Improving the Efficiency of Light-Duty Vehicle HVAC Systems using Zonal Thermoelectric Devices and Comfort Modeling

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Project Relevance / Objectives

**Project Goal:** Identify and demonstrate technical and commercial approaches necessary to accelerate deployment of zonal TE HVAC systems in light-duty vehicles

**Program Objectives:**
- Develop a TE HVAC system to optimize occupant comfort and reduce fuel consumption
- Reduce energy required from AC compressor by 1/3
- TE devices achieve $\text{COP}_{\text{cooling}} > 1.3$ and $\text{COP}_{\text{heating}} > 2.3$
- Demonstrate the technical feasibility of a TE HVAC system for light-duty vehicles
- Develop a commercialization pathway for a TE HVAC system
- Integrate, test, and deliver a 5-passenger TE HVAC demonstration vehicle

**FY2011 Objectives:**
- Select a TE HVAC architecture to fully evaluate and design
- Model system behavior and comfort response of alternative architecture
- Estimate energy savings from use of TE HVAC architecture
- Design & test HVAC elements and control strategies using vehicle buck
- Develop candidate n-type TE material; design proof-of-principle TE HVAC module
- Develop detailed systems-level component requirements and specifications
Team Structure

Ford
Vehicle-Level Design & Test, Systems Integration, CAE Modeling, Hybrid Systems, Materials Analysis

Visteon
HVAC systems, CFD, Comfort Models, CAD, Subassembly Fab. HVAC Electronics, Vehicle Integration & Instrumentation

Amerigon
TE System Models & Design, Advanced Devices, CCS, Module Production, TE Electronics

Ohio State Univ.
New TE Materials

ZT Plus
Advanced Material Manufacturing

NREL
Comfort Models & Correlation, Ancillary Load Reduction

Ford Test Facilities
Garages Wind Tunnels Proving Grounds
Technical Approach

• Develop test protocols and metrics that reflect real-world HVAC system usage

• Use a combination of CAE, thermal comfort models, and subject testing to determine optimal heating and cooling node locations

• Develop advanced thermoelectric materials and device designs that enable high-efficiency systems

• Design, integrate, and validate performance of the concept architecture and device hardware in a demonstration vehicle
Phase 2 Task Overview

**System-level HVAC architecture design**
- Develop test conditions & occupant comfort metrics
- Determine vehicle-level performance acceptance criteria
- Assess and enhance thermal comfort tools
- Develop and assess HVAC system architectures through detailed CAE analysis
- Develop models to assess baseline HVAC and TE HVAC system power budget and fuel consumption

**TE HVAC system and materials research**
- Initiate pilot-process development for p-type TE materials research
- Begin n-type TE materials research
- Extend TE systems model & build liquid-to-air prototype TED hardware for validation studies

**Success Criteria**
- CAE modeling of TE HVAC architecture indicates required comfort levels can be achieved
- System modeling shows the TE HVAC architecture can achieve reductions in energy usage from baseline vehicle
- Research plan for TE materials and devices shows a specific path to deliver a technically and commercially viable TE system
Task 1: CAE & Comfort Analysis

Assessment of a Zonal-HVAC Equipped Vehicle

- Computational Fluid Dynamics (CFD) assesses the temperature performance and airflow characteristics of zonal-HVAC equipped vehicles.
- Thermal Comfort/Sensation modeling will predict whole body thermal response for all test cases and vehicle configurations.
- These modeling tools analyze and compare the performance characteristics of zonal-HVAC equipped vehicles to the baseline vehicle to ensure equal or better performance.
Air Chamber Evaluation System (ACES) – Half Buck

- Fusion ½ Buck has been installed into the ACES System for the next level of evaluation
- Capability to independently control various distributed HVAC elements has been incorporated
- ACES setup is being used to validate CAE Comfort Model predictions and will include Wind Tunnel Testing conditions as a baseline
- Testing to start end of 3Q2011
Thermal Sensation/Comfort Analysis Options

- Evaluating multiple modeling approaches
- AcuSolve CFD / RadTherm / UCB path show good potential for prediction of thermal sensation and comfort

AC pull down test

<table>
<thead>
<tr>
<th>Time (minutes)</th>
<th>Predicted Sensation</th>
<th>Predicted Comfort</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subject 1: Sensation</td>
<td>8/10</td>
<td>8/10</td>
</tr>
<tr>
<td>Subject 1: Comfort</td>
<td>Just Comfortable</td>
<td>Just Comfortable</td>
</tr>
<tr>
<td>Subject 2: Sensation</td>
<td>8/10</td>
<td>8/10</td>
</tr>
<tr>
<td>Subject 2: Comfort</td>
<td>Just Comfortable</td>
<td>Just Uncomfortable</td>
</tr>
</tbody>
</table>

Very Hot, Hot, Warm, Slightly Warm, Neutral, Slightly Cool, Cool, Cold, Very Cold, Very Comfortable, Comfortable, Just Comfortable, Just Uncomfortable, Uncomfortable, Very Uncomfortable
Thermoelectric Device Design: Modeling, Design & Testing

Current Efforts –

- Updated Phase 1 CAE model to size and develop Phase 2 designs in support of initial vehicle level requirements.
- Model used to understand parasitic loses in potential design architectures and down select design options.
- Custom high performance liquid heat exchanger has been designed and is being fabricated for the Phase 2 device.
- Calorimeter instrumentation upgraded to provide more data on the design and improve accuracy.

TED Calorimeter Apparatus

TED Calorimeter Apparatus

Liquid HEX CFD
Porosity increases $zT$ of p-type Bi$_{0.5}$Sb$_{1.5}$Te$_3$

- p-type research efforts focus on reduction in thermal conductivity to increase ZT and optimal doping to improve power factor
- Lab-scale tests reveal peak $zT$ level ~ 1.2 (p-type)
- n-type materials are being evaluated to determine optimal doping and processing strategy
- This effect will be scaled to practical thermoelectric alloys and synthesis routes
Baseline Vehicle Testing: HVAC Performance & Thermal Comfort

**Hot Ambient Testing**

- **Temperature (°C):**
  - 43°C: 6 / -1.5 (16 min)
  - 32°C: 5 / +0.5 (12 min)
  - 28°C: 5 / +1.0 (8 min)

**Cold Ambient Testing**

- **Temperature (°C):**
  - -18°C: 4 / -1.0 (17 min)
  - -5°C: 4 / -1.0 (12 min)
  - +5°C: 4 / -1.0 (8 min)
Modeled Energy Usage

- Cooling energy consumption is initially high due to large demand on blower and A/C compressor.
- Heating energy consumption is delayed due to delay in heater core warm-up.
Summary

- HVAC system energy consumption is substantial (but mostly off-cycle) and must be considered when developing technology for improving overall real-world vehicle efficiency

- A Zonal TE HVAC architecture becomes more viable as vehicles evolve towards higher levels of electrification and engineering attribute criteria accounts for quantitative occupant-based comfort metrics

- Our current project focus is on developing methods to optimize climate system efficiency while maintaining occupant comfort at current levels using new technology, architecture, and controls approaches

- Project is on target to meet Phase 2 milestones and deliverables by the end of 4Q11

- Hardware design-freeze will occur early 1Q12 and subsystem design, build, and test is planned to be completed by this time next year
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