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THERMAL MANAGEMENT SYSTEM MODELING AND OPTIMIZATION FOR HEAVY HYBRID ELECTRIC MILITARY VEHICLES[1]

S. Park
M. Kokkolaras
University of Michigan
Ann Arbor, MI

A. Malikopoulos
General Motors
Warren, MI

B. AbdulNour
J. Sedarous
General Dynamics Land Systems
Sterling Heights, MI

D. Jung
University of Michigan-Dearborn
Dearborn, MI

ABSTRACT

A thermodynamics-based Vehicle Thermal Management System (VTMS) model for a heavy-duty, off-road vehicle with a series hybrid electric powertrain is developed to analyze the thermal behavior of the powertrain system and investigate the power consumption under different vehicle driving conditions. The simulation approach consists of two steps: first, a Series Hybrid Electric Vehicle (SHEV) powertrain is modeled; the output data of the powertrain system simulation are then fed into a cooling system model to provide the operating conditions of the powertrain components.

Guidelines for VTMS configuration was developed based on the vehicle simulation results and the operating conditions of powertrain components. Based on the guidelines, a VTMS configuration for the hybrid vehicle was created and used for designs of experiments to identify the factors that affect the performance and power consumption of each cooling system. Design space exploration techniques are then applied to investigate trade-offs and determine near-optimal size of components such that power consumed by fans and pumps is minimized. Finally, gradient-based optimization is used to fine-tune the component sizing subject to performance and geometry constraints. The cooling system design study demonstrates that the configuration and sizing of an SHEV cooling system is different from that of a conventional cooling system because of additional heat sources, increased complexity of component operations and interactions, and the dependency of parasitic power consumption on driving modes.

INTRODUCTION

Series Hybrid Electric Vehicles (SHEVs) for military applications can offer improved fuel economy, exportable electric power, enhanced low speed maneuverability, and low acoustic signature for stealth operation. Compared with conventional vehicles, however, SHEVs need additional powertrain components such as a generator, driving motors, a battery pack, and a power bus, all of which make the thermal management system more complicated. Moreover, military vehicles need more reliable thermal management system for the vehicle's survivability because combat vehicles are operated under desert-like conditions allowing a high tractive effort to weight ratio. Thus, a more strategic approach is required when designing a thermal management system for military SHEVs. Increased cooling demands in SHEV and additional hardware make it challenging to provide an effective cooling system that has minimal impact on fuel economy and cost. Typically, SHEVs tend to have a dedicated cooling system for the hybrid components due to their different requirements. The additional cooling system increases the hardware, cost, weight, and affects the vehicle fuel economy. Packaging issue is another critical challenge in Vehicle Thermal Management System (VTMS)

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development. Even though larger VTMSs offer better cooling performance, their size is limited by the packaging space in the vehicle. Therefore, smaller VTMSs are preferred during vehicle development while they can fulfil cooling requirements.

In SHEVs a cooling pump driven by an electric motor, not by the engine, is used for the cooling circuit of the hybrid components since the hybrid components need cooling even when the engine is not running. Cho et al. [1] investigated the benefits of controllable electric pumps over mechanical pumps in cooling systems of medium duty diesel engines. They found that the usage of electric pumps can reduce the pump power consumption and enables downsizing of the radiator. Besides these benefits, the usage of electric pump makes the architecture of cooling circuits for hybrid components relatively flexible. However, flexibility raises the issues of cooling circuit architecture optimality due to increased system complexity and parasitic power consumption. Numerical simulations can be an efficient tool to assess various design concepts and architectures of the system during early development stages compared with experiments relying on expensive prototypes. Nevertheless, only a few studies on VTMSs of HEVs using numerical approaches are found in the literature. For example, Traci and Acebal [2] demonstrated that a numerical approach could be used for thermal management system design of HEVs. They created a cooling system model of an electric hybrid combat vehicle that uses a Diesel engine as a prime power source while storing power in a central energy storage system consisting of a flywheel and a battery. They conducted parametric studies on the ambient temperature effect on the fan power consumption and the component operating temperature effect on the system size. Park and Jaura [3] used a commercial software to analyze the under-hood thermal behaviour of an HEV cooling system and studied the effect of the additional hardware on the performance of the cooling system. They also investigated the effect of an electronic module cooler on the conventional cooling system. Park and Jung [4] developed a comprehensive VTMS model for a SHEV and analyzed power consumption and performance. However, these previous studies did not deal with the sizing and configuration of the VTMS. In addition, the effects of driving conditions were not considered in the previous studies although the performance and power consumption of the VTMS, being the main objectives of VTMS design, are very sensitive to powertrain operation which in turn depends on power management strategy and driving conditions.

In this study, numerical system simulations of the VTMS and vehicle powertrain system are used to develop an efficient VTMS design for an SHEV. Cooling performance requirements, parasitic power consumption, temperature stability, packaging, and operating mode are taken into consideration in designing the VTMS.

MODELING

The operating condition of the VTMS cannot be separated from the operating conditions of the vehicle because the heat generation from heat sources is entirely dependent on the operating conditions of each component. In this study, both SHEV and VTMS models are developed for simulating the VTMS performance. A vehicle simulation is performed first to obtain operating conditions of powertrain components over driving cycles. This information is then fed as input to the VTMS simulation.

Series Hybrid Electric Vehicle Modeling

A series hybrid propulsion system for a 20 ton off-road tracked vehicle model was created using the Vehicle-Engine SIMulation (VESIM) environment, a modeling and simulation environment that provides a system library for straightforward generation of vehicle models [5]. This library includes electric components for modeling hybrid-electric powertrains [6]. The virtual Series Hybrid Electric Vehicle (SHEV) created in this study is composed of a diesel engine, a generator, a power bus, a battery pack, and two drive motors. The specifications of the vehicle were selected to match as close as possible to a typical tracked combat vehicle, which are listed in Table 1.

In the SHEV, all the engine power is converted to electricity and stored in the battery or directly used by the motor. The drive motors are powered by the electricity from the engine or the battery, based on the vehicle driving mode. The motor functions as a generator in the regenerative mode.

Table 1. Specification of Selected Series Hybrid Vehicle.

Component	Type	Specification
Vehicle	Tracked Vehicle with Series-Hybrid Electric Powertrain	20 ton
Engine	Turbocharged Diesel Engine	300 kW
Generator	Permanent Magnetic	300 kW
Motor	AC Induction	2 × 150 kW
Battery	Valve Regulated Lead-Acid	18Ah/120 modules
Maximum speed	(Governed)	72 km/h

SHEVs have three driving modes: discharging mode, charging mode, and braking mode. In the discharging mode, the battery is the prime power source. If the power demand of the vehicle exceeds battery capacity, the engine is activated to supplement power demand. In charging mode, the engine/generator is the prime power source. If the State of Charge (SOC) reaches the lower allowable limit, the engine supplies additional power to charge the battery. Once the power demand from the vehicle is determined by the controller, the engine is operated at the most efficient operating point to maximize the fuel economy. In braking mode, regenerative braking is activated to absorb the braking power. However, if the braking power required by the vehicle is larger than the capacity of the motor or the battery, friction braking is used.

VTMS Modeling

Configuration

The design of a hybrid VTMS configuration requires a systematic approach because the electric components such as generator drive motor, power bus, and battery do not operate simultaneously and have different operating temperatures. Thus, we developed guidelines for VTMS configuration based on the vehicle simulation results and the operating conditions of powertrain components (heat sources). Table 2 lists the control target temperatures of the powertrain components and the vehicle simulation results under a grade load vehicle driving condition (7% up-hill road, 48 km/h). The reason why this particular condition was used for the system configuration will be explained in next section. The heat generation from each powertrain component is important for component sizing because a heat source with larger heat generation requires larger capacity of cooling system. The control target temperature of each component reflects the maximum allowable temperature that should be maintained by the cooling system, which is critical for the arrangement of VTMS components. The table also groups components that operate simultaneously, which should be considered when allocating components to cooling towers.

Taking the vehicle simulation results into consideration, the guidelines for the configuration of the VTMS are suggested as follows:

(1) Radiators for different heat source components are allocated into two towers based on the operating groups.
(2) The radiators are arranged in the order of maximum operating temperature (control target temperatures).
(3) Electric pumps are used for electric heat sources.

Table 2. Vehicle Simulation Results for Configuration of VTMS (for grade load condition).

Component	Heat generation (kW)	Control Target Temperature (°C)	Operation group
Engine	190	120	A
Motor / controller	27	95	B
Generator / controller	65	95	A
Charge air cooler	13	-	A
Oil cooler	40	125	A
Power bus	5.9	70	C
Battery	12	45	D

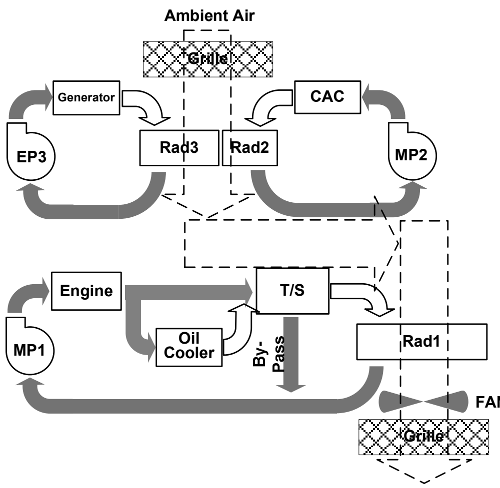
(4) The condenser of the compartment Air Conditioning (A/C) system is placed in the cooling tower where the heat load is relatively small.
(5) The battery is assumed to be cooled by the compartment A/C system due to its low operating temperature (Lead-Acid, 45 °C).

Based on these guidelines, a VTMS configuration for the hybrid vehicle was created as illustrated in Fig. 1. The VTMS is separated into two cooling towers depending on the operating group. As can be seen in Table 2, the engine, generator, charge air cooler and oil cooler always work together; heat is thus generated simultaneously. Therefore, if all these components are integrated in one cooling tower, the operation of the fan can be minimized resulting in parasitic loss reduction. The components related to power generation are located in cooling tower 1 and the components related to vehicle propulsion are located in cooling tower 2. In tower 1, the cooling air induced through the grille goes into radiators 2 and 3, which are responsible for the cooling of the generator and charge air cooler, and then goes into radiator 1 which is responsible for the cooling of the engine module. In tower 2, the cooling air goes into the A/C condenser first and then goes into radiator 1, which is responsible for the cooling of the power bus and radiator 2, which is responsible for the cooling of drive motors.

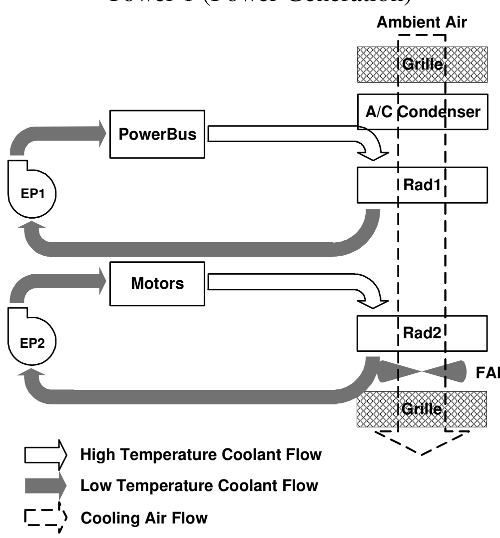
Every electric component has its own cooling circuit because the target temperature and the operating mode are different.

Component Modeling Approach

The VTMS component models were developed at different levels of fidelity based on thermal load



Tower 1 (Power Generation)



Tower 2 (propulsion)

Figure 1: Schematic of VTMS Configuration (Rad: Radiator, EP: Electric Pump, MP: Mechanical Pump, T/S: Thermostat, CAC: Charge Air Cooler).

significance, and in "parametric" form to enable design optimization. Each component model consists of sub-models including heat generation, heat transfer, pressure drop, and flow rate. Components can be categorized as follows depending on their function within the VTMS: heat source, heat sink, and media delivery components. The integrated system model predicts quantities such as coolant temperatures, flow rates, pressure drops across individual components, and power consumptions of pumps and fans.

Diesel engine, electric generator, drive motor, and power bus are the main heat source components considered in this study. A lumped thermal mass model was used for the temperature calculation of all heat source components; the temperature of each component is calculated from the balance of heat generation by the component, heat transfer to the coolant, and heat transfer to the ambient. The heat transfer to the ambient includes convection and radiation.

Heat sink components are heat exchangers that reject heat to the ambient air. The thermal resistance concept using two-dimensional finite differences (2-D FDM) developed by Jung and Assanis [7] is used for modeling the radiator. The same modeling technique is also used for the charge air cooler. The only difference between a charge air cooler and a radiator is that heat is transferred from the compressed charge air to the coolant in a charge air cooler while heat is transferred from the coolant to the cooling air in a radiator. An A/C condenser rejects the heat from passenger compartment to the cooling air. Heat addition model is used for the condenser. In this study, the heat rejection rate from the condenser is assumed to be constant. The oil cooling system has an oil circuit including an oil pump and a heat exchanger between oil and coolant. The effectiveness-NTU method [8] is employed for the oil cooler model, and a performance data based model is employed for the oil pump.

The function of media delivery components is delivering and controlling the coolant or the cooling air. Media delivery components include the coolant pump, cooling fan, and thermostat. The coolant pump model calculates the coolant flow rate based on the pump operating speed and the total pressure drop along its cooling circuit. The coolant flow rate is calculated using the pump performance map, which consists of flow rate, pressure rise and pump speed. In cooling circuits of electric heat sources, the pump and fan driven by electric motors control the component temperature by managing the motor speeds. A conventional cooling system with a mechanical pump is used for the engine cooling circuit. The thermostat in the engine cooling circuit is a three-way valve that prevents over-cooling by channeling the coolant to the radiator or to the by-pass circuit. The valve opening is determined by the temperature and hysteresis characteristics of the thermostat. The thermostat temperature is calculated using a lumped thermal mass model. The coolant flow rates to by-pass circuit and to radiator circuit are determined at the point where the pressure drops of two circuits are balanced. The cooling fan model is similar to the pump model. The cooling fan model calculates the cooling air flow rate based on the fan speed and the total pressure drop across grilles, radiators, and fan shroud.

Baseline Design

Driving Conditions

The thermal management system should be capable of removing all the waste heat generated by the hardware under extreme operating conditions. Thus, three typical extreme conditions for VTMSs were considered to determine the most severe one. The three conditions are grade load, maximum speed, and off-road, as summarized in Table 3. These conditions were simulated, and the most severe condition was subsequently used for sizing the cooling system components.

Table 3. Vehicle driving conditions.

Condition	Grade load	Max. speed	Off-road
Vehicle speed	48 km/h	72 km/h	48 km/h
Road profile	7% (uphill)	flat	Uneven road
Ambient temp.	40ºC	40ºC	40ºC

Figure 2 shows the operating conditions of the engine, generator, drive motor, and battery under grade load driving condition. The vehicle switches between the charging and discharging modes during the driving cycle. The drive motor speed follows the speed of the vehicle, but the other components are controlled by the hybrid vehicle controller based on the driving mode.

Figure 3 compares the histories and average value of engine BMEP (in the parentheses) under three driving conditions. Engine BMEP during grade load condition is higher than that under other conditions. High engine BMEP

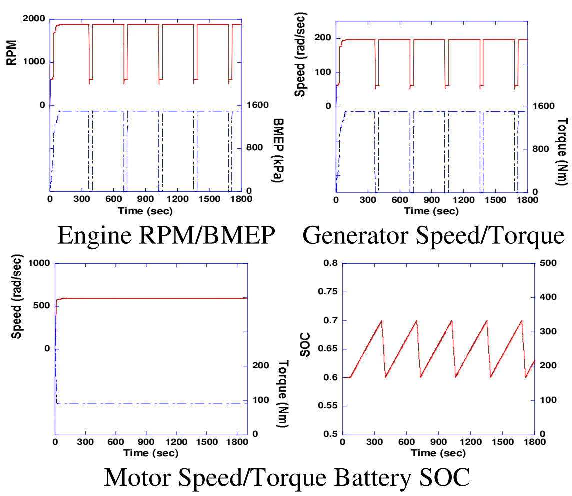


Figure 2: Operating conditions of Heat Sources under Grade Load Condition.

means there is large heat rejection from the engine, which accounts for most of the vehicle heat load. The heat from electric components under grade load condition is also higher than those under other driving conditions because the components operate at a higher load under grade load condition for the engine. The vehicle simulation results help us conclude that the grade load condition is the most severe condition for the VTMS; therefore, the grade load condition was used for VTMS design and optimization.

Component Design

VTMS design has two main constraints: packaging and cooling performance. To address the packaging constraints, the vehicle size within which the VTMS is to be installed must be determined. Since the vehicle selected in this study is a 20 ton off-road tracked vehicle, dimensions from a typical light tank was used to determine the VTMS size. Table 4 lists the specifications of a light tank. Based on the data, size constraints are applied to radiator size because the radiator occupies large area to reject the waste heat to the ambient. Considering the vehicle dimension, the size constraints of 1.2m in width and 0.6m in height are applied to the radiator width and height. The height of radiators are fixed to 0.6m and the width of radiator is assumed to be larger than 0.3m because, if the aspect ratio of the radiator gets larger, the performance of the radiator drops due to the uneven velocity profile of cooling air.

Radiator and coolant pump are the main VTMS components that determine the cooling capacity. The baseline radiator and pump sizes are found by iteration. The component sizing of VTMS should be conducted using severe driving condition Thus, the sizes of the VTMS components are determined iteratively under grade load condition. First, the vehicle simulation is conducted to get the operating condition histories of the powertrain

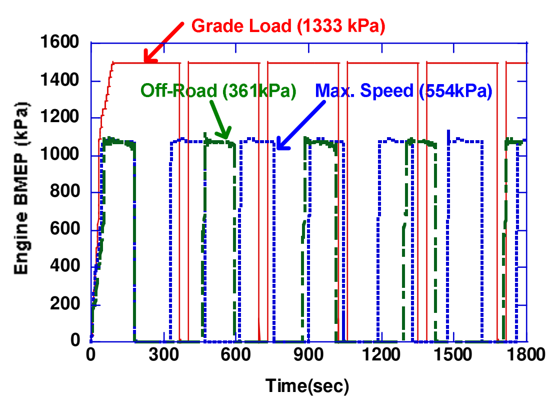


Figure 3: Comparison of Brake Mean Effective Pressure of Engine under Three Driving Conditions.

Table 4. Specifications of a Light Tank (M24).

Crew	5 (Commander, gunner, loader, driver, co-driver)
Length	5.56m (with gun) 5.03m (without gun)
Width	3m
Height	2.77m
Weight	18.4 tonnes

components under grade load condition. Then the data of operating condition histories of the powertrain components are used as input data for the VTMS simulation. The VTMS simulation is repeated changing the pump and radiator sizes until the VTMS fulfills the cooling requirements of the SHEV. The width, height, and thickness of each radiator and pump sizes are changed so that the VTMS can control the component temperatures below their control target temperatures. Table 5 shows the radiator and coolant pump sizes determined by the simulation, which are used as the baseline design of optimization.

DESIGN OPTIMIZATION

The primary design objective is to minimize the size of cooling components (e.g., pumps, radiators, fan, and grille), parasitic losses, and power consumption while maintaining a difference between actual and desired operating temperature for each component (e.g., engine, CAC, oil, electric machines, and power bus) that is less than or equal to zero. The VTMS configuration shown in Fig. 1 is used as the baseline VTMS configuration and the VTMS sizing was conducted for the grade load condition using the baseline values listed in Table 5.

Table 5. Sizing Result of Radiator Size (Width x Height x Thickness) and Pump Scaling Factors for Baseline design of VTMS.

Component	Radiator Size (width × height × thickness(m))	Pump Size (Scaling Factor*)
Engine & Oil Cooler	0.8×0.6×0.051	1.4
Charge Air Cooler	0.2×0.6×0.051	0.13
Generator	0.6×0.6×0.051	0.35
Motor	0.4×0.6×0.102	0.41
Powerbus	0.4×0.6×0.102	0.27

*The pump sizes are scaled from reference pump (460 lpm @ 4644rpm)

Driving Conditions and Design Variables & Constraints

In the 7% grade load driving condition, the vehicle's speed is equal to 30 mph, and the ambient temperature is 40ºC. Employing this extreme scenario ensures that the optimal VTMS design can maintain the operating temperature of each component below the maximum allowable under the most severe driving conditions.

The VTMS model was developed in the Matlab/Simulink environment, and iSIGHT was employed to optimize the baseline VTMS design. A mapping between the Matlab/Simulink and iSIGHT variables was established to communicate the design variables between the selected optimization algorithms in iSIGHT and the analysis variables defined in Matlab/Simulink. An "m"-file was created and called from iSIGHT to load model parameters and execute the Matlab/Simulink model. Another mapping was generated to link Matlab/Simulink outputs to iSIGHT. The design variables and constraints of this study are listed in Table 6. The scaling factors for each cooling component varied the baseline design to a range of ±10%. The constraints were defined to reflect the difference between actual and desired operating temperatures.

Design of Experiments (DoE)

The Design of Experiment (DoE) design exploration technique was utilized to identify significant components, sensitivities, and interactions. Specifically, orthogonal arrays [9] were employed to study the effect of component size to the system's response (operating temperature of each component, e.g., engine, CAC, oil, electric machines, and power bus). In addition, packaging constraints should be

Table 6. Design Variables of VTMS Components and Constraints of Design Optimization.

	Powertrain Component	Variables		Constraints
		Pump Scaling Factor	Radiator Scaling Factor	Temperature Difference ($T_{Actual}-T_{Target}$)
Tower 1 (Power Generation)	Engine	T1PP1	T1RR1	T1Y5
	Oil Cooler			T1Y6
	Charge Air Cooler	T1PP2	T1RR2	T1Y3
	Generator	T1PP3	T1RR3	T1Y1
Tower 2 (Propulsion)	Power bus	T2PP1	T2RR1	T2Y1
	Motor	T2PP2		T2Y2

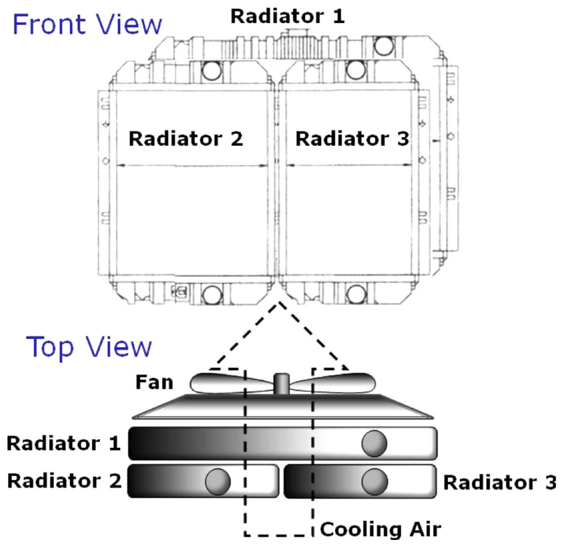


Figure 4: Packaging constraint of radiators in tower 1 (total width of radiators 2 and 3 has to match width of radiator 1)

satisfied, i.e., in case of tower 1, the total width of radiator 2 and 3 should be equal to the width of radiator 1, as illustrated in Fig. 4. The VTMS configuration shown in Figure 1 is used as the baseline VTMS configuration and the VTMS sizing was conducted for the grade load condition using the baseline values listed in Table 5

<u>DoE formulation for Tower 1</u>

In implementing the DoE for tower 1, the objective is to minimize the size of components, and thus parasitic losses and power consumption, subject to maintaining the difference between actual and desired operating temperature for each component to be less than or equal to zero, and subject to geometric constraints. The problem is formulated as follows:

$$\begin{aligned} &\min \ \mathrm{T1PP1}+\mathrm{T1PP2}+\mathrm{T1PP3}+\mathrm{T1}RR1+\mathrm{T1}RR2+\mathrm{T1}RR3 \\ &\text{subject to} \ \ \mathrm{T1Y1}-368\le 0 \\ &\qquad \mathrm{T1Y3}-353\le 0 \\ &\qquad \mathrm{T1Y5}-393\le 0 \\ &\qquad \mathrm{T1Y6}-398\le 0 \\ &\text{where} \ \ \mathrm{T1}RR3=\frac{(0.8\cdot \mathrm{T1}RR1-0.2\cdot \mathrm{T1}RR2)}{0.6} \end{aligned} \tag{1}$$

For tower 1, the DoE revealed the cooling component effect on maintaining the desired operating temperature, as illustrated in Fig. 5. It is noted that the size of radiator 1, fan and grille assembly has the major impact compared with other VTMS components.

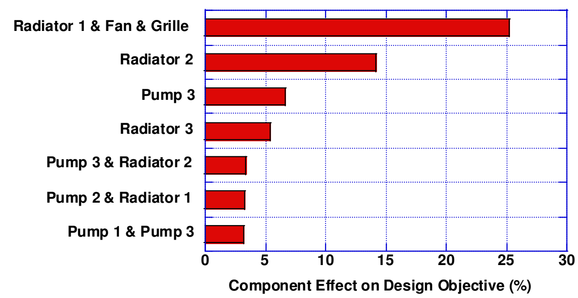


Figure 5: Significance of components.

The interaction effect of the radiator 1/fan/grille assembly with radiator 2 and pump 3 is illustrated in Fig. 6. If the size of the assembly is increased, then the size of radiator 2 and pump 3 can be decreased without violating the

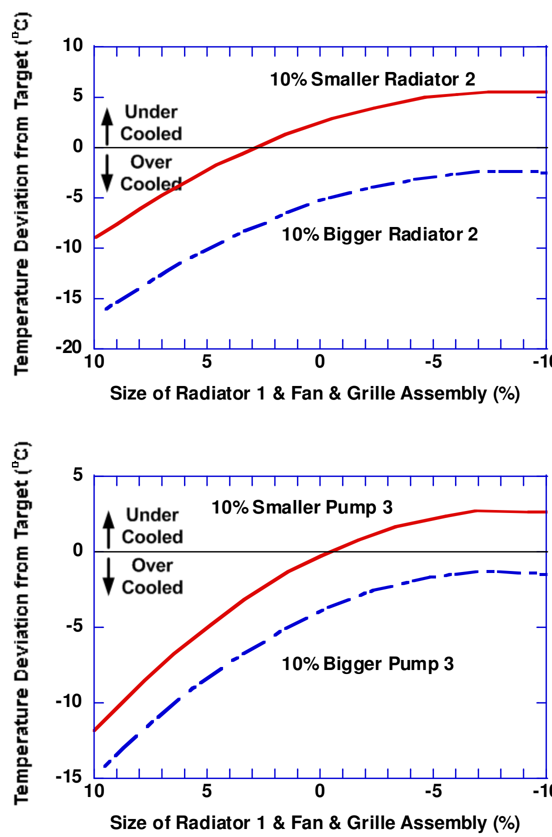


Figure 6: Interaction effect of radiator 1/fan/grille assembly with radiator 2 and pump 3.

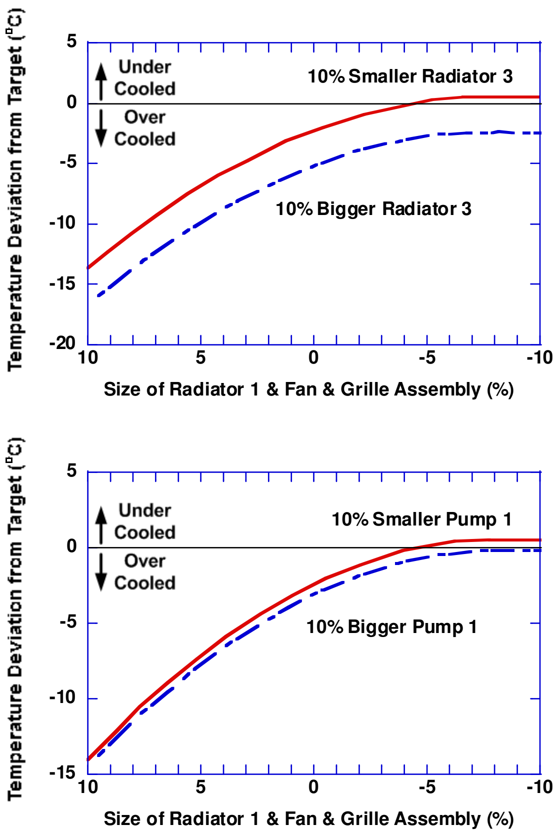


Figure 7: Interaction effect of radiator 1/fan/grille assembly with radiator 3 and pump 1.

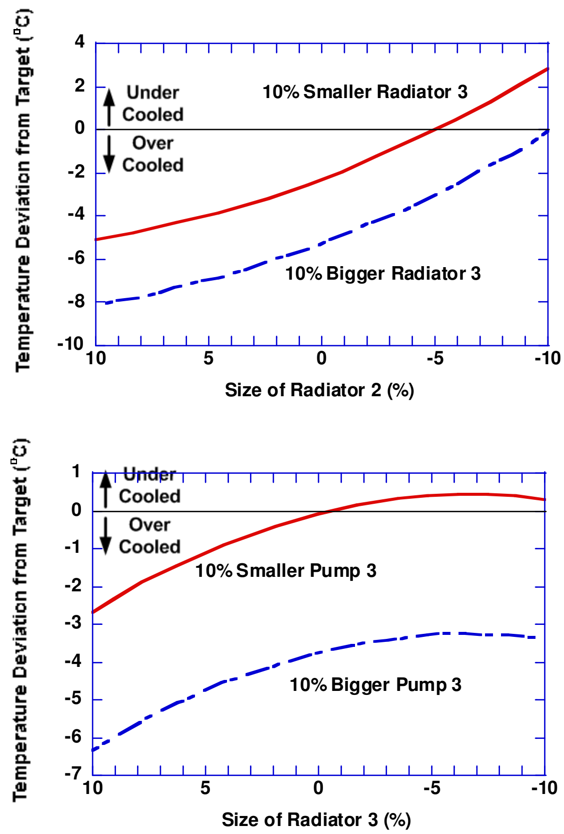


Figure 8: Interaction effect of radiator 3 with radiator 2 and pump 3.

constraint of the actual operating temperatures (i.e., actual operating temperatures be equal to or below the desired ones); however, if the size of the assembly is decreased by 10%, then the size of radiator 2 and pump 3 must be increased accordingly so to not violate the temperature constraints.

Similarly, the interaction effect of the radiator 1/fan/grille assembly with radiator 3 and pump 1 is illustrated in Fig. 7. If the size of the assembly is increased, then the size of radiator 3 and pump 1 can be decreased without violating the temperature constraints; if the size of the assembly is decreased by 10%, then the size of radiator 3 and pump 1 can even be decreased by almost 10% without violating the temperature constraints.

Finally, the interaction effects of radiator 2, radiator3 and pump3 are shown in Fig. 8. If the size of radiator 2 is increased, then the size of radiator 3 can be decreased without violating the temperature constraints; however, if the size of radiator 2 is decreased by more than 5%, then the size of radiator 3 needs to be increased to satisfy the temperature constraints. If the size of radiator 3 is increased, then the size of pump3 can be decreased without violating the temperature constraints; however, if the size of radiator 3 is decreased, then the size of pump 3 cannot be decreased without violating the temperature constraints.

The optimal design derived from the conducted DoE minimized parasitic losses, i.e., the power consumed by the fan and pumps was reduced as illustrated in Fig. 9.

<u>DoE formulation for Tower 2</u>

Similarly, in implementing the DoE for tower 2, the objective is to minimize the size of components, and thus parasitic losses and power consumption, subject to maintaining the difference between actual and desired operating temperature for each component to be less than or equal to zero, and subject to geometry constraints. The problem is formulated as follows:

$$\begin{aligned} \min\ & \mathrm{T2PP1}+\mathrm{T2PP2}+T2RR1 \\ \text{subject to}\ & \mathrm{T2YY1}-343 \le 0 \\ & \mathrm{T2YY2}-368 \le 0 \end{aligned} \qquad (2)$$

For tower 2, DoE revealed the cooling component effect on maintaining the desired operating temperatures, as illustrated in Fig. 10. It is noted that the baseline design turned out to be the optimal design. By decreasing further the size of components the system will be under-cooled.

The derived optimal design of DoE study was evaluated by simulating the VTMS for the grade load condition and it was found that the derived design meets the requirement of the VTMS for the vehicle.

Optimization of Final Configuration and Baseline Design

The baseline design of the VTMS was optimized utilizing the sequential quadratic programming optimization algorithm available in iSIGHT. The objective was to minimize the size of components, subject to maintaining the difference between actual and desired operating temperature for each component to be less than or equal to zero, and subject to the radiator packaging constraints. The results are summarized in Table 7.

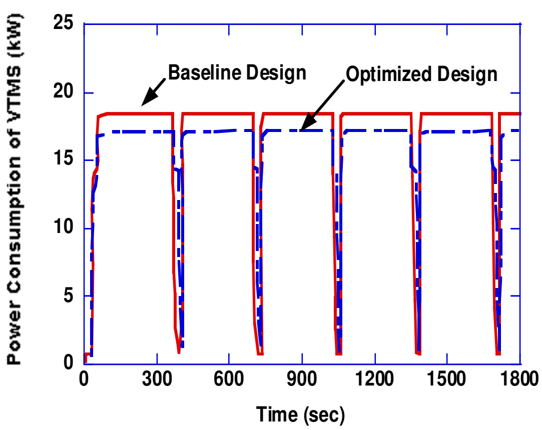


Figure 9: Power consumed by fan and pumps.

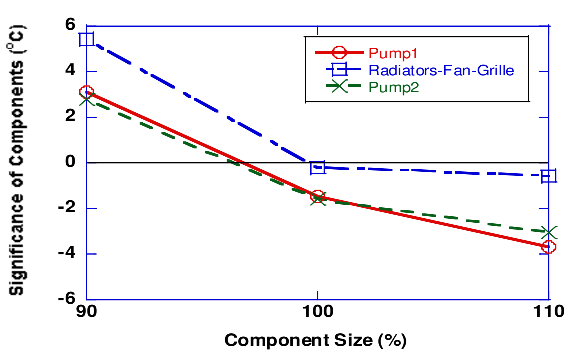


Figure 10: Significance of components.

Table 7. Results of VTMS Component Optimization.

	Powertrain Component	Variables	
		Pump Scaling Factors	Radiator Scaling Factors
Tower 1 (Power Generation)	Engine	0.9	0.983
	Oil Cooler		
	Charge Air Cooler	0.9	0.964
	Generator	1.004	0.989
Tower 2 (Propulsion)	Powerbus	0.9	1.025
	Motor	0.9	

SUMMARY

An analytical, comprehensive VTMS model has been developed, and a VTMS configuration for a heavy duty tracked SHEV has been created according to guidelines suggested by the results of vehicle simulation for different and extremely demanding operating conditions of military vehicle. The baseline design was optimized using design exploration techniques to minimize the size of VTMS component and the parasitic loss while fulfilling cooling requirements. Specifically, designs of experiments (DoE) were utilized to identify the significant components, sensitivities, and interactions of the VTMS, and nonlinear programming was subsequently used to size the components subject to performance and geometry constraints.

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