Thermal Management

in Automobiles

It is common knowledge that electronics in automobiles has become more and more sophisticated and that the power consumption only seems to increase. In recent years, the proliferation of gasoline-electric hybrid cars has created new cooling problems with electronics that control large amounts of current. This, of course, is in addition to the challenges of keeping vehicle occupants comfortable, engines cool and maintaining low aerodynamic drag under a wide range of environmental conditions. All of these considerations highlight the importance of analyzing thermal management for the automobile as a system rather than as independent components.

The Toyota Prius hybrid automobile contains many examples of vehicle electronics that present new thermal challenges to vehicle designers. In a US Department of Energy evaluation of the Prius' electric drive system [1], it was found that peak energy dissipation could be over 5kW. This would be unheard of in traditional vehicle electrical systems, and traditional air-cooling would be insufficient.

The Prius' motor controller is based on insulated gate bipolar transistors (IGBTs), which are cooled by a cold plate. A water and ethylene glycol coolant circulates through the cold plate and through internal passageways in the motor/generator housing. This coolant loop is separate from that of the internal combustion engine, since it operates about 30°C cooler [2]. The heat exchanger for the electronics cooling loop is attached to the main vehicle radiator, and can be seen in Figure 1.

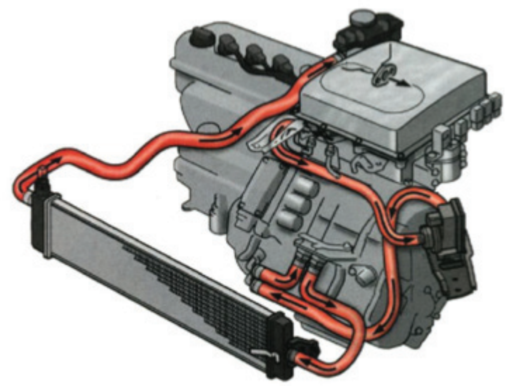

Figure 1. Toyota Prius Secondary Cooling Loop [3].

In the current Prius model, the battery pack comprises 28 flat modules and weighs about 40 kg [4]. It is fitted with an air cooling system with a four speed fan, the fan speed being determined by the battery temperature [5]. The cooling air is received from the passenger cabin, and expelled to the vehicle exterior. (See Figure 2.) One of the important details of cooling the battery pack is keeping the temperature of all the modules as uniform as possible. This maximizes the performance and the life of the battery. To this end, there are air passages between all of the modules, and they are cooled by a parallel, rather than series, airflow.

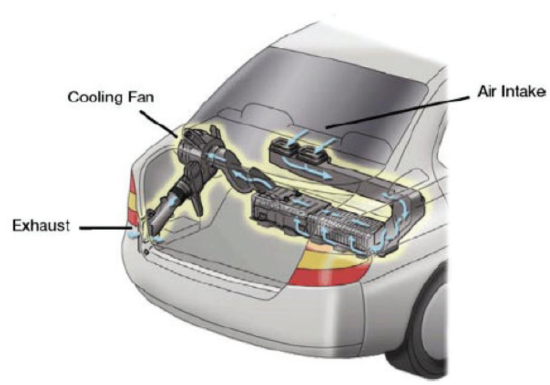

Figure 2. Toyota Prius '04+ Battery Cooling System [3].

The introduction of LED headlights poses another interesting problem for thermal management. The efficiency and quick "on-time" have made LEDs popular for brake lamps and other auxiliary lighting, but their low power levels have not needed specialized thermal management. Debuting in the Audi R8 sports car [6], the compact and efficient LED headlamps allow vehicle stylists new freedom while requiring unique thermal solutions.

The LED chips do not produce as much heat in the form of IR compared to traditional halogen headlights, but they do generate heat that must be dissipated at the rear of the chip. At a glance, it could appear that keeping the LEDs cool would be straightforward. However, as the headlights are on the exterior of an automobile, there are additional considerations, such as ice buildup on the headlight lenses. Because the LEDs produce much less IR than other headlights, the lenses do not get warm, and ice can build up on them much more easily.

Engineers at Cadillac came up with a fan-based active cooling system for the LED headlamps in the Escalade SUV that not only keeps the junction temperature within specification, but also circulates warm air forward to de-ice the headlight lenses [7].

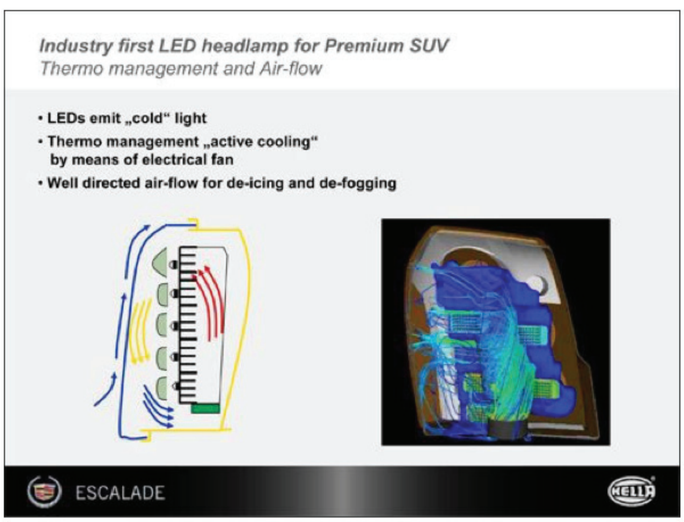

Figure 3. Cadillac Escalade LED Headlight Model [8]

Of course, thermal management is not simply focused on the new and emerging technologies available to automakers. Alternators, which have been in automotive use since the 1960s, are an interesting illustration of system interdependence when it comes to thermal management in cars. As electrical systems in cars have developed, the power output of the alternator has increased accordingly. From the 60s to today, typical alternator power outputs have increased from 500 W to 2-3 kW [9]. At the same time, underhood temperatures have increased and airflow has decreased for aerodynamic and noise considerations. While all of these changes have happened, the package size of the alternator has stayed relatively unchanged.

Thermally, the primary point of concern in an alternator is the rectifier bridge, which comprises several diodes. The thermal losses of these diodes increase in direct proportion to the alternator output, so as the output power has increased fivefold or more, so has the heat dissipation of the rectifier diodes. In order to meet these demanding conditions, diode packaging was developed with higher case temperature limits, but this only helped to a small degree. Most of the thermal improvement has come by more sophisticated heat sink design and the use of FEA at first, and later, CFD. The ability to analyze the air flow within the alternator has enabled engineers to increase heat flux from the diodes to the underhood air. The level of improvement is illustrated in Figure 4 below, where UA is the inverse of thermal resistance. Units are listed along the bottom of the chart with their respective data.

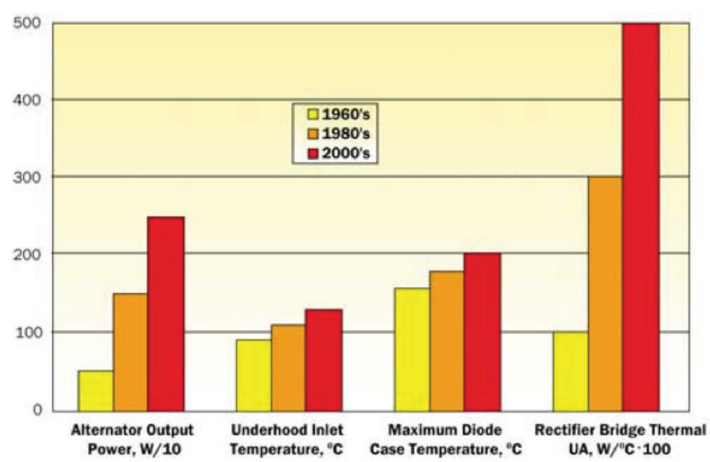

Figure 4. "Historical Thermal Developments In Alternators" [9].

Examples such as these illustrate the complexity and interdependence of components in an automobile. The efficiency of the Prius' electric drive system depends in part on the temperatures of components such as the battery.

The cooling of the battery, however, depends partly on the conditions in the cabin of the vehicle.

In another loop, the operation of the drive system, and the heat it generates, greatly influences the overall system conditions. The evaluation of these complex systems has necessitated the use of computer modeling techniques.

The problem with modeling large systems with many components is that it requires a large amount of computing power and a lot of time. One way to simplify system modeling with complex components is to use “multi-resolution” analysis. Raman et al. describe one such method using conventional CFD analysis for the overall system, but replacing components with artificial neural networks (ANNs) [10]. ANNs model the behavior of a component without having to model and mesh all of its internal parts. One way to create an ANN is to “train” it to mimic the behavior of a component simulated by CFD. To tie the ANN and CFD analyses together, a multi- resolution software package is utilized that controls the various types of simulation software and routes the appropriate data between them.

When incorporated into a system analysis, the ANN shows the behavior of the component as it interacts with the system. Raman et al. modeled the interior of a car containing three simplified electronic components. When doing a full CFD analysis of the system, almost 17% of the mesh cells were dedicated to the electronics. Using a multi-resolution analysis with CFD and ANN models, the simulation time was more than halved, and the results can be seen to be very similar in Figure 5 and Figure 6.

It should be noted that in their analysis, simple models were used to simulate the electronics. Raman et al. estimate that if the simulation was performed with realistically complex models of the electronics, 70-90% of the overall mesh would be dedicated to the electronics. It can be imagined that the performance advantages of using ANNs could be much greater in analyses with complex electronic components and more of them.

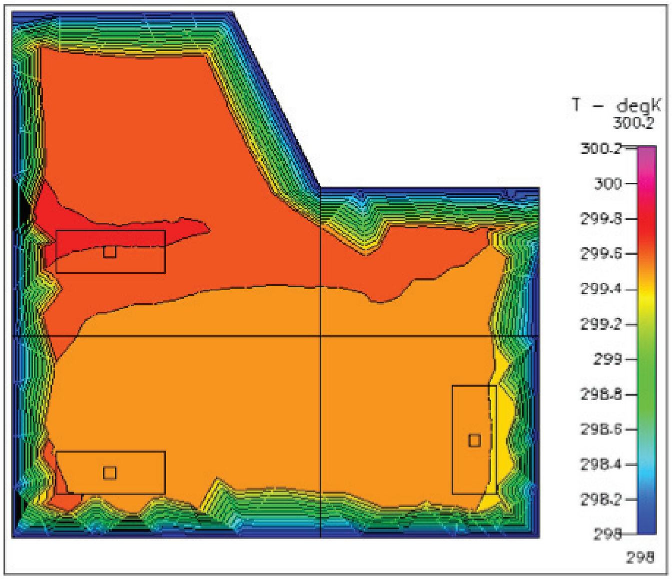

Figure 5. Fully Resolved Thermal Simulation [10].

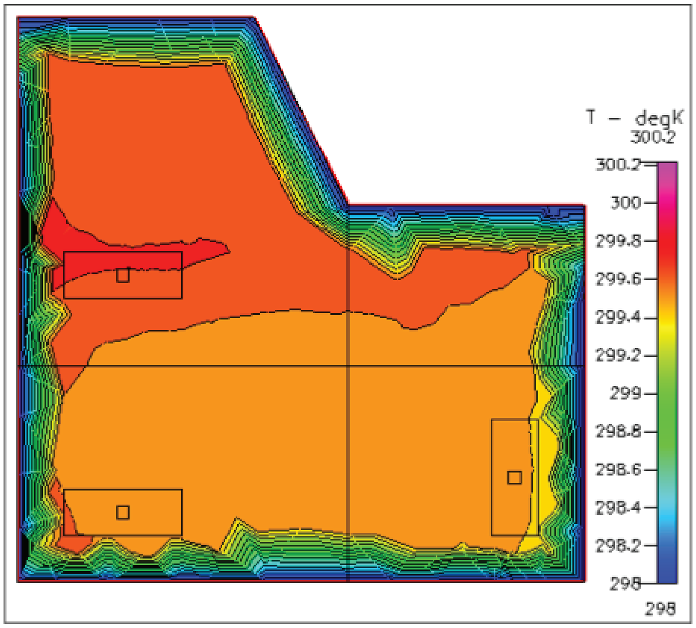

Figure 6. Multi-Resolution Thermal Simulation [10].

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