National Renewable Energy Laboratory
*Innovation for Our Energy Future*

# LDV HVAC Model Development and Validation

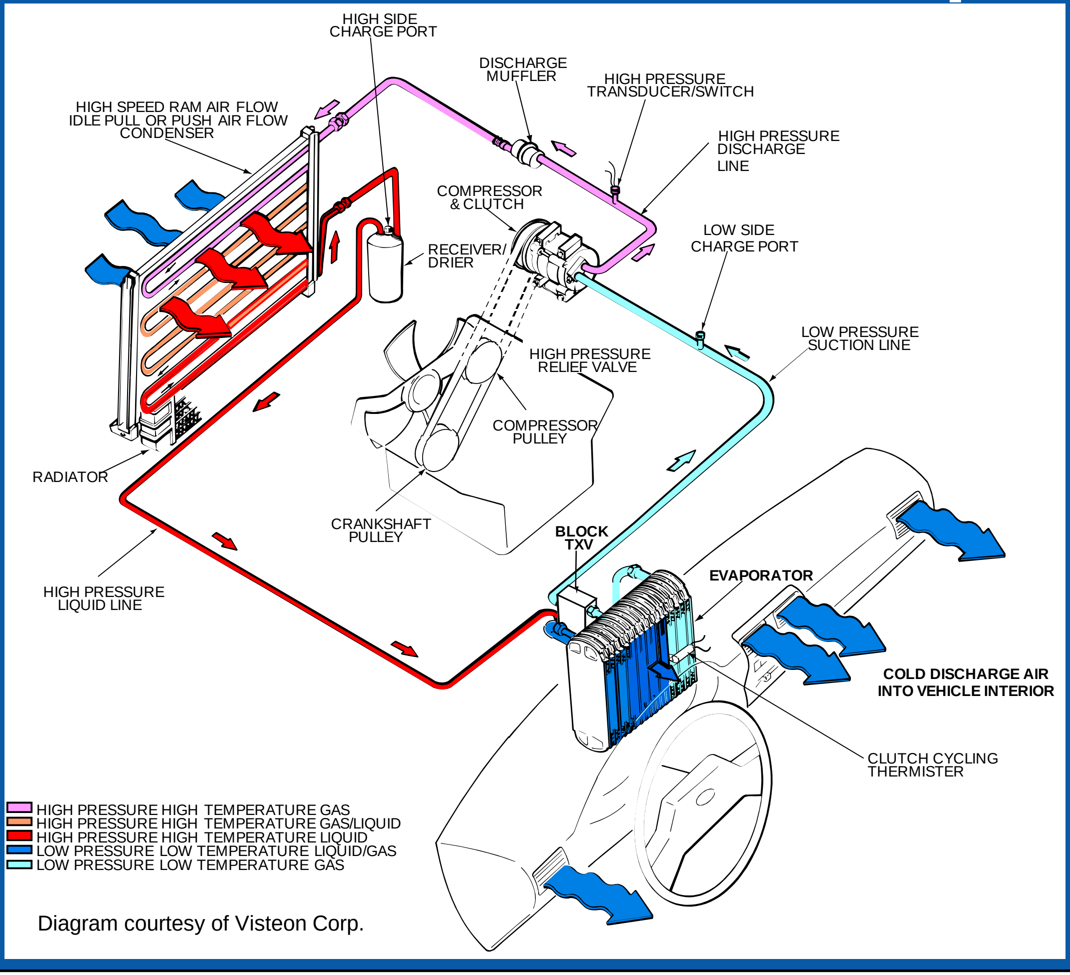


Diagram courtesy of Visteon Corp.

**U.S. Department of Energy Annual Merit Review**

**Presenter:**
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**National Renewable Energy Laboratory**

**P.I. : John Rugh**

**Wednesday May 11, 2011**

**Project ID: VSS045**

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

# Overview

## Timeline

- Project start date: FY11
  (leverage FY10 CoolCalc work)
- Project end date: FY12
- Percent complete: 25%

## Barriers

- Cost
- Computational models, design and simulation methodologies
- Constant advances in technology (require modeling and simulation tools to be updated)

## Budget

- Total project funding
  - DOE share: $300k
  - Contractor share: $0.00
- FY10 Funding: $0k
- FY11 Funding: $300k

## Partners

- Collaboration
  - Argonne National Laboratory
  - Visteon
- Project lead: NREL

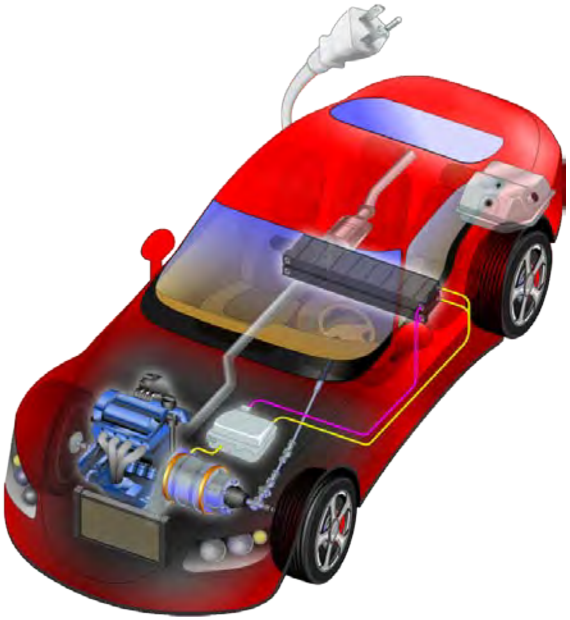
# Project Description - Relevance

## THE CHALLENGE

- A/C load is the largest auxiliary load.
- A/C loads account for more than 5% of the fuel used annually for light duty vehicles in the US*
- A/C load can have a significant effect on EV, PHEV, HEV performance.
  - Mitsubishi reports that the range of the i-MiEV can be reduced by as much as 50% on the Japan 10-15 mode when the AC is operating**
  - Hybrid vehicles have 22% lower fuel economy with AC on***
- Increased cooling demands by EV may impact AC system

## THE OPPORTUNITY

- Reducing A/C load will lead to increased acceptance of electric vehicles.
- Tool needed to assess impact on advanced vehicles.
- Will help to achieve the president's goal of 1 million EV by 2015.



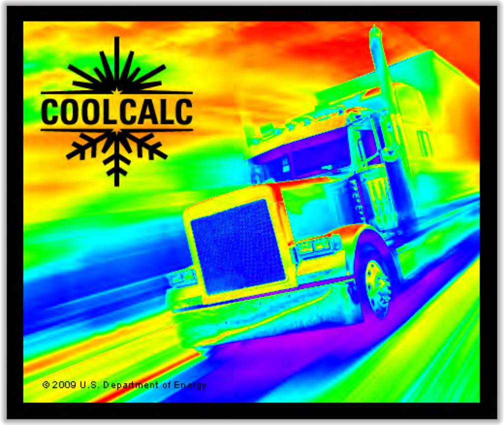
* *Rugh et al,* 2004 Earth Technologies Forum/Mobile Air Conditioning Summit.
** Umezu et. al, 2010 *SAE Automotive Refrigerant & System Efficiency Symposium*
*** *INEL – in Vehicle Technologies Program 2007 annual report, p145.*

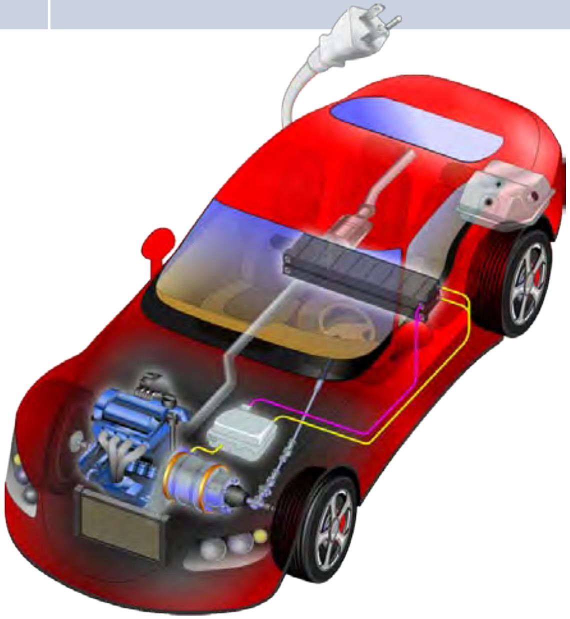
# Objectives - Relevance

- 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
  - To assist light-duty vehicle modeling, the A/C model framework developed in FY10 for heavy-duty vehicles will be modified to support light-duty vehicle simulations.
  - This light-duty A/C model will provide the basis for future development of a detailed, validated, heavy-duty vehicle A/C model.
- FY11 Objectives
  - Develop a light-duty vehicle (LDV) A/C model that simulates A/C performance and generates electrical and mechanical loads.
  - LDV A/C components will be developed and implemented in the model framework.
  - LDV A/C system simulations and the interface with Autonomie will be demonstrated.

# Milestones - Relevance

| Dates | Month | Key Milestone |
|---|---|---|
| 2010 | Apr | • CoolCalc AC model framework demonstrated |
| 2010 | Sept | • AC model framework integrated into CoolCalc |
| 2011 | August | • DOE Milestone summary report<br>• Demonstrate LDV system simulation<br>• Demonstrate integration with Autonomie |



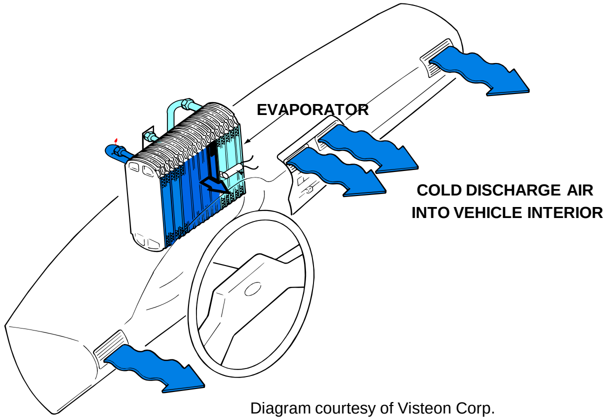



Diagram courtesy of Visteon Corp.

# Approach- Matlab/Simulink based simulation tool

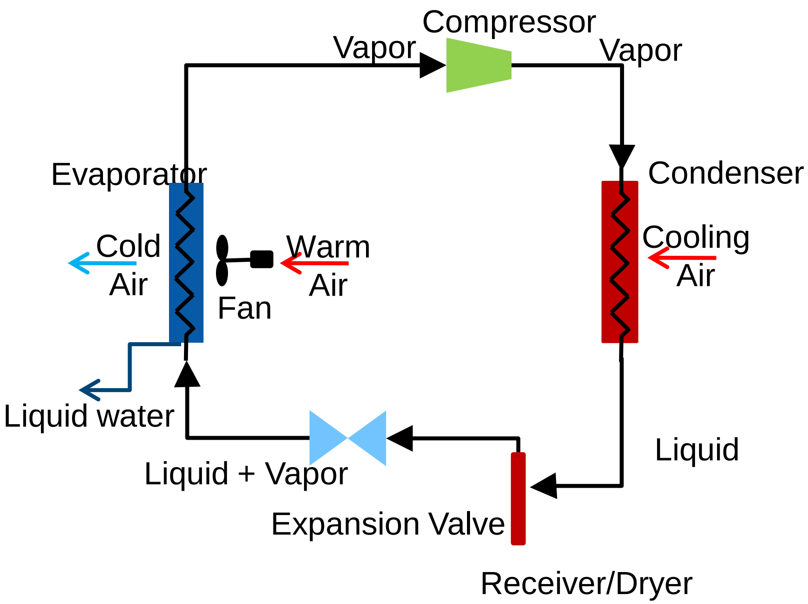
- Easily interfaced to Autonomie vehicle simulation tool.
- Flexible software platform, capable of modeling vapor compression refrigeration cycle.
- Model refrigerant lines and the heat exchangers as 1D finite volumes, accounting for the length-wise distribution of refrigerant and flow properties.
- Include all major components, such as the compressor, the condenser the expansion device, the evaporator, and the accumulator/dryer (receiver/dryer) in the refrigeration system.
- Is the basis for future development of a detailed, validated, heavy-duty vehicle A/C model.

# LDV HVAC Model - Accomplishments

## AC system model development

- 1-D Finite element formulation
- Fully transient model
- Model built up from line components
- Compression with adiabatic or volumetric efficiency as input

## Detailed models built up from basic line building block.



# LDV HVAC Model - Accomplishments

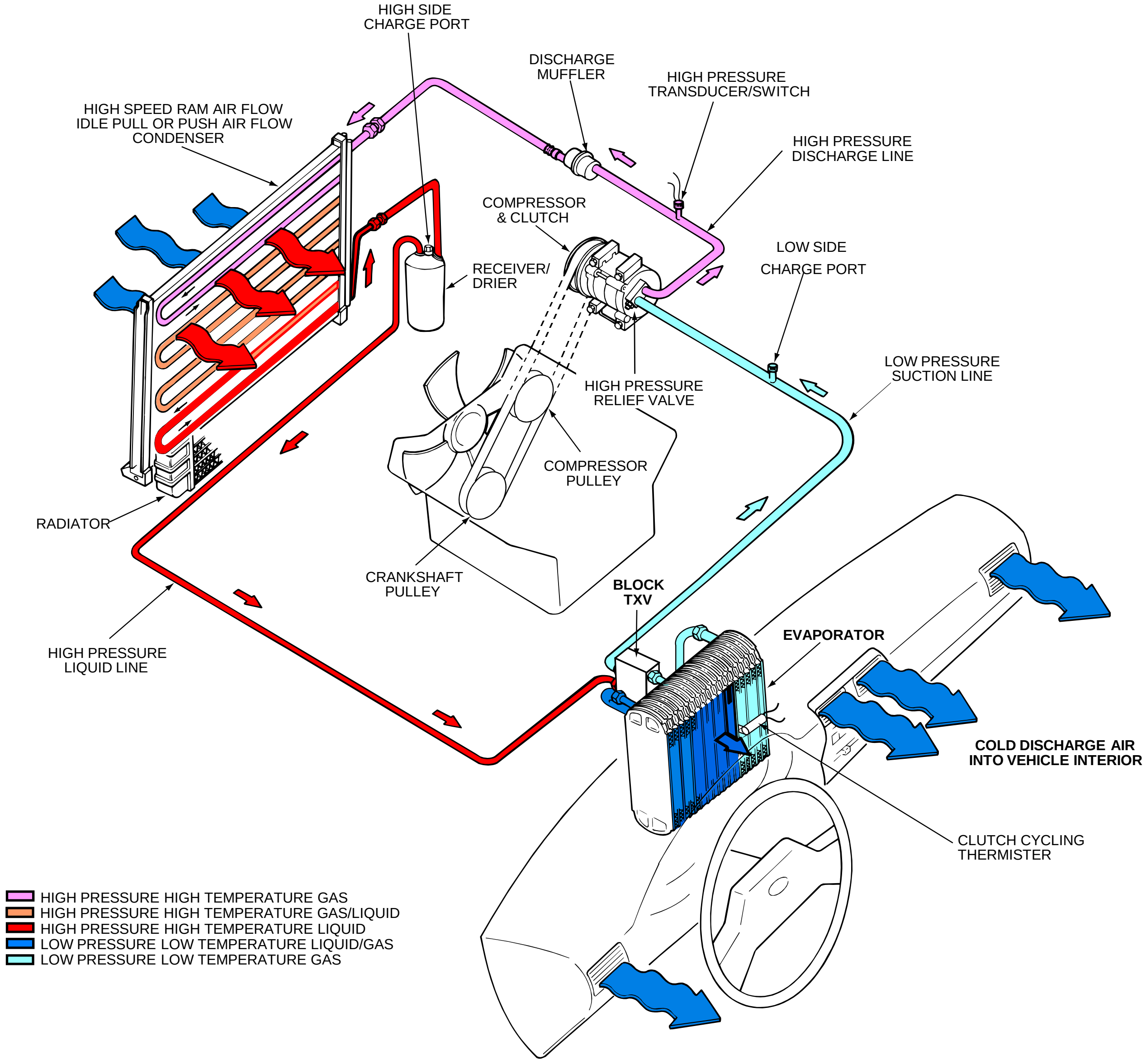



Diagram courtesy of Visteon Corp.

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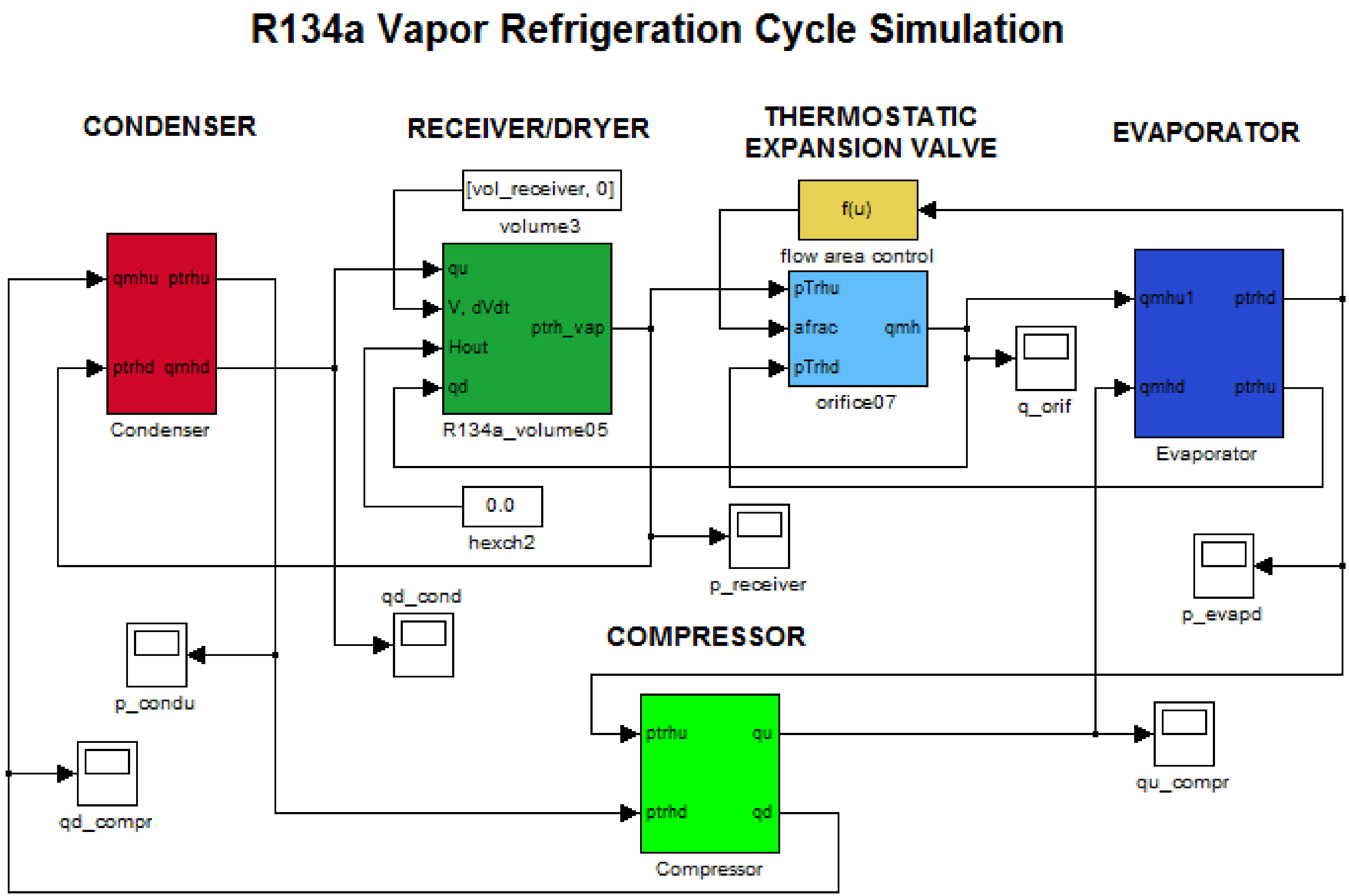
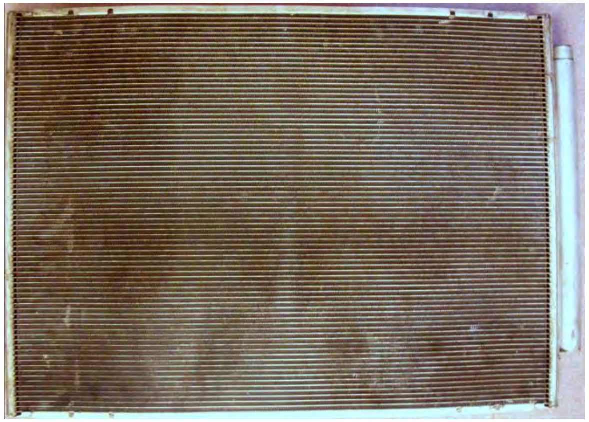


# LDV HVAC Model - Accomplishments



## Development of Component Models

## Example:  Condenser Model

## Complex heat exchanger

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

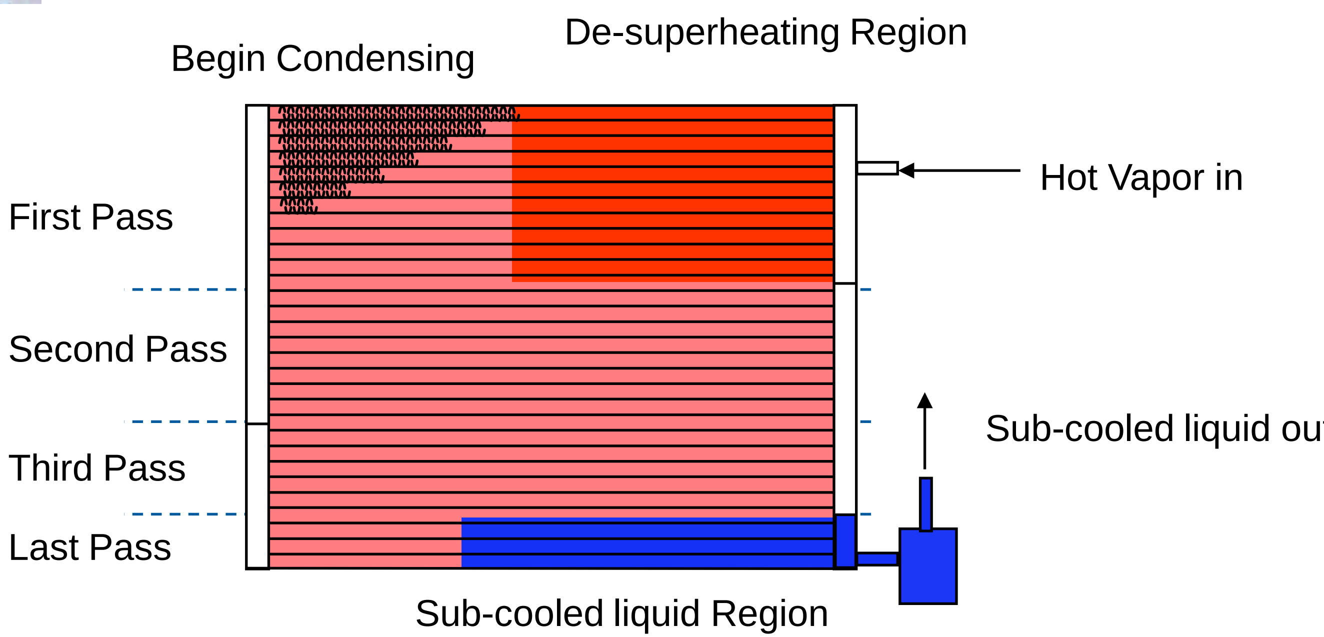
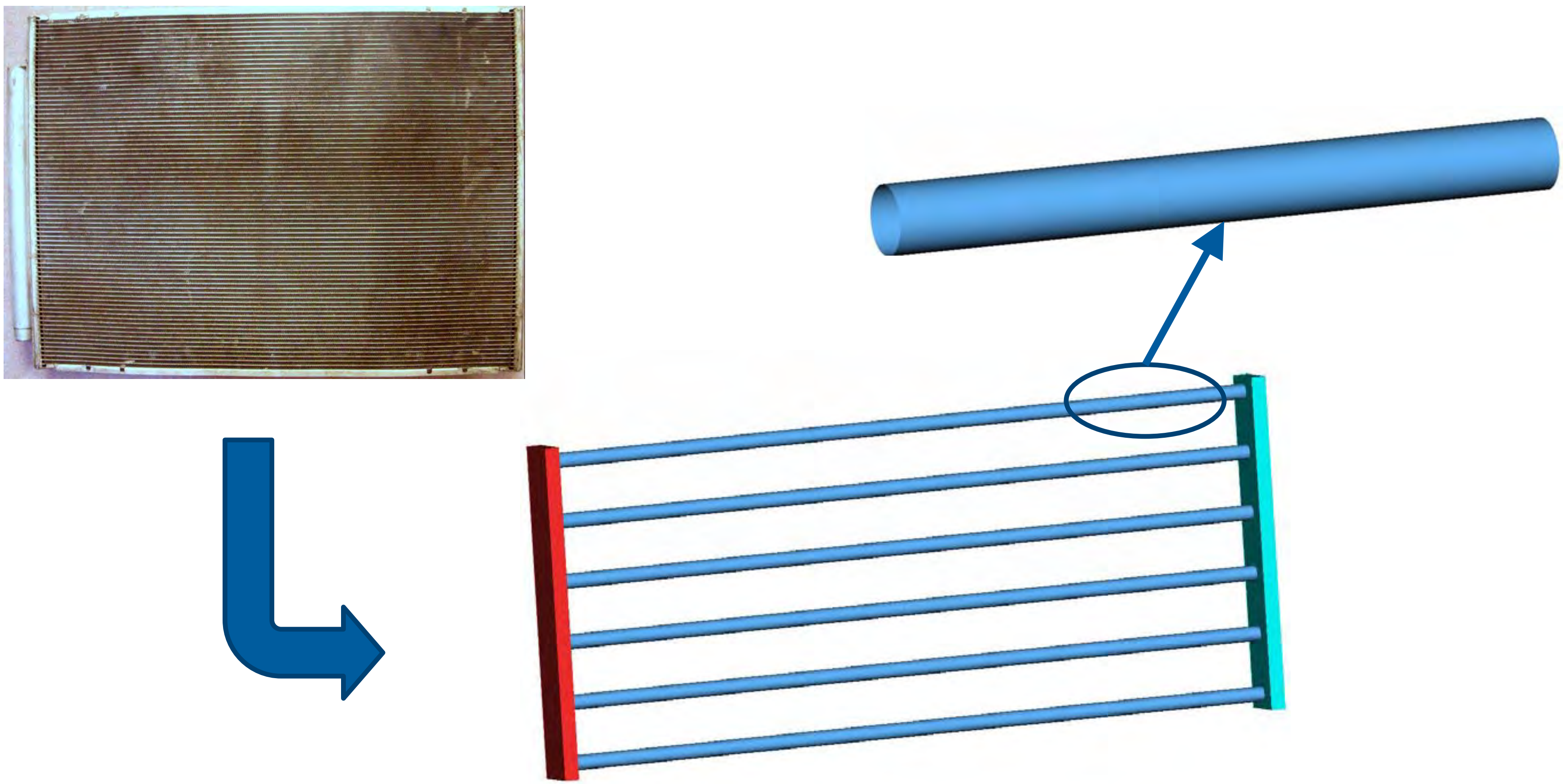



Diagram courtesy of Visteon Corp.

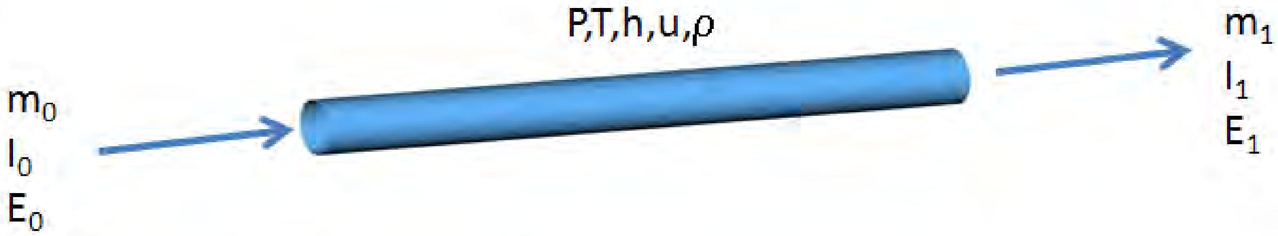
# LDV HVAC Model - Accomplishments



# LDV HVAC Model - Accomplishments

## 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:

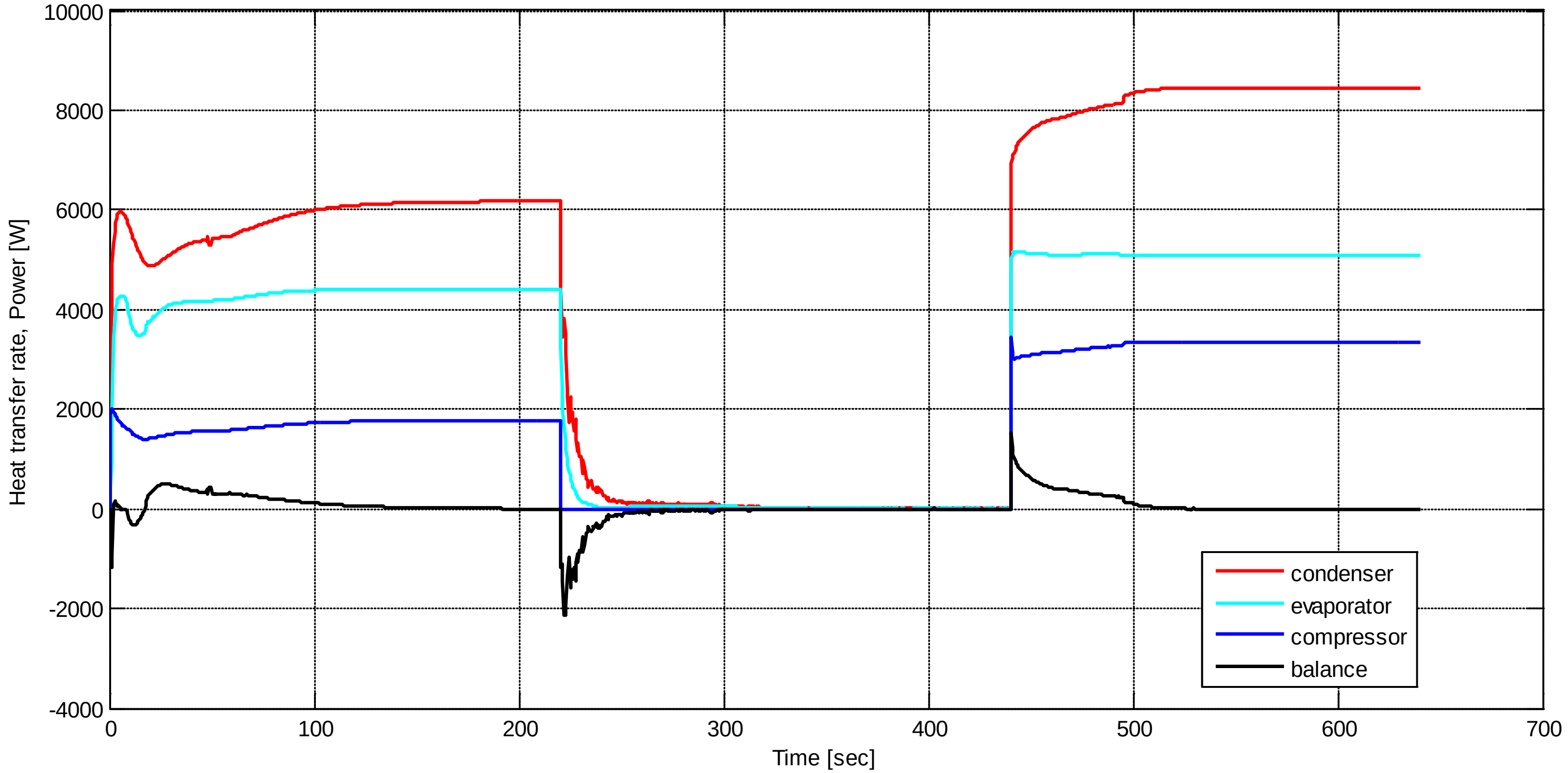
$$\frac{dE}{dt} = A v_{in}\left(p_{in} + u_{in}\rho_{in} + \rho_{in}\frac{v_{in}^2}{2}\right) - A v_{out}\left(p_{out} + u_{out}\rho_{out} + \rho_{out}\frac{v_{out}^2}{2}\right) + Q_{tr}$$

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)

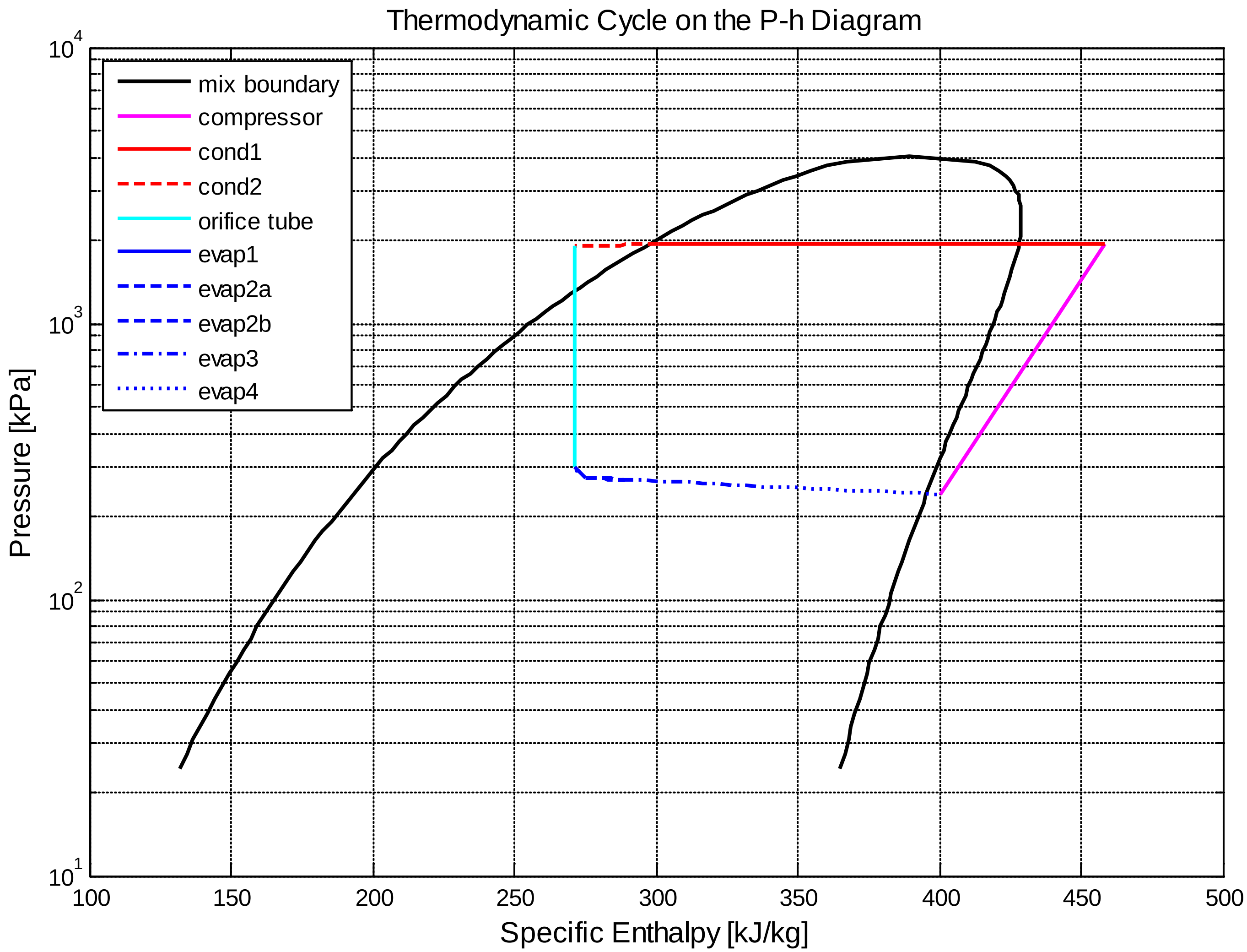
# LDV HVAC Model - Accomplishments

## System Model Transient Example



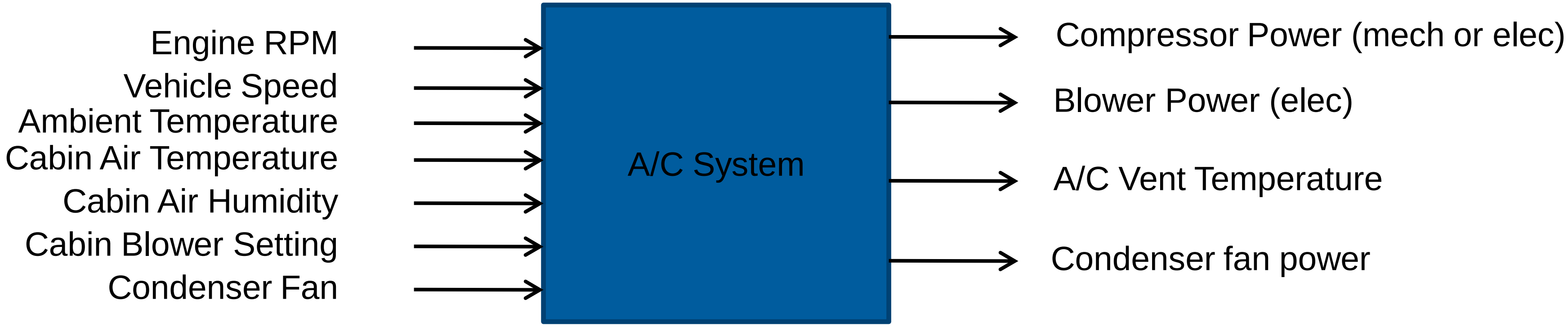
# LDV HVAC Model - Accomplishments

## System Model Transient Example



# LDV HVAC Model - Accomplishments

## System Integration
## A/C system inputs/outputs
## into/out of Automomie data bus



# Collaboration

- Argonne National Lab
- Visteon Corp.

# Future Work

- FY11
  - Complete component development.
  - Continue system development.
  - Develop simplified cabin thermal model.
  - Demonstrate integration with Autonomie.
  - Demonstrate LDV AC system simulations.
- FY12
  - Validate the LDV air conditioning model.
  - Add detail to the LDV air conditioning model as required.
  - Evaluate cabin thermal model.
  - Develop LDV AC system simulations for several classes of vehicles (small, midsize, suv, etc.).

# Summary

## DOE Mission Support

- AC use can account for significant portion of the energy used by LDV.
- Reducing AC energy use is essential to achieving the president's goal of 1 million electric drive vehicles by 2015.

## Approach

- Develop a Matlab/Simulink based model which is both flexible (to model various AC systems) and accurate.
- Interface AC model with Autonomie vehicle simulation tool, so that effects of AC use on vehicle efficiency can be modeled.

# Summary

## Technical Accomplishments

- Developed a Matlab/Simulink model of light duty vehicle HVAC system
  - 1D finite element basic line building block
  - AC system components developed
  - AC system performance demonstrated
  - Interface to Autonomie
  - Easy to change system and components based on input parameters

## Collaborations

- Argonne National Lab
  - Integration of AC model into Autonomie
- Visteon Corp.

# Contacts

## Special thanks to:

**Lee Slezak**
*Advanced Vehicle Technology Analysis and Evaluation*
*Vehicle Technologies Program*

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*Vehicle Technologies Program*

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# Technical Backup Slides

# Pressure Drop in Refrigerant Lines

The Darcy-Weisbach Equation: $dp = f\frac{L}{D}\rho\frac{v^2}{2}$

From which the term used in the momentum equation:

$$F_{wf}(= dpA) = -Af\frac{L}{D}\rho\frac{v|v|}{2}$$

The pipe friction factor for laminar flow (***Re*** < 2300): $f = \frac{64}{Re_D}$

The pipe friction factor for turbulent flow (***Re*** > 2300):

$$f = \frac{1.325}{\left[\ln\left(\frac{e}{3.7D} + 5.74/Re^{0.9}\right]^2}$$

where ***e*** is the relative roughness of the pipe inner surface.
(This latter equation is an explicit approximation formula for the well known Colebrook equation)

# Heat Transfer Equations Currently Implemented

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

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

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

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

where the film coefficient can be calculated with an equation valid on circular pipe placed in 90 degree cross-flow:

$$\overline{Nu_{D,a}} \equiv) \ \frac{\overline{h_a}}{k_a} D = C \, Re_{D,a}^m Pr_a^n (\frac{Pr_a}{Pr_s})\text{^}0.25$$

The actual coefficients ***C***, ***m***, ***n***, can be modified for a particular geometry