Advances in Modeling and Simulation of Vehicle Thermal Management Systems

“Variable-Fidelity, Multi-System Analysis”

Ben Zandi, Ph.D.
TES International LLC
Outline

- The Need for Vehicle Thermal Management Systems
- Role of Modeling & Simulation
- Traditional M&S Approaches - Advantages/Disadvantages
- Hybrid Methodologies:
  - Multi-System Analysis Approaches
  - Variable-Fidelity Analysis Approach
- Examples:
  - High-Powered Electronics with coupled Electrical Field
  - Cooling system with Complex Radiator Model
  - Electronics Rack with Liquid cooled Trays
Vehicle Thermal Management

Vehicle thermal management is becoming critical, as it impacts safety, reliability, passenger comfort, performance and fuel economy.

- Extremely harsh underhood environment.
- Increasing number of heat sensitive electronic components.
- Higher power densities.
- Electric drive systems requiring active thermal management.
- Ever-shrinking vehicle underhood space allocation.

Efficient thermal management systems must be developed:
- Focus on optimizing heat acquisition from various sources.
- Provide clear procedures for management and rejection of this heat.
Modeling & Simulation

Modeling and Simulation techniques are indispensable tools in the design of thermal management systems.

Benefits:
- Reduce development cycle times
- Evaluate multiple design iterations
- Identify potential problem areas
- Reduce number of prototypes and testing cost
- Significantly increase success rates of physical testing
- Obtain thermal information throughout the system

Model correlation and validation is critical
Numerical Simulation - Approaches

There are two approaches used in commercially available thermal analysis software packages:

**Detailed 3D CFD/CHT Approach**
- High accuracy
- Time consuming modeling
- Requires high expertise
- Computer resource intensive
- Uns suited for rapid-prototyping and “what-if”

**1D Approach using Networks**
- Fast modeling and simulation time
- Ideal for rapid-prototyping
- Not suited for all components
- Must be validated thru testing and/or detailed analysis
- No information provided within the system

Linking software packages with no access to the source core is very difficult.
Variable-Fidelity Multi-System Approach

- Hybrid approach to bridge the gap between “speed” and “accuracy”.

- Rapid analysis with desired degree of detail.

- Provides the ability to link and couple various model types; from simple network based to complex 3D models.

Advantages:

- Allows applying detailed, and thus more computationally intensive, analysis only where needed.

- Allows application of realistic boundary conditions.
Multi-System Analysis Approach

- Allow subdividing a very complex thermal systems into subsystems that share one or more boundaries.

- Multi-system analysis refers to simultaneous, coupled and synchronized numerical simulation of \textit{two or more models}.

- Combine existing models.

- The models need not be constructed using the same type (\textit{i.e., Thermal Solid, CFD, Electrical})
EX1: High-Powered Electronics Electrical/Thermal/CFD Coupling

Geometry

Components, traces and other conductors from sources in various formats.

Heat Generation

Two main contributors:
- Component losses
- Joulian dissipation due to current flow in traces and connectors

Conjugate internal heat transfer
- Conduction
- Internal natural convection (using CFD)
- Internal thermal radiation

Cooling to underhood ambient
- Ambient natural convection and radiation
Coupled Thermal/Electrical/CFD

Temperature Distribution - Components & Board

Temperature Distribution - Traces & Connectors
Variable Fidelity Analysis Approach

A complete thermal modeling and simulation environment that offers a variety of methodologies for modeling a variety of cooling systems and components, in a single package.

- Right tool for the job
- Avoids any unnecessary “overhead”
- Network model comprising of:
  - Bernoulli links (Simple Links)
  - Flowbars (1D CFD)
  - Extended thermal network (R/C network system)

Direct coupling of network models with 3D CFD/CHT Component models.
  - CFD in-the-loop Coupling (Battery cells, Engine Water-jacket ...)
  - Embedded Flow-Bar Coupling (Coldplates, Liquid cooling ...)
**1D – 3D Coupling: CFD in the loop**

- Used when one or more flow components are represented via 3D CFD models.

- The CFD components will run, automatically in parallel and synchronized, exchanging necessary inlet/exit parameters.

- Can be used to create complex components using the highest fidelity approach, only when required (i.e., hybrid battery cells, engine/cylinder head flow passages).
Ex2: CFD in-the-loop
1D – 3D Coupling: Embedded Flowbars

- Used when a segment of the flow network passes through solid structures.

- Ideal for modeling of complex heat exchangers, cold-plates, and other liquid cooling channels.

- Mapping of the convective conductance can be from:
  - Channel flow correlations,
  - Previous CFD analysis,
  - Heat-exchanger performance charts and data
  - Test data libraries
Ex3 - Network/3D Thermal System Model of a Military Vehicle Cooling System

System Overview – Network Model

Top View of Vehicle Cooling System

Cold-plate with Embedded Flow Passages

Electronics System and Cooling Circuit
Electronic Rack with Coldplate Trays

Electronic Boxes

Liquid-Cooled Trays
Electronic Rack with Coldplate Trays

Rack Cooling Channels

Liquid to Air Cross-Flow Heat Exchanger
Electronic Rack with Coldplate Trays - Results

Temperature and Flow
Component Definitions

Switching Stack

Models of the IGBTs and Diodes are created using variable Power Dissipation values.
Closing Remarks

- Modeling and simulation techniques are valuable tools for design and evaluation of thermal management systems.

- Efficient analysis of today’s vast array of thermal system components requires:
  - A variety of modeling techniques.
  - Seamless coupling of component models using different methodologies.
  - The ability to switch from one modeling approach to another.
  - Ease of use