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Vehicle and Systems Simulation and Testing

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U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

IV.I. Light Vehicle HVAC Model Development and Validation

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IV.I.1. Abstract

Objective

- 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 (A/C) 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.
- Expand capabilities of Autonomie to include A/C loads in fuel economy simulations.

Approach

- Develop a flexible, open source, transient A/C model based on first principles 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, and Release A/C model plug-in for Autonomie.

Major Accomplishments

- Developed a transient A/C model based on first principles that simulates A/C performance and generates mechanical or electrical loads.
- The line model was enhanced to improve robustness and the heat transfer correlations were improved.
- The model was extensively validated to data provided by Visteon.
- Delivered standalone model to Visteon and GM.
- Integration into Autonomie was demonstrated and A/C models delivered to Argonne National Laboratory.
- First public release of open source A/C model.

Future Activities

- Alternative models of expansion devices will be developed and applied to investigate control strategies.
- Simplified solution options will be developed for more rapid, less detailed analysis, with a focus on vehicle co-simulation with Autonomie.
- A reasonable default A/C model will be built for class 8 heavy-duty vehicles.
- NREL will also work with Argonne National Laboratory's Advanced Powertrain Research Facility (APRF) to conduct vehicle-level A/C system performance validation.
- An updated A/C system model version will be released.

IV.I.2. Technical Discussion

Background

When operated, the A/C system is the largest auxiliary load on a vehicle. A/C loads account for more than 5% of the fuel used annually for light-duty vehicles in the United States [1]. A/C loads can have a significant impact on electric vehicle (EV), plug-in hybrid electric vehicle (PHEV), and hybrid electric vehicle (HEV) 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 [2]. The advanced powertrain research facility at Argonne National Laboratory has reported a nearly 20% reduction in range in the Nissan Leaf operating on the UDDS cycle [3]. HEVs have 22% lower fuel economy with the A/C on [4]. Increased cooling demands from the battery thermal management system in an EV may impact the A/C system. Air conditioning in heavy-duty vehicles also uses significant fuel in both down-the-road and idle conditions. A flexible, open source analysis tool is needed to assess the A/C system impact on advanced vehicles. Industry has expressed a need for both a standalone A/C system model as well as an A/C model that can co-simulate with a vehicle simulator such as Autonomie. This model expands the capability of Autonomie to address industry needs.

Introduction

The A/C system contains complex flow, thermodynamics, and heat transfer. On the refrigerant-side, the flow is transient and both compressible and two phase. Calculating refrigerant properties near the phase transitions can also be computationally difficult.

Air flow through the condenser can vary widely, depending on vehicle speed and condenser fan speed. Heat is transferred from the refrigerant through the oil film and to the metal heat exchanger surface, then from the heat exchanger surface to the air.

Simulation of air flow through the evaporator must account for condensation of water vapor from the humid air stream. The result is that the mass flow of air through the evaporator is constantly changing. The latent heat of water vapor condensation can account for a significant portion of the evaporator heat load. Heat is transferred from the air through the layer of condensed water on the heat exchanger surface to the metal of the heat exchanger, then through the oil film to the refrigerant.

A cabin model is also needed to provide a realistic load on the evaporator. The cabin model must consider all the major pathways of heat transfer into the cabin, including solar and convective loads from the environment, heat from the engine compartment, and sensible and latent heat loads in the air stream.

Approach

Matlab/Simulink was chosen as the platform to develop the model. Using this platform has several advantages. Autonomie is also built on Simulink, which will facilitate integration of the model into Autonomie. Matlab/Simulink is widely used in industry, so the standalone, open source version of the A/C model can be widely distributed.

The A/C system simulation uses control volume simulation blocks and line simulation blocks. Conservation of mass and energy is implemented in the zero-dimensional control volume blocks. Conservation of mass, momentum, and energy are implemented in the one-dimensional line simulation blocks. The mathematical description is shown in Figure 1. All refrigerant thermodynamic and material properties are determined from two-dimensional tables based on specific internal energy and density. The receiver/dryer and headers are modeled with the control volume blocks. The heat exchanger elements are modeled with the line simulation blocks. Condensation of water from air is accounted for in the evaporator model.

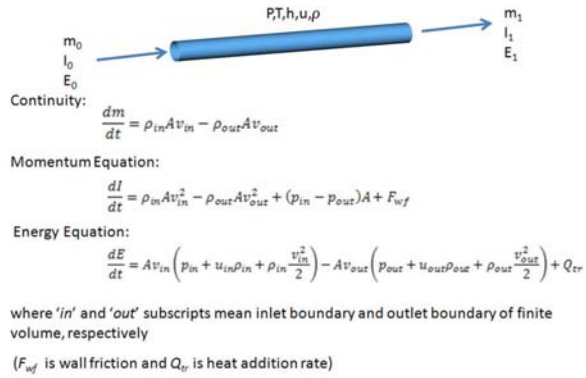

Figure 1. Conservation equations solved in refrigerant lines.

Heat transfer correlations are needed to account for the heat transfer from the air to the tube wall and from the tube wall to the refrigerant. The process is illustrated in Figure 2.

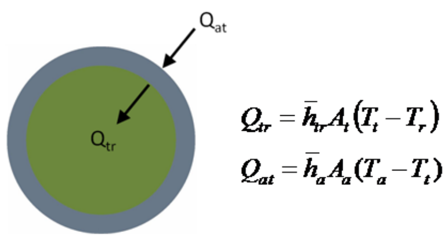

Figure 2. Tube to refrigerant and air to tube heat transfer schematic.

Separate heat transfer correlations are used for the air to tube heat transfer (Q_{at}) and from the tube wall to the refrigerant (Q_{tr}). The heat transfer correlation for the air to tube wall heat transfer (h_a) is based on the Chang and Wang [5] correlation for heat transfer in compact heat exchangers with louvered fins. The heat transfer correlation for the tube wall to refrigerant (h_{tr}) is based on the Chen [6] correlation and the Dittus-Boelter [7] correlation.

A schematic illustrating how the condenser model is built up from line blocks is shown in Figure 3. This condenser has four passes. Each pass consists of several flat tubes connected to a common header. The model assumes equal flow per flat tube, so the flow in each pass is a multiple of the flow in a single flat tube. Each flat tube in the condenser has several parallel channels. The refrigerant flows in the parallel channels are also assumed equal, so the flat tube refrigerant flow can be modeled as a multiple of the flow in a single channel. A single channel is then divided into a number of lengthwise segments, and each segment is modeled as described in Figure 1.

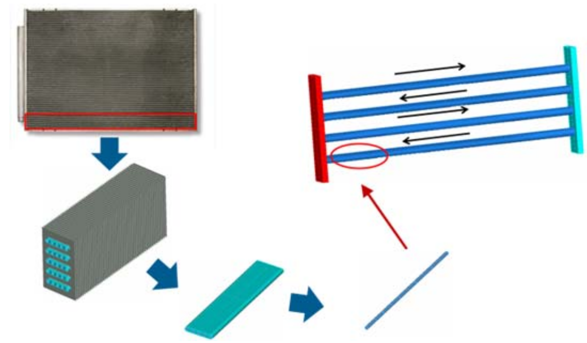

Figure 3. Condenser model schematic.

At the outlet of the condenser a single volume element is used to model the receiver-dryer component.

The thermostatic expansion valve (TXV) shown in Figure 4a is modeled as a two-phase equilibrium orifice flow model. A proportional with integral (PI) controller is used to adjust the orifice opening to maintain a set superheat at the outlet of the evaporator. This approach does not include the dynamics of the mechanical bellows, spring, and plunger in a TXV, but it does capture the performance of the refrigerant flow needed to maintain a set refrigerant superheat at the evaporator outlet. A recently developed, more detailed version of the model calculates the valve flow area opening based on the static balance of forces on the moving valve stem, and calculates the delayed response of the bulb temperature to change in evaporator exit temperature based on a user-input characteristic time.

The evaporator was modeled similarly to the condenser. In the evaporator model, the condensation of water vapor on the exterior of the tubes is also accounted for. The suction line leading from the evaporator to the compressor was not modeled. However, the refrigerant vapor pressure drop in the suction line and the effect on refrigerant properties were included.

The compressor shown in Figure 4b was modeled using a compressor map or lookup table. Both volumetric efficiency and isentropic efficiency as a function of compressor rpm and pressure ratio were used to evaluate refrigerant flow and compressor power. An electrically driven version of the compressor model was also developed. The electrical compressor is not dependent on engine speed, so controls had to be developed to adjust the compressor speed based on cooling demand.

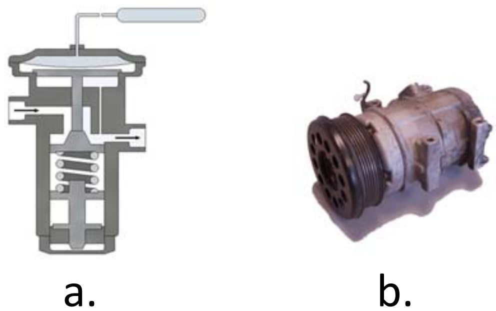

Figure 4. a. Thermostatic expansion valve, b. Compressor.

A cabin model was developed last year for incorporation with the A/C model [8]. The model is a lumped thermal mass with inputs for the thermal loads (Figure 5). This year the model was enhanced by splitting the thermal mass into interior (seat, console, instrument panel, etc.) and exterior (roof, doors, etc.) masses.

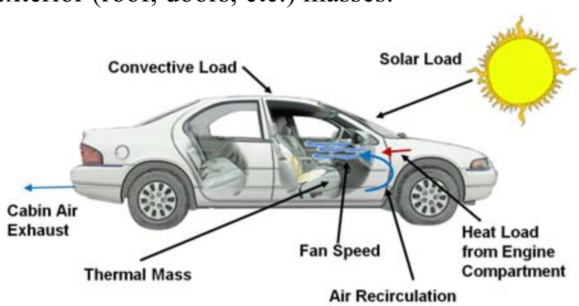

Figure 5. Vehicle cabin thermal parameters.

A schematic illustrating the integration of the A/C and cabin model with Autonomie is shown in Figure 6. The blue and green lines indicate the information flow between the A/C model and the cabin model. The black lines show the information flow to and from Autonomie.

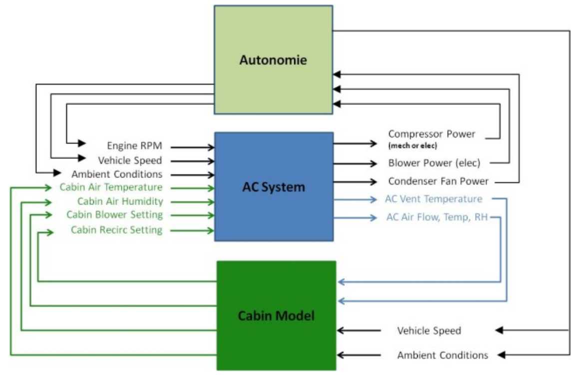

Figure 6. System integration schematic

A dead band temperature control and high- and low-limit pressure controls were implemented in the mechanical compressor A/C model. A more sophisticated PI controller for the compressor was implemented in the electric A/C model.

Results

Validation

In FY 2011 the A/C model was evaluated for functionality. In FY 2012 the model was extensively validated against data sets provided by Visteon. The data sets represented various conditions, including vehicle speed from idle to 60 mph, several blower speed settings, ambient conditions, and condenser airflow rates. The measured and calculated refrigerant flow rates for 22 conditions are shown in Figure 7. The results show very good comparison to measurements. The average error between simulation and measurements is 1.7%. The data have been non-dimensionalized to preserve confidentiality.

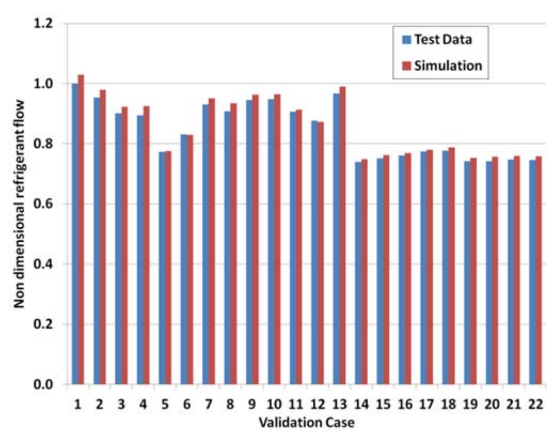

Figure 7. Non-dimensional refrigerant flow rate.

The measured and calculated heat transfer from the condenser for the 22 conditions in the data set is shown in Figure 8, and the comparison of evaporator heat transfer is shown in Figure 9. The data in Figures 8 and 9 have been non-dimensionalized to preserve confidentiality. The average error between the measured data and the simulation results is 1.9% for the condenser and 2.7% for the evaporator.

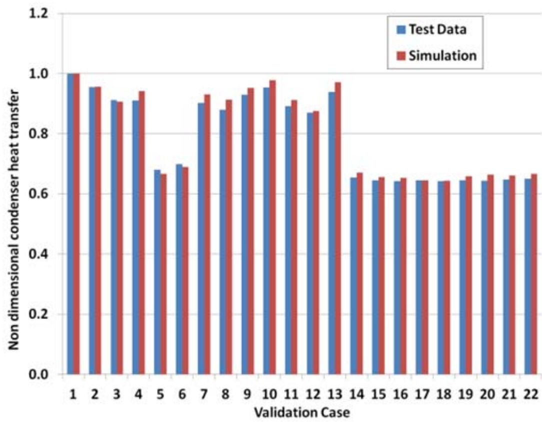

Figure 8. Non-dimensional heat transfer from condenser.

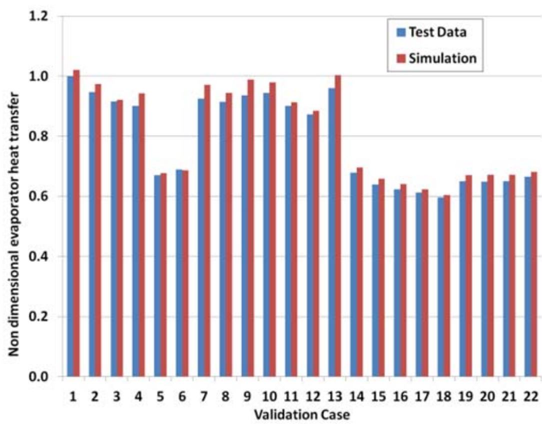

Figure 9. Non-dimensional heat transfer from evaporator.

The results show that the model can correctly predict heat transfer from the heat exchangers.

Figure 10 shows the comparison of evaporator outlet air temperature. The average error between measured data and simulation results was 1.8% for the evaporator air outlet temperature.

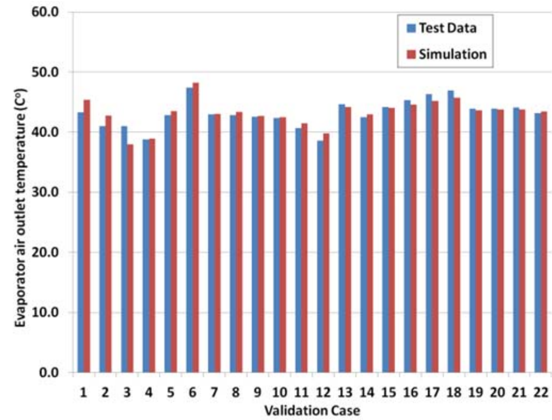

Figure 10. Evaporator air outlet temperature.

The results show that the model can correctly predict the performance of this complex, multi-pass heat exchanger.

Figure 11 shows the complete thermodynamic cycle on a P-h diagram. This figure is representative of the results obtained for each of the 22 points and shows that the model correctly predicts the thermodynamics of the refrigeration cycle.

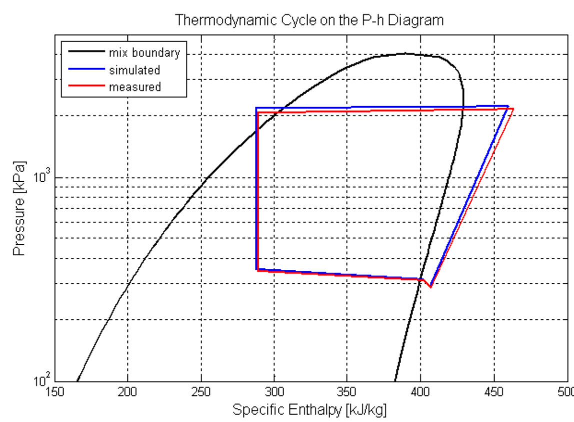

Figure 11. Thermodynamic cycle.

Autonomie Integration

The integration of the NREL A/C model into Autonomie is illustrated in Figures 12 through14. The upper-level Simulink block diagram of the A/C model is shown in Figure 12, and the Simulink diagram of the A/C model and cabin model is shown in Figure 13. Figure 14 shows the component level of the A/C Simulink model.

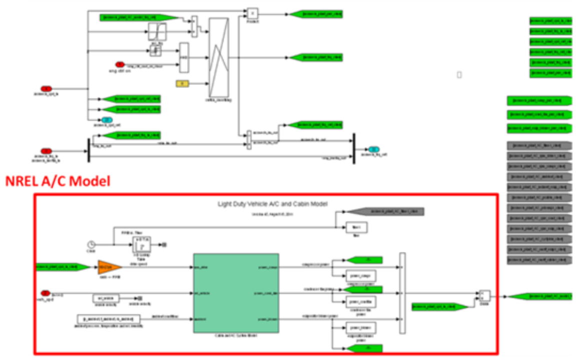

Figure 12. Top level of the Simulink A/C model.

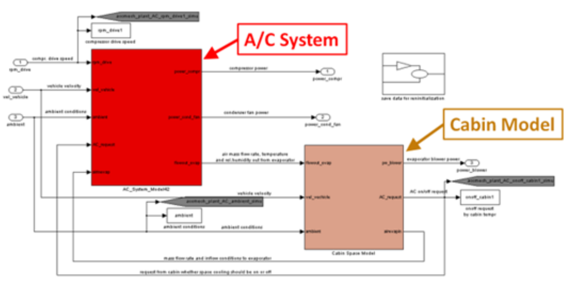

Figure 13. A/C system and Cabin model

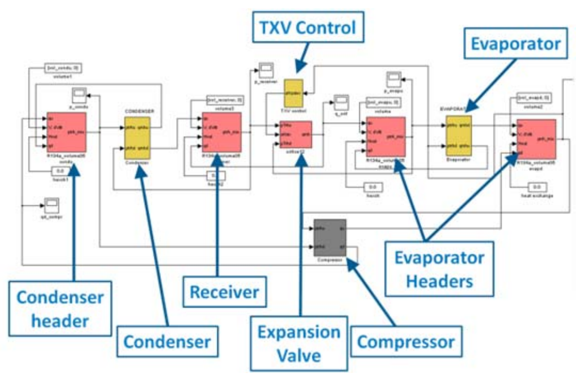

Figure 14. Component level A/C system block diagram.

The A/C model was co-simulated in Autonomie using a default midsized automobile on the SC03 drive cycle. Figure 15 shows engine and compressor speed in rpm. The compressor follows the engine rpm. The compressor power, and condenser and evaporator heat transfer dynamics all follow the rapidly changing compressor speed. Note that the compressor begins to cycle at approximately 90 seconds (as indicated by the vertical dashed line) because the cabin temperature has reached its set point.

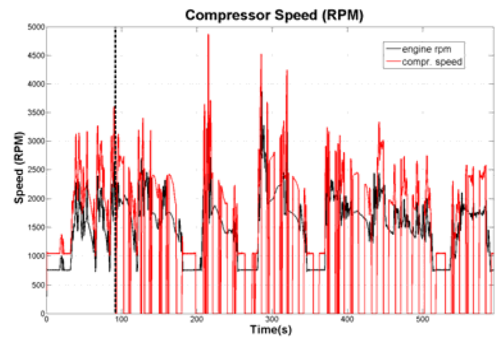

Figure 15. Engine and compressor speed.

Figure 16 shows the compressor power requirement and the condenser and evaporator heat transfer. This model uses a mechanically driven compressor, so the compressor power and heat transfer are affected by the rapidly changing engine rpm as well as the cycling of the compressor.

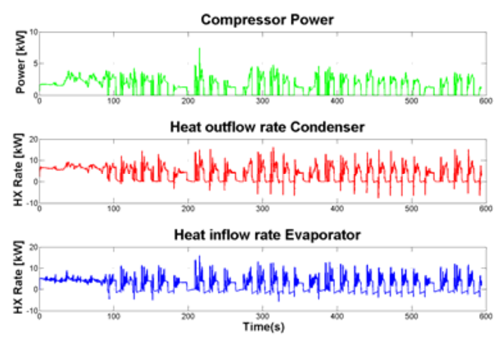

Figure 16. Heat transfer and compressor power.

Figure 17 shows the cabin air temperature and the dead band control signal. The dead band control switches the compressor off when the cabin temperature falls below the “target offset” temperature and switches the compressor back on when the temperature rises above the target temperature. The model cycles the compressor capturing the behavior that occurs in an actual automotive A/C system.

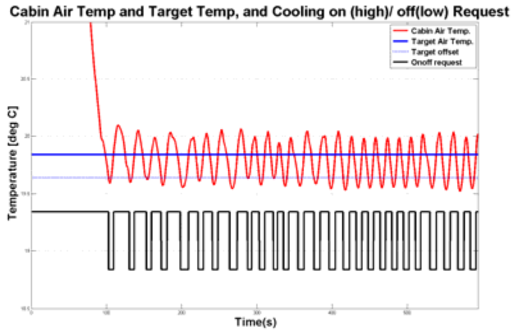

Figure 17. Cabin air temperature, control signal, and control upper and lower limits.

The simulation results show that the use of A/C results in a reduction in fuel economy of 14.7 percent, with an A/C COP of approximately 2.

Conclusions

A Matlab/Simulink model of a light-duty vehicle HVAC system was developed. The system is built up from components. The components were developed using a one-dimensional finite volume basic line building block. The line building block was enhanced to improve robustness and speed. The heat transfer correlations used in the model were enhanced. The model was extensively validated to component and system data provided by Visteon. The model results were within 2 percent of the test data. A version of the model was also developed that uses an electrically driven compressor.

The model was co-simulated in Autonomie using a default midsized automobile over the SC03 drive cycle. The results show a 14.7% increase in fuel consumption with A/C on.

A standalone version of the A/C model was released to key industry partners. The standalone model as well as the Autonomie integrated model was released to the public in September.

References

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2. Umezu et al., 2010, SAE Automotive Refrigerant & System Efficiency Symposium.
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5. 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.
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7. F. W. Dittus and L. M. K. Boelter, “Heat Transfer in Automobile Radiators of the Tubular Type,” *Publications in Engineering*, Vol. 2, p, 443, University of California, Berkeley (1930).
8. 2011 NREL annual report to DOE, “LDV HVAC Model Development and Validation,” VSST Vehicle Simulation and Modeling.

IV.I.3. Products

Publication

1. Paper offered for SAE congress 2013.

Patent

1. Software Copyright CoolSim.

Tools & Data

1. NREL's open source HVAC model, CoolSim, has been released in standalone and Autonomie software plug-in versions

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