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ABSTRACT

This paper describes a vehicle-level simulation model for climate control and powertrain cooling developed and currently utilized at GM. The tool was developed in response to GM's need to speed vehicle development for HVAC and powertrain cooling to meet world-class program execution timing (18 to 24 month vehicle development cycles). At the same time the simulation tool had to complement GM's strategy to move additional engineering responsibility to its HVAC suppliers. This simulation tool called "e-Thermal" was quickly developed and currently is in widespread (global) use across GM. This paper describes GM's objectives and requirements for developing e-Thermal. The structure of the tool and the capabilities of the simulation tool modules (refrigeration, front end airflow, passenger compartment, engine, transmission, Interior air handling …) is introduced. Model data requirements and GM's strategy for acquiring component data are also described. The paper includes an example of a typical application of the tool with sample output from the simulation and some comparison to actual test data from a vehicle under the same test scenario.

INTRODUCTION

The HVAC/Powertrain Cooling (HVAC/PTC) engineering function in General Motors is in a race to adopt new methodologies and tools which speed product development at reduced costs. This paper will describe e-Thermal; an analytical tool developed by GM to speed HVAC/PTC development at the sub-system, system and vehicle level. This tool employs 1-D thermal and fluid models of HVAC/PTC components, fluid networks, air handling hardware and powertrain (engines and transmissions) coupled with simplified control models to simulate the complete transient behavior of the vehicle for climate control (interior heating and cooling) and powertrain cooling test scenarios. As such e-Thermal can in many cases replace and/or supplement vehicle-level hardware testing performed on-road or in climatic wind tunnels resulting in faster, cheaper and more robust HVAC/PTC system development. This paper describes e-Thermal's development goals, model architecture, model functionality, and simulation capability (correlation to test data).

TOOL DEVELOPMENT GOALS

GM HVAC/PTC has developed several system-level analytical performance simulation tools over the past several decades. e-Thermal was intended to build on the momentum of these tools while overcoming several operational difficulties as follows:

1. Usability of the tool for all HVAC/PTC engineers with varying roles,

2. Availability of the tool for all HVAC/PTC engineers with varying roles

3. Correct balance of accuracy versus run-time speed of the simulation

4. Facilitating acquisition and implementation of HVAC/PTC component data for varying levels of supplier involvement and design responsibility

5. Flexibility and expandability of the tool

6. Right-sizing GM internal support effort (manpower and other IT cost)

In order to meet these needs e-Thermal development requirements were established as follows:

1. Tool must be PC-based (rather than run on workstation to meet availability need)

2. Tool must have a reasonably intuitive Graphical user Interface (to address usability need)

3. Tool must leverage 1-D energy and momentum representations of system components, fluid loops and air handling subsystems (appropriate trade-off of between accuracy, resolution, and run-time speed)

4. Tool must have both a component library as well as user-defined component models (to facilitate component data needs)

5. Tool must have an underlying data, model and user interface architecture that allows the tool to grow with new component and system technologies.

6. Tool must leverage (as much as possible) commercially available user interface, database and thermal modeling software (to balance GM support need)

As such, the first version of e-Thermal was launched in December of 2001 as a Microsoft Windows-based application that was available to the GM HVAC/PTC engineering community. e-Thermal utilizes thermal models developed in Sinda/Fluint (a 1-D thermal and fluid network simulation tool by Cullimore and Ring Technologies) that results in models with simulation times that are typically real time or faster, depending on number and types of modules chosen and the complexity of the drive scenario to be simulated. It also utilizes a GM proprietary Graphical User Interface (GUI) developed by an outside software firm that is flexible and expansible (see figure 1). The GUI and component data are archived and distributed in MS Access databases. e-Thermal currently allows users to couple simulations with GM's corporate vehicle driveline model (in Matlab/Simulink) so that the interplay between HVAC/PTC thermal performance and overall vehicle dynamics (e.g. thermally induced shift pattern changes, engine r.p.m. adjustments, …) seen in actual vehicle tests are reflected by the simulation.

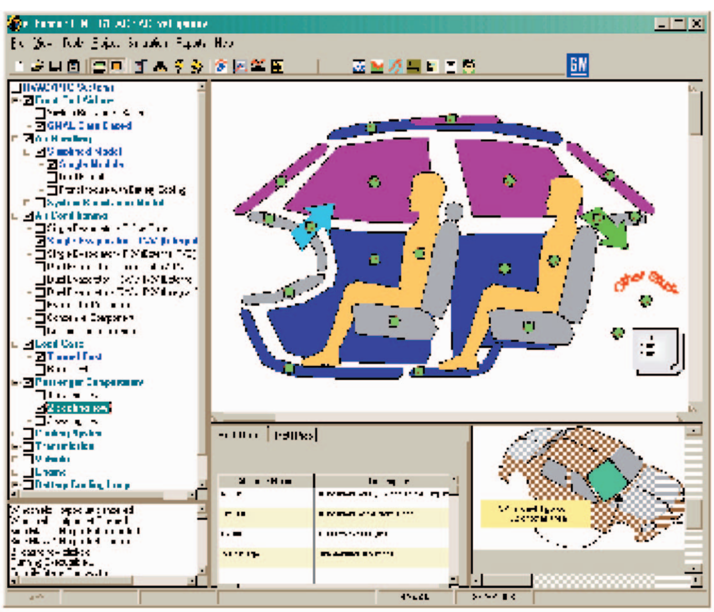

Figure 1 - e-Thermal Graphical User Interface (GUI)

MODEL ARCHITECTURE

e-Thermal is built around the concept of modules. In particular e-thermal is broken into nine distinct modules as shown in Figure 2. Each module can have numerous variations that reflect varying model complexity and/or varying HVAC/PTC hardware arrangements. For example, the interior air handling module allows the user to choose between modeling schemes which are highly empirical and rely heavily on performance maps from sub-system testing or simulation. However, the interior air handling model also has an analogous modeling scheme which utilizes detailed blower, motor and heat exchanger performance data to predict the same values that were derived through a table look-up on in the simplified model.

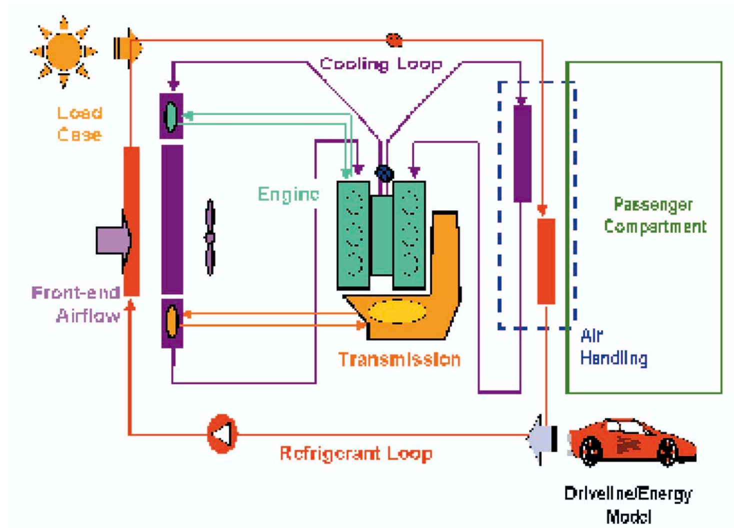

Figure 2 - e-Thermal Modules

Modules can vary in hardware content and/or complexity, however each modules definition has key distinct inputs and outputs that are required to allow their integration into the e-Thermal architecture. Figure 3 shows a general data flow diagram and an example of a specific data flow diagram for the passenger compartment module. The diagrams show the input data required from users as well as the inputs required from other e-Thermal modules (Note: the architecture dictates that this input can only come from simulations of the noted module or it must be supplied by the end user in the absence of the modules). The diagram also illustrates the intrinsic module outputs (those desired /required by the end user) as well as those outputs that are required by other e-Thermal modules. e-thermal users are encouraged to use their experience and knowledge to understand which modules are required for a simulation and which modules can be neglected . In this way overall input complexity can be reduced and in many cases required input quality can be enhanced where the user has better data for required inputs rather than relying on a module to simulate the required input. Additionally, reduced complexity models result in faster simulation run-times.

The module architecture also allows for future expansion and enhancement of the system-level simulations. Since e-Thermal's introduction, new modules for power electronic cooling loops have been integrated to support hybrid vehicle development.

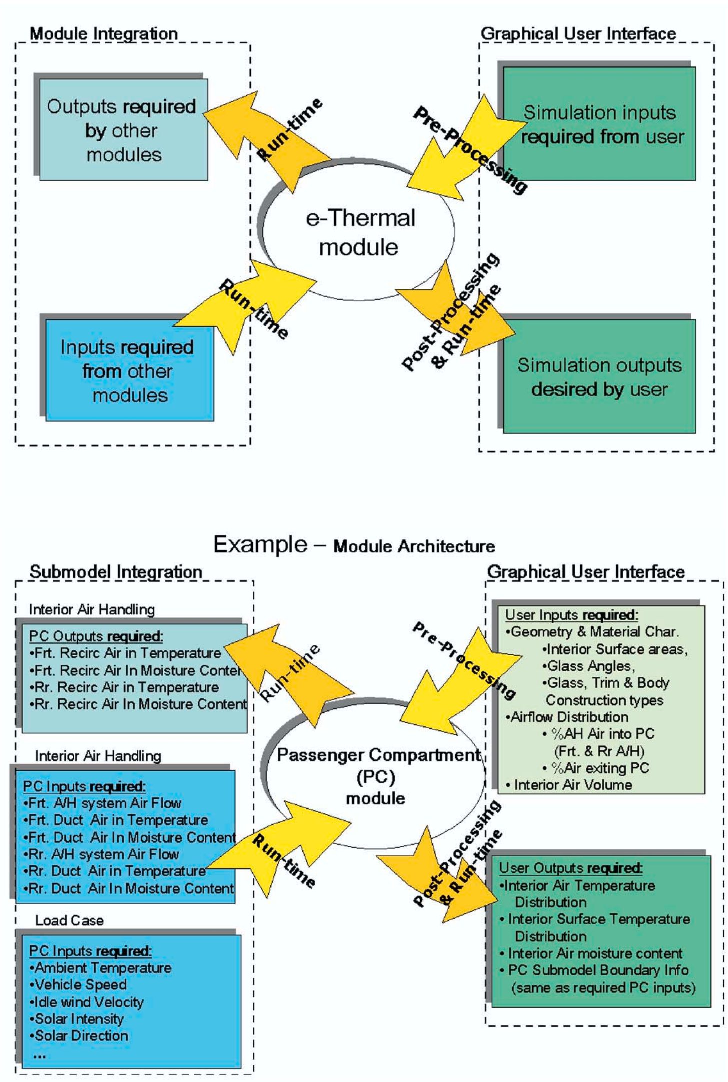

Figure 3 – e-Thermal Module Architecture

MODULE FUNCTIONALITY

The next several sections will describe the basic functionality and capability of each e-Thermal module.

FRONT END AIRFLOW MODULE

The front end airflow (FEA) module provides estimates of airflow through all the heat exchangers (e.g. radiator, condenser, oil cooler) typically packaged into the front end of the vehicle. The FEA module utilizes two different modeling schemes; a simplified "GMAL" model which estimates front end airflow from a performance map derived from isothermal vehicle-level wind tunnel tests and a second "resistance-based" model which utilizes heat exchanger airside pressure vs. flow data, fan/motor performance maps, and front end "characteristic-curves" to predict heat exchanger airflow.

The simplified airflow model is generally used for "legacy" vehicle programs where detailed component data was not acquired and a vehicle front end "characteristic curve" was not developed. The "characteristic curve" is a modeling construct which backs out the airflow pressure potential (e,g. pump-characteristic) and engine compartment resistance as a function of vehicle speed. The simplified FEA model instead uses a table look-up of heat exchanger airflow as a function of vehicle speed and fan state. At idle conditions it provides a transient empirical estimate of front-end inlet airflow temperature rise due to the recirculation of hot under hood airflow.

The resistance-based FEA model is generally used for new vehicle programs where detailed component data (generally from HVAC/PTC suppliers) is required as part of the commercial sourcing agreement. The vehicle characteristic curve can be developed from CFD analysis of the front end or from front end airflow measurements acquired during full vehicle aerodynamic testing. Further, the location of the heat exchangers and fan components (relative to each other) must be input. This model like the simplified model has an empirical model of front-end recirculation/leakage at idle. This model also estimates fan motor current draw for electrically powered systems. Both models have input for system control logic (dubbed "fan modulation") based on common vehicle inputs (coolant temperature, A/C head pressure, vehicle speed, …).

AIR HANDLING MODULE

The air-handling (AH) module provides estimates of airflow and temperatures throughout the interior air handling components (HVAC Modules). Like the FEA module, the AH module utilizes two main modeling schemes; a "simplified model" and a system resistance based model. Similar to the FEA simplified model, the air handling simplified model utilizes tabular HVAC flow measurements from isothermal vehicle/bench tests to estimate the airflow through the HVAC heat exchangers (typically Evaporator and heater core) and airflow into the passenger compartment. The resistance based AH model utilizes much more detailed component-level air-side pressure drop data (heat exchangers, blower, blower motor…) to estimate the airflow, pressure drop and current draw of the Interior air handling system. This module also integrates heat exchanger energy addition (loss) and computes the various airflow temperatures along the path of the HVAC module. Module variants exist to handle front-only HVAC systems as well as front and rear HVAC configurations (typically used on van and sport-utility vehicles)

REFRIGERANT MODULE

The refrigerant (AC) module provides estimates of refrigerant heat exchange at the refrigeration component's heat exchange as well as refrigerant pressures, temperatures and mass flow rates around the system. The system tracks the distribution of charge and the effects of charge level on system performance. The evaporator model predicts both latent and sensible heat transfer with the HVAC Module Air. The module has numerous plumbing variations to handle various combinations of numbers of evaporators and/or different styles of expansion devices (e.g. single evaporator - orifice tube, dual evaporator –dual TXV). The underlying refrigerant model utilizes two-phase heat transfer correlations and predictions of refrigerant quality are available at inlet and outlet of all the refrigerant components. Currently, e-Thermal only provides R134a as a working refrigerant and has a very large R134a component database. The architecture can easily be expanded to handle other refrigerants given that component performance data specific to the desired refrigerant is available.

ENGINE MODULE

The engine (EN) module provides estimates of heat exchange to the coolant and engine oil. At the heart of the engine model is a per unit cylinder thermal model of the engine that predicts. [1,2,3]

1. heat generation and exchange due to combustion,
2. thermal conduction between the engine structural components,
3. convective heat exchange of coolant, oil and under hood air with the engine structure,
4. frictional heat generation in the cylinder, and
5. thermal inertia based upon the material types and mass.

These unit cylinder models are combined with appropriate coolant and oil plumbing circuit models to represent 4,6,8,10 and 12 cylinder engines in V and inline configurations (5 cylinder inline also). The model utilizes correlations based on average in-cylinder conditions over 720^o of crank angle. These heat transfer correlations are fine-tuned to best represent specific GM engines based on engine heat rejection test data. The model requires inputs of Air/fuel ratio, intake air temperature and pressure, fuel mass flow rate, spark advance and engine brake power which are expected to come from a vehicle driveline/energy model or from actual test data. The model also requires inputs of coolant temperature, pressure and volume flow rate that typically come from the coolant module.

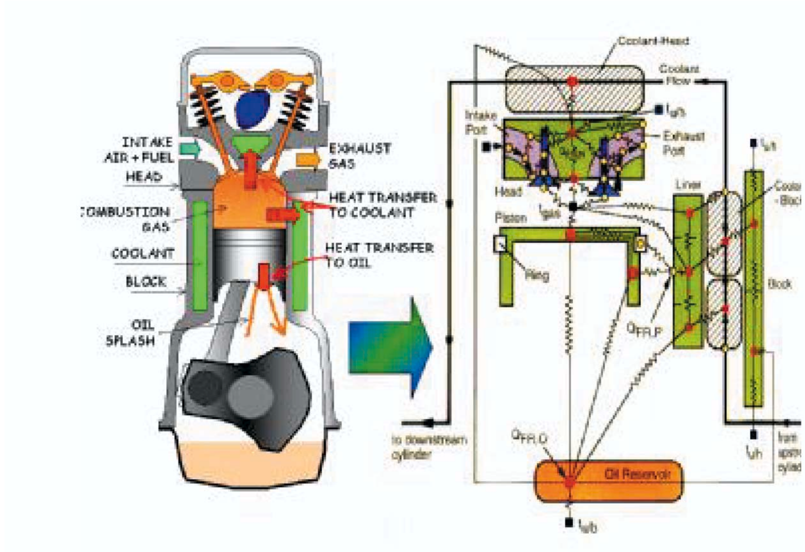

Figure 4 - Engine Cylinder heat exchange and resulting thermal network

COOLANT LOOP MODULE

The cooling loop (CS) module is responsible for estimating the coolant flow rate through each component (Radiator, Heater, Oil Coolers etc) as well as estimating the distribution of heat rejected by the engine to the cooling system. Two modeling schemes for the cooling loop modules are utilized in e-Thermal. The first scheme utilizes flow bench test data from GM lab tests. The second modeling scheme estimates the coolant flow rates (and pressures) by finding the operating point on the pump pressure rise curve and overall component resistance curve. The module uses performance data (heat transfer and pressure drop characteristics) for each component (Radiator, Heater, Thermostat etc) that is obtained via component data standard documents from HVAC/PTC suppliers who manufacture the component.

The coolant loop module has the capability to handle both front and rear HVAC modules (single and dual heater cores) as well as various options for thermostat location (engine inlet vs. outlet). It also allows different locations for transmission and engine oil coolers (in the inlet tank, outlet tank or parallel to radiator) as well as capability to handle Fuel-Operated heaters.

TRANSMISSION MODULE

The transmission (TR) module in e-Thermal is used to provide estimates of transmission oil temperature and flow rate (to and from the oil cooler). The model also provides temperature estimates of most of the transmission components and structure. The model incorporates a detailed pumping network for the oil and thermal network for the major components and structure. These elements estimate;

1. The distribution of oil flow in the transmission as a function of transmission operating state
2. The convective heat exchange between the oil and the components/structure,

3. The thermal conductance between the components and structures, and
4. The convective heat transfer between the underbody air and the transmission.

The model is fine tuned using pump flow data from benches along with flow distribution data from test and analytical modeling from the transmission manufacturer. The transmission oil cooler heat exchange and oil pressure drop data is submitted by HVAC/PTC suppliers. The model utilizes heat generation estimates for the gear sets, torque converter, oil pumps and transmission operating data (gear state, torque converter state/slip, input engine r.pm., oil pressure…), which are expected to come from a vehicle driveline/energy model or from actual test data.

PASSENGER COMPARTMENT MODULE

e-Thermal's passenger compartment (PC) module provides estimates of interior air and surface temperatures throughout the passenger compartment along with an estimate of the average moisture content of the interior air. The passenger compartment predicts lower, mid and upper level average air temperatures at each seating location. It also computes surface temperatures at each major body, trim and glazing component in the passenger compartment. Each of these temperature estimations are determined by comprehending the multi-mode heat-transfer effects as follows:

1. Solar absorption and transmission through the glass
2. Solar absorption of transmitted solar load (from glass) into interior trim and body elements
3. Convection to interior air from interior surfaces
4. Radiation exchange between interior surfaces
5. Advection /mixing of air flows within the passenger compartment
6. Convection to exterior air from exterior surfaces
7. Radiation exchange between exterior surfaces and vehicle surroundings
8. Conduction from interior to exterior surfaces

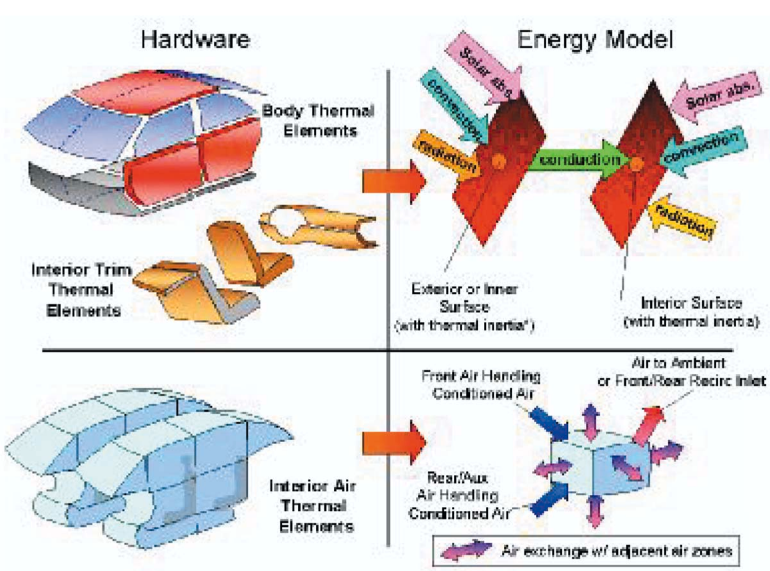

Figure 5 - Passenger Compartment Thermal Elements

A simplified occupant model is provided to estimate sensible and latent heat exchange with the vehicle interior (through convection, radiation and evaporation). The PC model requires users to define surface areas and thermal construction types for all major interior surfaces (e.g. glass, doors, roof, I.P. ….). Thermal construction types define interior/exterior thermal inertia, interior-to-exterior conductivities, emmisitivities, and solar absorption properties. These are cataloged in a construction library according to the type of interior surface. Glass elements also require the user to specify orientation angles, solar transmission and glass thickness parameters. The user also specifies the distribution of conditioned airflow (from the interior air handling module) entering the passenger compartment as well as the distribution of airflow exiting the passenger compartment. The e-Thermal passenger compartment module has variants for vehicles with one seating row (sports cars, pick-up trucks …) , two seating rows (sedans, coupes, …) and three seating rows (vans, sport-utilities …)

LOADCASE MODULE

The loadcase (AM) module is to e-Thermal what a test procedure or specification is to physical vehicle hardware. The loadcase allows the user input:

- Time-varying vehicle operating conditions (e.g. vehicle speed, ignition state, road grade, …)
- Transient environmental conditions (e.g. ambient air temperature, solar intensity, road temperature…)
- HVAC control head settings (e.g. HVAC fan setting, temperature door setting, ….) as a function of time.

The loadcase model also allows the user to specify the initial temperature conditions for each module.

SIMULATION CAPABILITY EXAMPLE

This section will compare e-Thermal simulation results to actual vehicle test data for a heater warm-up test condition. The vehicle under consideration is a production small sport-utility vehicle with 2 seating rows. The powertrain consists of a 2.2L 4-cylinder gasoline engine and a CVT-type transmission. The testing scenario is a heater warm-up at 40 kph into stabilized operating points (60kph and idle) at an ambient temperature of –20^{o}C. The actual test vehicle data was acquired using a development vehicle in a climatic wind tunnel. Specific vehicle test conditions are given in Table 1-1.

TABLE 1-1 – Test Procedure/Conditions

Test segment	Ambient Temp. (^{o}C)	Veh. Speed (kph)	Air Supply Mode	Air Flow Setting	Air Discharge Mode
Warm-up	-20	40	OSA*	High	Heat
Stabilized Comfort	-20	60	OSA	Low	Heat
Idle	-20	0**	OSA	High	Heat

* OSA – 100% Outside Air to Air Handling
** at Idle, Tunnel wind set to 5kph

The thermal model was developed in e-Thermal. Refrigerant and transmission thermal modules were not included in the simulation as their thermal interactions were expected to be negligible for this test scenario. Simplified versions of air handling, front end airflow and cooling system models were selected as vehicle-level tests had been run to generate the required performance maps. Vehicle design and development engineers supplied general plumbing and system information. HVAC/PTC heat exchanger component data was generated and submitted by the HVAC/PTC supplier for the program utilizing GM component data standard templates [4]. GM Powertrain supplied the engine thermal and power generation performance data. The vehicle driveline model (Matlab/Simulink) was available from the GM Energy and Drivability engineering function. The vehicle-level requirements for this test scenario focus on:

- Time to reach heater core coolant in temperature during warm-up,
- Time to reach lower or “floor” air temperatures during warm-up and stabilized floor air temperatures (front and rear seats) at idle
- Time to reach upper (or “breath-level”) air temperatures during warm-up and stabilized upper air temperatures (front and rear seats) at idle.

Figures 6-9 show the agreement between coolant, heater discharge air temperatures, and interior air temperatures (floor-level and breath-level).

As can be seen the figure 6, e-Thermal does a reasonably good job of predicting coolant temperatures throughout the duration of test. At idle the model under predicts stabilized temperatures; this is thought to be due to higher under hood air temperatures in the actual vehicle compared to those used in e-Thermal. Work is under way to enhance the predications of under hood boundary conditions at idle.

Figure 7 shows the agreement between heater core discharge air temperature and measured heater duct air temperatures. The agreement is reasonably good except at idle, which can be linked to the under prediction of coolant temperatures at this condition

As can be seen in figures 8-9, The prediction of interior air temperatures is reasonably good except for the prediction of front floor temperatures which in the test were 5-7^{o}C cooler than e-Thermal’s prediction. This difference is largely related to the measurement technique, which utilizes several local air temperatures. In contrast the model’s prediction is volume-averaged across the floor well. As would be expected idle interior air temperatures are lower than interior air temperatures measured during the vehicle test.

e-Thermal can be similarly applied to compartment cooling test scenarios (hot weather soak and cooldown tests, A/C stabilized points) as well as powertrain cooling test scenarios (vehicle trailering tests, wide open throttle powertrain cooling tests) with similar success at predicting key transient thermal behaviors (fluid pressures, temperatures, and flow rates).

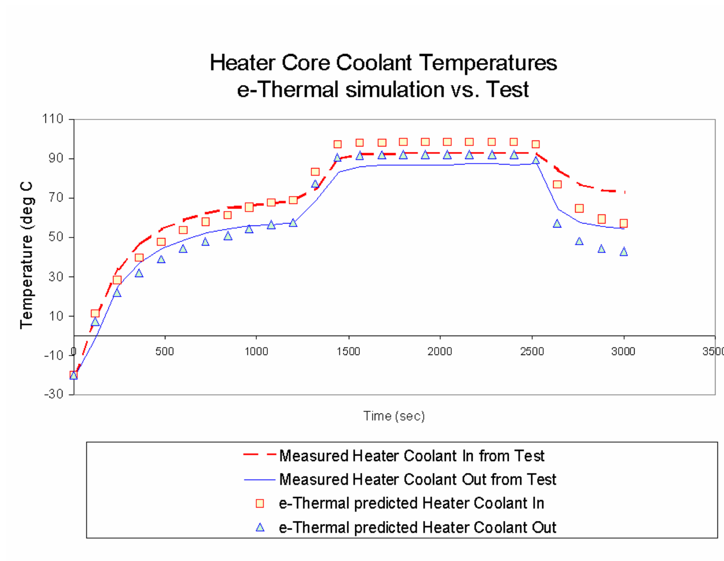

Figure 6 - coolant temperature comparison

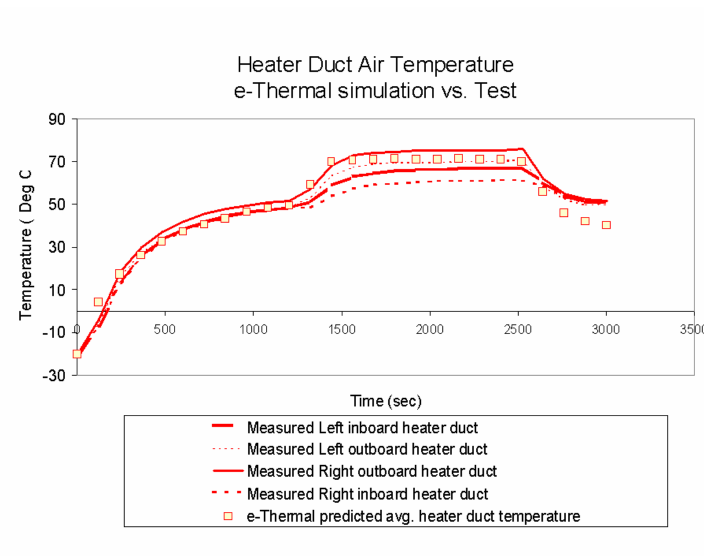

Figure 7 - heater core air out temperature comparison

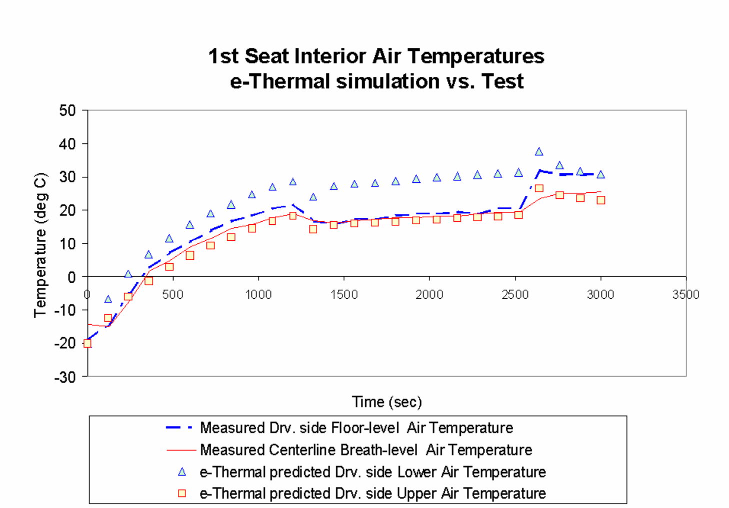

Figure 8 - 1st Seat Interior air temperature comparison

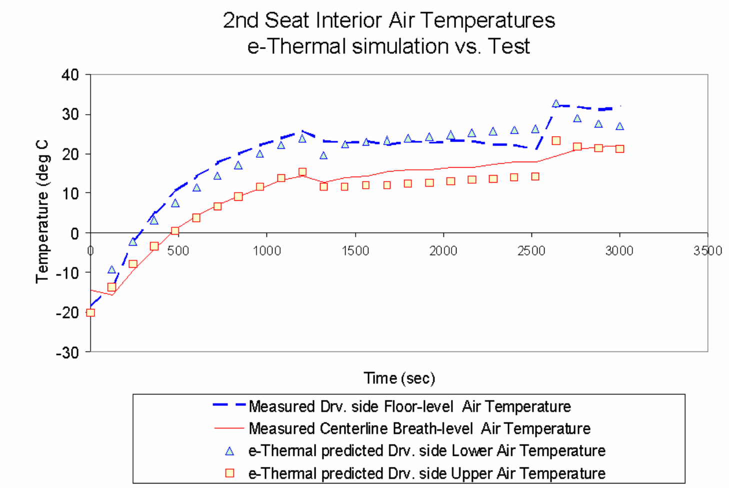

Figure 9 - 2nd Seat Interior air temperature comparison

Conclusion

The purpose of this paper was to describe e-Thermal and demonstrate its ability to simulate full vehicle testing. e-Thermal has now been in use by the GM HVAC/PTC engineering community for three years and is being continually developed to improved model accuracy as well as the addition of capabilities to match HVAC/PTC functions and technologies that are being planned (or explored) for future program use. The following are the major observations that have come out of the GM's experience exercising e-Thermal in our product development process:

1. GM's e-Thermal tool illustrates that it is possible to construct simulations models for vehicle-level HVAC and PTC tests that are reasonable accurate and highly reflective of performance trends when compared to physical tests (e.g. instrumented response from on-road or tunnel-based vehicle tests). GM is on a path of reducing road and climatic tunnel testing of "physical" vehicle properties and speeding the vehicle development process through the use of this tool.

2. GM has developed HVAC/PTC component data standards and the HVAC/PTC supplier community has illustrated that they have the capabilities to provide component performance data throughout the vehicle development cycle through the use of both component tests and component analytical models. As usage of vehicle-level and subsystem-level HVAC/PTC performance simulation by OEM and suppliers grows there is a growing need to develop industry-wide component performance data standards and a global repository to minimize the effort and cost of producing and maintaining this data. Also, the development of industry accepted fluid property calculation routines for common refrigerants, coolants, oils, and air (moist) would help data issues associated with the usage of component performance data.

3. While GM's goal is to replace physical tests with analytical tests, great care must be taken to balance model capabilities with test objectives. Given the complexity of the thermal models and the huge amount of vehicle and component data that is required to develop a vehicle-level analytical model, simulation is not a means to the end for physical testing. GM's vehicle-level performance prediction capability is and will continue in the short term to be best used to quantify the expected amount of change in performance given a known performance level (A vs. B analysis). High confidence in absolute performance prediction (e.g. duct temperature +/- 1°C) is at a minimum a decade away at the level of resources currently devoted to supporting and developing this type of model.

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