

CFD and Thermo-Fluid Systems Modeling for Underhood Thermal Analysis

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Motivation

- An optimal design of vehicle thermal system is important for energy efficiency
 - Less than one-third of the total fuel energy provides useful mechanical work
 - Remainder is lost through the exhaust system and heat rejection
- Determination of accurate temperature distributions in an engine is critical to achieve fuel efficiencies through cooling system optimization and radiator size reduction
- A predictive analytical capability can help redesign underhood configuration while meeting new energy efficiency and emissions requirements
 - Shorten component design and test cycles using a validated high-fidelity but also a practical simulation tool



Objectives

- Address unique heavy-vehicle underhood thermal control challenges to improve energy efficiency
 - An integrated analysis approach to fully characterize thermal-flow conditions in the underhood compartment of heavy vehicles
 - Combined use of 3-D Computational Fluid Dynamics (CFD) and 1-D thermo-fluid systems models
- Specific focus on issues related to EPA emission regulations that require redesign of underhood compartments
 - Emission control technologies like cooled EGR and after-treatment devices increase engine heat rejection to both coolant and air
- Validation of integrated analysis approach via collaborations with Caterpillar and Cummins
 - Two separate engine configurations and a range of operating conditions
 - Evaluate the effect of cooling system and ventilation air flow on heat rejection and component temperatures



Modeling Approach

- Both CFD and thermo-fluid systems models have inherent limitations
 - CFD is computationally prohibitive for simulations of the entire system
 - Systems models oversimplify multi-dimensional flow and heat transfer
- Combined use of CFD and system models offers unique advantages
 - System model accounts for thermal energy balance and heat distribution inside the engine through 1-D network of flow loops
 - CFD model addresses multi-dimensional flow and heat transfer wherever needed
 - Reduced input data requirements: Combined model needs basic ambient conditions and component performance curves
 - Data exchange between 1-D and 3-D models for flow splits, heat-fluxes, and surface temperatures



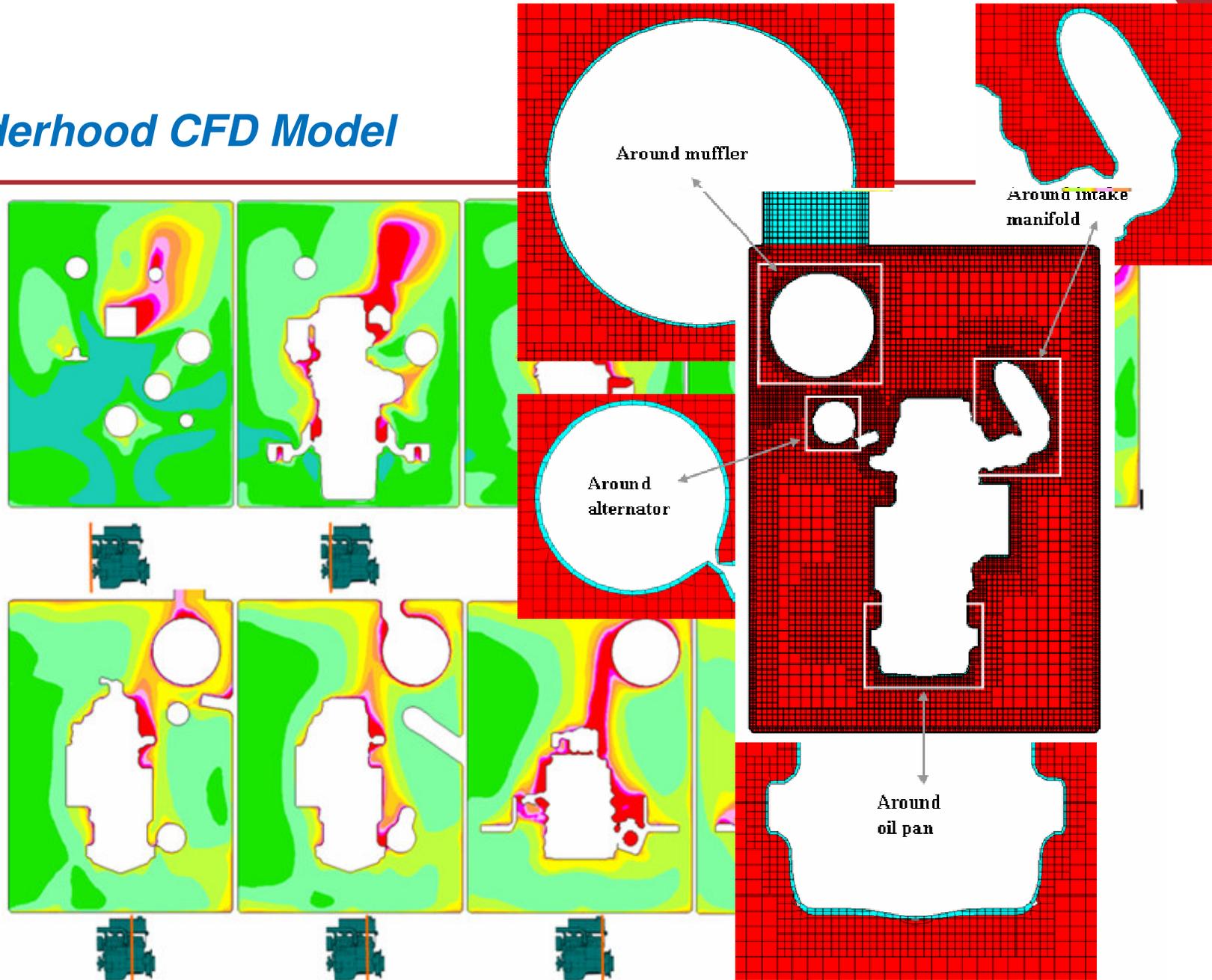


Underhood CFD Model

- Analysis of underhood ventilation air flow and temperatures require multidimensional CFD techniques
 - Model development generally starts with the CAD data of the underhood compartment
 - Various commercial CFD software can be used to generate unstructured mesh for the complex geometry with selective grid refinement
 - *STAR-CD and FLUENT are used in ANL efforts for projects with Caterpillar and Cummins*
- Wide range of turbulence model and boundary condition options are assessed and “best practice guidelines” established
 - Reynolds-Averaged Navier Stokes (RANS) turbulence models provide reasonable accuracy with practical computational requirements
 - Influence of ambient conditions is best captured by modeling beyond just the underhood compartment



Underhood CFD Model



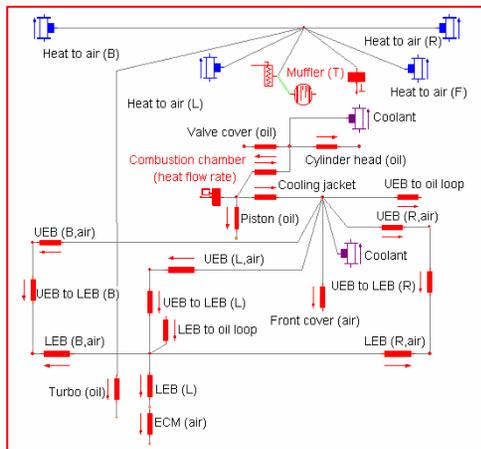


System Model: Network of Flow Loops

- 1-D representation of engine internal flow loops combined with a lumped-parameter approach to characterize the thermal interactions between them through the engine structure as the major conduction paths
 - Simplifies the complex engine system by discretization based on known heat transfer paths under equilibrium conditions
 - Predicts the complete thermal system performance and calculates thermal energy balance
- Commercial software *FLOWMASTER* for solution of analytical equations of mass, momentum, and energy in reduced dimensions combined with empirical correlations for component behavior (pumps, valves, heat exchangers...)
- Analyze interactions of the engine with the coolant, oil, and ventilation air loops
 - Heat generated from combustion is considered to be transferred to various discrete component surfaces (e.g., cylinder head, valve cover, front cover, engine block, cylinder head, ECM, etc.) through specified conduction paths

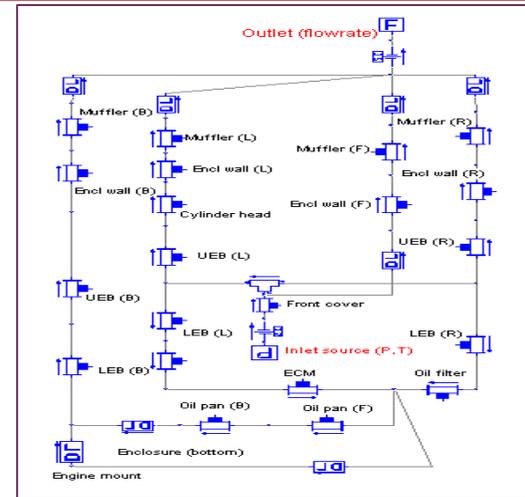


System Model: Network of Flow Loops

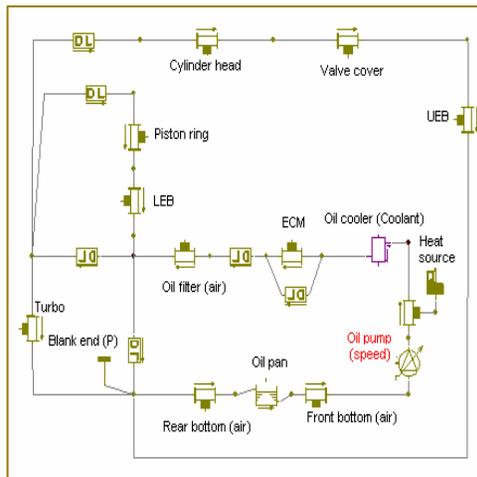
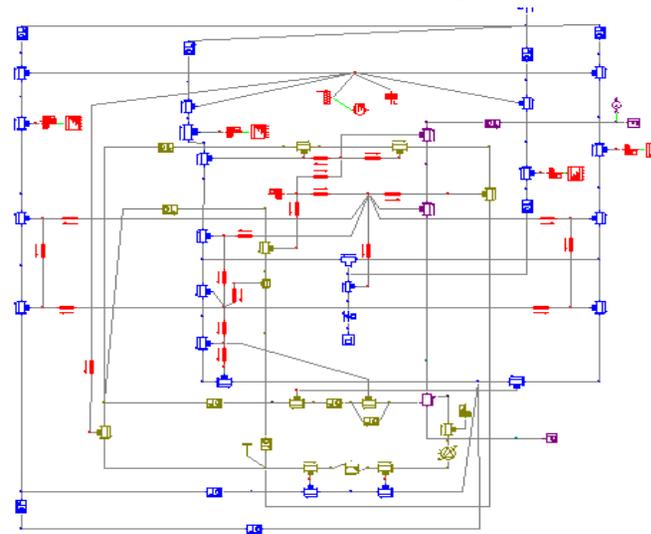


Engine Structure

Underhood Air Loop

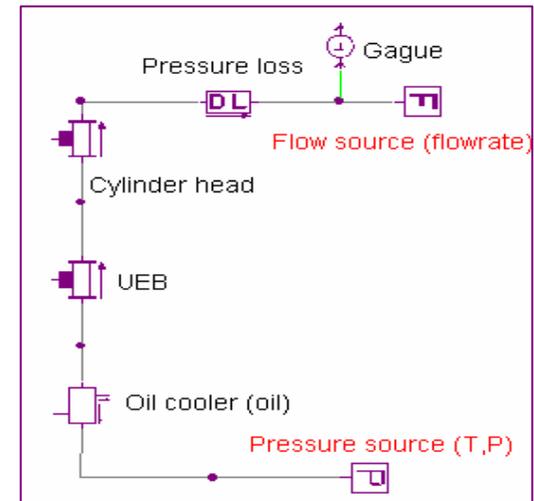


Assembled Multi-Loop Model



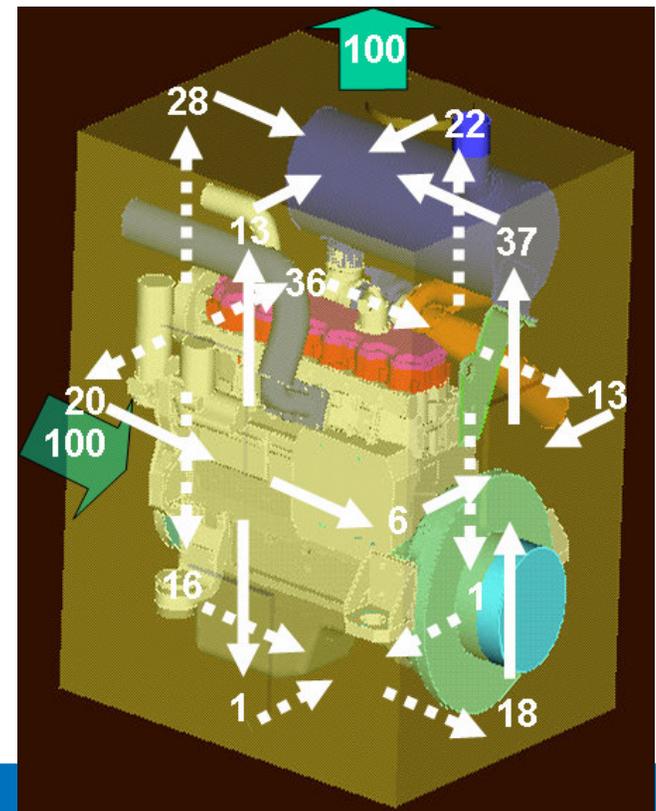
Lubrication Oil Loop

Coolant Loop



Integrated Underhood System Simulations

- Engine system model requires flow rates and inlet temperatures as boundary conditions for air, oil, and coolant loops
 - Accounts for cooling system response and thermal energy balance
 - Predicts heat rejection to air via engine structure and other heat generating components
- CFD model use system model predictions as surface heat flux boundary conditions for various engine components
 - Calculates underhood air flow field and temperatures
 - CFD results are “reduced” to provide the system model with data on flow splits and heat transfer coefficients
- An iterative process between the two models is needed to assure consistent solutions
 - Convergence between 1-D and 3-D solutions is established after 6-7 sequential runs



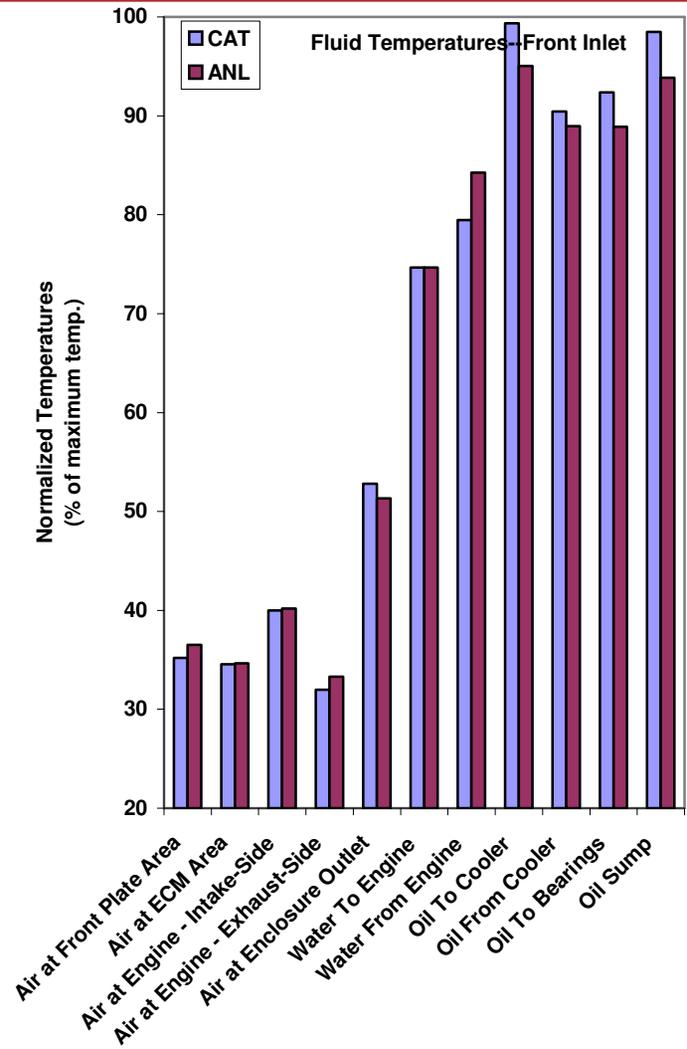
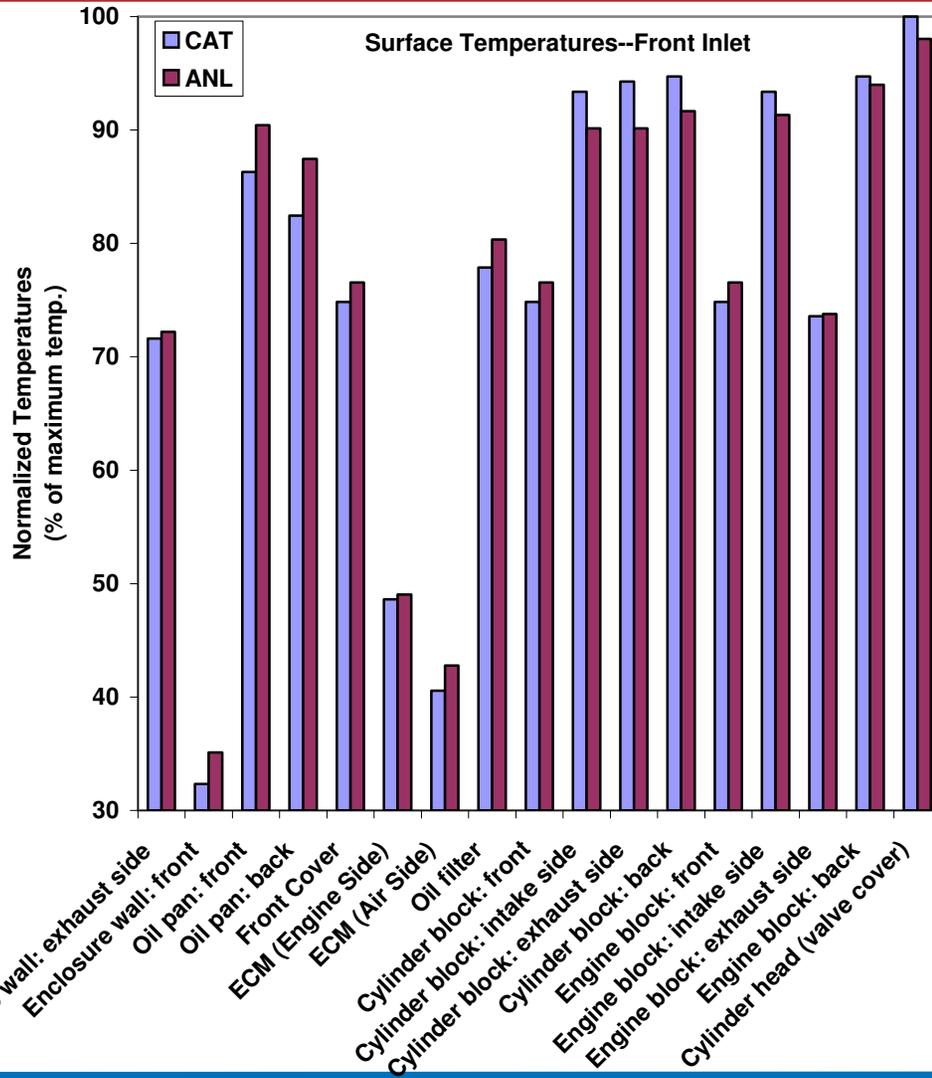


Summary of Caterpillar CRADA

- Thermal analysis of an off-road machine engine with unique underhood thermal challenges
 - High auxiliary loads, no ram air
 - Divided engine and cooling system compartments
- Maintaining acceptable underhood temperatures in a well-sealed engine enclosure is important for component performance
 - assessment of component temperatures is an important element of design cycle
 - a predictive analytical capability is needed to identify hot-spots
- As part of a CRADA, experiments are conducted at Caterpillar to study the effects of ventilation on heat rejection in a prototypical test-rig
- An integrated 1-D and 3-D model of the test rig is built at ANL to predict component temperatures for various air inlet locations and flow rates
 - Good agreement with experiments for all inlet configurations and flow rates



Summary of Caterpillar CRADA





Scope of Cummins CRADA

- New project on diesel engine thermal analysis, initiated in February 2006
 - Address design challenges related to emission control technologies needed to meet the new diesel engine emission requirements
 - Help optimize cooling system size while meeting the new emission requirements and cooling specifications
- An extension of integrated analysis approach to predict underhood flow field and temperatures for a conventional truck with diesel engine
 - Determine underhood flow paths and component surface temperatures
 - Predict hot spots and air-intake/cooling-fan air recirculation risks
- Cummins provide technical data needed for the model development and analysis, and perform thermal performance tests needed for validation
 - Benefits to a large spectrum of manufacturing community



Scope of Cummins CRADA

- An opportunity to understand the effect of EGR and after-treatment devices on diesel engine thermal performance
 - Higher engine heat rejection to both coolant and ventilation air
 - Higher underhood temperatures with potential hot spots
- Significant modifications in cooling system design
 - Additional models for radiator, condenser and the heat-exchangers for turbo-charger and EGR-cooler are needed
 - *In current model these components are included as heat sinks with specified flow rate and temperature*
 - Corresponding component models for fan, pumps, compressor, thermostat and valves are also needed for a complete cooling system model





Conclusions

- An optimal design of vehicle thermal system is essential for energy efficiency since most of total fuel energy is thermally wasted
 - Significant fuel efficiencies can be expected from optimization of cooling system and reductions in radiator size through simulations
- A novel methodology developed to determine the ventilation air flow needs in an engine enclosure and its effect on the thermal balance
 - An integrated analysis capability that needs only the basic ambient/operating conditions and component performance curves
 - Applicable to a spectrum of heavy-vehicle underhood thermal analysis
- Initial assessments using data from Caterpillar tests
 - CFD for 3-D flow field and the rate of heat transfer between engine and air
 - Systems model to determine temperature distributions in engine structure and components, coolant, lubrication oil loop, and ventilation air loops
 - Good agreements with experiments for a range of configurations/flow rates



Future Work

- A new project to extend the integrated analysis approach to predict underhood flow field and temperatures for a conventional truck with diesel engine as part of a new CRADA with Cummins
 - Development of additional models for cooling system simulation
 - Address specific thermal-control challenges related to use of EGR and after-treatment devices
- Opportunities with truck manufacturers to further test the models for realistic underhood configurations (Cummins project will likely involve an OEM)
- Opportunities for integration with powertrain system analysis software
 - Account for overall (thermal and mechanical) energy balance
 - Quantify fuel economy and performance for warm-up, idle, cruise and heavy-load conditions
 - Simulate the effect of exhaust back-pressure on engine performance, torque and fuel consumption, etc.