Improving Energy Efficiency by Developing Components for Distributed Cooling and Heating Based on Thermal Comfort Modeling [Thermoelectric (TE) HVAC]

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Overview

Timeline

- Start date – November 2009
- End date – July 31, 2013
- Percent complete – 25%

Budget

- Total funding: $9,097,593
  - Government* share: $4,548,796 (DOE obligations thru March 2011: $3,667,764)
  - Contractor share: $4,548,797
- Expenditure of Gov't funds in
  - FY10: $465,471 (11/09-9/10)
  - FY11: $1,474,025 (10/10-9/11)

Barriers & Targets

- Early stage of development for thermoelectric (TE) devices in automotive HVAC applications
- TE coefficient of performance > 1.3 to cool and > 2.3 to heat
- Reduce HVAC energy by > 30%

Partners

- Interactions / collaborations
  - *University of California – Berkeley:* Thermal Comfort testing & modeling
  - *Delphi Thermal Systems:* HVAC component development
  - *University of Nevada – Las Vegas*: Thermoelectric materials research
- Project lead – *General Motors*

* we thank the California Energy Commission and the DOE Vehicle Technologies Program for their support and funding of this project

Objectives - Relevance

Primary DOE goal to use TE HVAC for distributed cooling/heating

- Reduce the fuel used to maintain occupant comfort by at least 30% through the localized use of thermoelectric technology
- Develop TE HVAC components that have a coefficient of performance > 1.3 for cooling and > 2.3 for heating, then integrate & test as a system in 5-passenger demonstration vehicle, followed by an extended range electric vehicle (Chevrolet Volt)
- Develop a Thermal Comfort model to predict the occupant physiological response to localized heating and cooling through human subject testing
- Enhance the Virtual Thermal Comfort Engineering CAE tool to differentiate comfort with localized heating & cooling future systems

Secondary DOE solicitation goal to improve efficiency of TE generators

- Develop new thermoelectric materials for engine waste heat recovery applications (to provide power TE HVAC climate loads)

Milestones – Technical Accomplishments

Through Quarter 1 2011

- Completed identification of initial set of components for distributed heating and cooling development – Mar. 31, 2010
- Complete build of mule vehicle with simulated TE devices for Thermal Comfort evaluation – Aug. 31, 2010
- Complete Design of Experiments for phase 1 testing of Mule and virtual vehicle – Nov 16, 2010
- Climatic Wind Tunnel tests for warm ambient occupant comfort evaluation demonstrate occupant preference for reduced localized airflow velocity – Dec 16, 2010
- Strategy and method to control distributed climate control system identified – March 10, 2011

Approach/Strategy

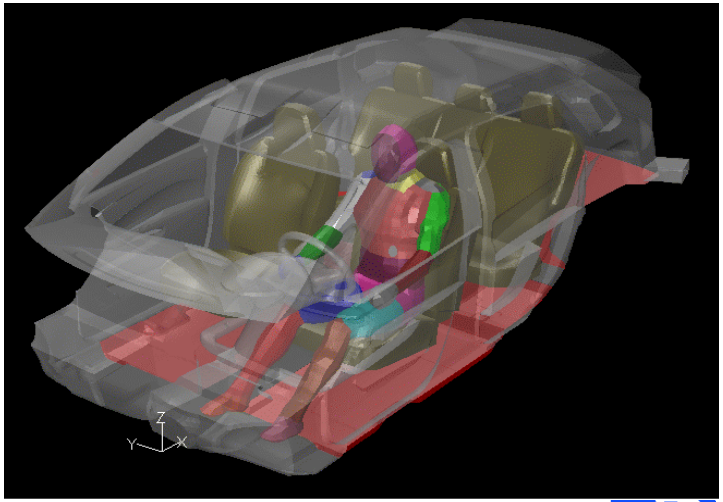
- **Applied Research – Phase 1**: Develop Thermal Comfort model of human responses to potential locations for distributed heating & cooling
  - Identified potential locations for distributed HVAC components and measured their physiological and psychological effectiveness
  - Used automotive mockup in the UC-Berkeley environmental test chamber and mule vehicle in Delphi Climatic Tunnel to perform human subject testing
  - Update UC-Berkeley's Thermal Comfort model as the "key component" of the Virtual Thermal Comfort Engineering (VTCE) computer-aided engineering (CAE) tool used by GM and Delphi Thermal Systems
- **Exploratory Development – Phase 2**: Develop the initial prototype HVAC components and evaluate on bench & mule vehicle
  - CFD and vehicle Design of Experiments (DoE) analysis
  - Functional intent component manufacturing and vehicle integration
  - Define control strategies and algorithms
  - Rebuild mule vehicle with design intent localized TE components

Approach/Strategy (cont.)

- **Advanced Development – Phase 3**: Develop final prototype HVAC components and evaluate on bench
  - Optimize control system to balance comfort and consumption
  - Estimate HVAC system efficiency improvements, (central system mass reduction and vehicle thermal load reduction)
  - Commercialize TE components for future production application
- **Engineering Development – Phase 4**: Integrate final local and central HVAC components into demo vehicle and optimize system performance
  - Build Hybrid demonstration vehicle
  - Test and evaluate distributed HVAC system
  - Calculate expected customer efficiency gain
  - Deliver vehicle and final report to DOE/CEC
- **HVAC Material/Waste Heat Recovery Research – Phase 5**: Develop new thermoelectric generator materials (concurrent with phases 1-4) to produce power for the TE HVAC climatic loads

Technical Accomplishments and Progress

- GM and Delphi selection criteria lead to the Cadillac SRX for this demonstration project. Utilizing a mule vehicle with automatic tri-zone HVAC systems and heated & cooled seats–an alternate powertrain is expected for final demonstration (critical for demonstration)
- Vehicle and occupants have been modeled for virtual evaluation
- Test and simulation procedures for local distribution evaluation established jointly between UC-B, Delphi and GM

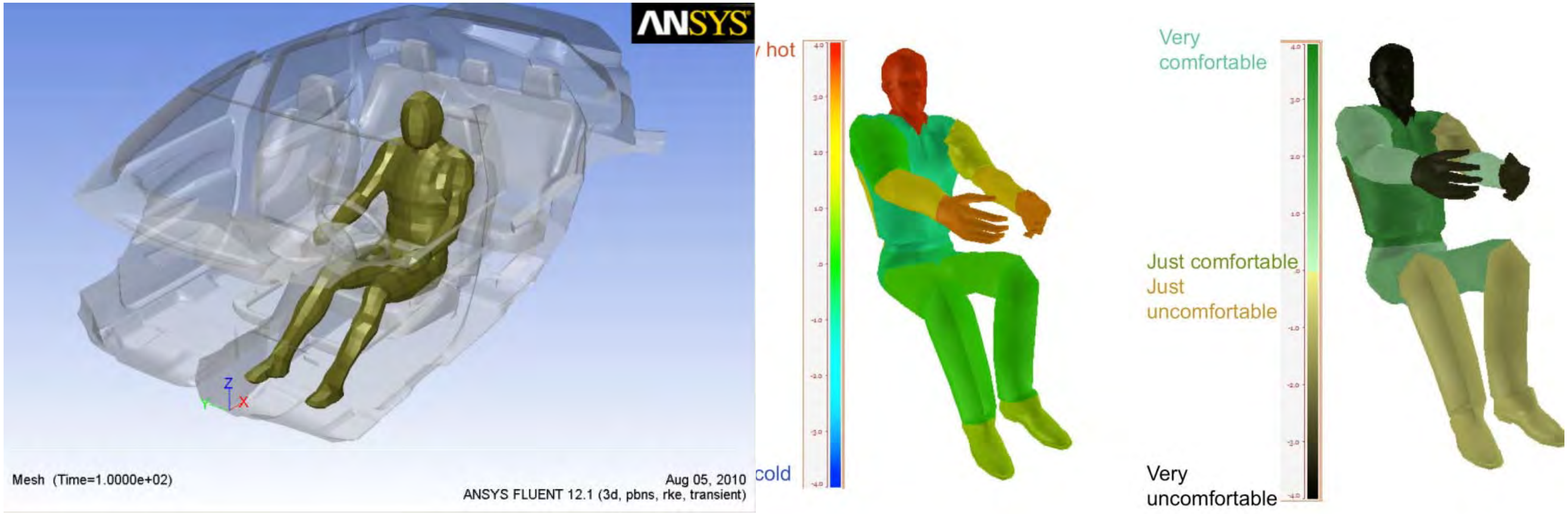


Technical Accomplishments and Progress (cont.)

- All phases of testing benefit from UC Berkeley thermal mannequin evaluation; providing detailed localized comfort measurement with an absence of psychological influence

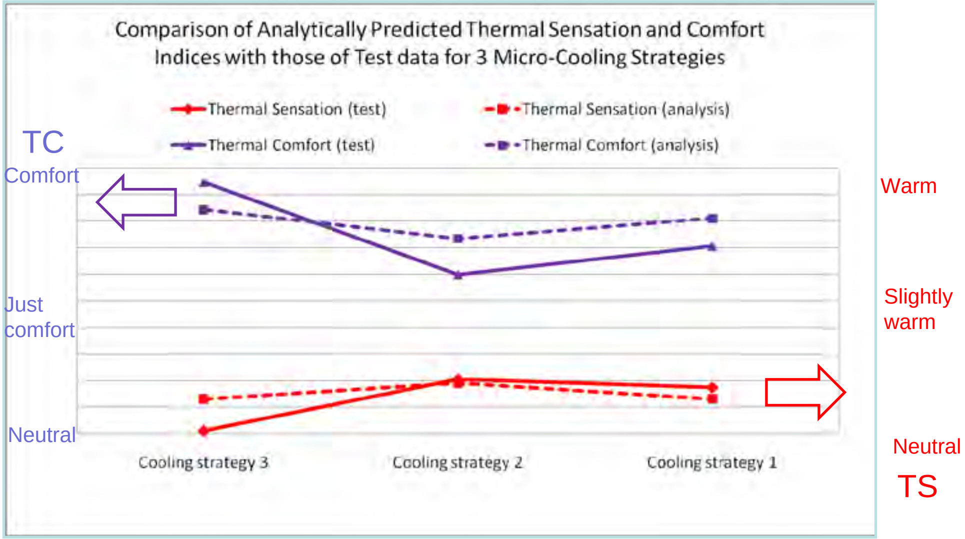
Technical Accomplishments and Progress (cont.)

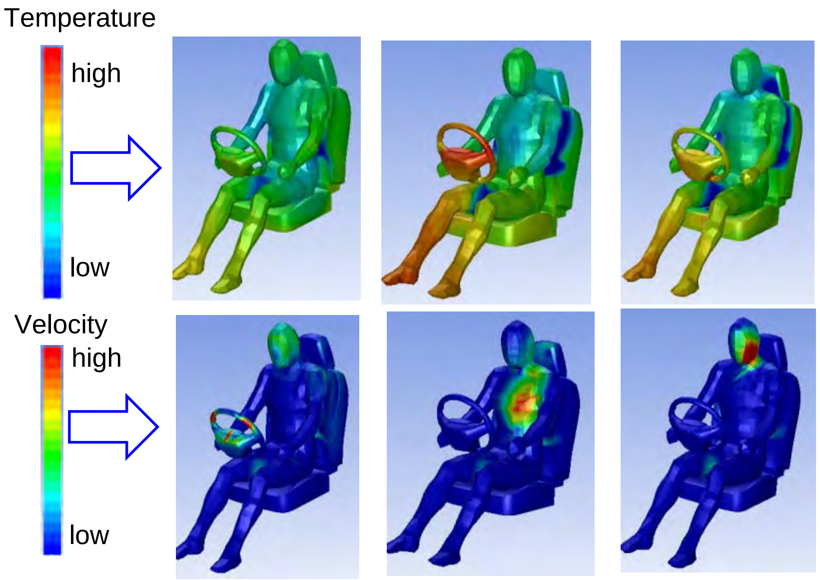
- Revisions to the Human Thermal Comfort model for localized cooling and heating correlate well with subjective and 16 segment thermal mannequin vehicle evaluations
- VTCE analysis guides localized component determination



Technical Accomplishments and Progress (cont.)

- Thermal comfort human subject testing data from UC Berkeley's environmental test chamber was used for GM's VTCE tool validation.





Technical Accomplishments and Progress (cont.)

- Delphi's Climatic Wind Tunnel testing used for emulated local spot cooling (September 2010)
- Conditioned air supply source installed in test vehicle, manifold distribution for rapid thermal variation and reconfiguration
- Mule Simulation report issued October 31, 2010

UC-B thermal mannequin and human subjects used to evaluate spot cooling

Technical Accomplishments and Progress (cont.)

Computational TE work at Univ. Nevada, Las Vegas:

- New approach for lattice thermal conductivity calculations:
  - Based on Boltzmann transport equation and first-principles density functional theory (DFT)
  - Identify the role of phonon scattering processes and their contributions to thermal conductivity.
- Nano-cluster doping in low thermal conductivity bulk nano-composites:
  - New states near the Fermi energy, absent with traditional impurity doping, for LAST-type TEs
- Phonon density of states & vibration modes and comparison with neutron scattering data:
  - Examine origin & role of low frequency phonon modes for PbTe and LAST-m TE materials
  - Explore atomistic mechanisms & intrinsic connections between structural & electronic degrees of freedom
- Energetics and nano-cluster-host interaction in LAST-m:
  - Competition between dipolar interaction and strain energy build-up at nano-cluster - host lattice interfaces

Technical Accomplishments and Progress (cont.)

Computational TE work at UNLV (cont.):

- Nanodopant-induced band modulation:
  - Sizable widening of the band gap driven by the nanodopant-induced strain field
  - Band split-off at the conduction band minimum caused by spin-orbit interactions in the nanodopant
  - Principles for optimizing thermoelectric properties of narrow band-gap semiconductor nanocomposites

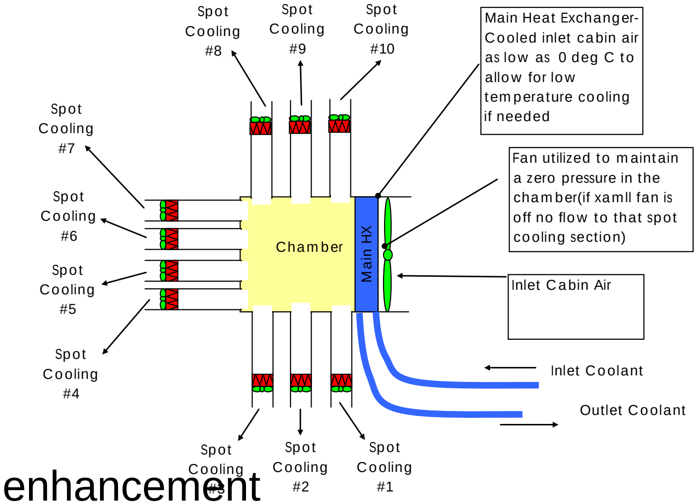
- Electronic band structure of NiSn Co-doped Skutterudites ($CoSb_3$):
  - NiSn doping causes band splitting near the conduction band minimum
  - New impurities states reduce band gaps, could be responsible for power factor enhancements

Experimental Materials Research at GM Global R&D:

- Neutron scattering studies of phonon density of states & phonon modes
- NiSn doping of Skutterudites for power factor enhancements
- New TE materials research

UNLV Summary: Research on new TE materials is advancing our understanding of key parameters for enhanced TE performance

Collaboration and Coordination with Other Institutions



- **University of California – Berkeley:**
  Human subject testing & Thermal Comfort modeling enhancement

- **Delphi Thermal Systems:**
  HVAC component development and testing

- **University of Nevada – Las Vegas:**
  Thermoelectric materials computational research

- **GM Vehicle Engineering:**
  Vehicle requirements, system integration

- **General Motors R&D:**
  CAE tool development and TE materials research

- Human subject and Mule testing benefit from live participation between GM, Delphi and UC-B: better correlation between test phases via accurate procedure duplication and application of superior thermal comfort knowledge

Proposed Future Work

- **Complete Phase 1 activities by Apr. 30, 2011**
  - Update the UC-B Thermal Comfort model and incorporate into the Virtual Thermal Comfort Engineering CAE tool
  - Complete identification of final set of components for distributed heating & cooling development – Apr. 30, 2011
  - Go/No-Go: Can final set meet the performance objectives?
- **Begin Phase 2 activities on May 1, 2011**
  - CFD and vehicle Design of Experiments (DoE) analysis
  - Functional intent component manufacturing and vehicle integration
  - Define control strategies and algorithms
- **Develop localized strategy for Chevrolet Volt**
  - Narrow the climate control induced variation in battery operating range between -10 to 32^{o}C (14 to 90^{o}F)

Summary – TE HVAC Project

- Relevance - The climate control system is the largest parasitic load on the powertrain, with strong FE and mass impacts.
- Approach - Optimize localized HVAC components for human comfort response using a refined Thermal Comfort model. Develop TE components that provide efficient localized heating & cooling of occupants
- Accomplishments – UC-B Thermal mannequin aids correlation of Virtual and Mule testing, VTCE tool refined to aid in evaluation of localized human heat transfer. Mule testing validated optimal locations for TE components
- Collaboration – UC-B, Delphi and GM meet twice per month to refine daily activity. The UC-B comfort tool integration by Delphi and GM's Virtual Thermal Comfort Engineering analysis allows rapid optimization of distributed HVAC components in future vehicles. UNLV TE material research is essential for the components Delphi will build in phase 2.
- Future Direction
    - Control system development to regulate system output for efficient thermal comfort
    - High Watt density cabin coolant heater development for efficient defrosting performance in a Chevrolet Volt