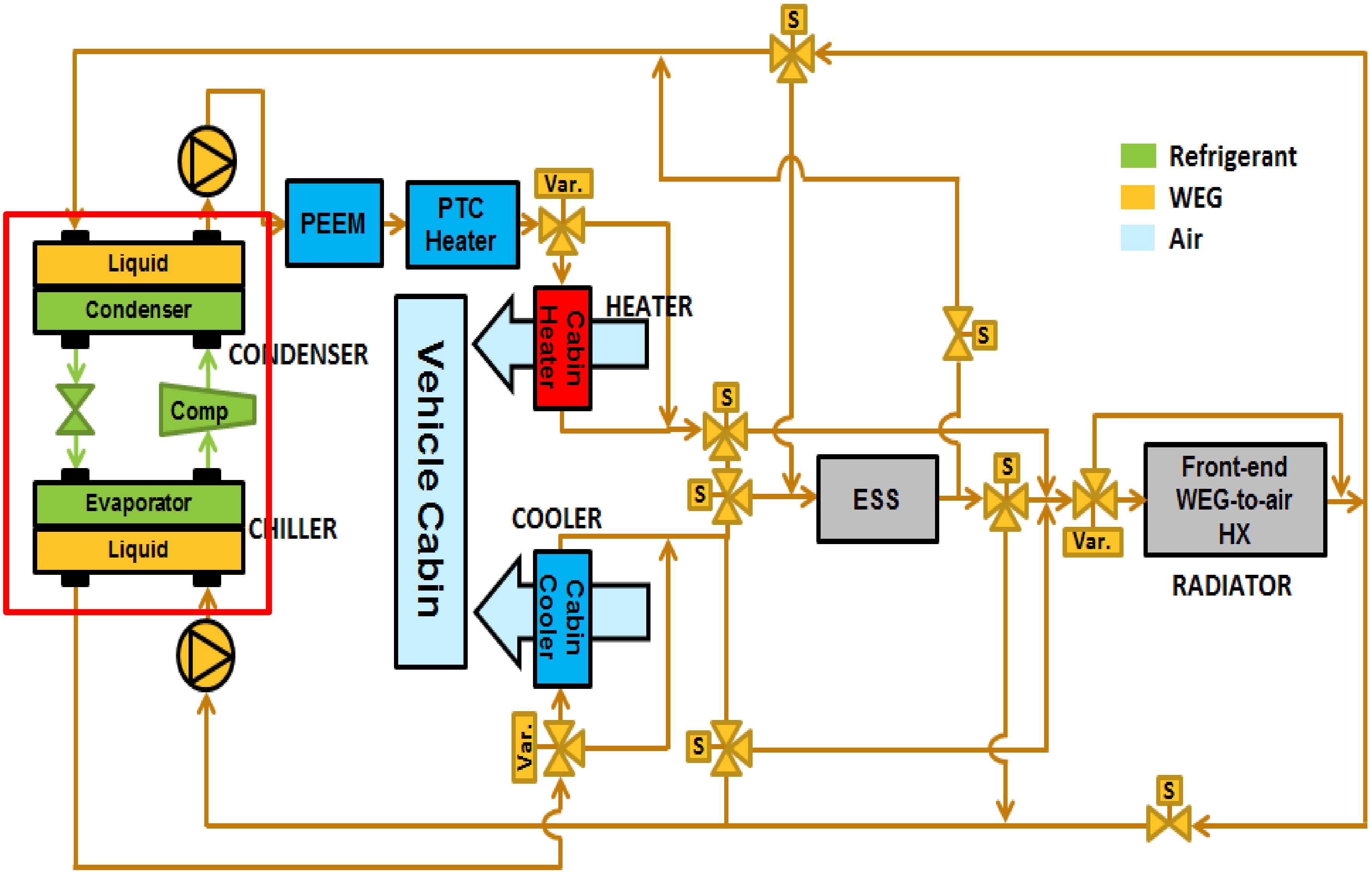




Sharp pressure increase indicates overcharging

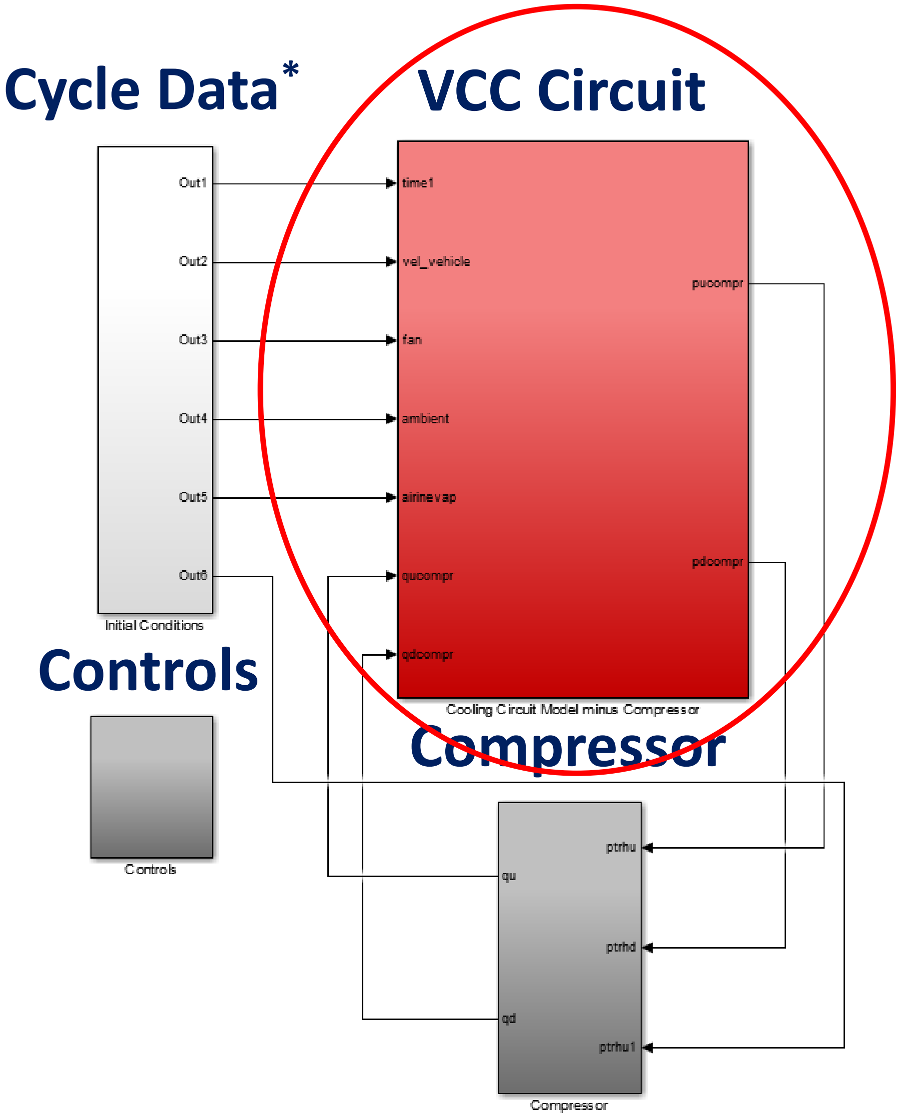
# Technical Accomplishments: Application

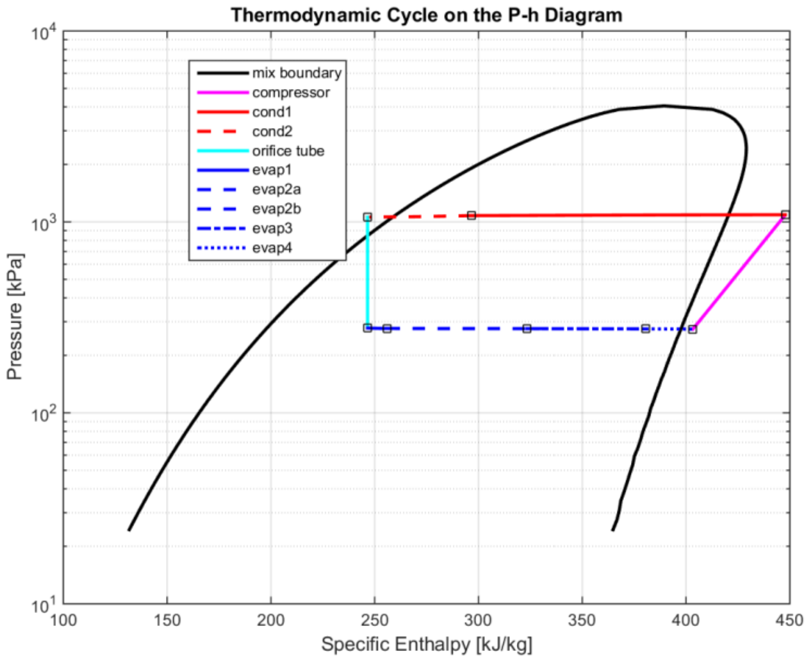
*Advanced Combined Fluid Loop*



# Top Level: A/C Model

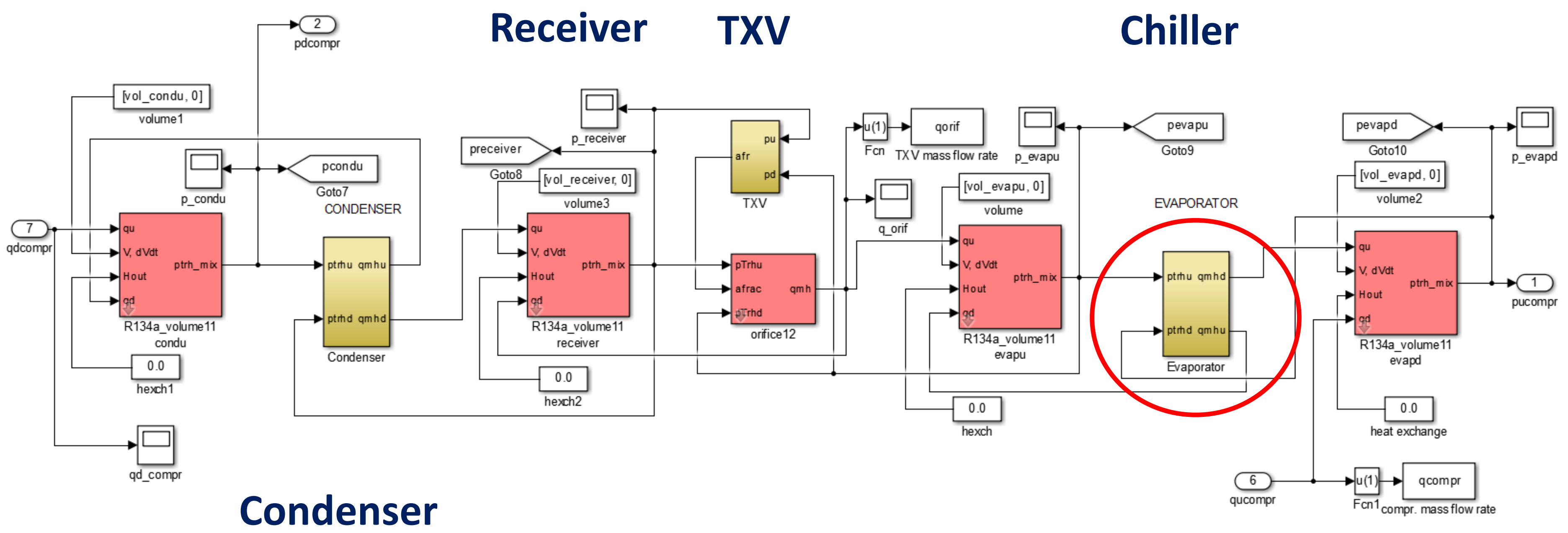
*Quasi-Transient model example*




**Cycle Data = Vehicle and ambient data*

# 2nd Level: Vapor Compression Cycle Circuit




- *Pink blocks are the bottom level*
- *Yellow blocks have blocks below them*

# Accomplishments: Chiller Model

*Using 1-D and 0-D blocks, various serial/parallel heat exchangers can be modeled*

**3 Pass Chiller**

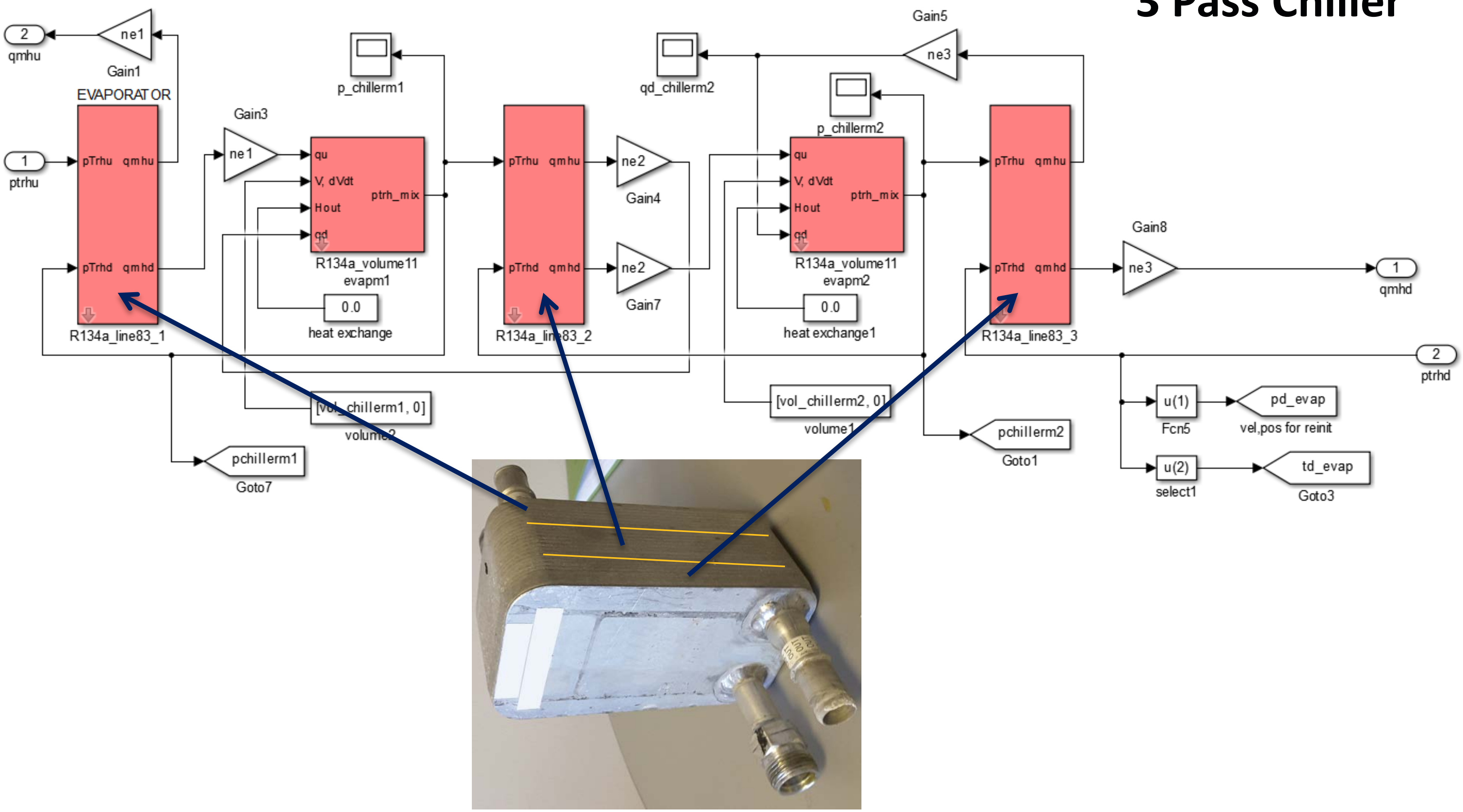
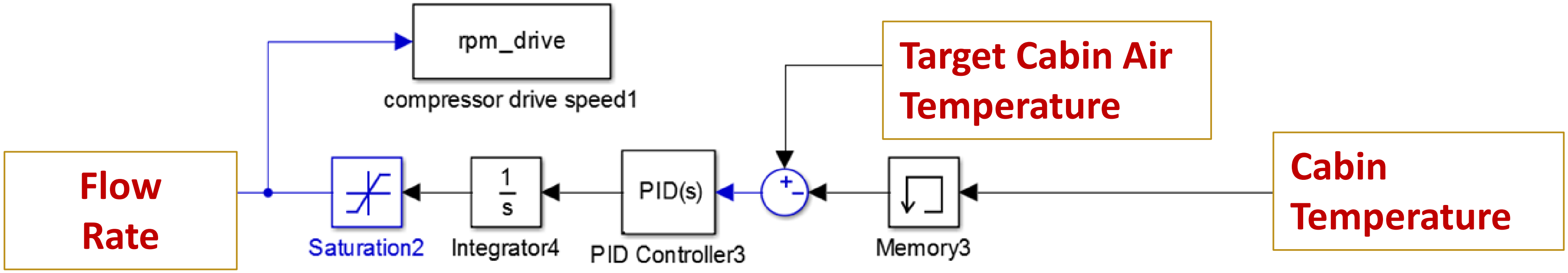


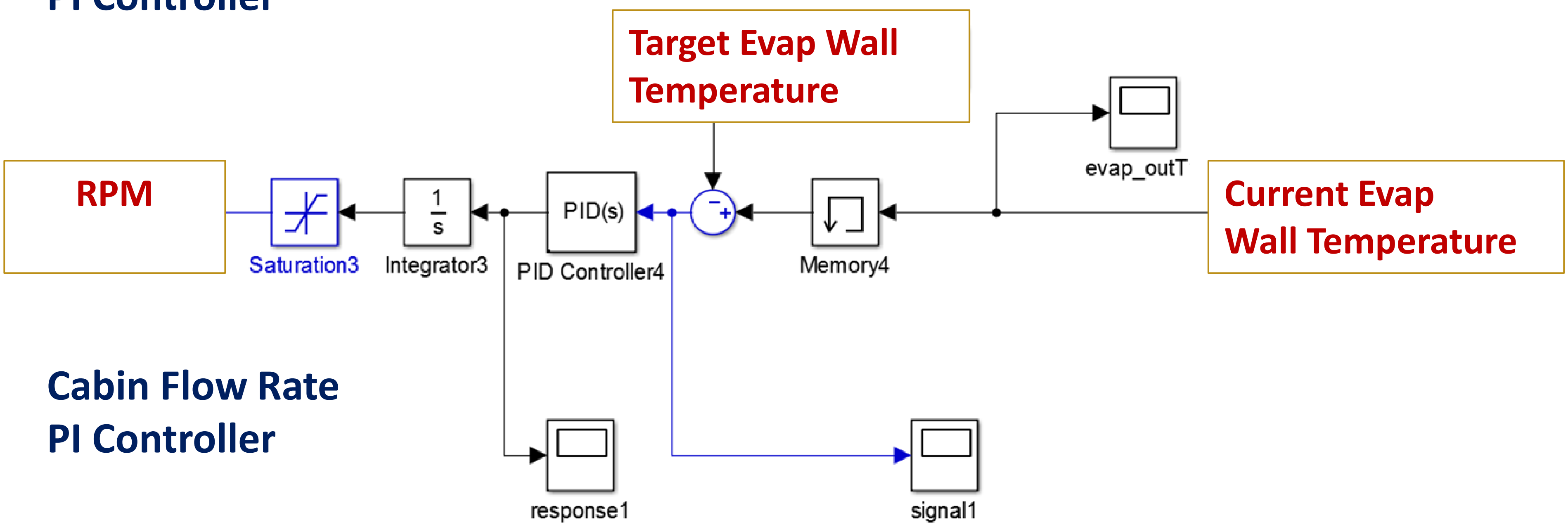

*Photo by: Gene Titov (NREL)*

# Accomplishments: System Control Model Implemented

*Added flexible controls of the system and modes*



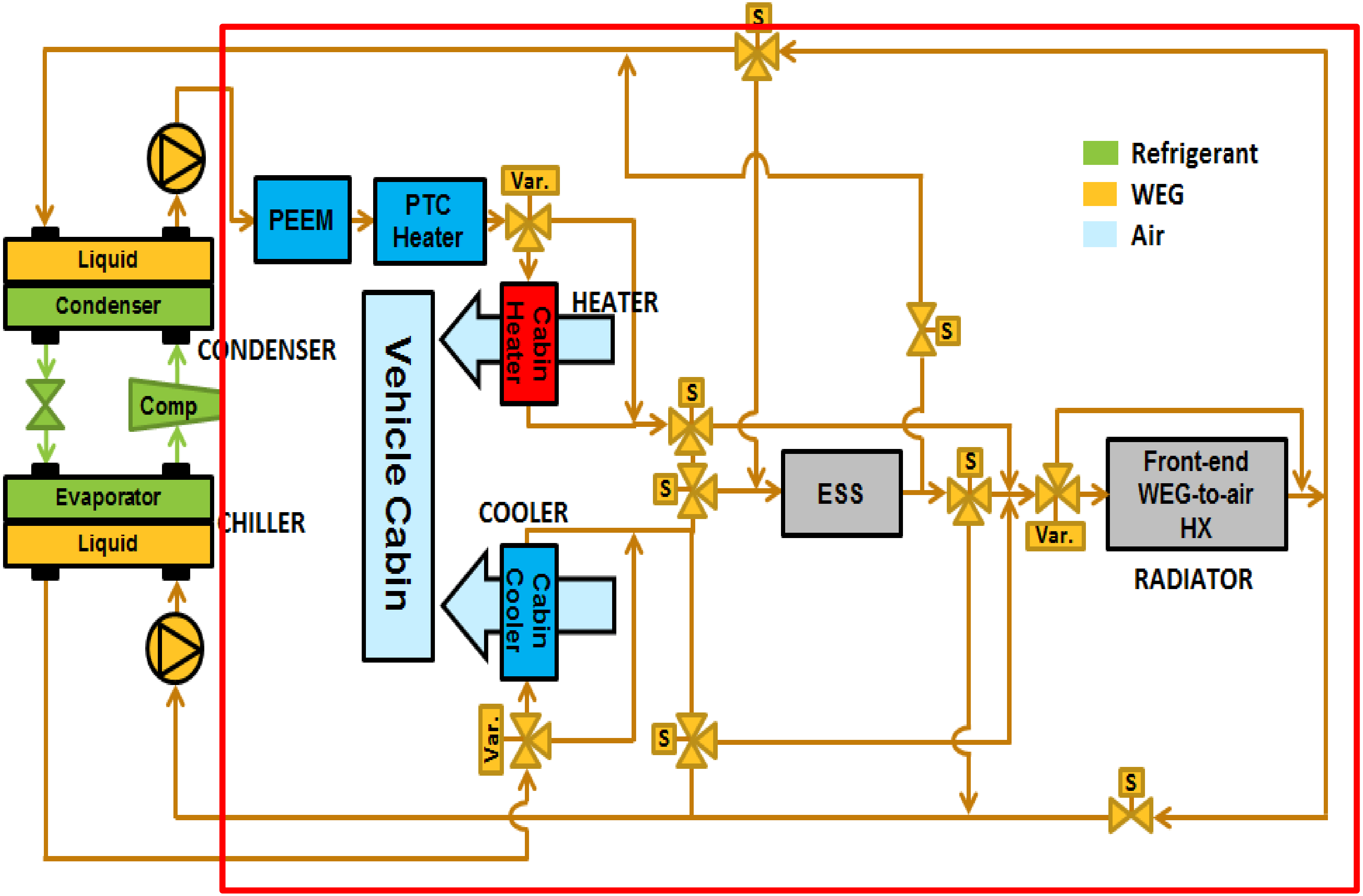

**Compressor speed PI Controller**




**Cabin Flow Rate PI Controller**

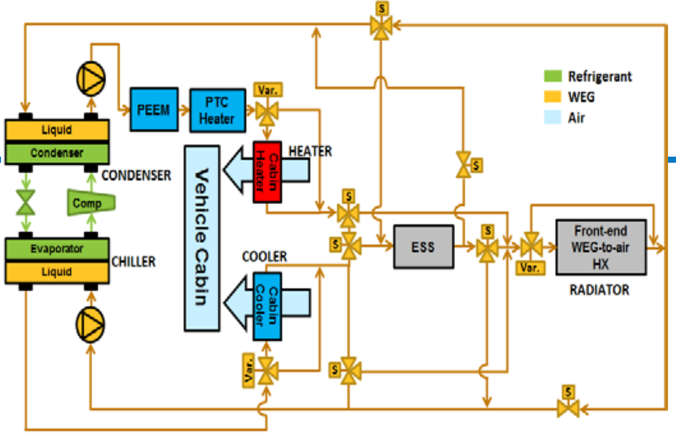
# Technical Accomplishments: Application

*Advanced Combined Fluid Loop*

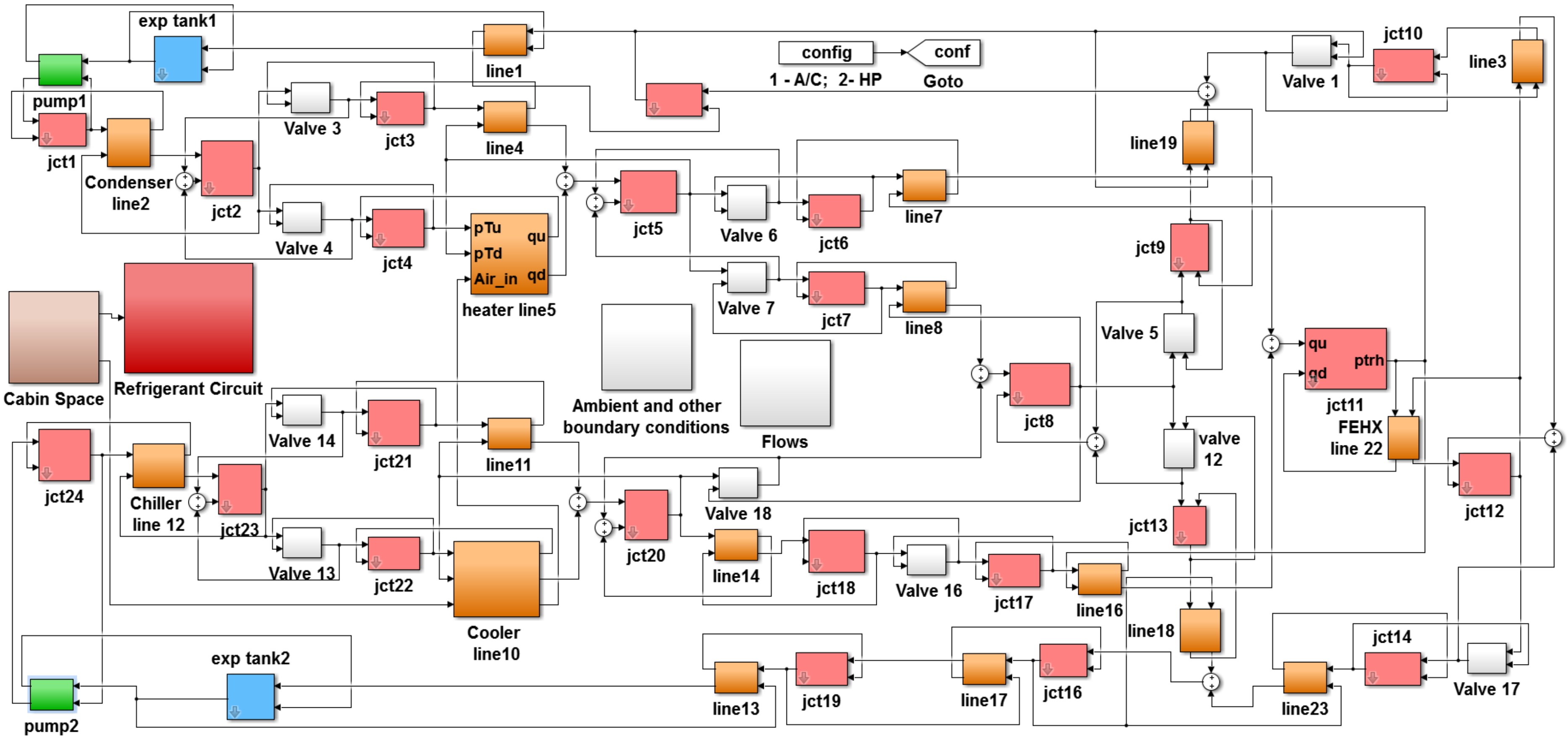


# Combined Loops A/C mode

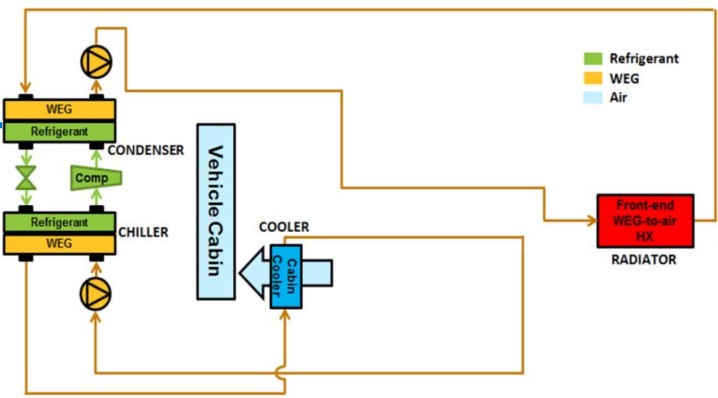
## *All Modes*



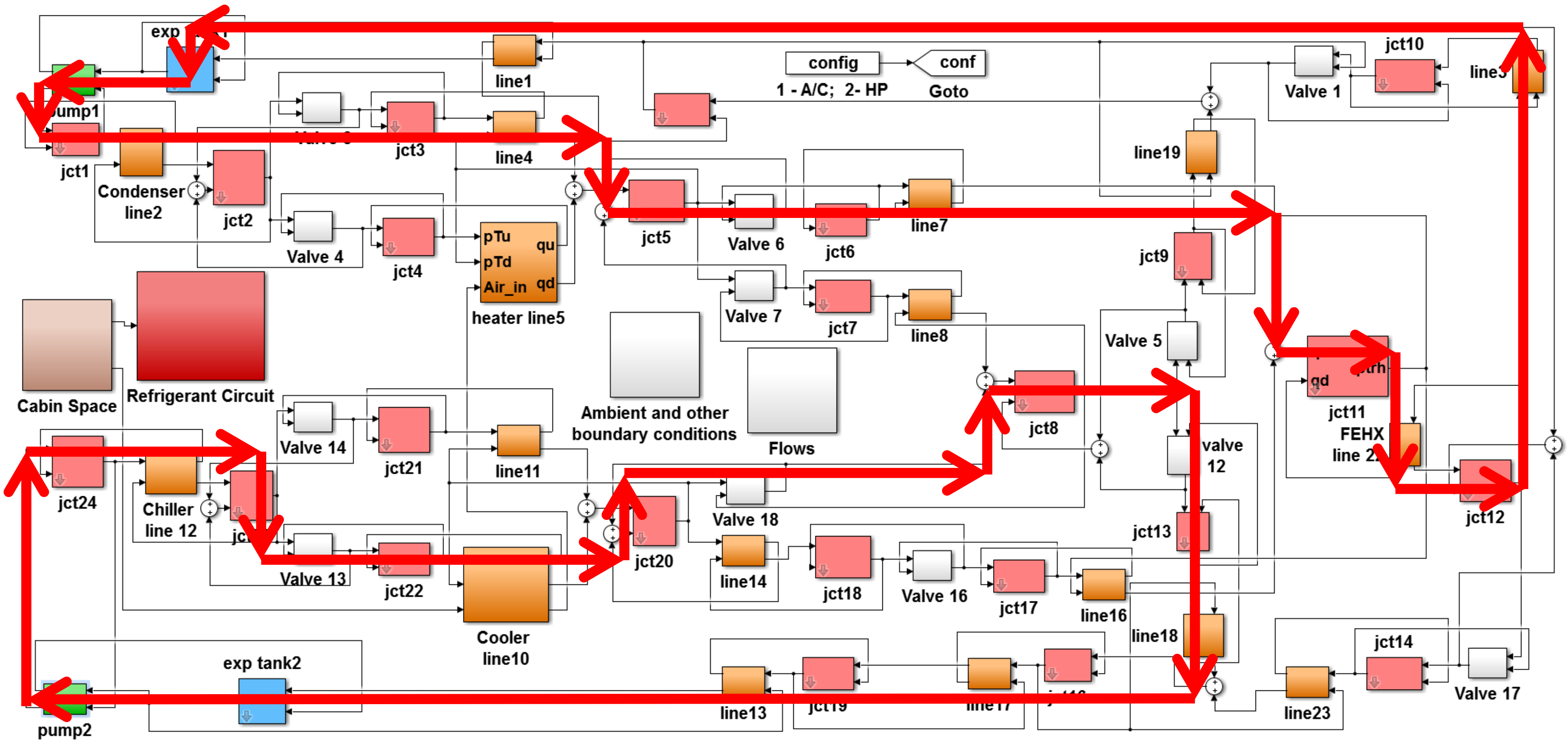

**The approach allows for a simple and natural manipulation with valves to define system modes**



# Combined Loops A/C mode
## *Active Cooling Mode*

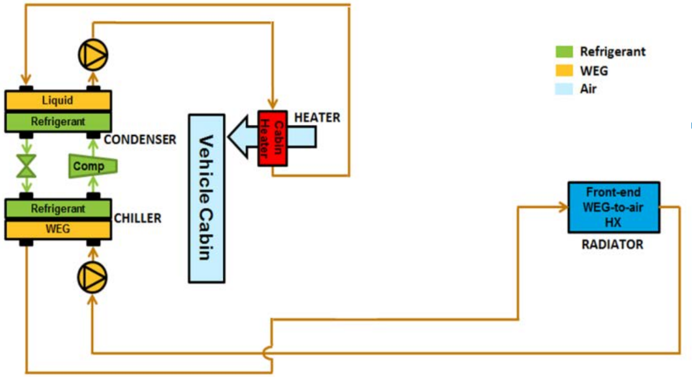



**By changing valve positions the model can be switched to active cooling mode**

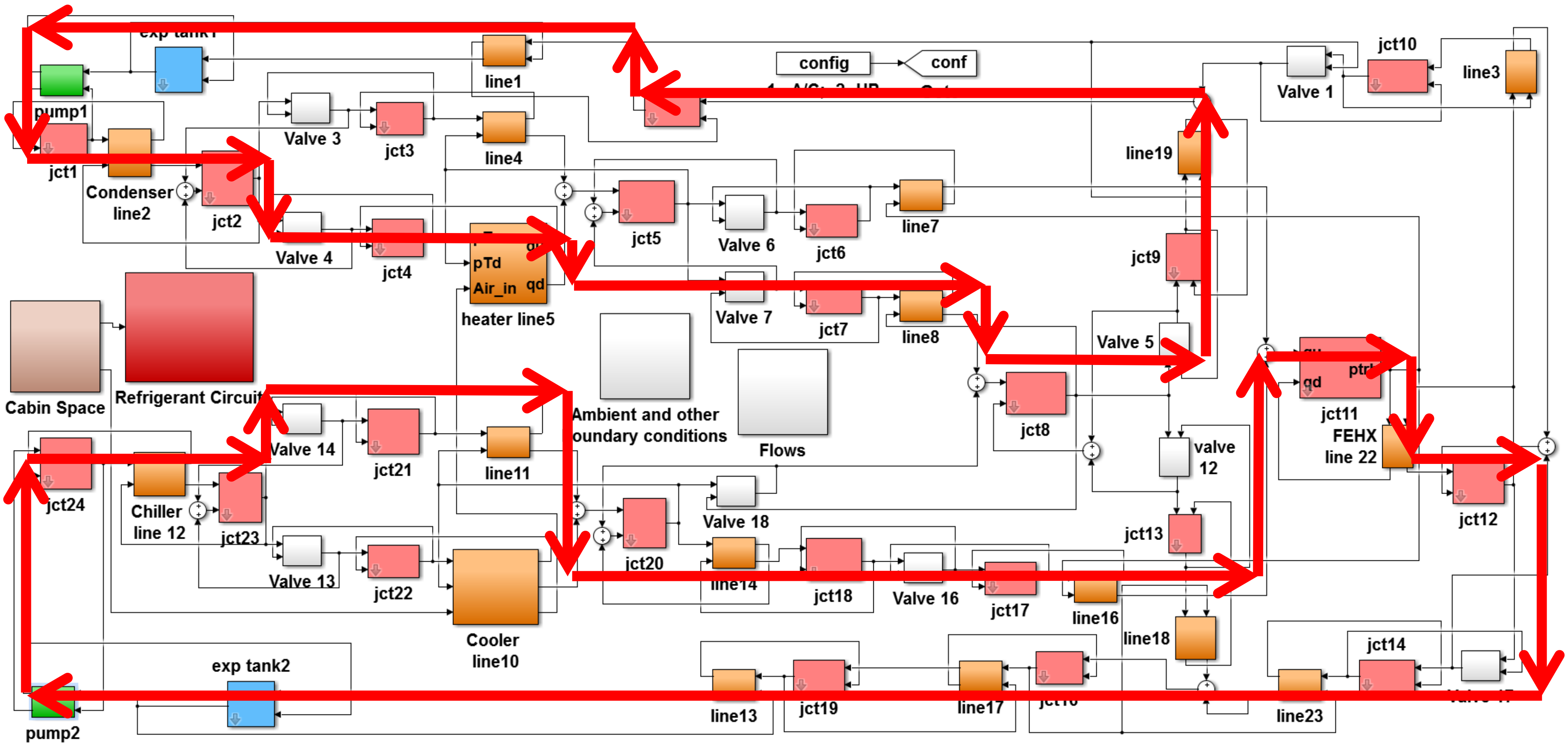


# Combined Loops Heat Pump Mode

## *Active Heating Mode*

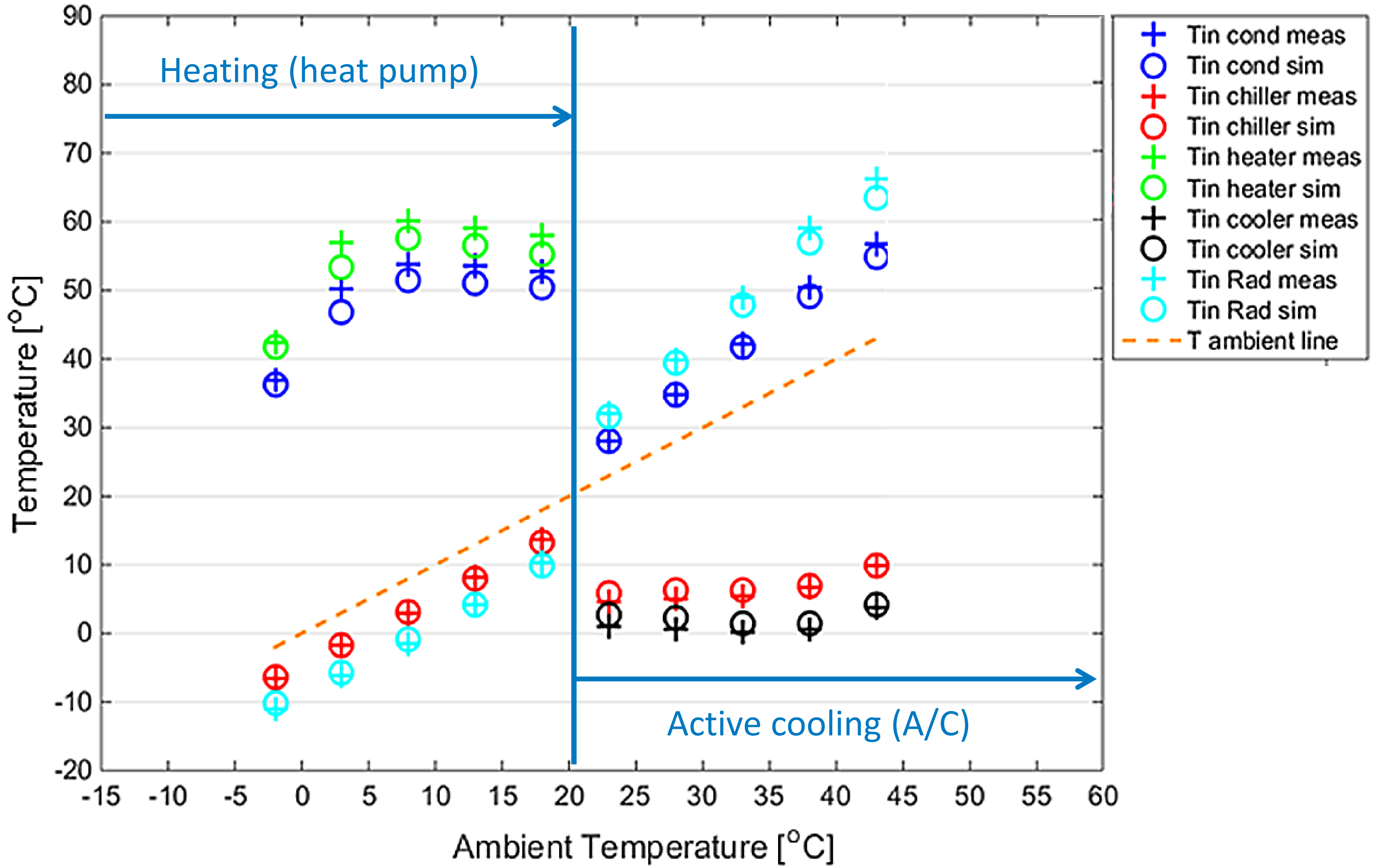



## A single model can be used to dynamically simulate various modes of operation



# Accomplishment: Simulated and Measured Coolant Temperatures

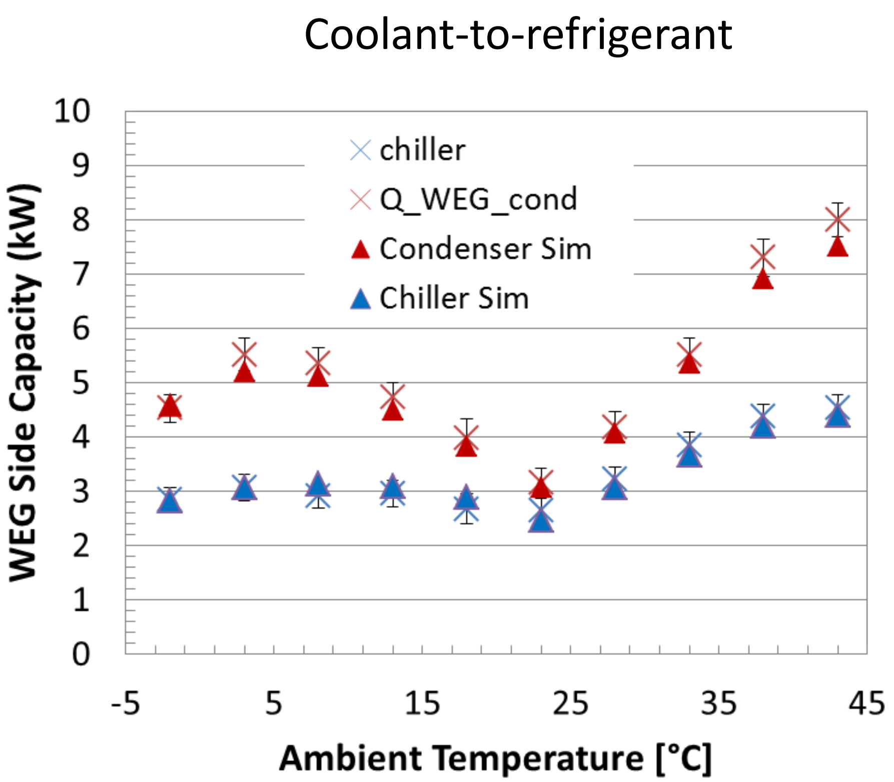
*Note mode switch of the front end heat exchanger (FEHX)*

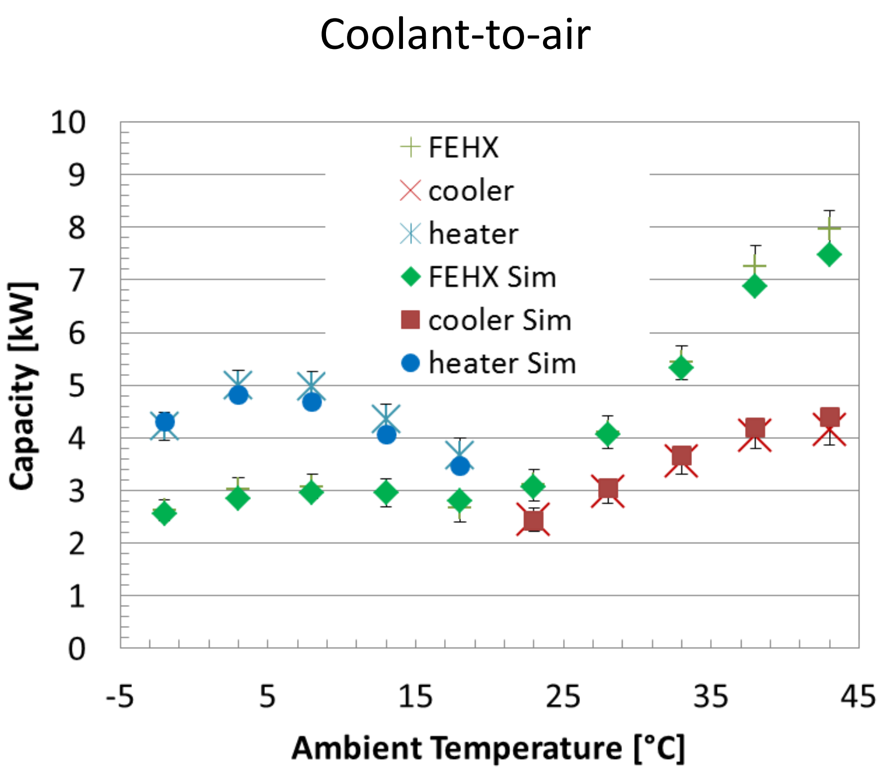



RMS=1.56%

# Accomplishments: Simulated and Measured Capacities (R134a)

*9 out of 10 points fall within 95% of uncertainty intervals*



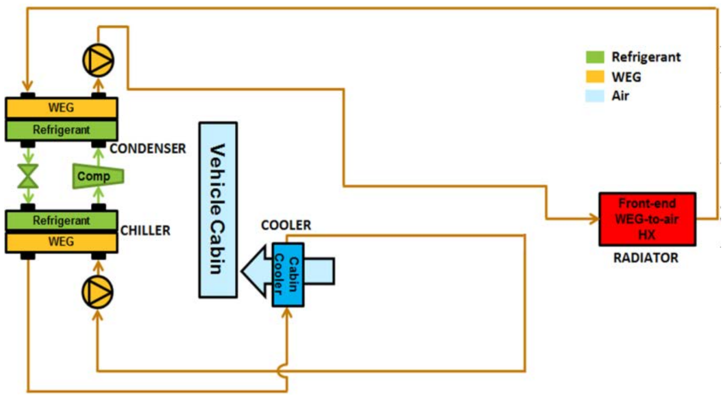




RMS=4.18%. Error bars show 95% confidence intervals for measurement uncertainties.

# Accomplishments: CFL Mode Control Test Case

*At 150 sec, valves change to switch from active cooling to heating mode*

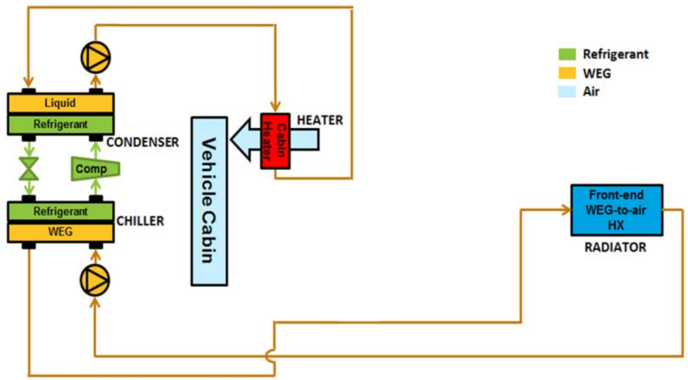
Active Cooling: -3kW

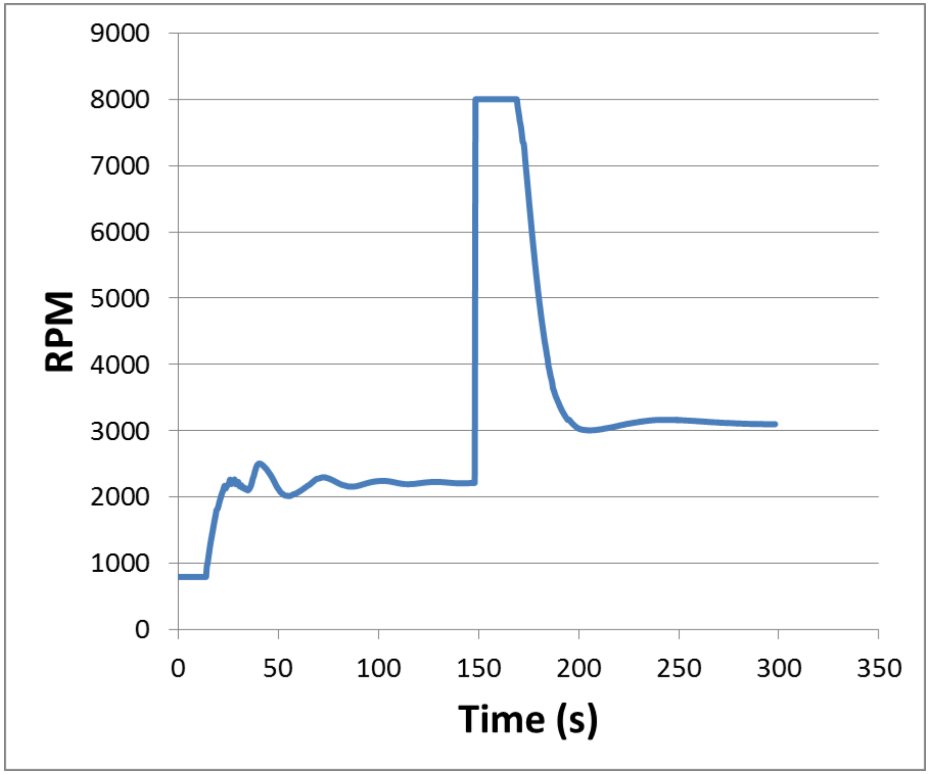



150 Sec

Switch valves

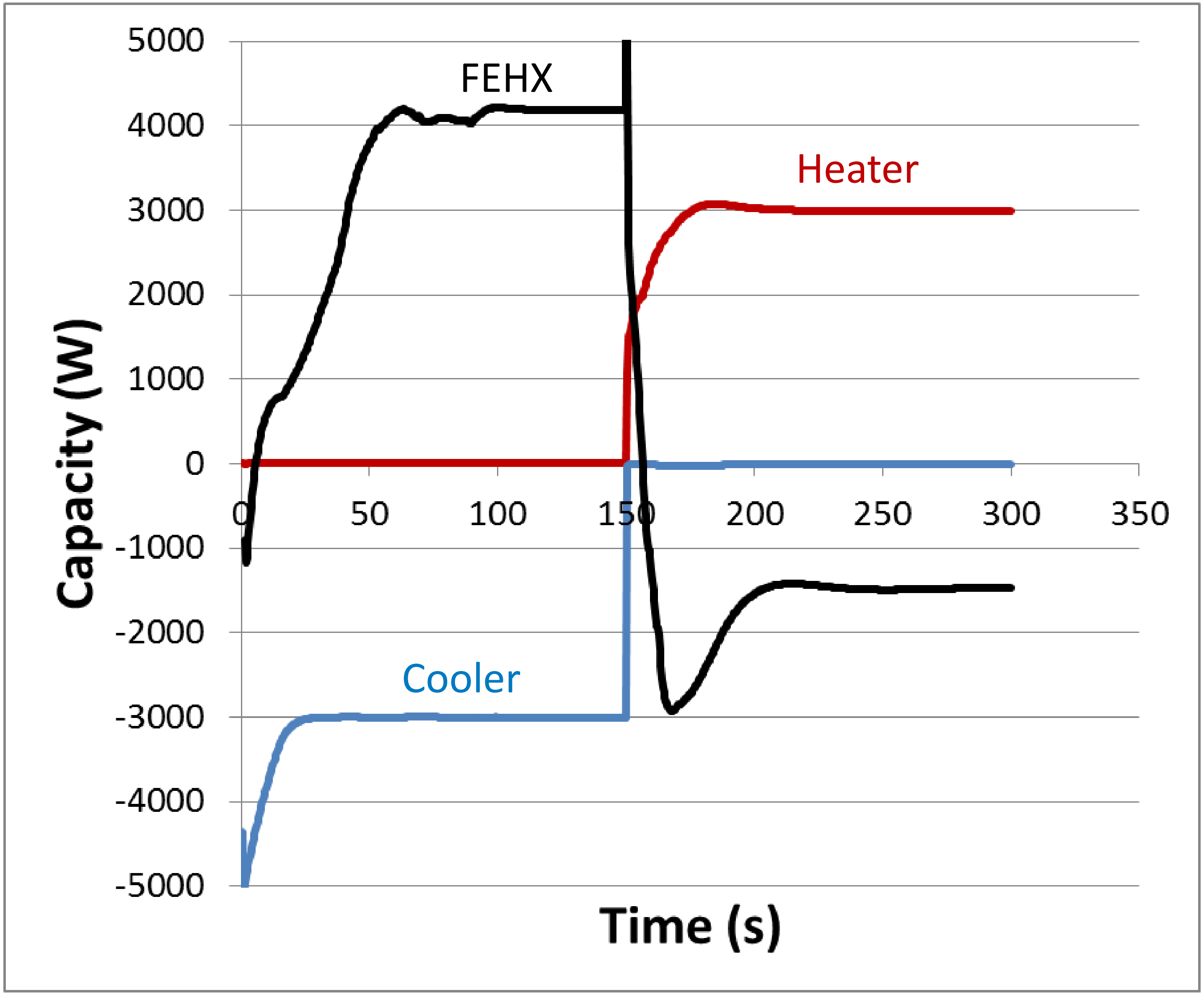
Active Heating: +3kW



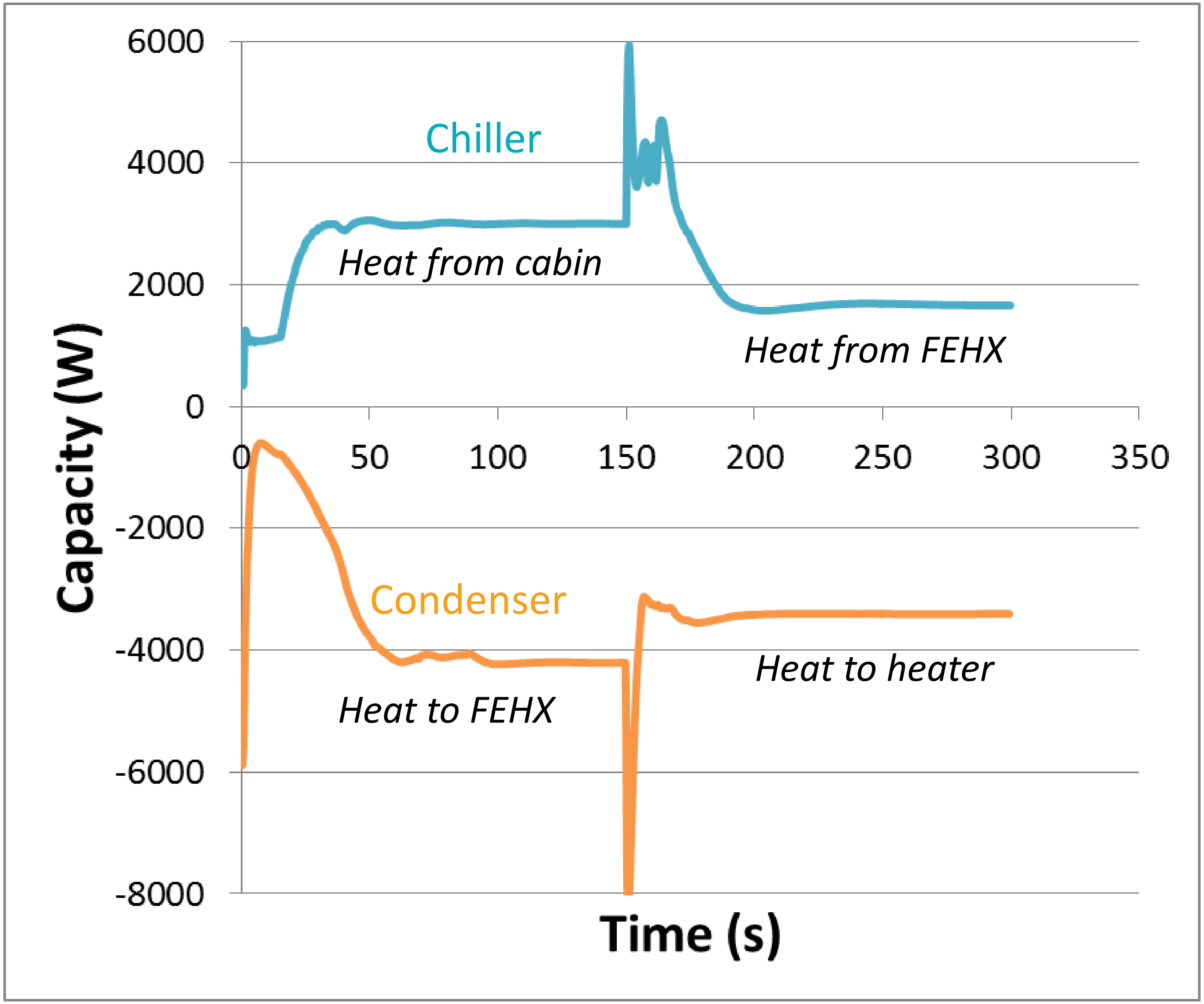
# Accomplishments: CFL Mode Control Test Case

*Coolant loops stabilize following a mode switch*



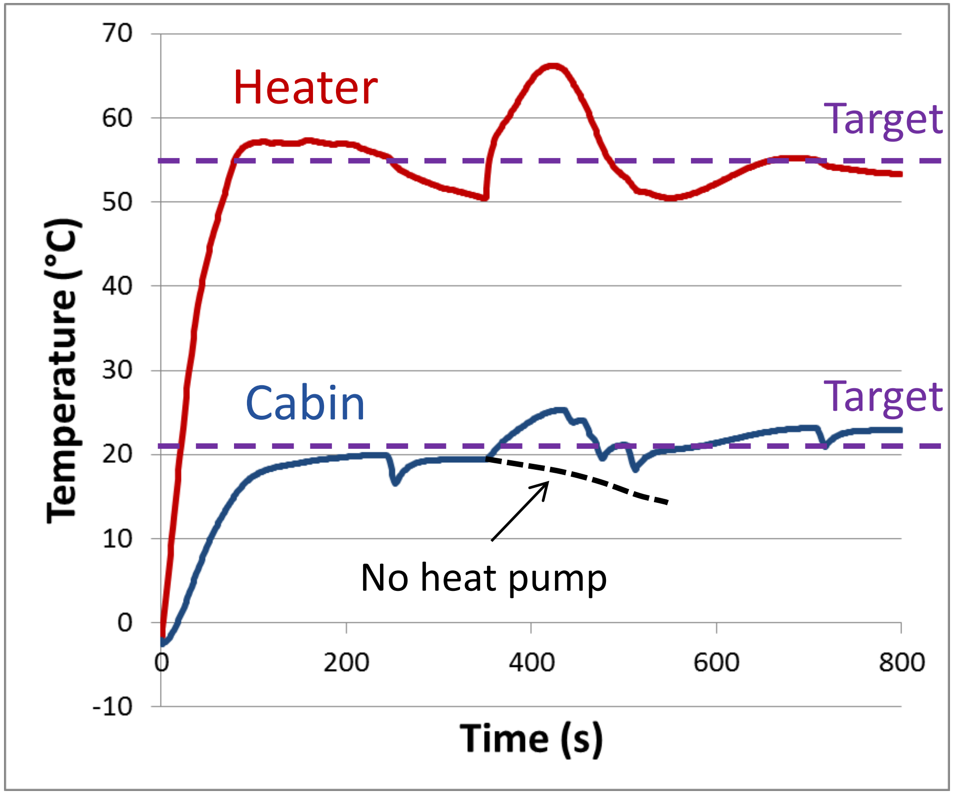
# Accomplishments: CFL Mode Control Test Case

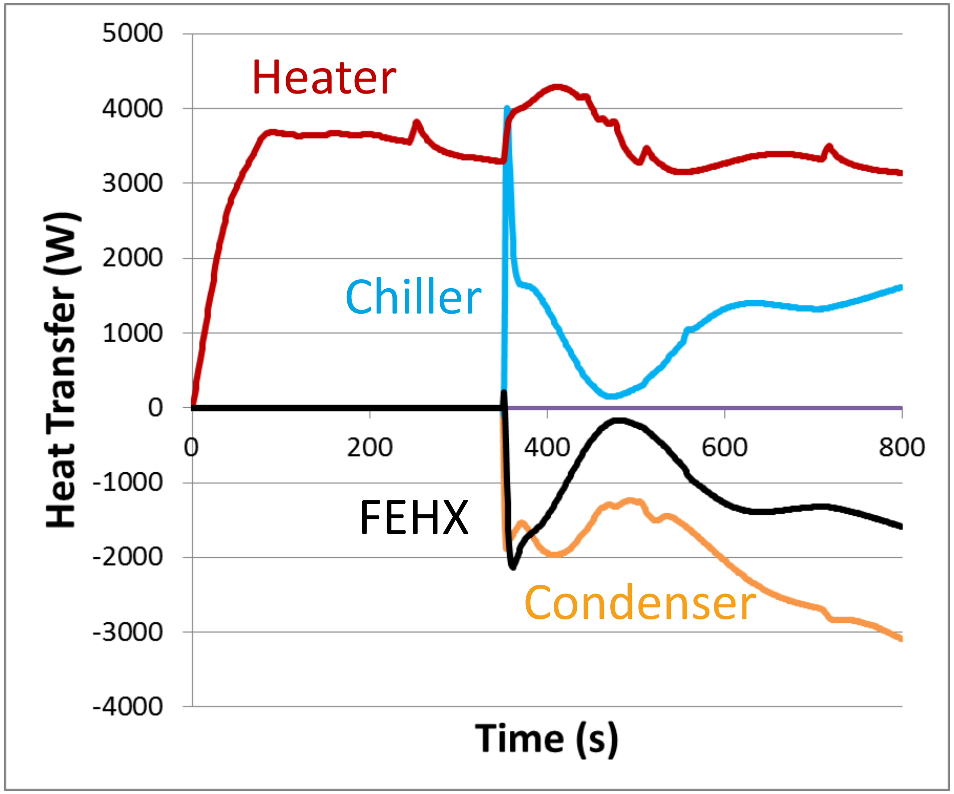
*Heat sources and sinks change as the system switches modes*



# Accomplishments: Control Algorithm Development Potential

*Select best mode for operating condition with declining waste heat*



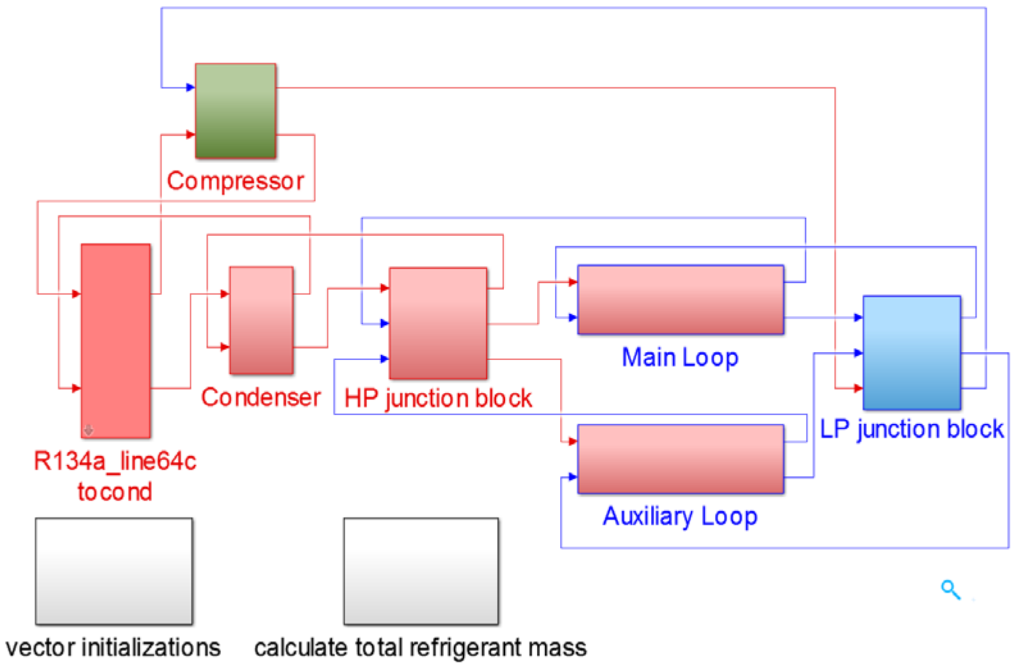

- **Ambient temperature at -2$^0$C**
- **PEEM heat assumed to linearly diminish from 5 kW to 0 kW**
- **After 350 seconds, model switches from free heating to heat pump mode to maintain the cabin temperature set point**

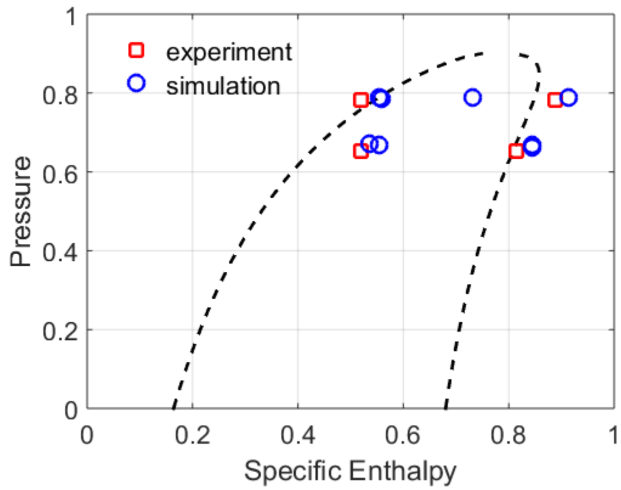
# Collaboration: Applications

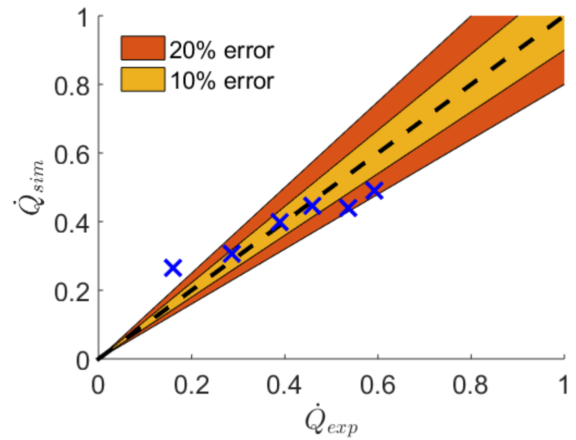
*Cummins and Oak Ridge National Lab*

- Provide high-fidelity simulations of proposed A/C architectures
- Understand the impacts on the vehicle load
- Provide support for future hardware-in-the-loop testing.

**CoolSim top-level model**



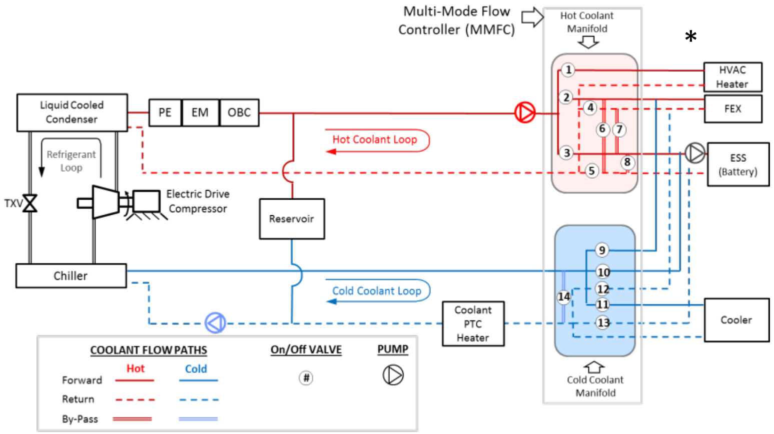



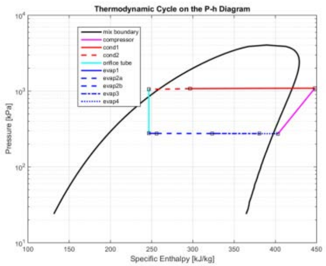



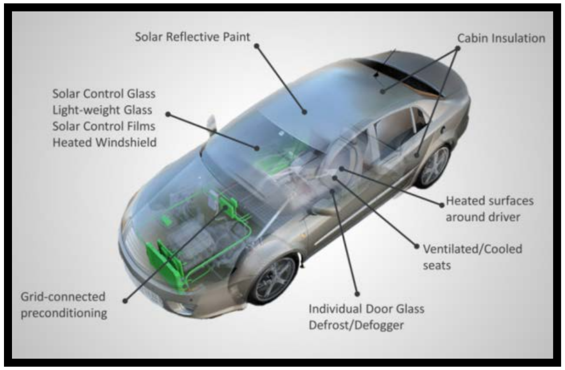
# Collaboration:

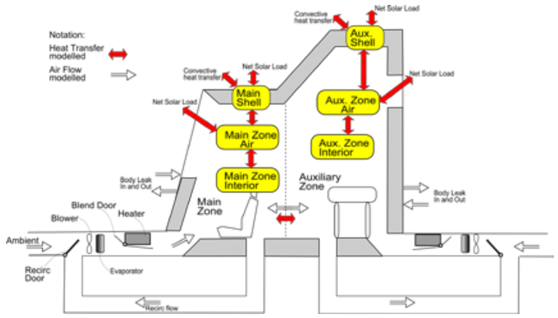
*Leveraging CoolSim on other projects*

- **MAHLE Behr – UTEMPRA FOA**
  - More operating modes than NREL CFL
  - Modeling and testing
- **NREL FOA with Huyndai & Hanon**
  - A/C system impact on vehicle
  - Coupling with CoolCalc analysis
- **Hannon-led FOA**
  - Thermal storage concepts
  - Advanced heat pump modeling
- **Daimler Trucks**
  - Supported SuperTruck
  - Assessing advanced HVAC concepts
- **Other collaborations**
  - ANL
  - In discussions with others




*Chowdhury, S., Zima, M. "Unitary Thermal Energy Management for Propulsion Range Augmentation (UTEMPRA)". DOE AMR 2015. Project ID VSS157

# Responses to FY15 AMR Reviewer Comments

**Comment:** The reviewer would like to see this program leverage the Cool Cab HD sleeper program and understand if there are other cooling philosophies that can be applied such as zoning, etc.

**Response:** NREL's detailed HVAC and thermal system model, CoolSim, is a critical part of the CoolCab HD sleeper national-level analysis. CoolSim provides the link between cab thermal loads and mechanical/electrical loads on the vehicle. These system details drive the coefficient of performance of the system, which is important to determining the vehicle load and resulting fuel use. As the reviewer suggests, these tools can be used together to understand other advanced cooling philosophies such as zoning, etc.

---

**Comment:** The reviewer asked if there is a commitment by DOE to maintain compatibility of these models and enough support to ensure that this capability will function long enough to provide significant return on investment (e.g., three to five years).

**Response:** We agree with the reviewer that providing support for the tool maintenance, improvement, and application over a period of time will strengthen this capability and add more value and increase return on investment. We believe this tool is adding significant value to DOE's program and our industry partners.

---

**Comment:** The reviewer indicated that the accomplishments appear in line with the program, although the reviewer would like to see the details behind the vehicle cabin model and whether this can be further optimized.

**Response:** CoolSim currently uses a fairly simple 1 or 2 air node model. Basic thermal mass, conduction, and convection are accounted for. Solar loads incident on the vehicle are an input. This model works well for basic simulation needs. However, NREL plans to develop a more detailed model for CoolSim, but these efforts have been delayed due to funding limitations.

# Proposed Future Work and Remaining Challenges

- **Continue model development**
  - Add oil loop modeling capability to expand into new areas of application
  - Integrate with CoolCalc for advanced cabin modeling
  - Add new thermal components (such as a detailed battery model)
  - Co-simulation with vehicle level models for advanced system design
- **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
  - Evaluate control strategies that optimize efficiency for advanced loop concepts
- **Improve Autonomie co-simulation**
- **Leverage model results for the VTCab project impact estimation**

# Summary

- Improved single-phase model to allow dynamic valve switching and flow direction reversal
  - Useful for simulations of complex coupled refrigerant and liquid coolant-based thermal sub-systems where modes of operation will change
  - Validated for steady-state CFL system operating conditions; 9 out of 10 simulated points are within the 95% measurement uncertainty band for capacity
- Demonstrated dynamic control, which will be used for advanced system design and impact quantification
- Added 1234yf refrigerant and internal heat exchanger model
- Collaborated with Cummins and ORNL on A/C system model
- Increased industry partnerships and leveraged developed tools for multiple advanced system projects

# Contacts and Acknowledgements

## Contacts


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


**A generic A/C system model is available at:**

http://www.nrel.gov/transportation/coolsim_disclaimer.html?accept

## Acknowledgements

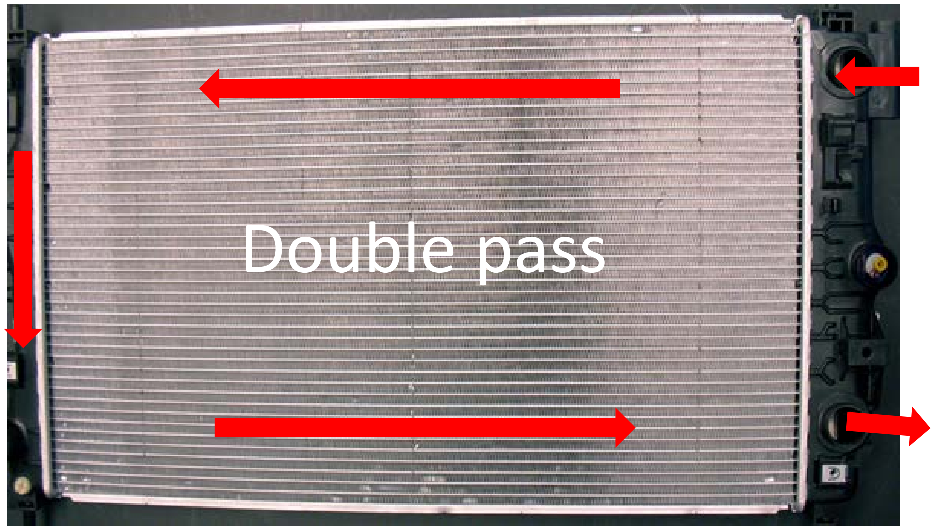

- The authors would like to thank David Anderson and Lee Slezak, Vehicle Systems Technology Managers for the U.S. Department of Energy's Vehicle Technologies Office for sponsoring this work
- The authors acknowledge contributions from
  - MAHLE Behr
  - Cummins
  - ORNL
  - Hanon

# Technical Back-Up Slides

# Technical Accomplishments:

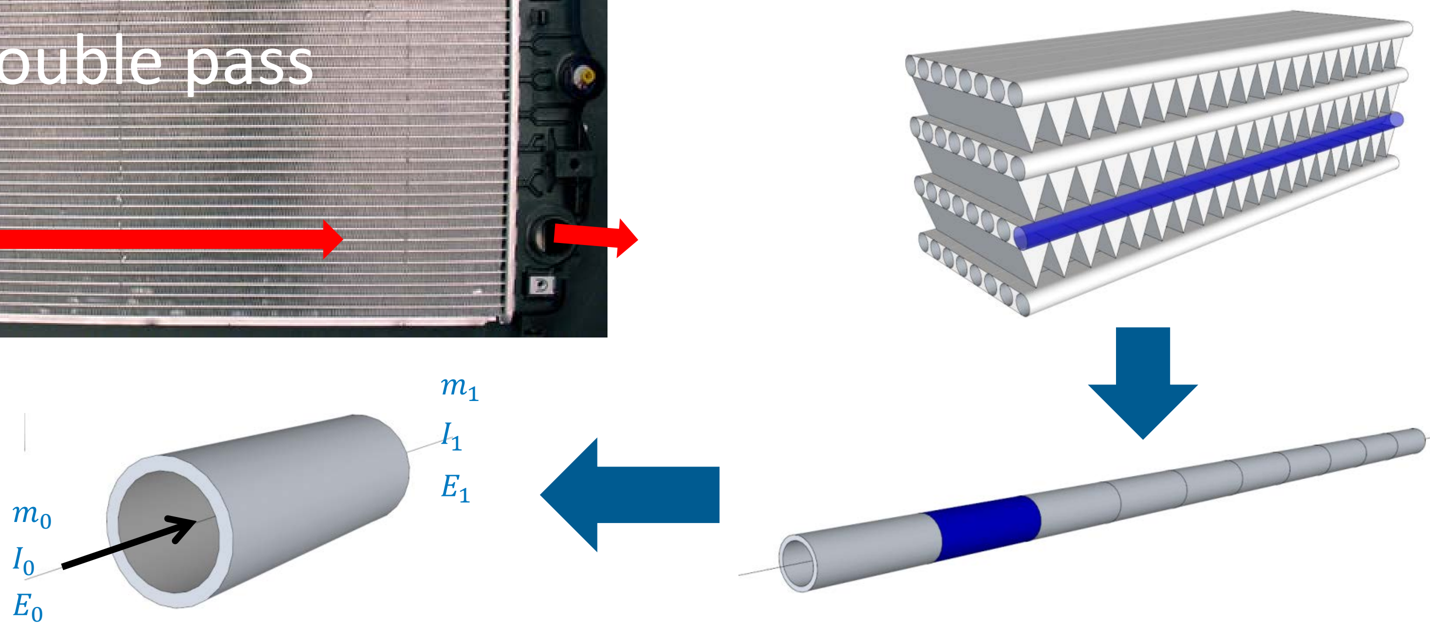
*Distributed parameter model*

### 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.

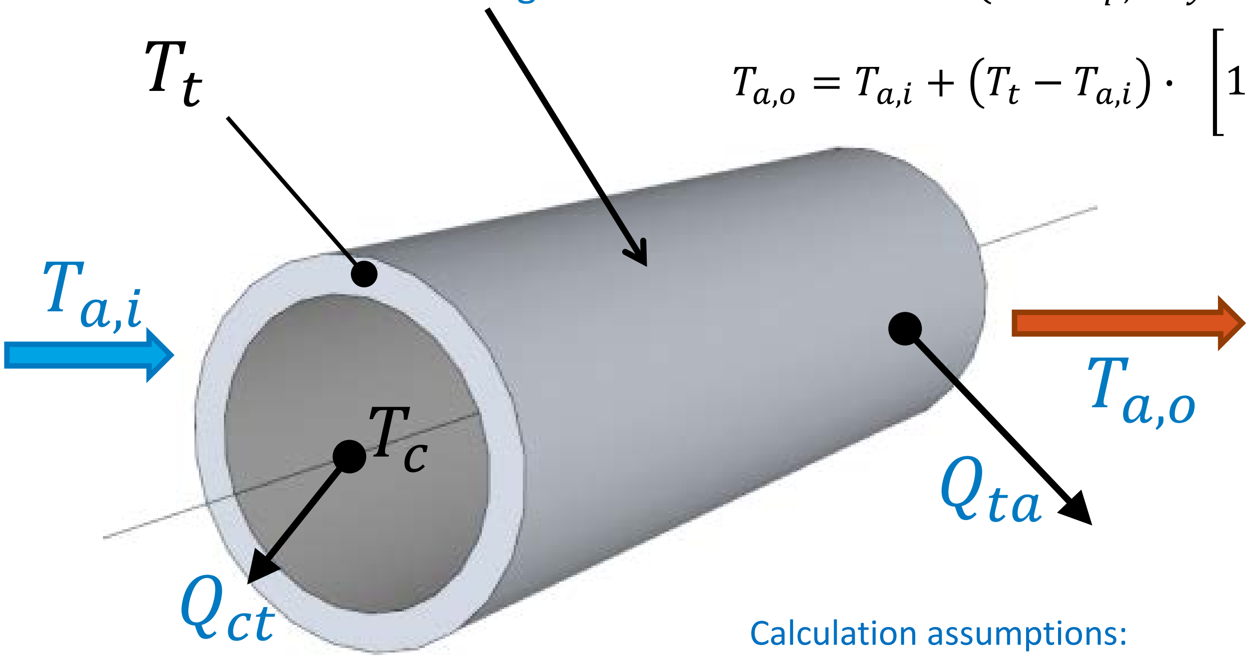
# Coolant Circuit Simulation

*Calculating heat transfer rates in line blocks*

## Methods used for distributed parameter component models

$$Q_{ta} = (\dot{m}_a \cdot C_{p,adry} + \dot{m}_w \cdot C_{p,aw}) \cdot (T_{a,o} - T_{a,i})$$

$$T_{a,o} = T_{a,i} + (T_t - T_{a,i}) \cdot \left[1 - \exp\left(\frac{-\bar{h}_{ta}\, A}{\dot{m}_a \cdot (C_{p,adry} + \omega\, C_{p,w})}\right)\right]$$




(Effectiveness-NTU (number of transfer units) method applied for each pipe segment for the air flow)

$$Q_{ct} = \bar{h}_{ct}\, A\, (T_c - T_t)$$

$$(\overline{Nu}_D \equiv)\, \frac{\bar{h}_{ct} D}{k} = 0.023 {Re_D}^{0.8} Pr^n$$

Calculation assumptions:

- $\bar{h}_{ct}$ obtained from Dittus-Boelter equation
- $\bar{h}_{ta}$ from correlations for louvered fin compact heat exchangers[1]
- Fin efficiency and wall thermal mass effects incorporated
- Temperature is constant across tube wall
- System accounts for possible water condensation.

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.