NREL
NATIONAL RENEWABLE ENERGY LABORATORY

A/C Model Development and Validation



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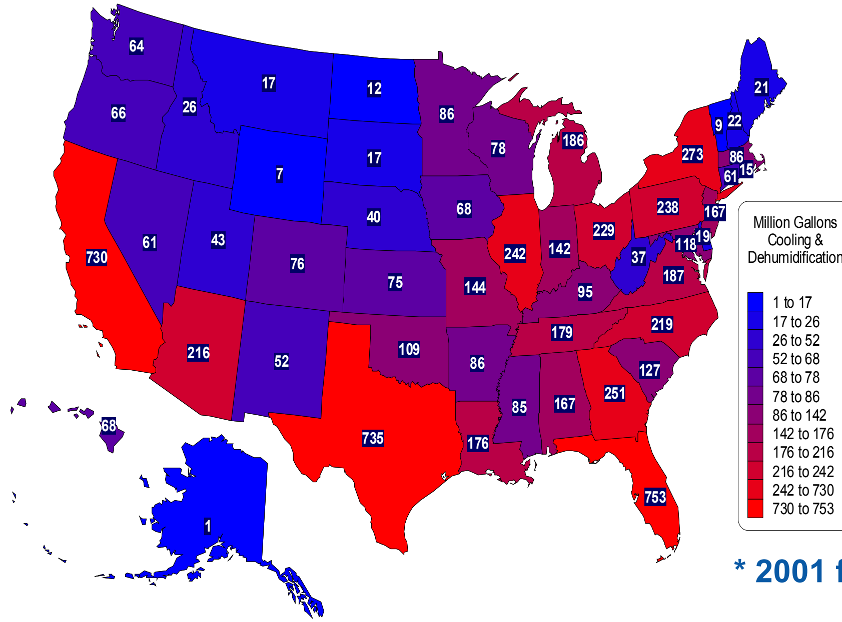
Project ID VSS045

Background

- **When operated, the A/C system is the largest auxiliary load**
- **A/C loads account for more than 5% of the fuel used annually for light-duty vehicles (LDVs) in the United States***
- **A/C load can have a significant impact on electric vehicle (EV), plug-in hybrid electric vehicle, and hybrid electric vehicle performance**
  - Mitsubishi reports that the range of the i-MiEV can be reduced by as much as 50% on the Japan 10–15 cycle when the A/C is operating**
  - Hybrid vehicles have 22% lower fuel economy with the A/C on***
- **Increased cooling demands by an EV may impact the A/C system**
- **Contributes to heavy-duty vehicle idle and down-the-road fuel use**



*** 2001 fuel use data**

* Rugh et al., 2004, *Earth Technologies Forum/Mobile Air Conditioning Summit*
** Umezu et al., 2010, *SAE Automotive Refrigerant & System Efficiency Symposium*
*** INEL, *Vehicle Technologies Program 2007 annual report,* p145.

Overview

Timeline

Project Start Date: FY11

Project End Date: FY13

Percent Complete: 50%

Budget

Total Project Funding:

DOE Share: $600K

Contractor Share: $0k

Funding Received in FY11: $300K

Funding for FY12: $300K

Barriers

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

Partners

- Interactions / Collaborations
  - Argonne National Laboratory (ANL)
  - Visteon
  - Daimler Trucks
- Project lead: NREL

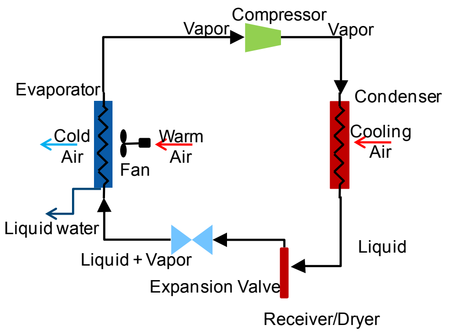
Relevance/Objectives

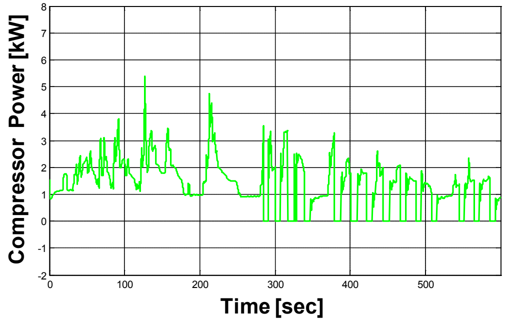
- Overall Objectives
  - The objective of this project is to develop analysis tools to assess the impact of technologies that reduce the thermal load, improve the climate control efficiency, and reduce vehicle fuel consumption
  - Develop an open source, accurate, and transient air conditioning model using the Matlab®/Simulink® environment for co-simulation with Autonomie®
  - Connect climate control, cabin thermal, and vehicle-level models to assess the impacts of advanced thermal management technologies on fuel use and range

- FY11/12 Objectives
  - Develop an LDV A/C model that simulates A/C performance and generates mechanical or electrical loads
  - Validate A/C components and system performance with bench data
  - Demonstrate co-simulation of A/C system with Autonomie®
  - Release A/C model plug-in for Autonomie®

Milestones

Date	Milestone or Go/No-Go Decision
04/31/2010	Demonstrated CoolCalc A/C model framework
07/31/2011	Demonstrated Autonomie® integration
08/31/2011	DOE milestone report on A/C model status and preliminary results
04/01/2012	Delivered stand-alone model to Visteon
05/01/2012	Deliver electric A/C model to ANL
06/01/2012	Complete initial validation
09/30/2012	• Complete summary report and do first release of the A/C model • SAE World Congress paper draft

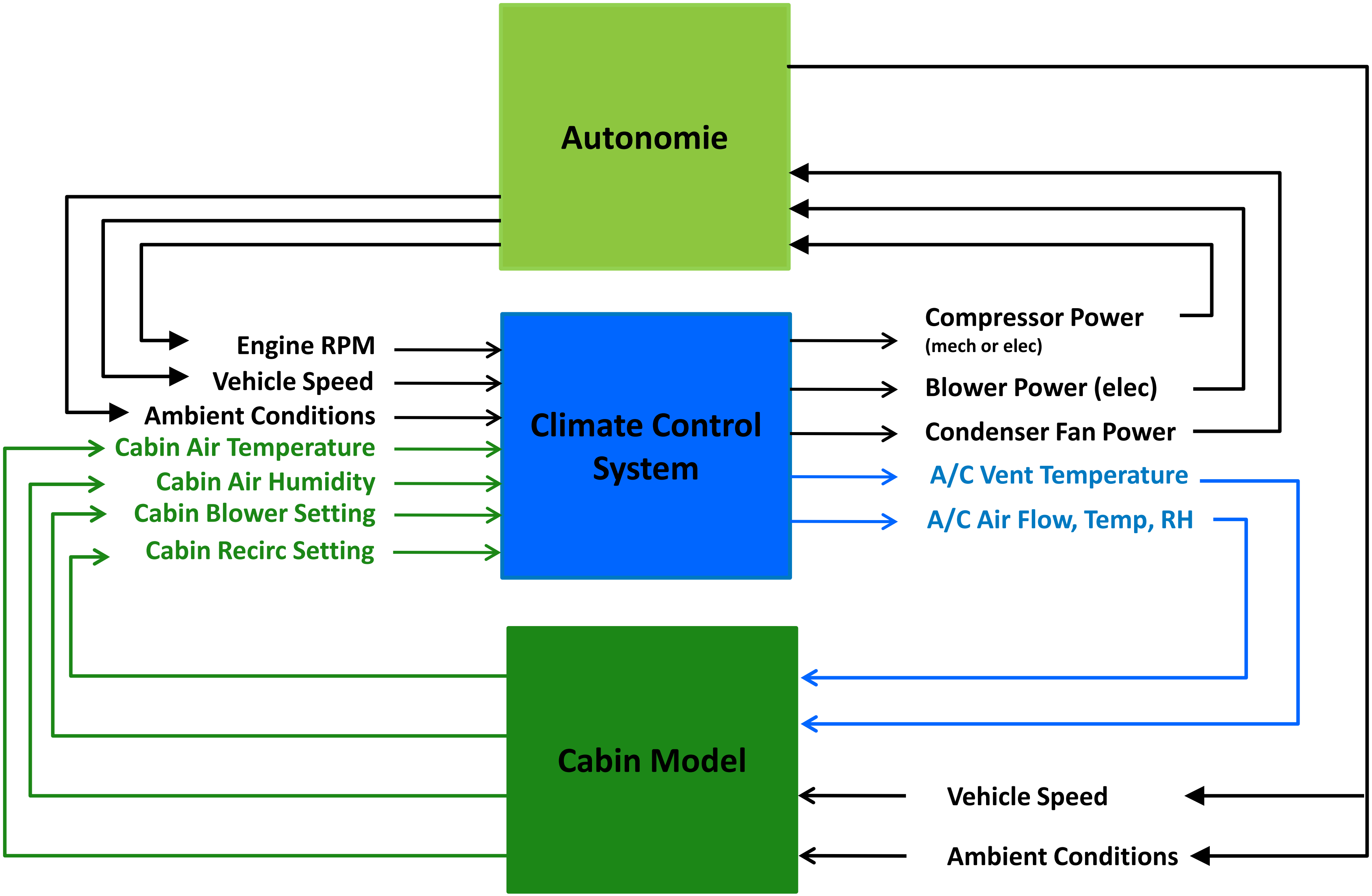




Approach – Matlab/Simulink-based tool

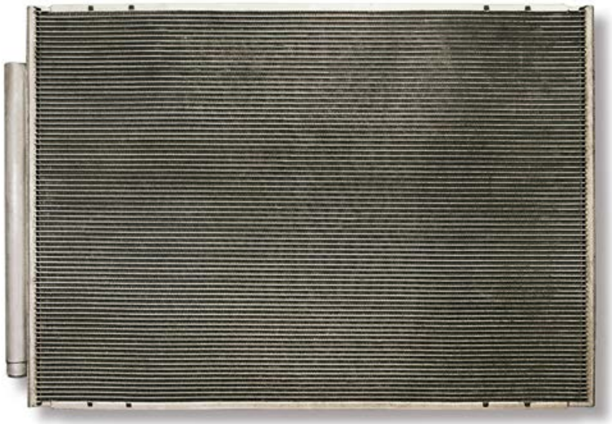
- A simulation tool based on first principles; conservation of mass, momentum, and energy are solved in 1-D finite volume formulation
- Tool will be open source and available to the public
- Easily interfaced to Autonomie® vehicle simulation tool
- Flexible software platform, capable of modeling vapor compression refrigeration cycle
- Model refrigerant lines and the heat exchangers as 1-D finite volumes, accounting for the lengthwise distribution of refrigerant and flow properties
- Include all major components: compressor, condenser, expansion device, evaporator, and accumulator/dryer (receiver/dryer)

Climate Control System Integration



A/C Model Development

Development of Component Models, Heat Exchanger



Complex heat exchanger

- Multiple passes
- Multi-channel tubes
- Micro channels
- Multiple refrigerant phases

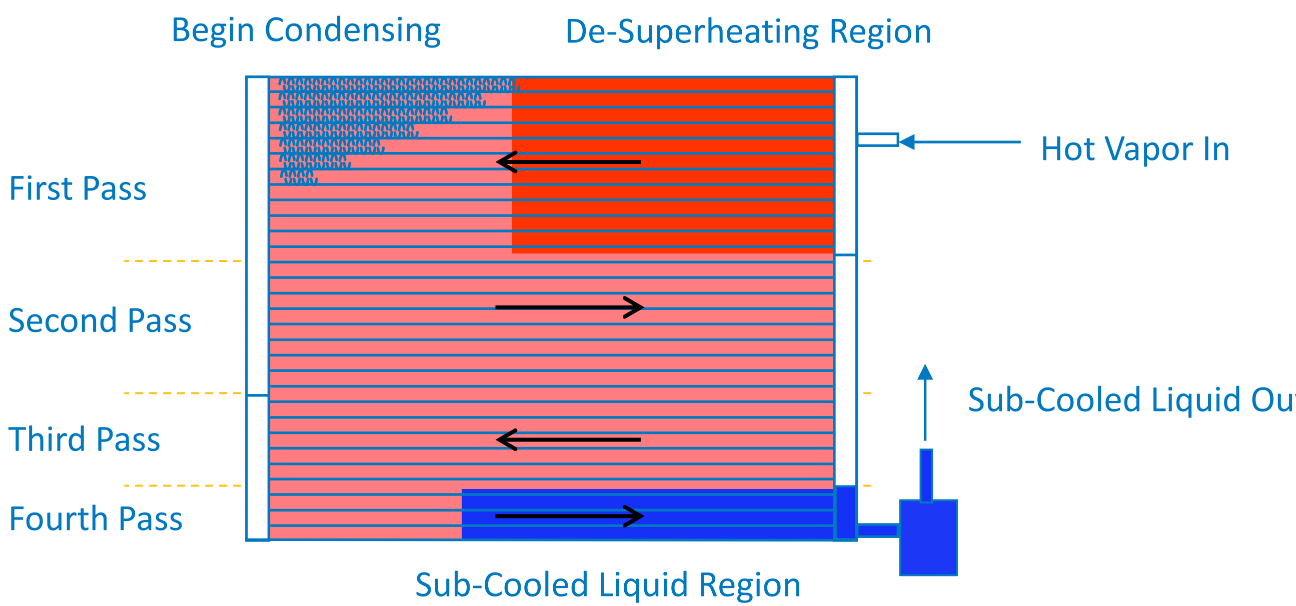
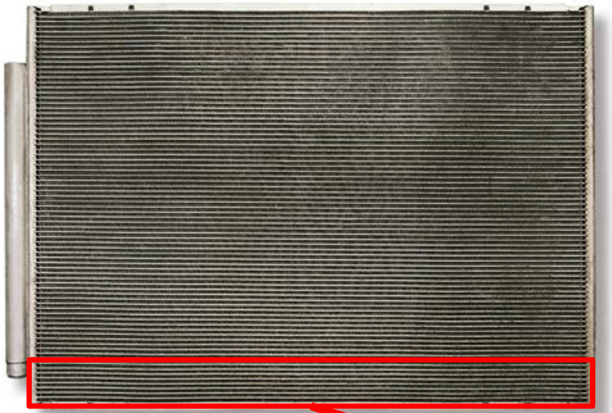


Diagram courtesy of Visteon Corporation

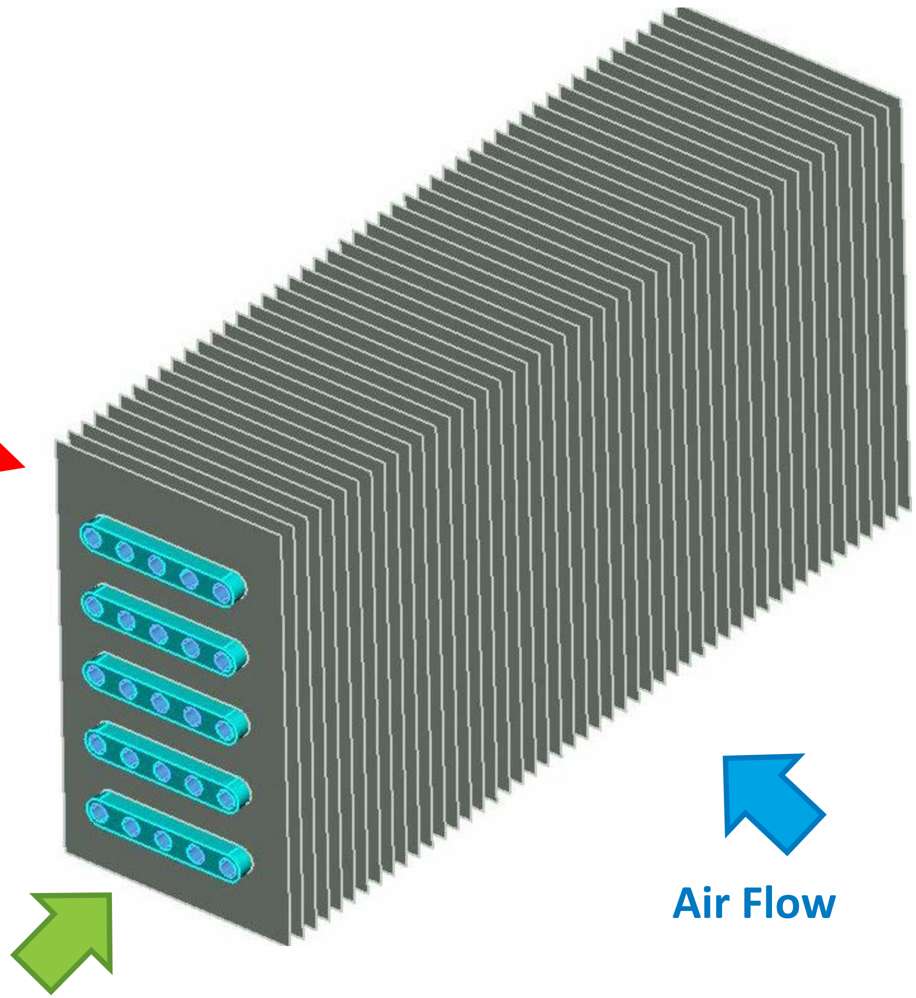
Four refrigerant passes in this example

A/C Model Development

Development of Component Models, Heat Exchanger



Representative section through condenser



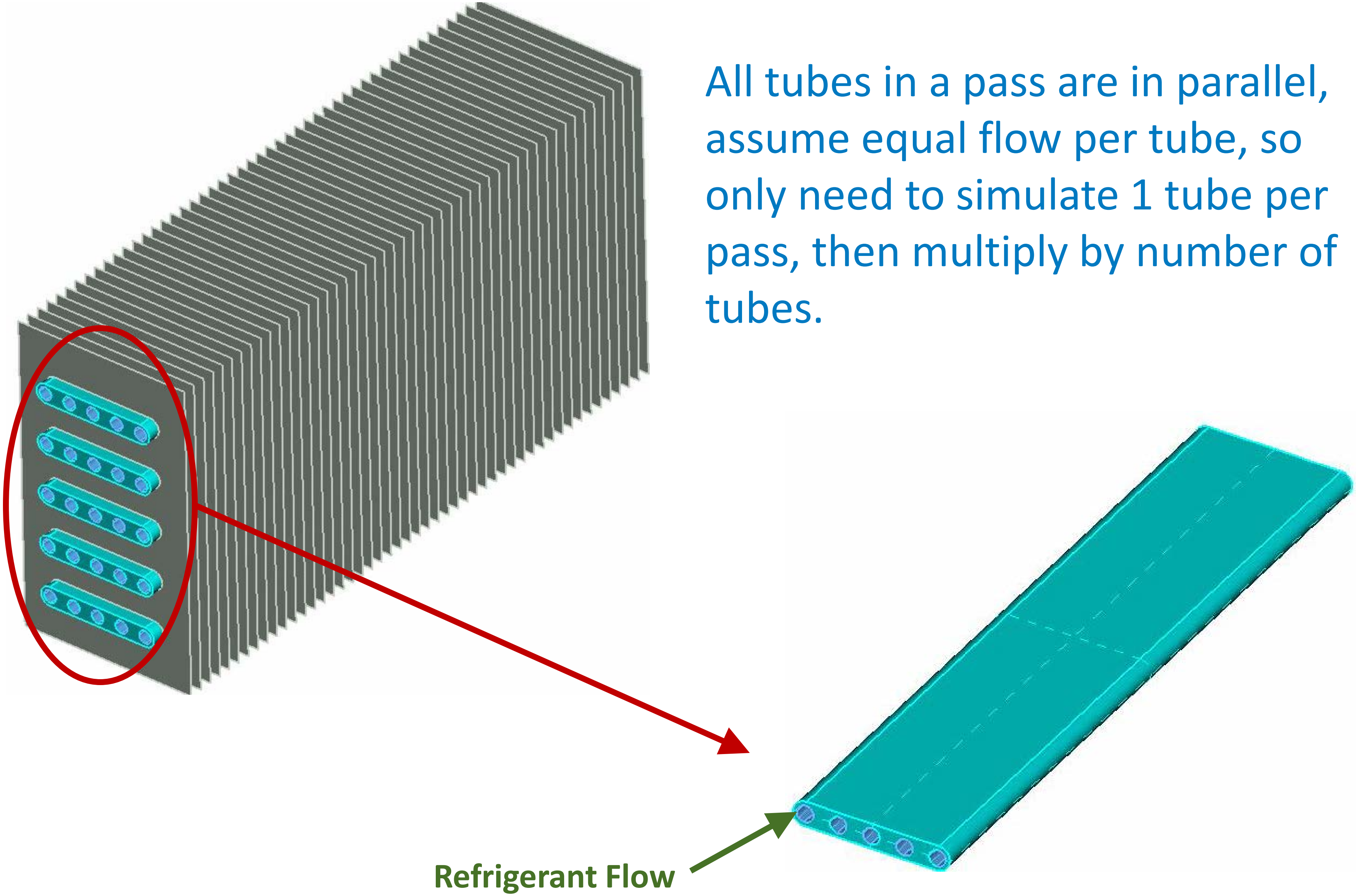
Note:

- Straight fins are shown, but they could also be louvered fins
- Round channels are shown but they could be square or other shape

A/C Model Development

Development of Component Models, Heat Exchanger

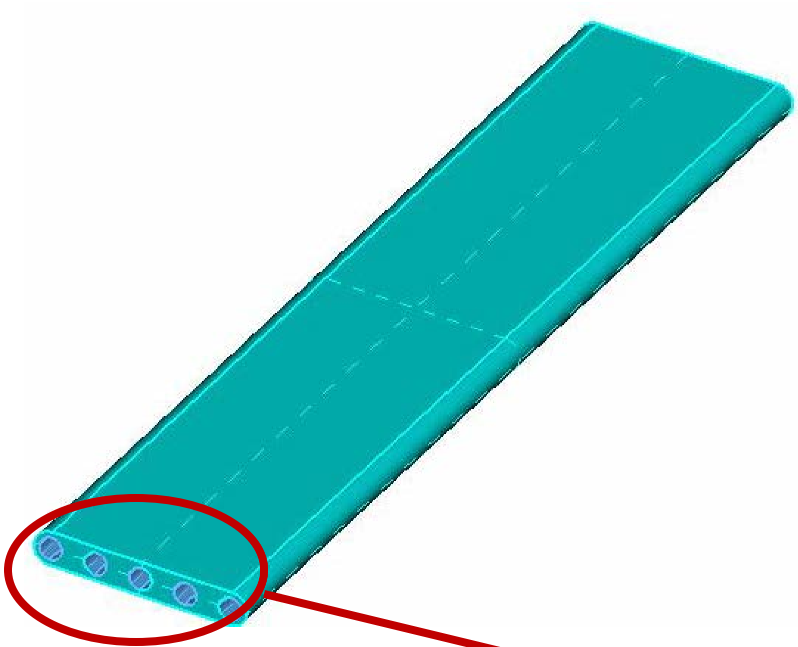
All tubes in a pass are in parallel, assume equal flow per tube, so only need to simulate 1 tube per pass, then multiply by number of tubes.

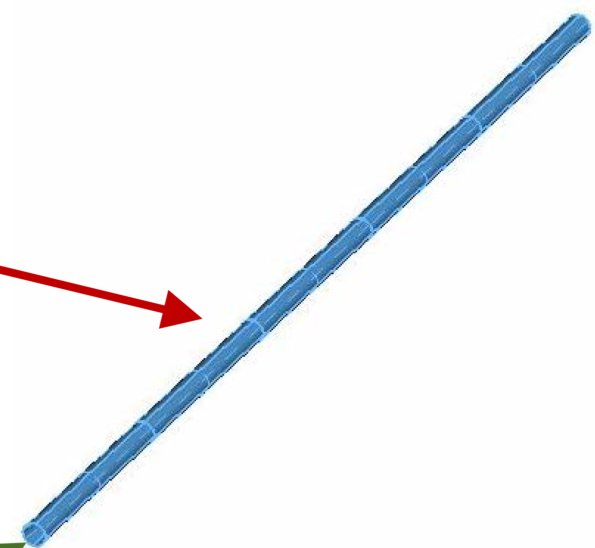


A/C Model Development

Development of Component Models, Heat Exchanger

All channels in a tube are in parallel, assume equal flow per channel, so only need to simulate 1 channel per tube, then multiply by number of channels.



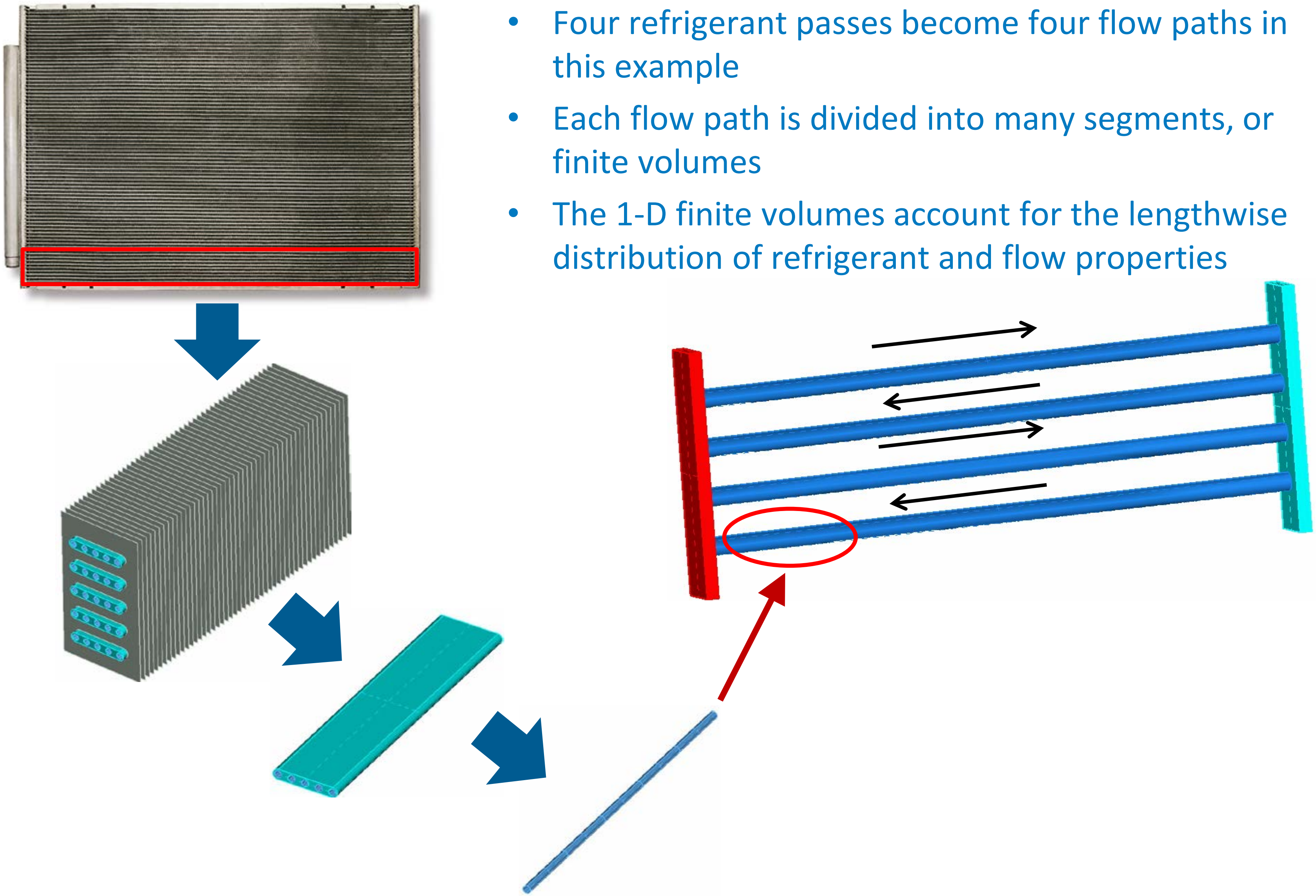


Refrigerant Flow

A/C Model Development

Development of Component Models, Heat Exchanger

- Four refrigerant passes become four flow paths in this example
- Each flow path is divided into many segments, or finite volumes
- The 1-D finite volumes account for the lengthwise distribution of refrigerant and flow properties

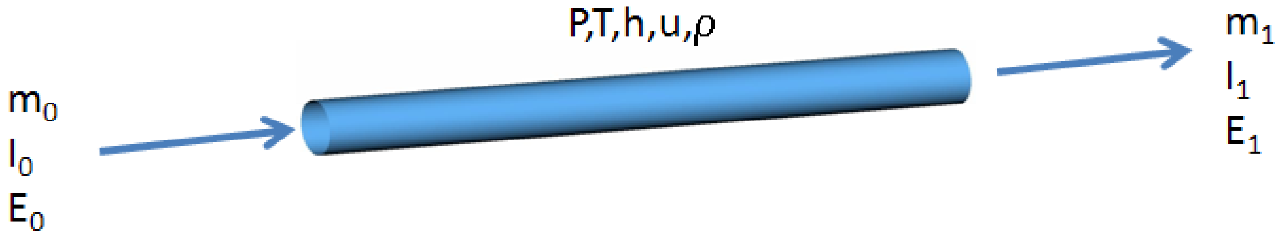


A/C Model Development

Development of Component Models, Line Segment

Conservation Equations Solved in Refrigerant Lines

(One-dimensional Finite Volume Formulation)



Continuity:

$$\frac{dm}{dt} = \rho_{in} A v_{in} - \rho_{out} A v_{out}$$

Momentum Equation:

$$\frac{dI}{dt} = \rho_{in} A v_{in}^2 - \rho_{out} A v_{out}^2 + (p_{in} - p_{out})A + F_{wf}$$

Energy Equation:

$$\frac{dE}{dt} = A v_{in}\left(p_{in} + u_{in}\rho_{in} + \rho_{in}\frac{v_{in}^2}{2}\right) - A v_{out}\left(p_{out} + u_{out}\rho_{out} + \rho_{out}\frac{v_{out}^2}{2}\right) + Q_{tr}$$

where '*in*' and '*out*' subscripts mean inlet boundary and outlet boundary of finite volume, respectively

(F_{wf} is wall friction and Q_{tr} is heat addition rate)

A/C Model Development

Development of Component Models, Line Segment

Heat transfer from air to pipe wall

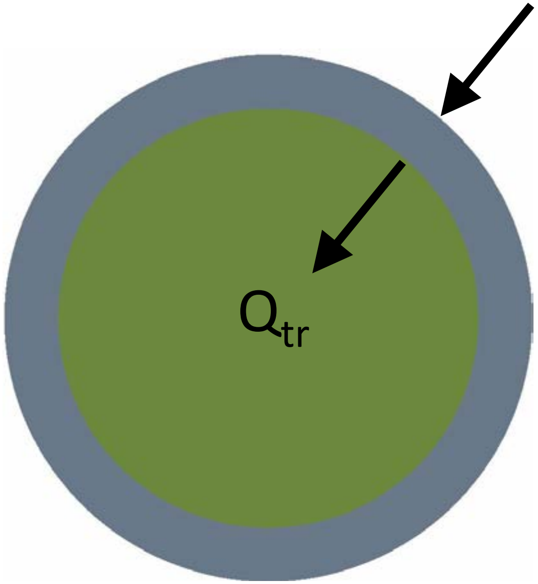
$$Q_{at} = \bar{h}_a A_a (T_a - T_t)$$

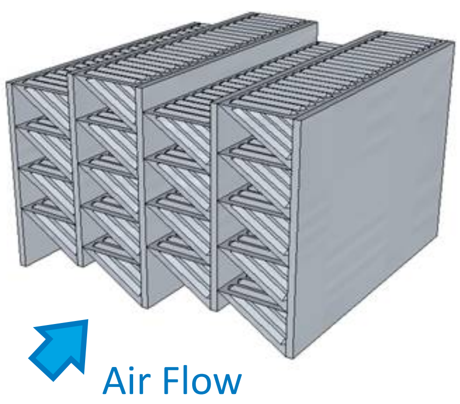
h_a is from Chang and Wang correlation for louver fin compact heat exchangers

Pipe wall to refrigerant

$$Q_{tr} = \bar{h}_{tr} A_t \left(T_t - T_r\right)$$

h is from Dittus-Boelter equation, and Chen correlation





Pipe is assumed to be radially isothermal, but heat capacity is accounted for

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

Chen, J.C. (1966). "A Correlation for Boiling Heat Transfer of Saturated Fluids in Convective Flow," *Ind. Eng. Chem. Process Ses. Dev.,* Vol. 5, No. 3, pp. 322-329.

A/C Model Development

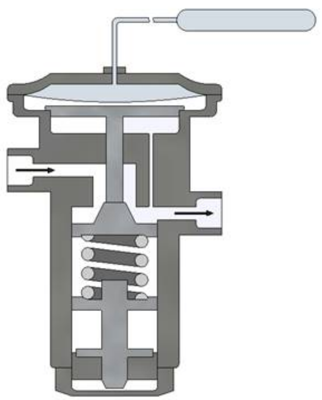
Compressor and TXV Models

- **Compressor**
  - Volumetric efficiency
  - Discharge enthalpy found using isentropic efficiency

[1]

$$\dot{m} = \rho_u \cdot \eta_{vol} \frac{dV}{rev} \cdot RPM/60$$

- **Thermal Expansion Device (TXV)**
  - Two-phase equilibrium orifice flow model
  - Feedback control on orifice flow area based on Evaporator-out superheat ('SH')

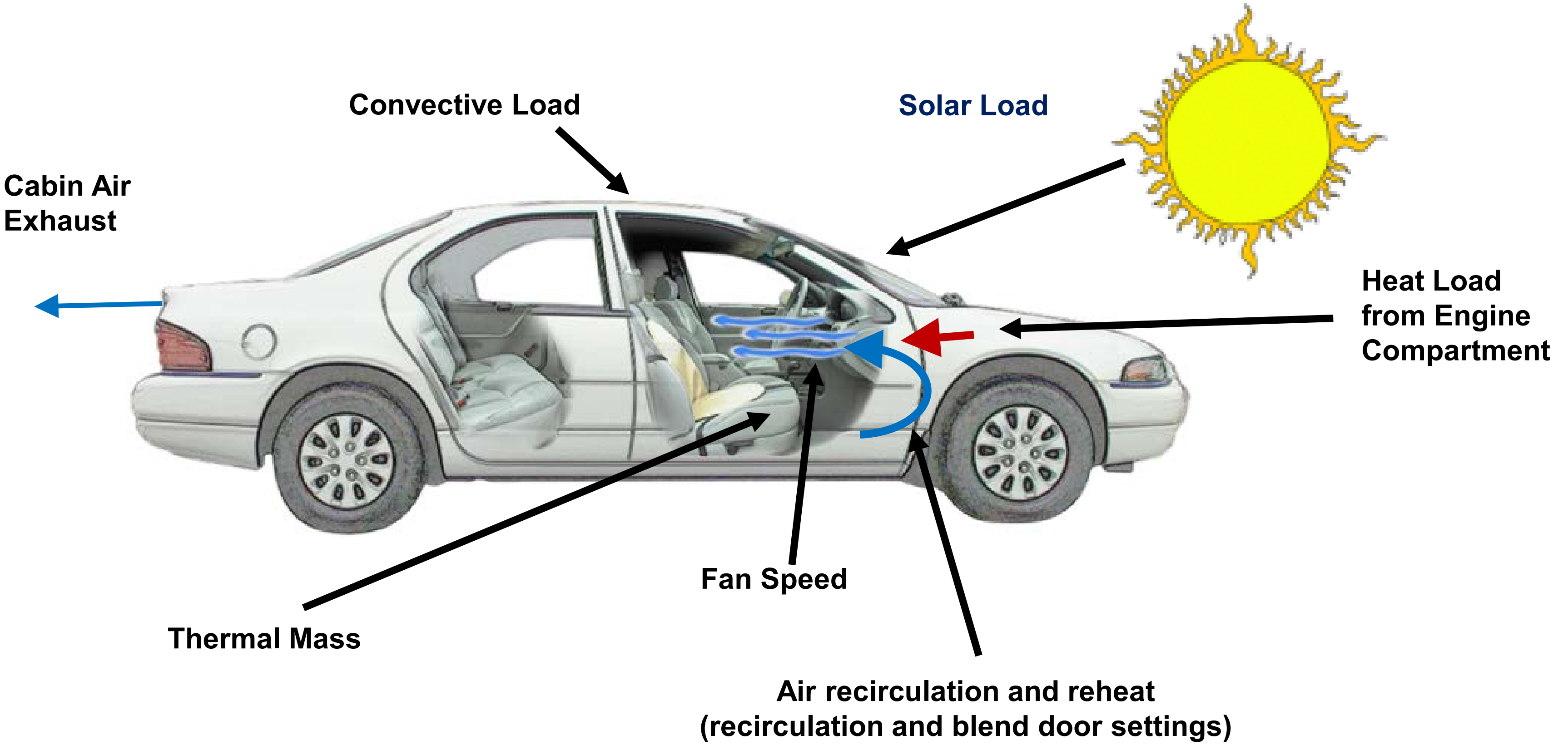


$$\dot{m} = C_d(\mathrm{d}P_e) \cdot \rho_{throat} \cdot v_{throat} \cdot A_{orif}$$

[1] Compressor photograph, NREL, John Rugh & Jason Lustbader

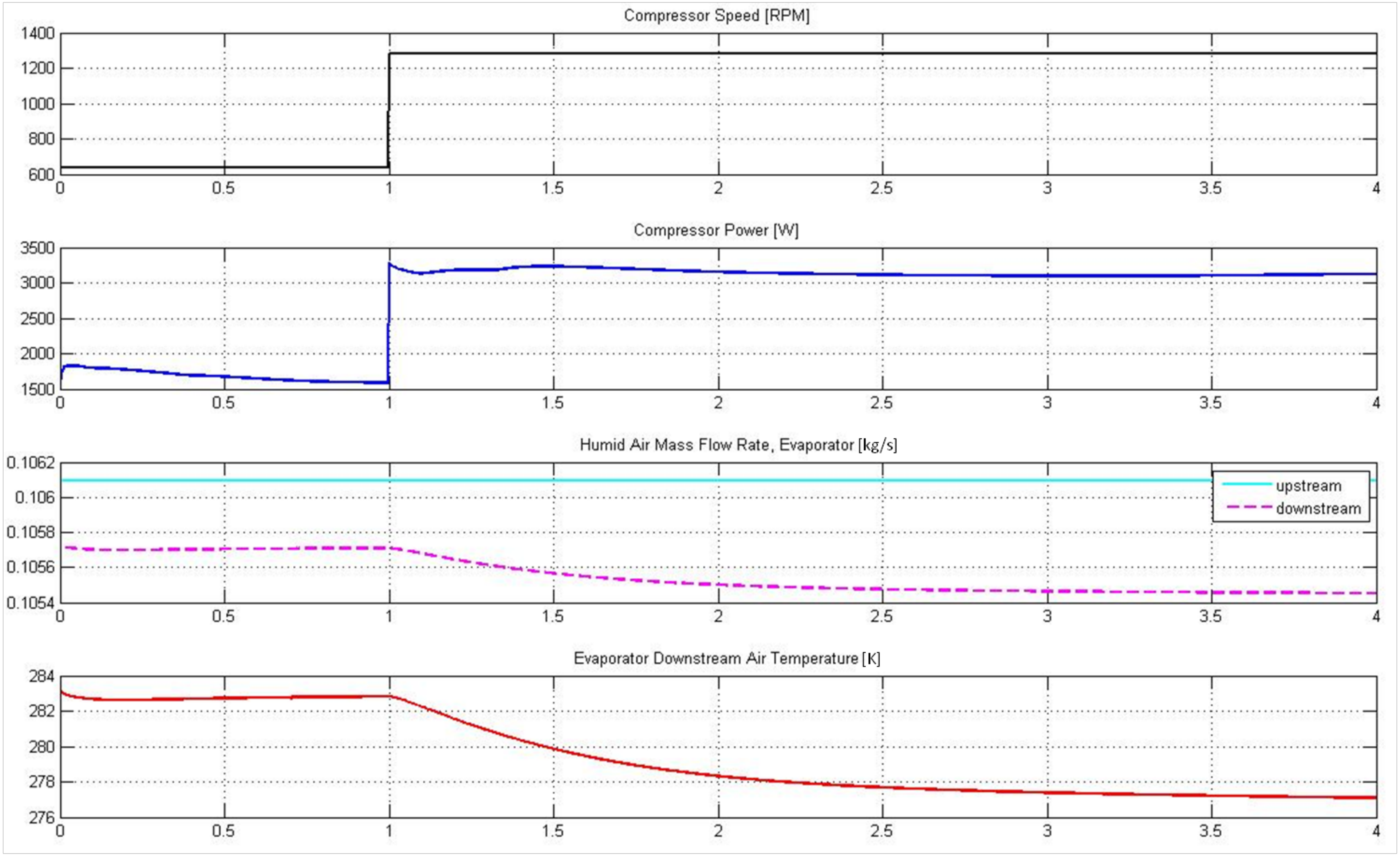
A/C Model Development

Single Zone LDV Cabin Model



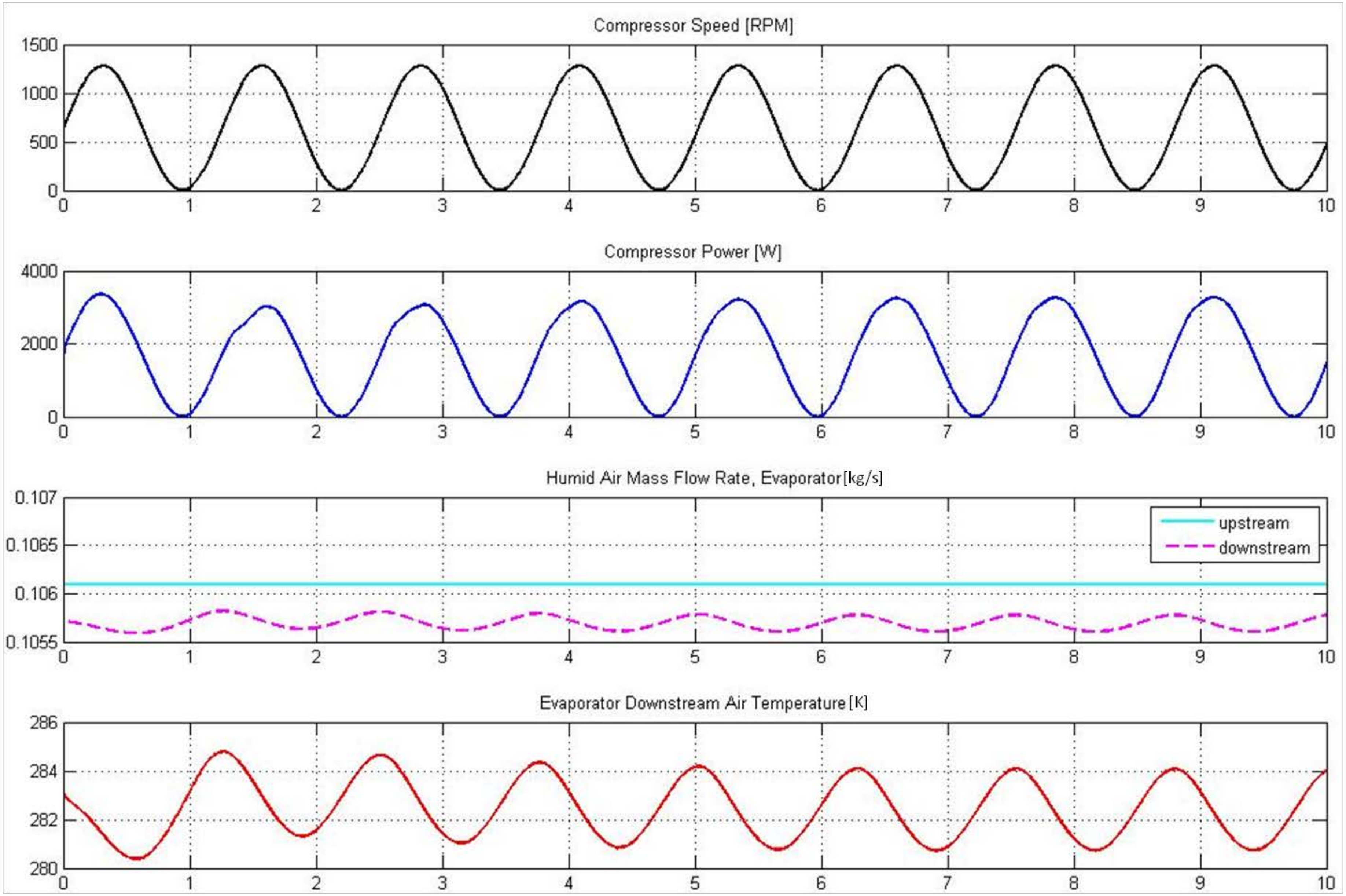
Results – Step Change Transient

Model Stable, Step Change to Engine RPM at 1 sec



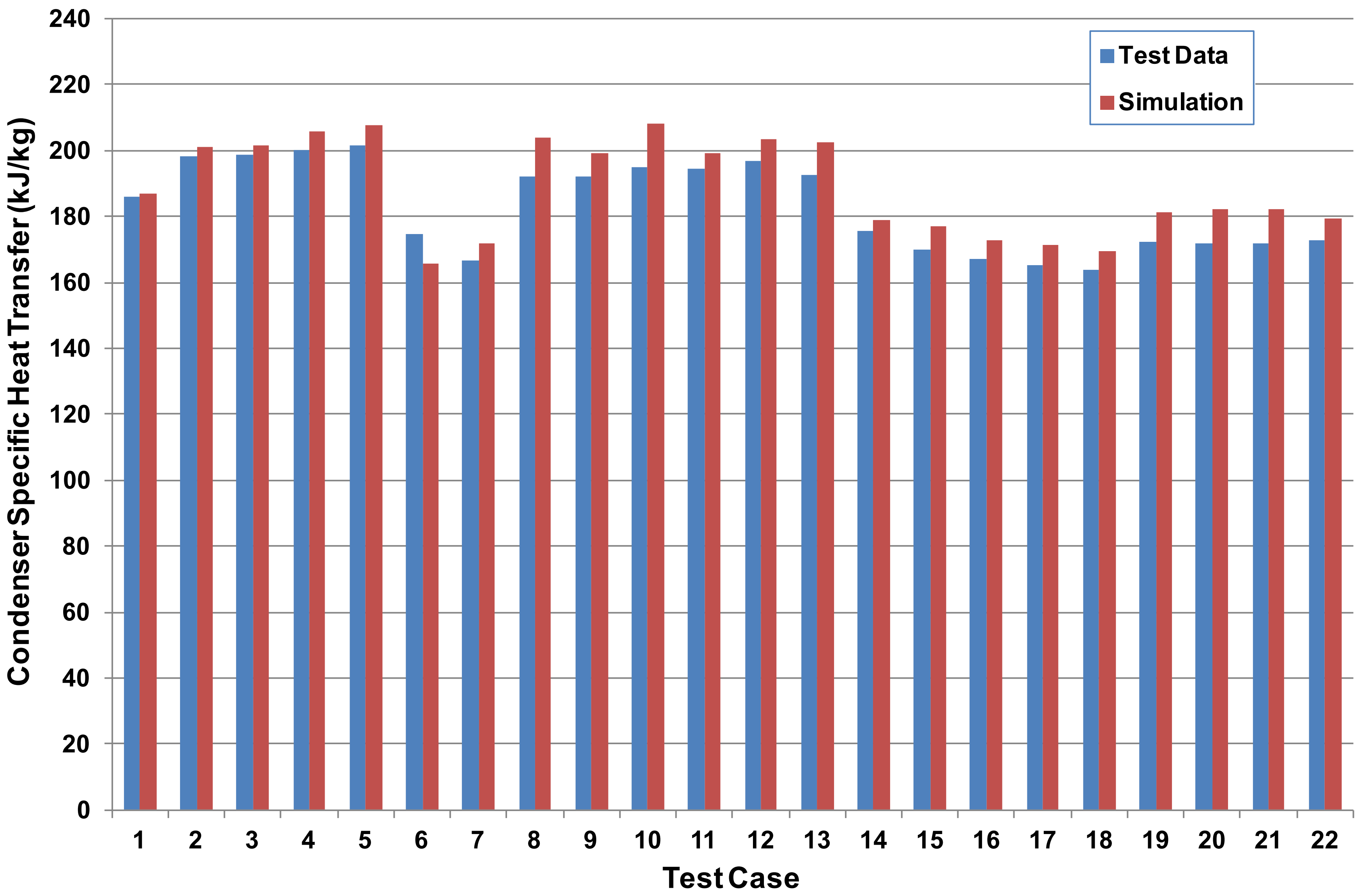
Results – Step Change Transient

Transient Response Reasonable



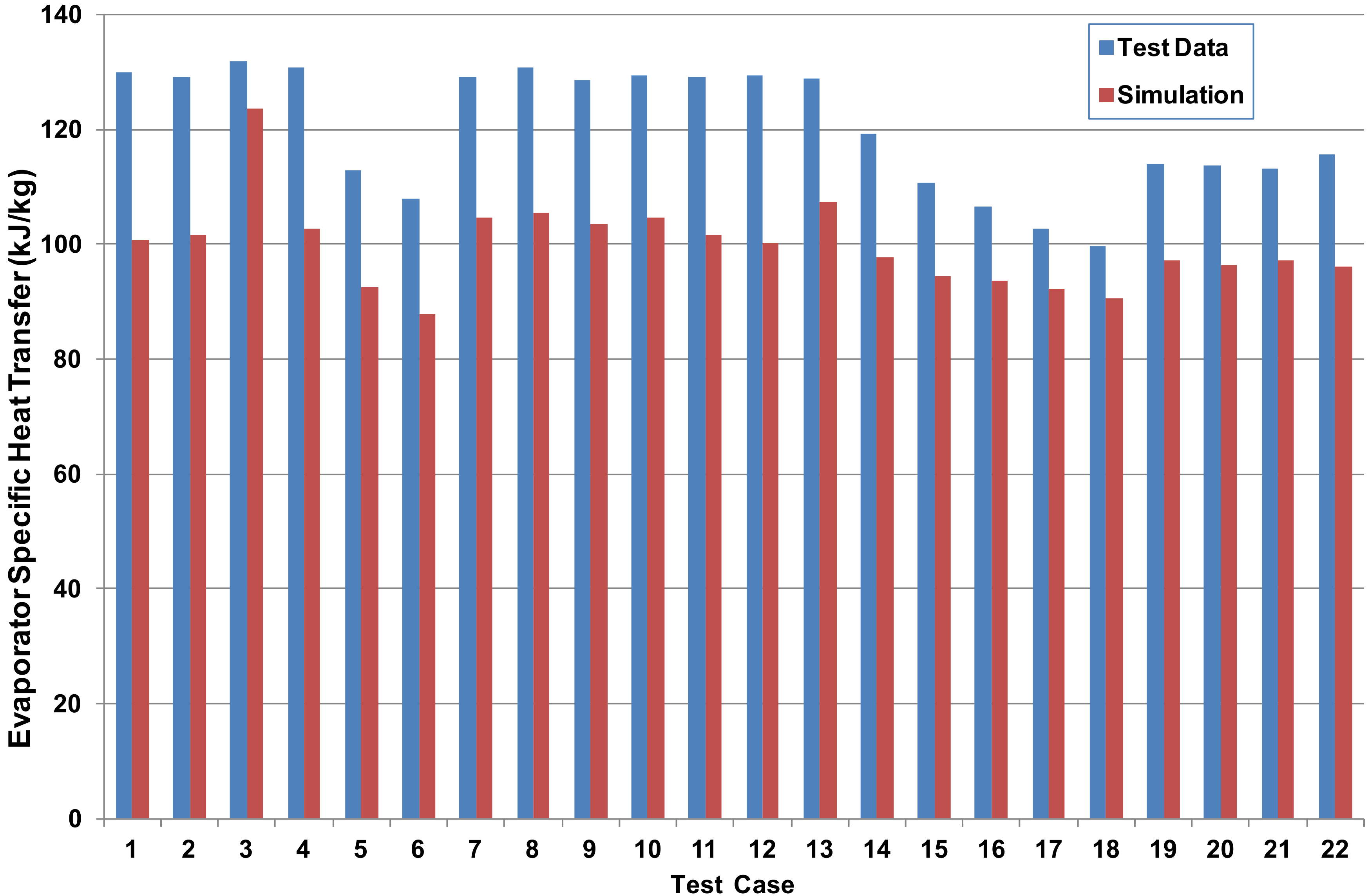
Results – Preliminary Component Validation

Condenser Heat Transfer Matches Well



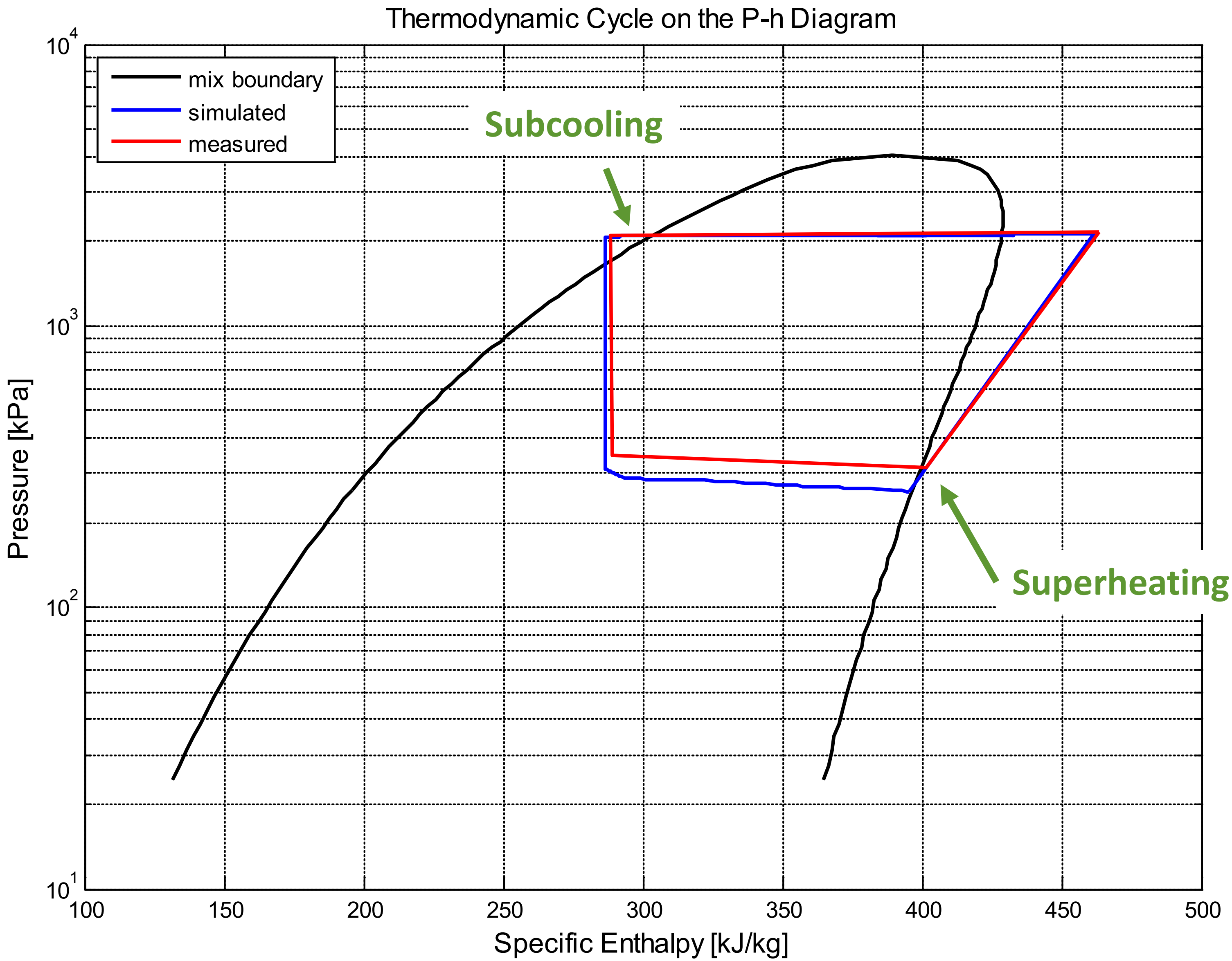
Results – Preliminary Component Validation

Evaporator Heat Transfer Matches within 16% on Average



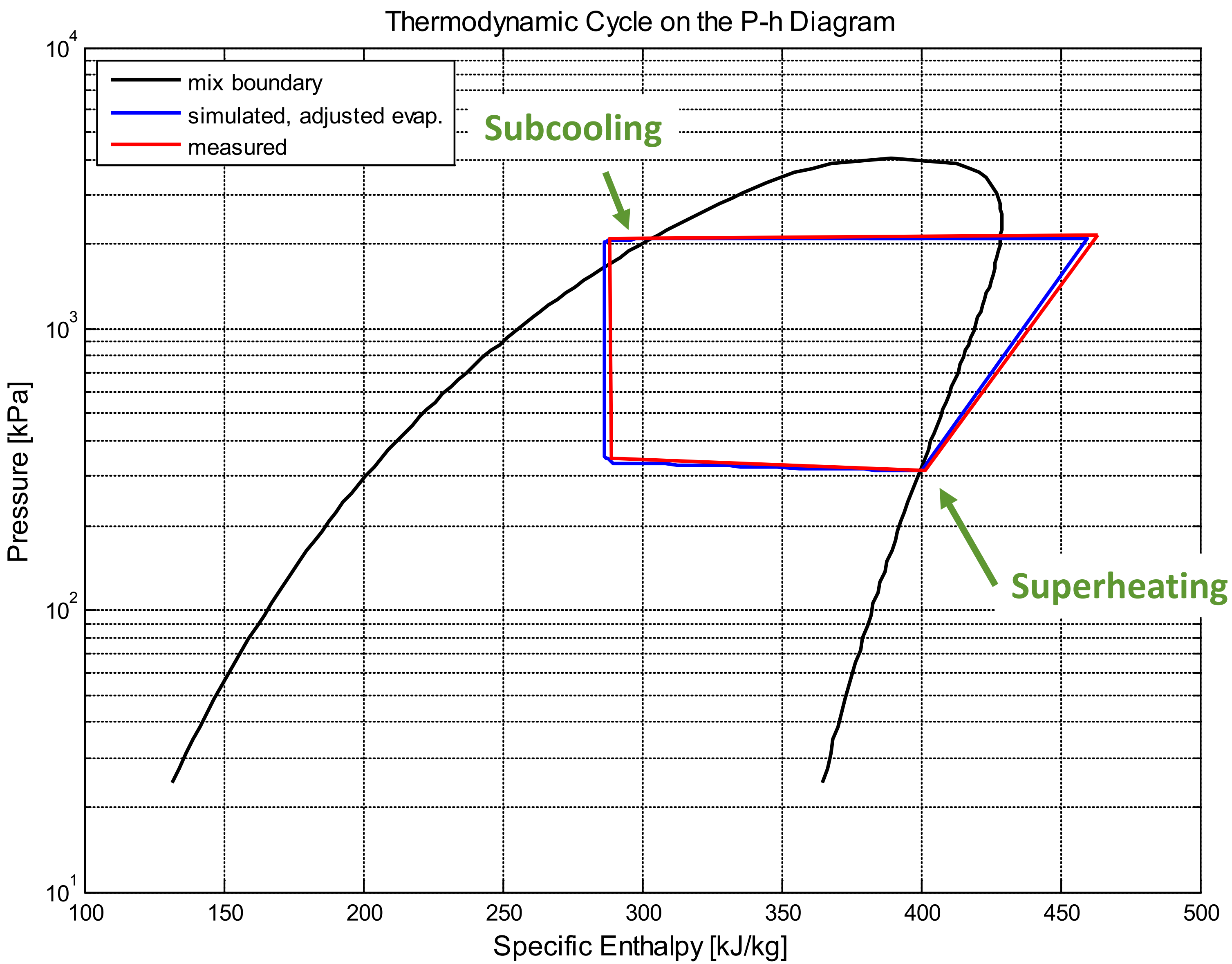
Results – Preliminary System Validation

Good Agreement for System Thermodynamic Cycle



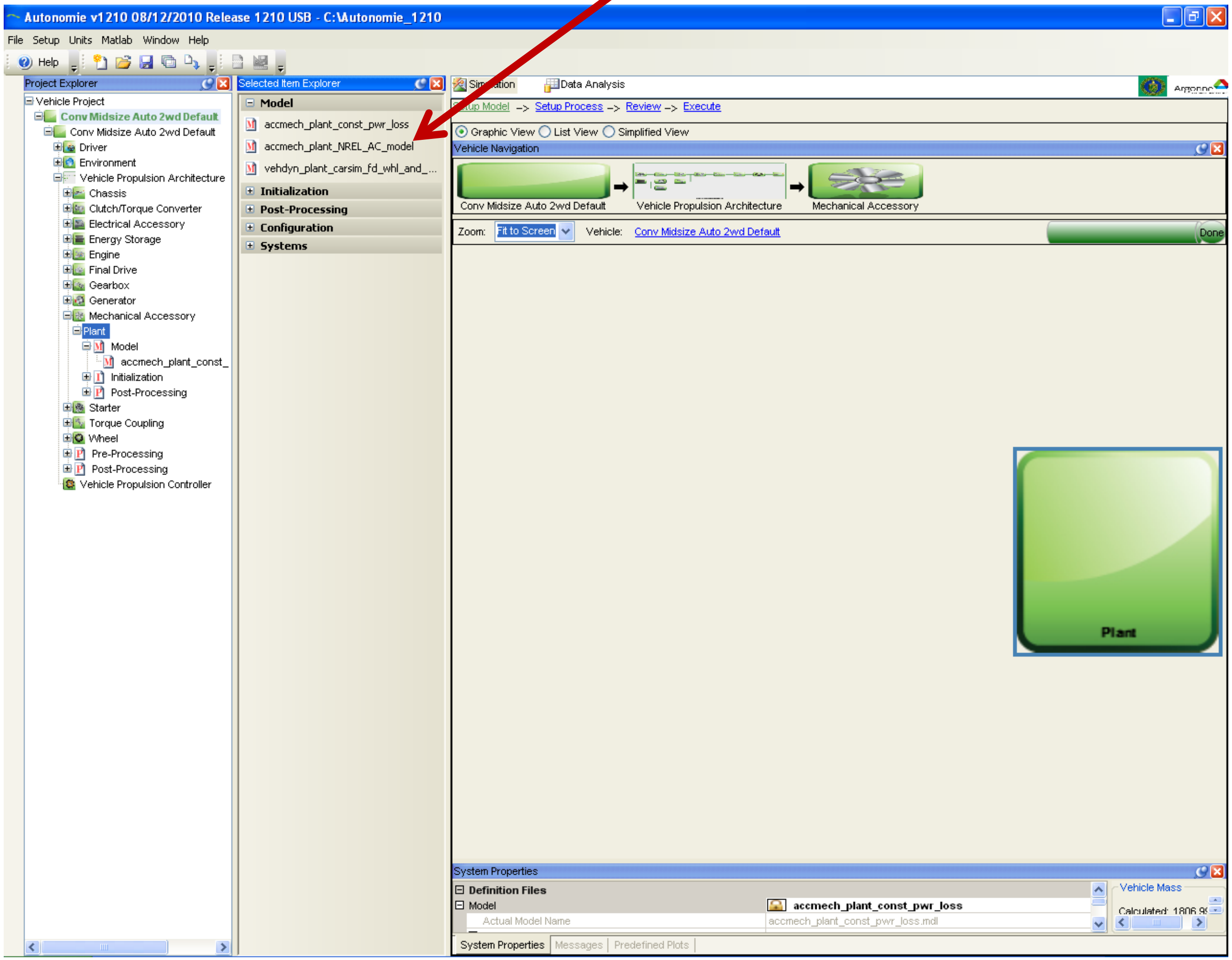
Results – Preliminary System Validation

With Corrected (adjusted) Evaporator Heat Transfer



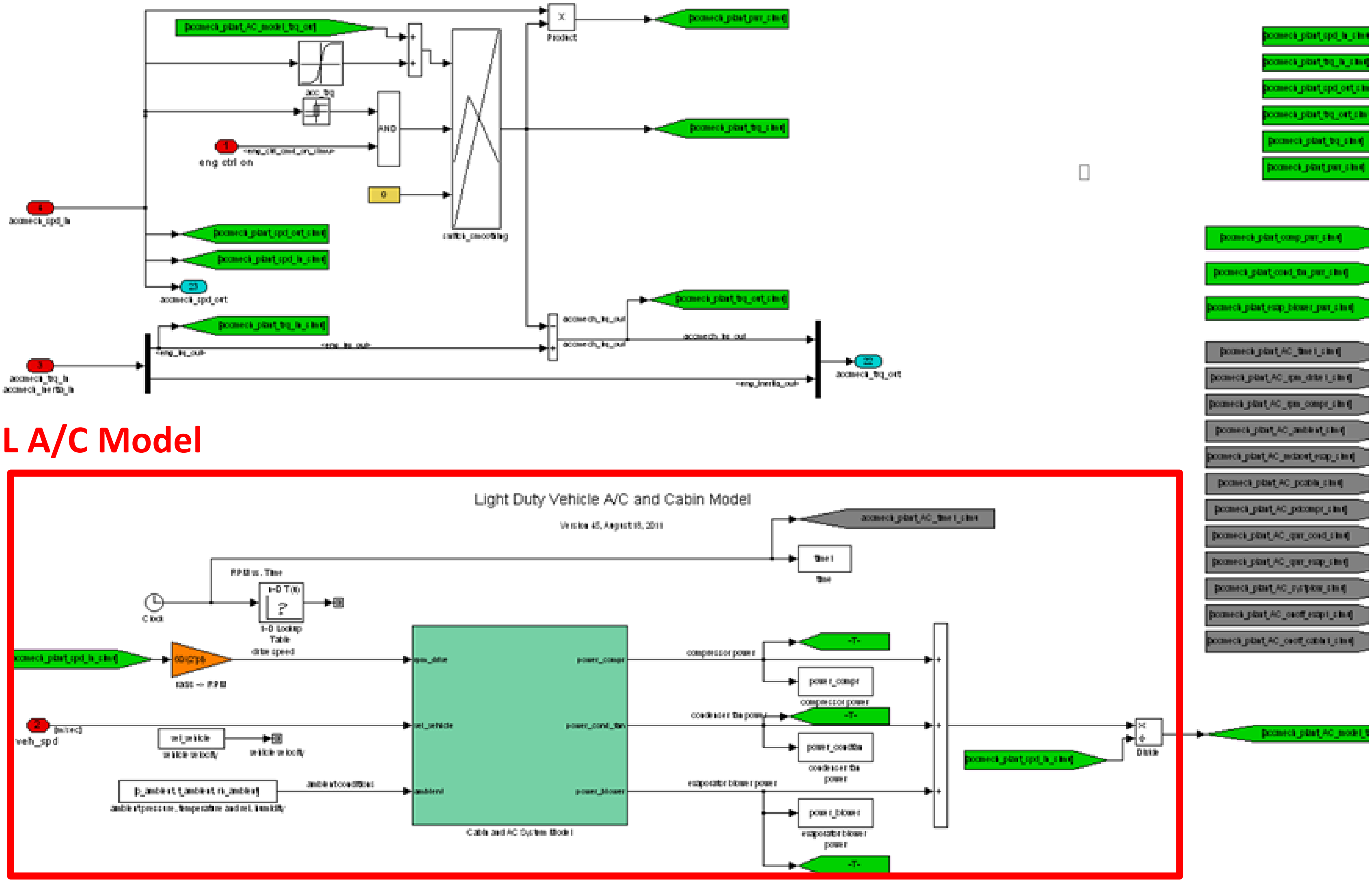
Results – Autonomie® Integration

A/C Model within Autonomie – accmech_plant_NREL_A/C_model



Results – Autonomie® Integration

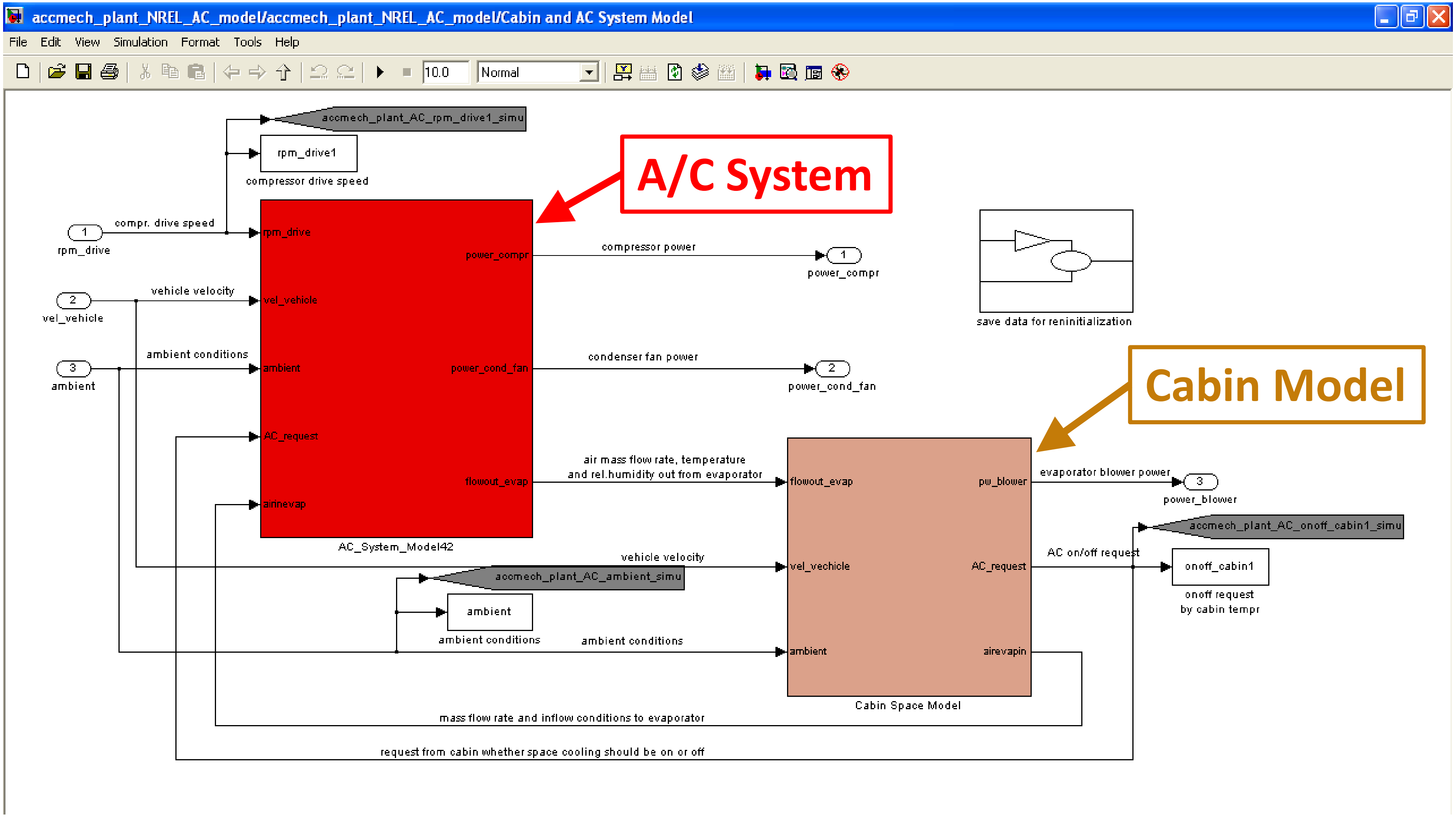
Top-Level Model



NREL A/C Model

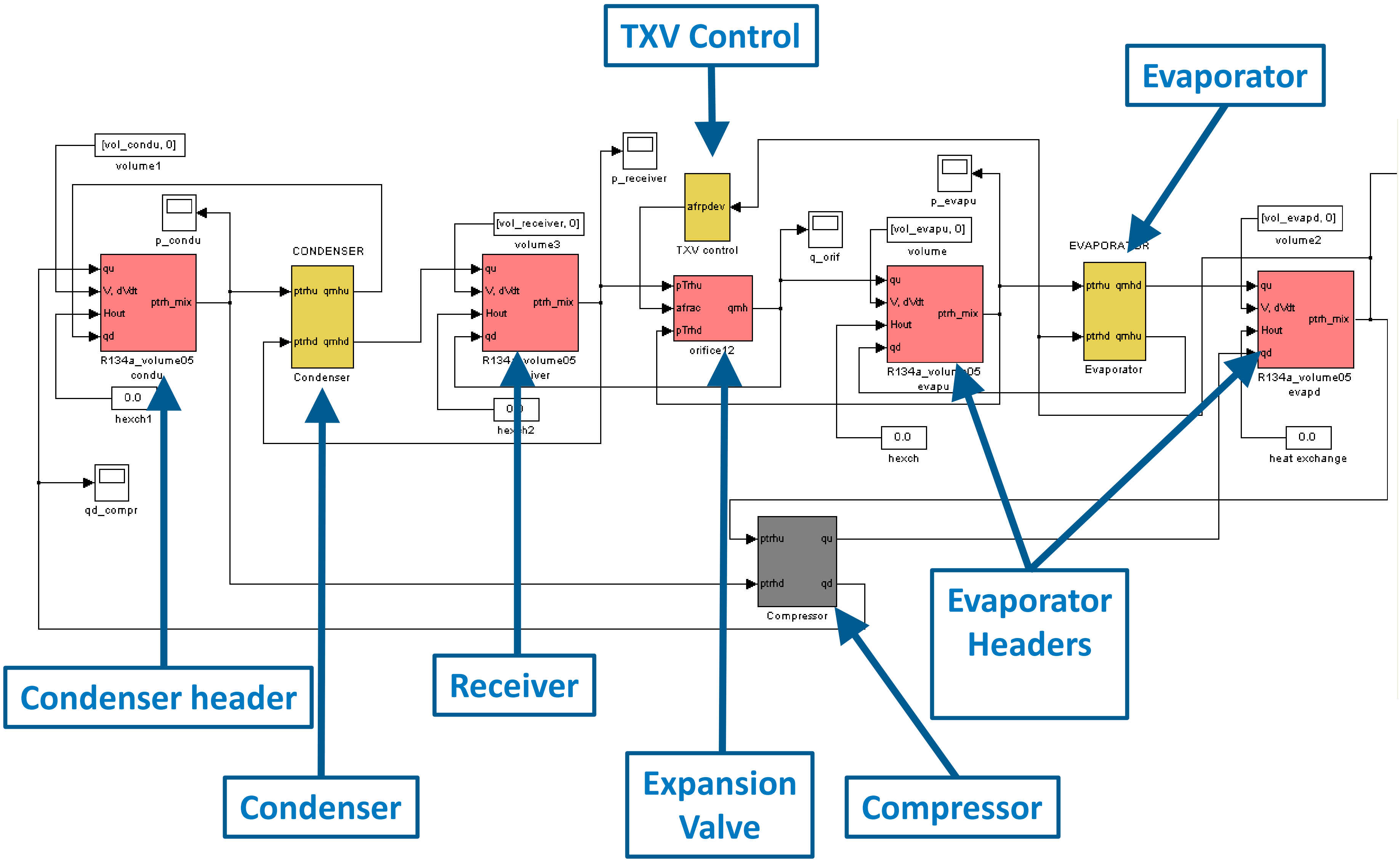
Results – Autonomie® Integration

Second-Level Model, A/C System and Cabin Model



Results – Autonomie® Integration

Third-Level A/C Model: Components



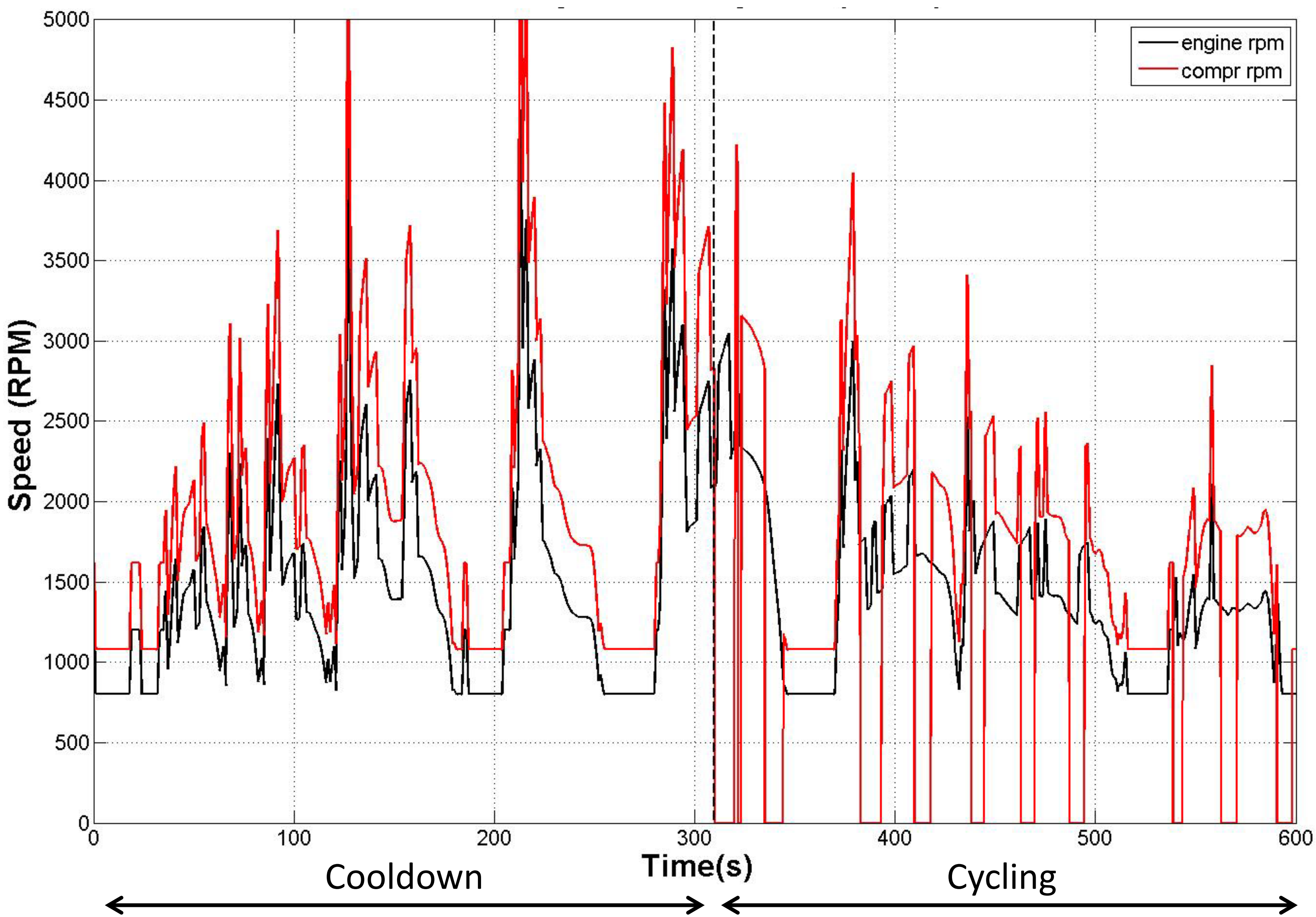
Results – SC03 Cycle

System Model SC03 Example

- **Simulated the A/C system incorporated in a vehicle**
  - Used SC03 drive cycle
  - Conventional 2wd Midsize Auto Default in Autonomie®
  - Demonstrated robust system performance and cabin cooldown
- **Conditions and Controls Settings**
  - Ambient temperature: 40°C
  - Cabin initial temperature: 60°C
  - Cabin initial relative humidity: 50%
  - Solar load: 1,300 W
  - Cabin target temperature: 20°C
  - Air Recirculation: 95%

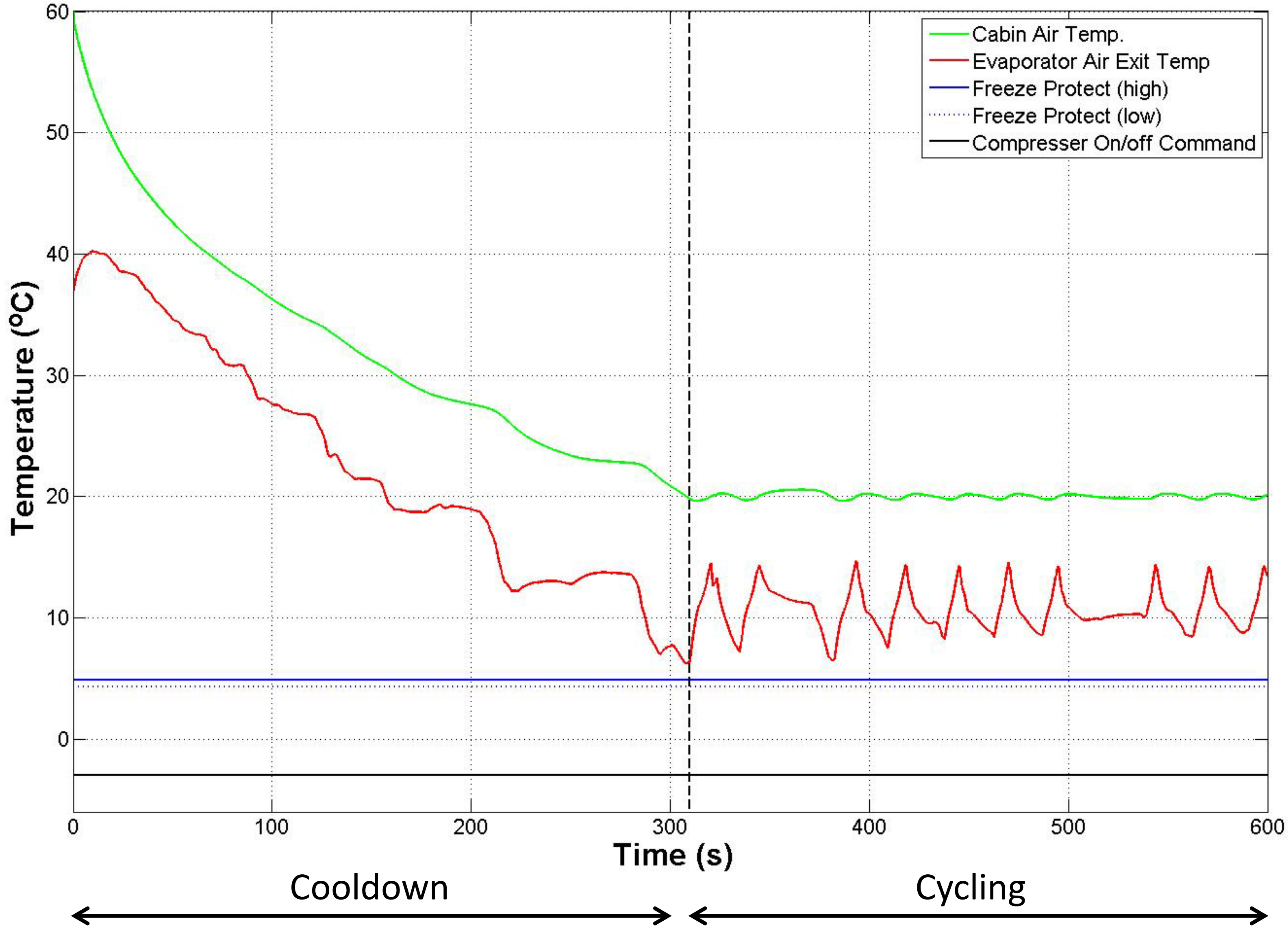
Results – SC03 Cycle

Engine and Compressor Speed



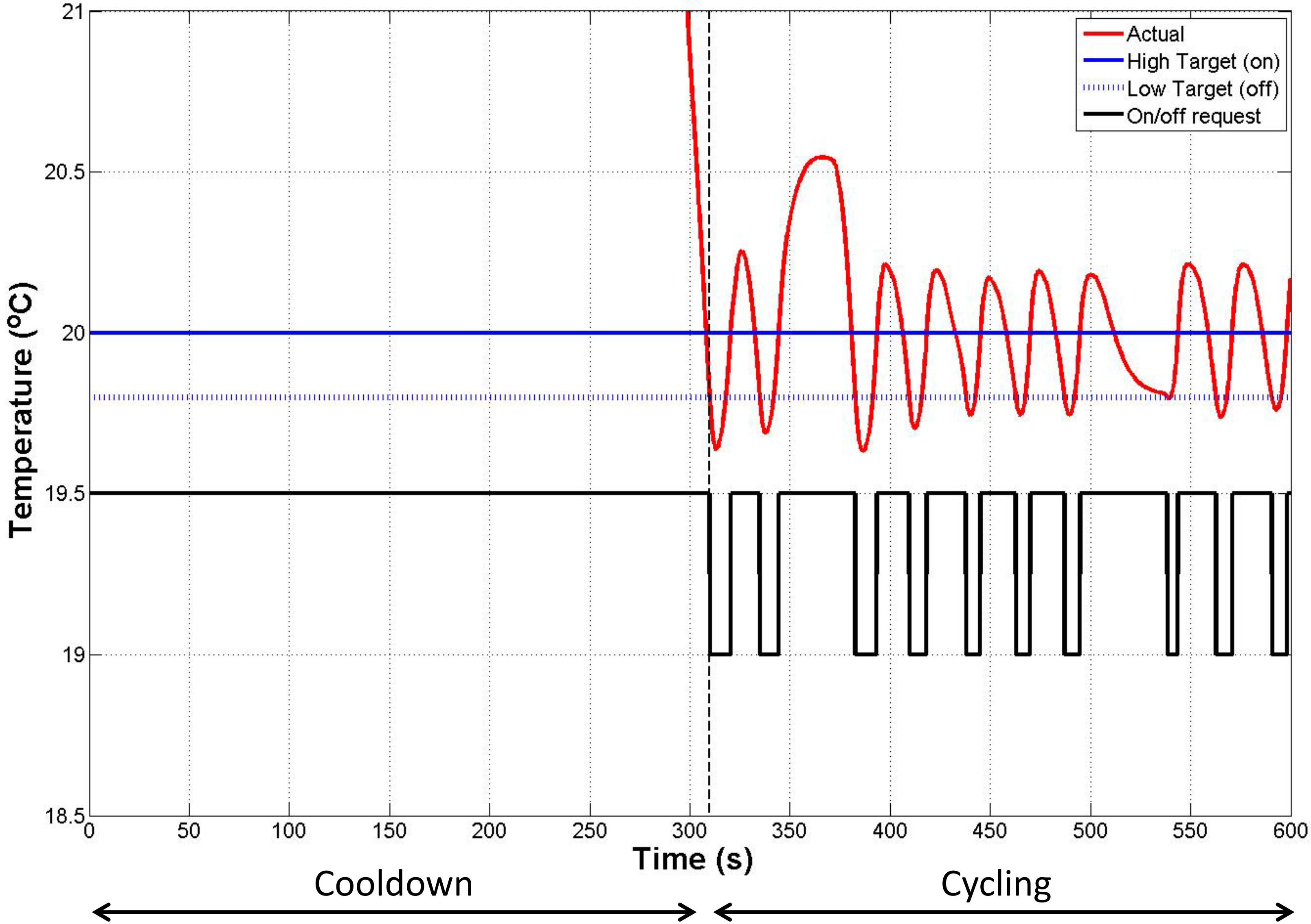
Results – SC03 Cycle

Evaporator and Cabin Temperatures



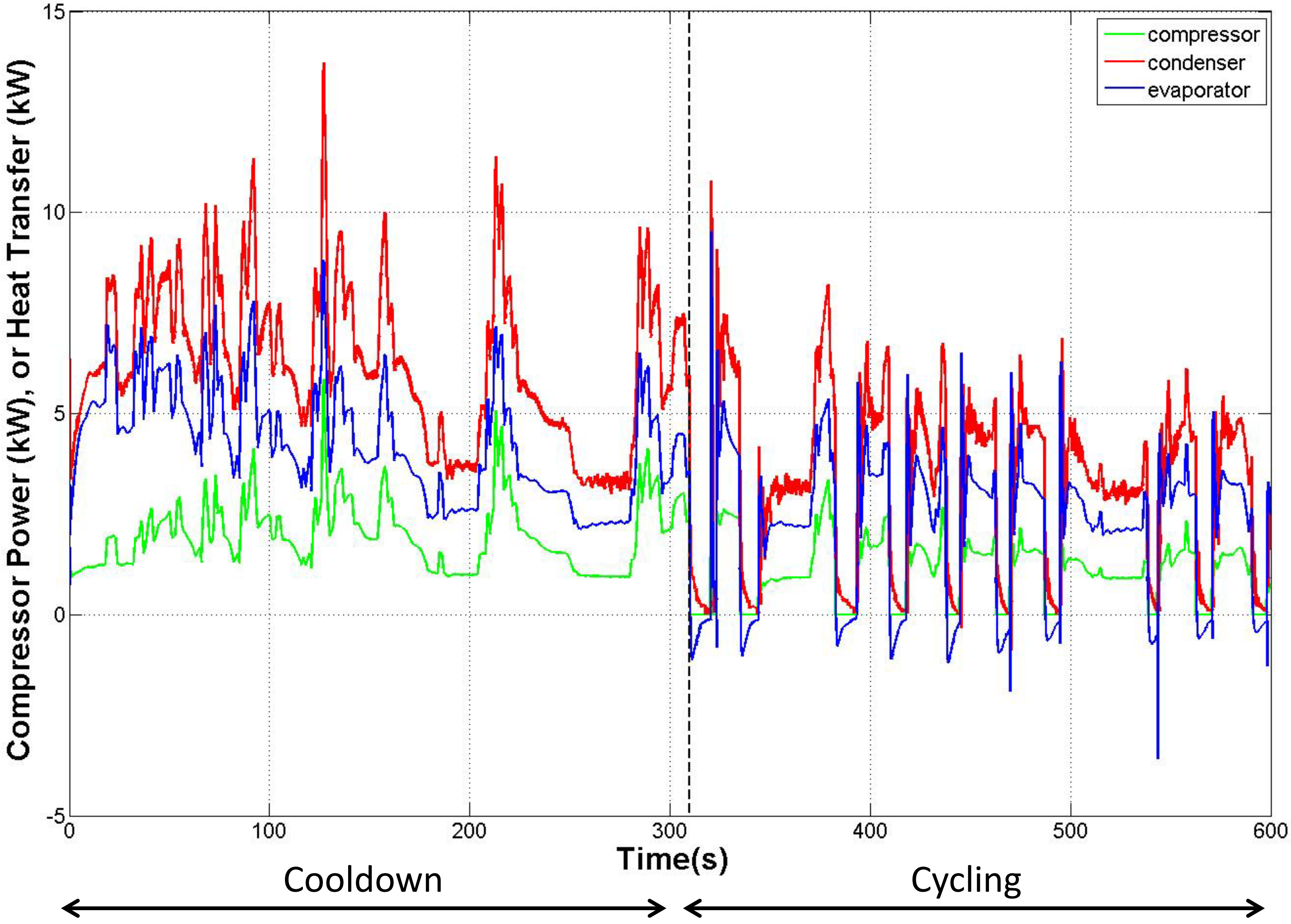
Results – SC03 Cycle

Temperature Control



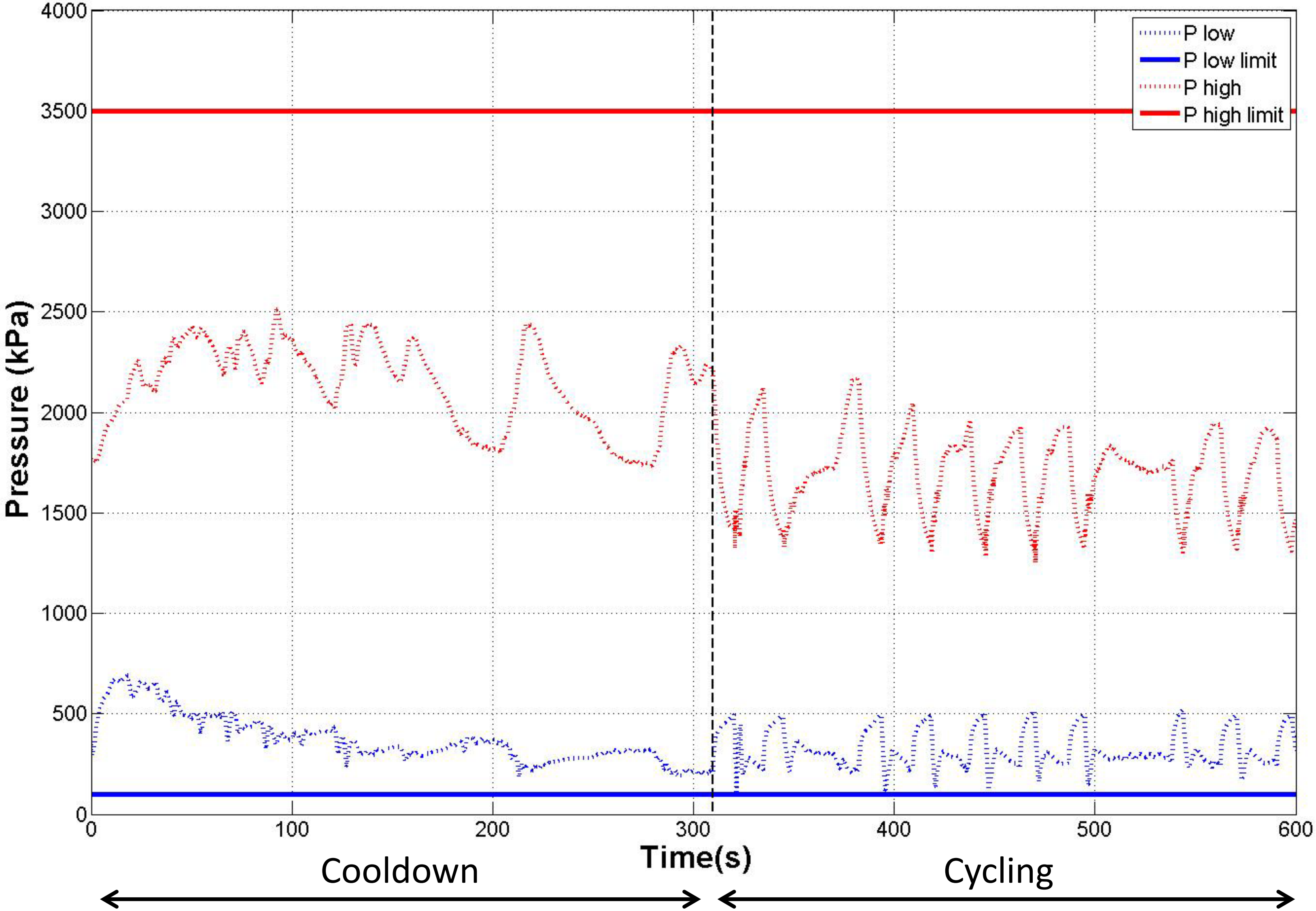
Results – SC03 Cycle

Heat Flow Rate and Compressor Power



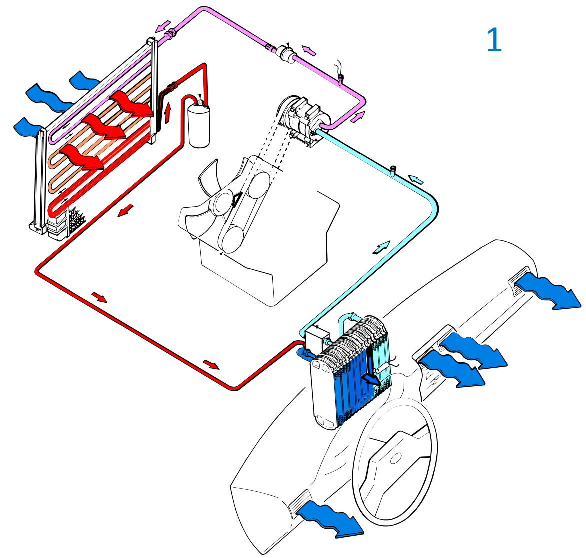
Results – SC03 Cycle

Pressure Control



Collaboration

- Argonne National Laboratory
  - Integration of A/C model into Autonomie®
  - Vehicle test data
- Visteon Corporation
  - Technical advice
  - A/C system and component test data
- Daimler Trucks
  - Support Super Truck work



1

2

1. Diagram courtesy of Visteon Corporation
2. Daimler Super Truck Logo, Courtesy of Daimler Trucks, 2011

Future Work

FY12

- Complete model validation
- Develop electric A/C model for Autonomie®
- Develop a large-vehicle A/C model
- Release publicly available Autonomie® plug-in

FY13

- Write user guide
- Develop A/C model for heavy-duty vehicles
- Add heating into the model
- Apply to light- and heavy-duty vehicles

Summary

DOE Mission Support

- A/C use can account for significant portion of the energy used by light-duty and heavy-duty vehicles.
- Reducing A/C energy use is essential to achieving the President's goal of 1 million electric drive vehicles by 2015.

Approach

- Develop a transient open source Matlab®/Simulink®-based HVAC model that is both flexible and accurate. Base model on first principles and do not rely on component flow and heat transfer data as input.
- Interface HVAC model with Autonomie® vehicle simulation tool to simulate effects of HVAC use on vehicle efficiency and range.

Summary

Technical Accomplishments

- **Developed a Matlab®/Simulink® model of light-duty vehicle A/C system**
  - 1-D finite volume basic line building block
  - Developed A/C system components
  - Demonstrated and verified A/C system performance
  - Modifiable system and components based on input parameters
- **Developed and demonstrated cabin model**
- **Interfaced to Autonomie®**
- **Validation in progress**

Collaboration

- **Argonne National Laboratory**
- **Visteon Corporation**
- **Daimler Trucks**

Summary – Acknowledgments

- **U.S. Department of Energy**
  - Patrick Davis, Vehicle Technologies Program
  - Lee Slezak, Vehicle Technologies Program
  - David Anderson, Vehicle Technologies Program
- **NREL**
  - Barbara Goodman, Director, Center for Transportation Technologies and Systems
  - Terry Penney, NREL Vehicle Technologies Program Technology Manager
  - Rob Farrington, Group Manager
  - John Rugh
- **Visteon Corporation**
  - John Meyer
- **Argonne National Laboratory**
  - Aymeric Rousseau

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.)

Heat Transfer Correlations Used in 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.

Heat Transfer Correlations Used in Model

Evaporator wall to refrigerant: $Q_{tr} = h_{tp} A_i (T_t - T)$

where the film coefficient is calculated with the Chen correlation:

$$h_{tp} = h_{FZ} S + h_L F$$

(composed of the sum of boiling and convective contribution)

h_{FZ} is the Forster-Zuber correlation for nucleate boiling

$$h_{FZ} = 0.00122 \left[\frac{k_L^{0.79} c_{pL}^{0.45} \rho_L^{0.49}}{\sigma^{0.5} \mu_L^{0.29} h_{LG}^{0.24} \rho_G^{0.24}} \right] \Delta T_{sat}^{0.24} \Delta P_{sat}^{0.75}$$

(h_{LG} is the latent heat of vaporization, subscript L is liquid phase, subscript G is vapor phase, ΔT_{sat} is the temperature difference between the inner tube wall [T_{wall}] and local saturation temperature [T_{sat}])

h_L is the liquid phase heat transfer coefficient given by the Dittus-Boelter correlation

$$h_L = 0.023 Re_L^{0.8} Pr_L^{0.4} \left(\frac{k_L}{d_i} \right) \qquad Re_L = \frac{\dot{m}(1-x) d_i}{\mu_L} \qquad Pr_L = \frac{c_{pL} \mu_L}{k_L}$$

Heat Transfer Correlations Used in Model

Evaporator wall to refrigerant (continued):

F is Chen's two-phase multiplier, and X_{tt} is the Martinelli parameter, which accounts for the two-phase effect on convection

$$F = \left(\frac{1}{X_{tt}} + 0.213\right)^{0.736} \qquad X_{tt} = \left(\frac{1-x}{x}\right)^{0.9} \left(\frac{\rho_G}{\rho_L}\right)^{0.5} \left(\frac{\mu_L}{\mu_G}\right)^{0.1}$$

S is the Chen boiling suppression factor:

$$S = \frac{1}{\left(1 + 0.00000253 Re_{tp}^{1.17}\right)} \qquad Re_{tp} = Re_L F^{1.25}$$

Chen, J.C. (1966). "A correlation for Boiling heat Transfer of Saturated Fluids in Convective Flow," *Ind. Eng. Chem. Process Ses. Dev.,* Vol. 5, No. 3, pp. 322-329.

Heat Transfer Correlations Used in Model

Heat transfer from air to pipe wall:

$$Q_{at} = \bar{h}_a A_o (T_a - T_t)$$

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

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

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.

A/C Model Development

Compressor Model

- Subscripts u and d are for upstream and downstream, respectively
- Mass flow rate:

$$\dot{m} = \rho_u \cdot \eta_{vol} \frac{dV}{rev} \cdot RPM/60$$

where $\eta_{vol} = \eta_{vol}(\frac{p_d}{p_u}, RPM)$ and dV/rev is the displacement per revolution

- Downstream enthalpy ($h_{d,actual}$) calculated using isentropic efficiency:

$$h_{d,actual} = h_u + \frac{h_{d,isentropic} - h_u}{\eta_{isentropic}}$$

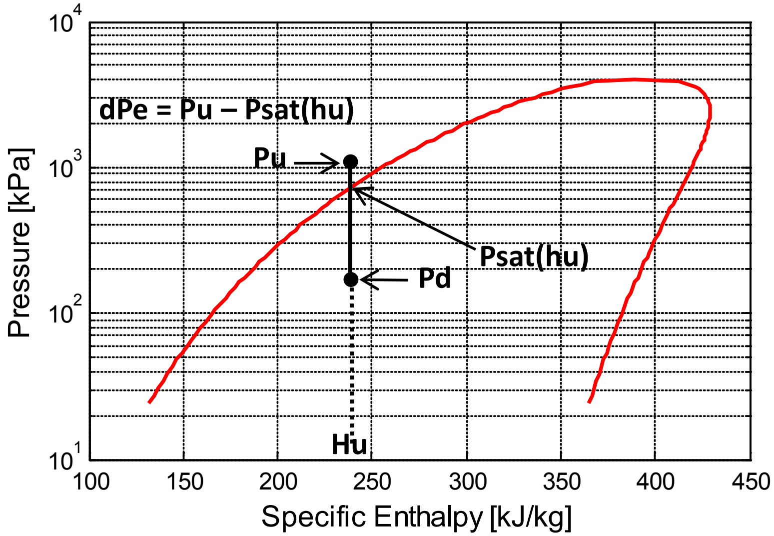
- where $h_{d,isentropic} = h(s_u, p_d)$ and $\eta_{isentropic} = \eta_{isentropic}(\frac{p_d}{p_u}, RPM)$

A/C Model Development

Thermal Expansion Valve (TXV) Model

- Two-phase equilibrium orifice flow model with feedback control on orifice flow area based on Evaporator-out superheat ('SH')
- Orifice flow model calibrated to measured data using a discharge coefficient that is dependent on dP_e

$$\dot{m} = C_d(\mathrm{d}P_e) \cdot \rho_{throat} \cdot v_{throat} \cdot A_{orif}$$



- Feedback control:

$$\frac{dA_{orif}}{dt} = -C \cdot (T_{SHtarget} - T_{SH})$$

- Large C results in quick convergence but may lead to hunting
- Small C results in slow convergence but avoids hunting