

Assessment of Advanced Thermal Management Systems for Micro-Hybrid Trucks and Heavy Duty Diesel Vehicles

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Abstract—Advanced thermal management systems (ATMS) have the potential to increase the life of the vehicle's engine and cooling system components as well as decrease fuel consumption and carbon emissions. This paper presents for the first time, an overview of several ATMS topologies and provides a critical assessment as to their power saving potential. Four systems have been modeled using a 1-D simulation tool to study the steady state energy flows in a vehicle operating with a constant duty cycle. The simulation results are used to determine the cooling system power consumption and the effect on fuel economy of the vehicle. It has been observed that a full electric cooling system is not viable for a vehicle with a low voltage electrical system.

Keywords — Cooling system; advanced thermal management; diesel engine; electric fan; electric pump; electric valve; micro-hybrid

I. INTRODUCTION

Since the beginning of the 20th Century, the thermal management system in heavy duty vehicles has undergone little change. A traditional diesel engine cooling system is shown in a simplified schematic in Fig 1. Combustion in the engine block produces energy. This energy is converted into mechanical energy and waste heat in the exhaust and engine block metal. The heat in the engine block metal is transferred to the coolant. A mechanical pump moves the coolant through the engine block. The coolant leaves the engine block and passes through a two way valve. When the fluid is cool, the valve diverts it back to the engine block. When it is hot, it diverts the fluid to the water heat exchanger. A mechanical fan moves air over the heat exchanger. Conduction and forced convection thus remove heat from the engine cooling system. More waste heat is removed from the combustion process through hot exhaust gasses. These hot gasses expand in a turbine driven supercharger also known as a turbocharger. The turbocharger compresses intake air that is fed into the engine for combustion. The act of compressing a gas causes it to heat up, so some of the heat energy is transferred from the exhaust gas to the turbocharged air. This compressed air is cooled by another heat exchanger with the same mechanical fan using forced air convection to remove heat energy from it.

In steady state operation, the rate of removal of heat from a heat exchanger can be expressed as:

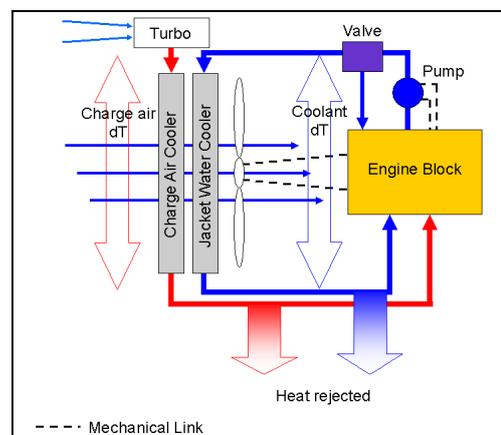


Figure 1. Schematic of a standard diesel engine cooling system

$$Q = \dot{m} \cdot C_p \cdot dT. \quad (1)$$

Q is the rate of heat removed in kW, \dot{m} is the mass flow rate of the internal fluid in $kg \cdot s^{-1}$, C_p is the heat capacity of the fluid in $kJ \cdot kg^{-1} \cdot K^{-1}$ and dT is the difference in temperature between the fluid entering the heat exchanger and the fluid exiting the heat exchanger in degrees Celsius.

The main problems with this cooling system arrangement are summarised here.

A. 1. Lack of Cooling System Control.

The mechanical fan and coolant pump are generally driven directly by the engine via a pulley arrangement. This means that coolant air flow and coolant fluid flow are a function of engine RPM only. There is no control over the way these components operate. This leads to over-cooling of the engine during the warm-up phase and under-cooling of the engine during city driving conditions where large transients of heat entering the coolant from the engine are seen as a result of heavy acceleration and braking. The bypass valve has a wax pellet that expands as it warms up and contracts as it cools down. There is no control over the operation of the bypass valve. Inherent hysteresis in the expansion and contraction of the wax

means that large transients in coolant temperature cannot be avoided.

B. 2. Reduced Cooling System Performance.

The “sandwiched” arrangement of charge air cooler and jacket water heat exchanger means that a high restriction is imposed on airflow. This reduces the air flow for a given fan speed. This means the pulley ratio is selected to achieve a higher fan speed in order to achieve the required airflow.

The limited range of movement of the wax based valve means that when fully open, the restriction imposed on fluid flow is still high. Thus, more power is required of the pump to move fluid through the engine block and a pulley ratio is selected to achieve this.

To avoid engine overheating, the valve operation point is set low enough that thermal transients don't peak above the maximum allowable engine temperature. However, it is desirable that the coolant temperature is kept as high as possible in order to increase the heat transfer for a given flow rate of coolant fluid and cooling air.

C. Parasitic Loads.

Every component that is running when it is not required represents a parasitic load on the drive train and hence an unnecessary consumer of excess fuel.

In the last decade, research has shown the benefits of increased electrification and control in the thermal management system. This is because ATMS allow a reduction of thermal transients in the coolant circuit compared to the on/off switching of thermal components and ATMS raise the overall operating temperature of the engine. The high electrical load that an ATMS will place on the vehicle's electrical system makes it more suited to a micro-hybrid vehicle where the system voltage is 42V or higher.

Ref [1] presented performance curves for standard vehicle oil and coolant pumps and compared them with advanced controllable electric pumps. They concluded that a 5% fuel efficiency improvement is possible by using these components alone.

It has been demonstrated in Ref [2] that, by removing the mechanical load from the vehicle drive train and replacing them with controllable, high efficiency electric components, the auxiliary load reduction imposed by the cooling system can be significantly reduced. Controllability of the coolant pump is highlighted as a distinct advantage in terms of power consumption in Ref [3] where a large reduction in power consumption is achieved by using a minimum flow control strategy. Ref [4] demonstrated the improved engine and vehicle cabin warm-up time by employing a low coolant flow control strategy and electric thermostat valve.

The advantages of using an ATMS have been investigated by modelling in 1-D simulation packages. Many commercial software packages exist that are designed to model an automotive cooling system. The 1-D, lumped parameter approach is employed in most cases. This is where each component's overall effect on the system is modelled rather than the way the component operates on its own. Wherever possible, measured data for cooling system components are entered into the program. The software then interpolates between these points

during the simulation. Ref [5] used this approach in developing a thermal management system modelling tool.

Alternatively, where a component has not been physically built or tested, a mathematical model can be constructed, Ref [6],[7]. Similarly, a simulation comparison of three cooling system topologies was carried out by Ref [8]. This was done by using mathematical models for every component. Special design parameters need to be input for every component such as fin pitch and material for heat exchangers and engine bore and stroke. This makes it possible to model theoretical systems where components may not have been constructed yet.

II. ATMS MODELS

An example of an ATMS is shown in Fig 2. Instead of one mechanical fan, there are several smaller fans driven independently by brushless DC motors. The wax based thermostat valve is replaced by an electronically controlled valve and the mechanical pump is replaced by an electric one. Control of all the components is implemented over a standard SAE J1939 CAN network.

The fully electric ATMS will be compared to other variations of advanced cooling systems. Fig 3 shows an ATMS consisting of an array of brushless DC fans only. All other components in the cooling system are the same as the base system. The advantage of this is that the complexity of the ATMS is reduced. The cost of the system is high due to the large number of power electronic components. Fig 4 shows a cooling system consisting of an electronic thermostat valve and electric pump. The fan is the same model as in the base system. The advantage of this ATMS is that the complexity and cost are both low. A degree of controllability is maintained but the accuracy will not be as good as with an array of electric fans. This is because the change in thermal performance is fastest with variation of the cooling air flow rate.

The same thermal management systems will be modelled for a micro-hybrid system using electric components with higher efficiencies. For the comparison, it is assumed that all auxiliary electric loads in both vehicles are turned off. This allows the base performance to be made the same for both the standard diesel vehicle and the micro-hybrid vehicle. Any improvement in performance is solely due to the improved efficiency of the electric components in the cooling system when

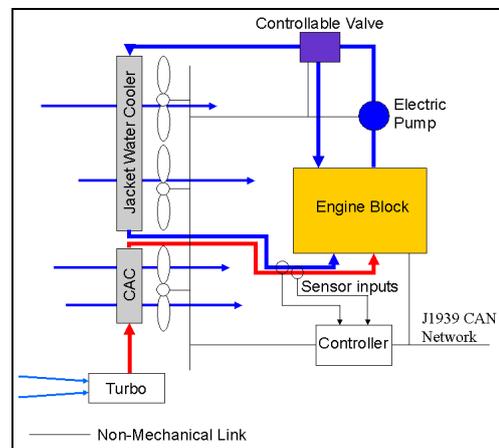


Figure 2. Full electric ATMS. The BLDC fans, BLDC pump and electronic valve are controlled over a CAN network

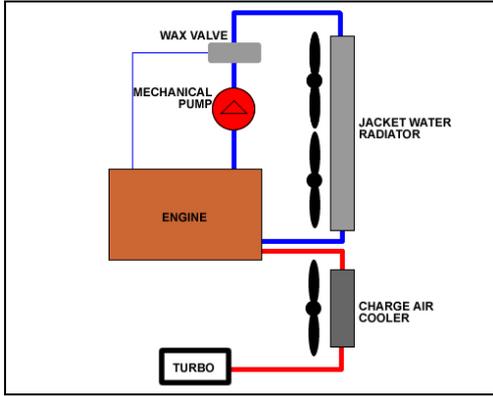


Figure 3. ATMS with an array of BLDC fans. All other components are the same as the base system

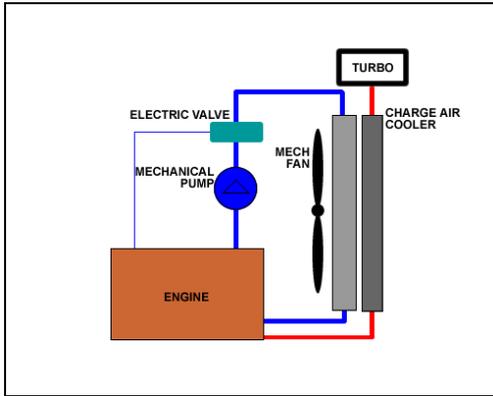


Figure 4. ATMS with electric pump and electric valve

operating at a higher voltage.

The systems have been modelled in KULI, a 1-D tool for the simulation of vehicular cooling systems. Rather than expressing the system components as mathematical models, real test data is used to create a performance map for each component. The performance map for an electric pump is shown in Fig 5. The red dots are the measured data for the pump. The mesh is the interpolation between the measured points and the fan laws were used to predict their performance outside of the measured range. The fan laws that were used are

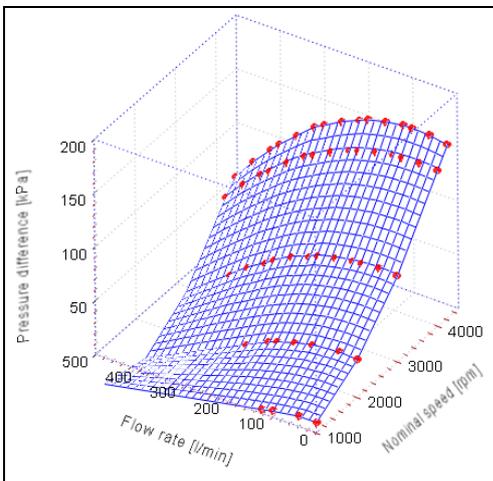


Figure 5. Performance map of a high flow rate electric coolant pump

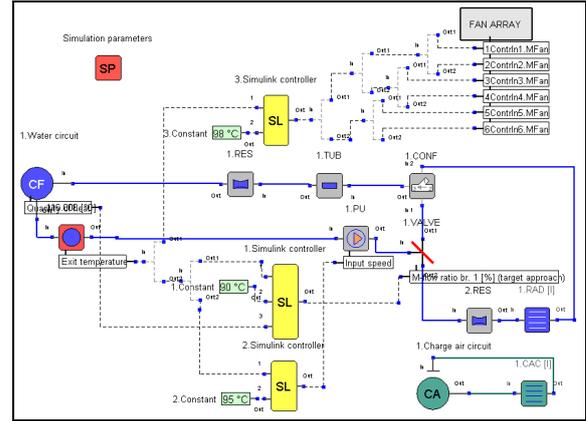


Figure 6. Full electric cooling system model in KULI

$$\frac{S_1}{S_2} = \frac{C_1}{C_2} \quad (2)$$

and

$$\frac{P_1}{P_2} = \left(\frac{S_1}{S_2} \right)^3, \quad (3)$$

S is the speed of the fan, C is the flow rate of the fan at a given speed and P is the power of the fan at a given speed.

The 1-D cooling system model for the fully electrified ATMS is shown in Fig 6. PID controllers were implemented with Simulink to determine the position of the electronic valve and speed of the pump and fans.

For each simulation, a steady state thermal load was selected. The engine RPM is varied over the simulation between a fixed minimum and maximum value. The ability of the cooling system to reject the engine heat with a varying engine speed was then determined. The power consumption of the devices was also calculated over the simulation using the component maps.

III. RESULTS

The initial conditions for the simulations are summarized in Table I. Each simulation was run for sixteen thousand seconds. The initial transient was ignored and the steady state result was used for the comparison. Table II shows the average power consumed by each cooling system in the steady state for the diesel vehicle with a 24V electrical system. Table III shows the power consumed by each cooling system in the steady state for the micro-hybrid vehicle with a 42V electrical system.

A qualitative comparison of temperature variation and vehicle fuel economy is shown in Table IV. The fuel economy improvement is proportional to the reduction in engine power required to achieve the same power as the base system at the wheels of the vehicle.

Fig 7 and Fig 8 show the coolant temperature and power consumption of the fan in the heavy duty diesel base cooling system. Fig 9 and Fig 10 show the coolant

TABLE I. SIMULATION CONDITIONS

Engine Speed	800-1200 RPM
Heat Rejection	100kW
Ambient Temperature	25deg.C

TABLE II. PARAMETRIC ANALYSIS OF ATMS TOPOLOGIES FOR A STANDARD DIESEL VEHICLE

System	Fan Power	Pump Power	Part Count	Cost
Base	15.2kW	3.1kW	Low	Low
Only Electric Fans	0.22kW	2.9kW	Medium	Medium
Electric Pump + Valve	15.2kW	0.04kW	Low	Medium
Fully Electric	0.2kW	3.6kW	High	High

temperature and total power consumption of the electric fans in the fully electric cooling system on the heavy duty diesel drive train. It is immediately obvious that in the steady state, fan power consumption is dramatically reduced and coolant temperature is raised. Less variation is observed in the coolant temperature in the fully electric cooling system.

IV. DISCUSSION

The steady state simulation results for the standard cooling system highlight the limitations of this particular cooling topology. At a high engine speed and relatively low thermal load, the thermostat continuously operates between its maximum and minimum positions. This causes the coolant temperature to remain at approximately 83deg.C. This low temperature reduces the efficiency of the combustion process in the engine and the viscosity of the engine oil.

It is clear from the power consumption results that the most power can be saved by employing an array of smaller, electric fans. The micro-hybrid vehicle could save up to 17kW when the cooling system is fully electrified. The standard diesel vehicle could save up to 14.5kW. At higher engine speeds, the power savings will be much greater since the mechanical fan power is proportional to

TABLE III. PARAMETRIC ANALYSIS OF ATMS TOPOLOGIES FOR A MICRO-HYBRID VEHICLE

System	Fan Power	Pump Power	Part Count	Cost
Base	15.2kW	3.1kW	Low	Low
Only Electric Fans	0.22kW	2.9kW	High	Medium
Electric Pump + Valve	15.2kW	0.05kW	Medium	Medium
Fully Electric	0.2kW	0.84kW	High	High

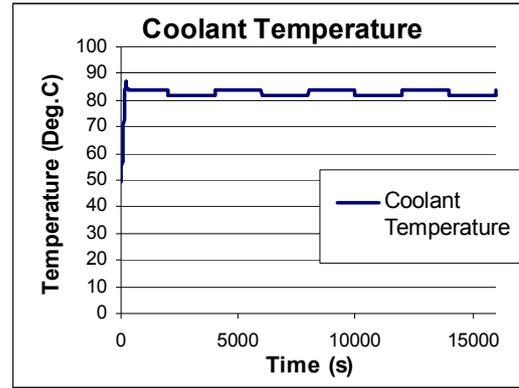


Figure 7. Base system coolant temperature

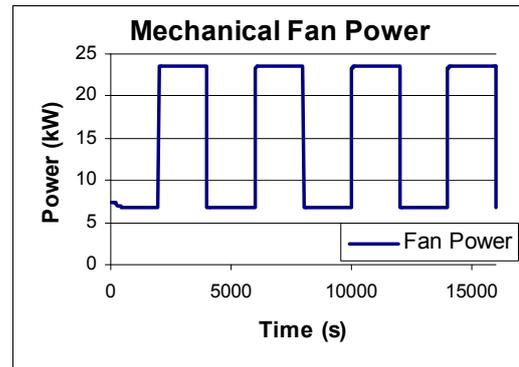


Figure 8. Base system fan power consumption

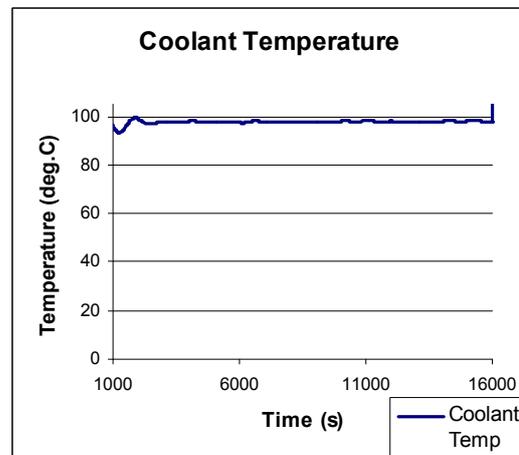


Figure 9. Full electric ATMS system coolant temperature

the cube of the speed ratio (3). It should be noted that the coolant pump model is based on the standard mechanical pump driven by an external motor. It would be impractical to electrify the coolant pump in a low voltage system because the size of the motor is prohibitively large. The micro-hybrid vehicle allows the implementation of a high voltage, high efficiency pump so a fully electric cooling system is viable for vehicles with a system of at least 42V.

The power consumption of the full electric ATMS system is greater than that of the ATMS system with electric fans only in the heavy duty diesel drive train. The opposite is true for the micro-hybrid drive train.

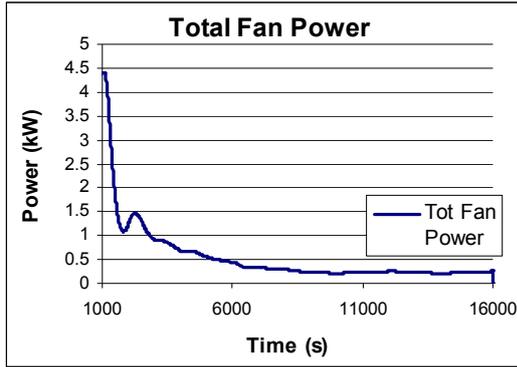


Figure 10. Full Electric ATMS system fan power consumption

The question remains whether the standard heavy duty vehicle electrical system is capable of delivering the required power or whether it has to be modified.

For example, a standard 24V, 260A alternator is not sufficient to power even the most basic ATMS. An ATMS with 8 brushless DC fans and standard mechanical pumps for the coolant and oil circuits, it will consume 4.8kW from the electrical system when running at full load. This leaves 1.4kW to run the rest of the electrical systems on the vehicle and maintain a healthy state of charge in the battery. This extra 1.4kW is only available when the engine is running at a high RPM. A high output, high efficiency alternator must be used as a result.

While an ATMS is applicable in both standard diesel vehicles and hybrid electric vehicles, the power requirement of the ATMS means that the implementation is much easier in a HEV where power is derived from high voltages instead of high currents. Ultimately, commercial vehicles will have to move to micro-hybrid or full HEV systems in order to implement controlled cooling. Measurements have been taken from a commercial, 24V electric coolant pump [9] running at full speed. Fig 11 shows the pressure drop across the pump as a function of flow rate under this operating condition. For a 400kW diesel engine, the required flow rate of 100GPM would only be achievable with a pressure rise of 7psi across the pump. The performance of the pump is limited by the current that can be accommodated in the machine. To achieve a higher pumping power, a higher voltage will

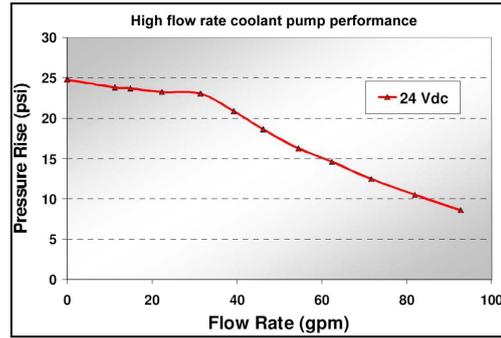


Figure 11. Performance of a high flow rate coolant pump [9]

have to be adopted.

This will also benefit a system employing an electric oil pump as the current power required of them makes them prohibitively large when operating at 24V, [10].

V. CONCLUSION

A comparative study of various ATMS topologies has been carried out by simulation using actual component test data.

It has been shown that the power consumption used by the cooling system can be dramatically reduced. The most important factor in this power reduction is replacing the standard mechanically driven fan with an array of small, electrically driven fans.

The highest power consumption reduction in the standard heavy duty diesel drive train has been obtained by electrifying only the fans in the cooling system. Full electrification is not viable in this drive train due to the low voltage power circuit. An even higher power consumption reduction is obtained by using electric components throughout the entire cooling system for the micro-hybrid drive-train where the system voltage is high enough to support more efficient electric loads.

While part of the power consumption reduction is from the increased efficiency and reduced size of components, another aspect of this is due to the reduced duty cycle of the components. For this reason, it is suggested that more work needs to be carried out looking at the control strategy for the ATMS.

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TABLE IV. COOLANT TEMPERATURE VARIATION AND RESULTATN FUEL ECONOMY IMPROVEMENT

System	Coolant Temperature (deg.C)	Standard Fuel Economy % Improvement	Hybrid Fuel Economy % Improvement
Base	83 +/- 2	-	-
Only Electric Fans	98 +/- 0.3	5%	5%
Electric Pump + Valve	98 +/- 2	1.1%	1.1%
Fully Electric	98 +/- 0.3	4.9%	5.8%

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