Case Study of Thermal Management for Mobile Multi-Media (MMM) Applications

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Abstract

Mobile Multi-Media (MMM) is a term used in the automotive industry to describe the growing use of consumer electronics, satellite-based navigation systems and Internet applications in the automobile. As an example of the thermal challenges that confront the use of such systems in the automotive environment, the mounting of a digital video disc (DVD) player on the roof of an automobile is considered in this paper. Of particular interest is the cooling of the optics region of the DVD player, which is critical to the operation of the mechanism. FLOTHERM simulations guide the design of the enclosure surrounding the mechanism, and extensive experimental studies help corroborate the results of the analysis. The application involves the use of a fan, which helps cool all interior devices including heat-sink mounted regulators and the DVD player. Despite venting the enclosure to channel air flow, analysis reveals that it is necessary to reduce heat dissipated inside the box to meet stringent boundary conditions. Discussions on the effect of solar heating of the roof and high voltage are also presented. Employing a hybrid approach of electrical reduction in power dissipation and mechanical reduction in thermal resistance, temperatures in the DVD enclosure are reduced to an acceptable level.

Description

MMM applications physically reside in various parts of the automobile, creating new electronic packaging challenges, especially for thermal management. The rear seat entertainment system considered in this paper consists of a DVD player in a sheet metal wraparound, housed in a plastic enclosure, which forms part of a roof-mounted console. The top of the console is about an inch below the headliner of the roof. A fan, operating in exhaust mode, removes heat from the interior of the wraparound, thereby cooling the DVD and the board-mounted regulators. Depending on the application, the roof headliner is opened out to some extent, and hence the top of the box (Fig. 1) is not completely closed.

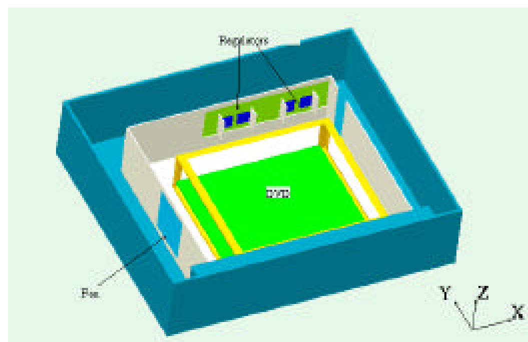

Fig. 1 Schematic showing the DVD mechanism outline in the plastic console

Preliminary experimental testing indicated that thermal problems may be experienced at high ambient temperatures with the existing design. Hence, an analysis effort was initiated to resolve potential thermal issues.

Objectives of the Thermal Analysis

- Evaluate the thermal limitations of the current design
- Provide solutions for improved heat sinking and venting

The unit is required to survive steady state operation at 65 °C ambient and 16 V operation. Reliability of the DVD mechanism drops steeply when the optics temperature exceeds 80 °C. Considering the limitations of the components, the following thermal criteria are chosen.

Criteria for Successful Thermal Solution

- DVD optics temperature must not exceed 80 °C when exposed to 65 °C ambient
- Regulator junction temperature must not exceed 125 °C in steady state

Analysis

Hand calculations

The four linear regulators on the main board of the unit are TO-220 packages mounted on a flat plate aluminum heat sink, about 100 mm x 50 mm x 3 mm in size. While this heat sink helps cool the regulators, it does not directly address the DVD mechanism. The fan provides the cooling effect for the DVD optics. At maximum flow, the fan can draw 4 cfm (cubic feet/minute) of air. If the fan directly vents to ambient, it is easy to estimate the rise in air temperature as it passes through the system, using the approximate relation

$$\Delta T = 1.8Q/V \qquad (1)$$

ΔT = rise in air temperature from entry to exit (°C), Q = total power dissipated in the box (W), V = fan volumetric flow rate (cfm)

Equation (1) indicates that, at best, 33 W of heat can be removed with a rise of 15 °C in air temperature. However, it should be noted that the existing design does not allow air to enter and leave the box. Instead, a recirculatory zone is set up inside the box which increases the air temperature. Nevertheless, the above equation is useful in establishing the limitations of the fan for the proposed power dissipation.

The junction temperature of any of the regulators on the heat sink can be computed using

$$T_j = R_{js}Q_r + R_{sa}Q_t + T_a \qquad (2)$$

T_j = junction temperature of the sink-mounted device (°C), T_a = ambient temperature (°C), Q_r = power dissipated at the regulator (W), Q_t = total power dissipated at the heat sink (W), R_{js} = thermal resistance from junction to heat sink (°C/W), R_{sa} = thermal resistance from heat sink to ambient (°C/W)

Prior experience indicates that the maximum air speed generated by the fan is about 2 m/s. The flat plate sink, subjected to forced convection with air speed 2 m/s parallel to the long edge, has a thermal resistance of 5.2 °C/W [1], but the heat sink is in close contact with the large sheet metal wraparound, which reduces the thermal resistance to R_{sa} = 3.2 °C/W. Typically, R_{js} can be reduced to 2 °C/W for TO-220 sized packages. With this information, Equation (2) can be used to establish limitations on Q_r, Q_t or T_a, to maintain T_j below 125 °C.

There are no simple hand calculations that enable a quick estimate of DVD optics temperatures. Analysis and experimentation indicates that the thermal resistance of a DVD player is dependent on the nature of venting, and that system level modeling of the entire air flow path is the best method of estimating optics temperatures.

Simulations

The analysis tool FLOTHERM, which is capable of solving combined CFD (computational fluid dynamics) and CHT (conjugate heat transfer) problems, is used. All known geometric and material details of the heat sink, sheet metal and plastic are modeled so that conduction, convection and radiation modes of heat transfer are simultaneously considered. To do full justice to the DVD mechanism, it is necessary to have a detailed submodel with all the motors, screwheads and devices. Here, a relatively crude model that approximates the air flow resistance of each side of the DVD player is created, with the circuit board explicitly modeled at the bottom of the mechanism. The logic device, spindle motor and sled motor of the DVD mechanism are modeled using cuboid blocks. For other components in the system, judicious use of FLOTHERM primitives such as blocks, resistances, fans and vents facilitates the creation of the complete system level thermal model.

First, a correlation study is performed to establish the validity of the model. This is accomplished by a lab test with the unit top open, operating at 12 V at an ambient of 25 °C. Fig. 2 shows a section (as viewed from the roof of the automobile) passing through the heat sink and the optics. An opening in the sheet metal wraparound brings air into the DVD, but it is clear that the middle of the unit needs better ventilation.

Table 1 Comparison between measured and predicted temperatures for 12 V operation, with open top

Location	Experiment	Simulation
Heat sink	**68-70 °C**	**68-73 °C**
Fan exit	**37 °C**	**37 °C**
Center of unit	**41 °C**	**40-42 °C**

As seen in Table 1, the correlation is good. Subsequent tests and simulations also reinforce the accuracy of the model.

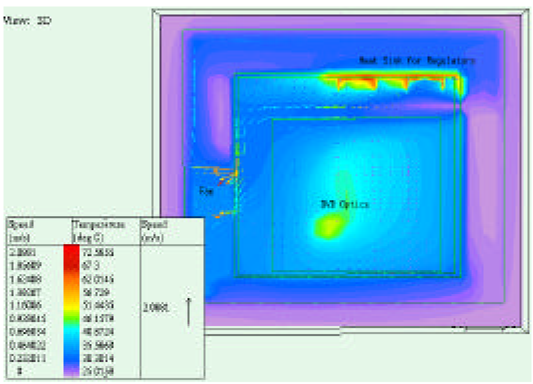

Fig. 2 Section through the enclosure showing temperatures and air speed vectors

The open console top, low voltage and low ambient temperature represent a benign environment for the unit. Experiments and simulations performed with a closed top, at 16 V and 25 °C, indicate the temperature rise at the optics is as high as 47 °C over ambient, and the regulators experience a 91 °C rise. Clearly, the objective of obtaining a temperature rise of 15 °C or lower at the DVD optics is not met.

Hence, the data indicates that the existing design is incapable of meeting the thermal criteria, both at the DVD optics and at the regulators. To reduce temperatures, the primary methods are to reduce power dissipation inside the box and to improve air flow in and around the hot components. After examining several scenarios of improving air flow using baffles and fan orientation, a hybrid approach of reducing power and adding vents is adopted. To reduce power dissipation, a switcher, which substantially reduces heat at the regulators, is added to the electrical circuit. No reduction in power is possible for the DVD mechanism: however, experiments indicate that the use of the switcher reduces temperatures at both the regulators and the DVD optics.

Table 2 Power dissipation (W) inside the box at high voltage (16 V)

	Without switcher	With switcher
Regulators	**26.5**	**12.5**
Mechanism	**8.5**	**8.5**
Main Board	**2.7**	**2.7**
Total Power (W) in box	**37.7**	**23.7**

Results with a Switcher

Experiments using a closed top over the box indicate that the removal of heat from the regulators reduces temperatures dramatically at all locations. During high voltage operation, the temperature rise at the optics is 27 °C, while the temperature rise at the heat sink is 40 – 45 °C over ambient. While this is a considerable improvement over the existing design, further reduction is needed to be able to survive 65 °C ambient.

To further reduce temperatures, air flow enhancement is pursued as a supplement to power switching. This can be accomplished using a larger fan, which is undesirable due to noise and reliability considerations. Baffles and air flow enhancements are preferable. The approach used here is to add vents in the side walls of the plastic housing, so as to allow ambient air to enter and leave the unit rather than recirculate inside the housing. Clearly, large vents provide larger cooling effect, but styling and structural considerations limit the size and placement of the vents. Fig. 3 shows four narrow slots (22 mm x 3 mm each) added to two sides of the plastic housing. The slots on the right side are positioned to enable inlet air through corresponding cutouts in the wraparound of the box, which directs air into the optics region of the DVD. While this does not allow a straight left-to-right air flow path which minimizes resistance to air flow, analysis indicates that the fan operates at a low pressure drop, drawing 3.2 cfm.

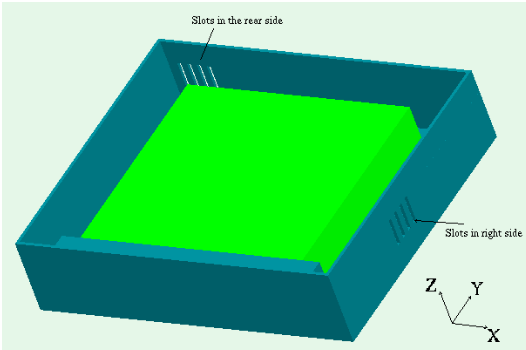

Fig. 3 Slots in the plastic housing to allow air into the box

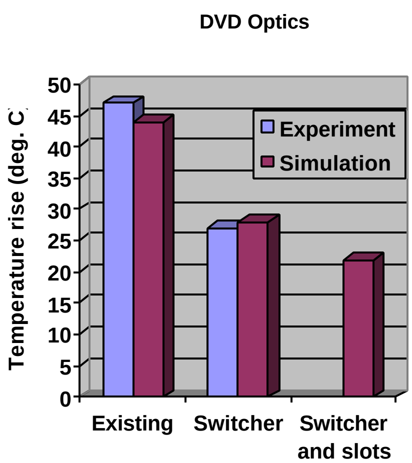

Fig. 4 Temperature rise over ambient at the DVD optics

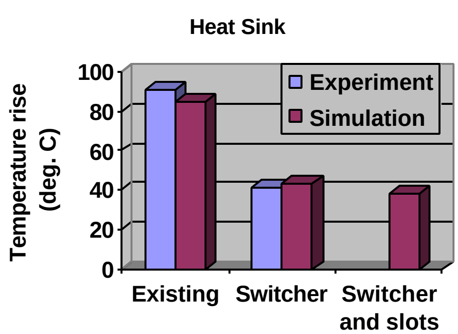

Fig. 5 Temperature rise over ambient at the heat sink

Analysis indicates that the slots reduce temperatures by about 5 °C at most points inside the box, resulting in a rise of 22 °C at the DVD optics and 36 °C at the heat sink. Figs. 4 and 5 summarize the improvements for the DVD optics and the heat sink respectively. With the switcher incorporated into the circuit, all the regulators on the heat sink are rated at 150 °C. This allows a further margin of safety in the design.

Based on the data, thermal resistance of the optics region of the DVD, which may be defined as R_{oa}=rise in DVD optics temperature/total power in box, is approximately 1.2 °C/W in the presence of the fan. With the slots, the resistance decreases to 0.9 °C/W.

Worst Case Analysis

The theoretical worst case scenario is steady state 16 V operation at 65 °C ambient, with all regulators and devices dissipating highest power. While it is obvious that, in the passenger compartment, ambient temperatures of 65 °C are unbearable for human occupants of the automobile, heating ducts near the console could potentially raise the ambient temperature during extremely cold conditions outside the vehicle. Taking into account statistical variations and tolerances on the resistances and voltages, the total heat dissipated at the heat sink is computed as 14.4. Fig. 6 shows the resultant temperatures. Analysis predicts that the heat sink reaches 114 °C and the optics are at 88 °C under these conditions. While the regulators are safe at these temperatures, the optics are above the limit by 8 °C (temperature rise over ambient is 23 °C). The highest tolerable ambient temperature for steady state operation is predicted to be 57 °C, to keep the optics at or below 80 °C.

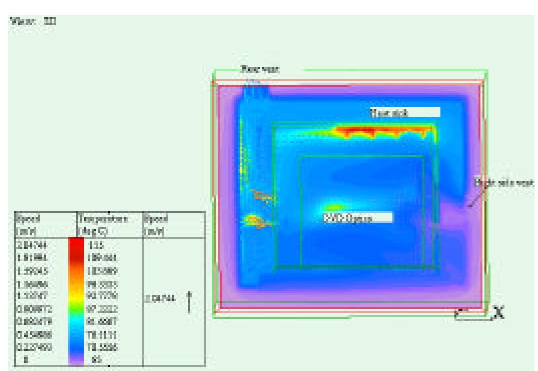

Fig. 6 Worst case thermal analysis

Roof and Sun Load

On hot and sunny days, considerable amount of heat can fall on the top of the roof, raising roof "skin" temperatures and potentially harming the roof-mounted DVD player. To address this concern, analysis is performed with the roof explicitly modeled. It is assumed that the solar flux is 1300 W/m^2, which results in over 1 kW of heat on the top surface of the roof. The vehicle internal ambient temperature is assumed to be 40 °C to simulate a realistic extreme scenario. The resultant roof "skin" temperature is over 110 °C, but the effect at the DVD optics location is minimal. The predicted DVD optics temperature is 63 °C, which is a rise of 23 °C over ambient. Hence, it is evident that the effect of sun load on the internal operation of the DVD is minimal. The reasons are the large distance (over an inch) separating the roof and the top of the DVD player, and the forced convection due to the presence of the fan (Fig. 7).

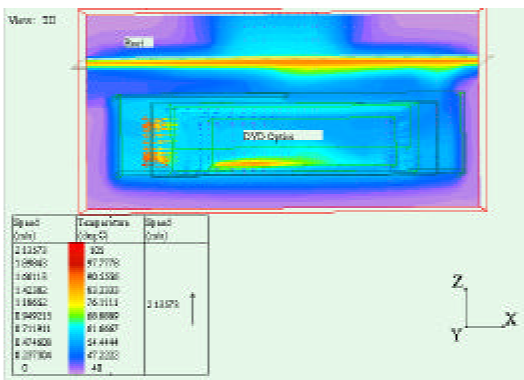

Fig. 7 Frontal view (fan on the left side) for the heated roof scenario

Transient Issues

The time taken by the devices and the optics to reach steady state conditions is typically about an hour of continuous operation, as measured in experiments. After a hot sun soak, if the vehicle air conditioning is turned on, the interior cools rapidly from the elevated temperature to a tolerable internal ambient. Of concern is the time taken by the optics to reach 80 °C while the ambient levels off. Experiments indicate that the DVD optics temperature stays below 80 °C after 40 minutes of exposure to a barely tolerable internal ambient of 40 °C, following more than an hour of a hot soak. In this study, no transient thermal simulation is undertaken to substantiate the experimental results.

Fan Issues

The fan is critical to the thermal management solution. At zero pressure drop, the maximum air flow is 4 cfm, and at no flow, the pressure drop is 20 Pa. This defines the fan characteristic, which is valid for a wide operating voltage range. Based on prior experience with the fan in radios [3], there does not appear to be a reliability issue with fan degradation over extended periods of time. The low flow resistance predicted by the simulation indicates that the noise levels are expected to be low. Reversal of the fan direction is possible if the unit is improperly assembled to the unit. Analysis predicts that the effect of fan reversal (blowing into the enclosure instead of out) on both the DVD optics and the regulators is minimal in this problem.

Future Work

This study uses a relatively crude model of the DVD mechanism to resolve system level thermal issues. For accurate system level analysis, without excessive detail, it is important to have a well-characterized and validated component level submodel of the DVD mechanism. This can be generated by subjecting the unit to tests in controlled environments, with and without fans, and deriving thermal resistance values for the DVD optics. It is preferable to have the suppliers of such mechanisms perform these measurements, so as to enable up-front assessment of the thermal robustness of the design. Compact libraries and models, such as those developed for IC packages [2], would greatly improve the speed and accuracy of system level thermal analyses.

Discussion

Experienced thermal analysts recognize that high accuracy (+/- 3 °C, for example) in system level analysis is difficult, if not impossible, to achieve. Nevertheless, it is becoming clear that in the demanding environment of the automotive interior, it is important to minimize the uncertainty in analysis and experiments to satisfy customer expectations. In this particular example, the limitations of the DVD player allow only a small rise in temperature from ambient, which drives the need for accuracy.

Another significant feature of this study is the interaction between the electrical and mechanical aspects. While it may have been possible to slightly improve the thermal performance by optimizing pressure drop and air flow through the unit, it is unlikely that a dramatic improvement could be affected at a reasonable cost by mechanical means alone. The incorporation of the switcher into the circuit does add cost to the unit, but eliminates the need to investigate exotic cooling solutions.

Conclusions

The paper offers a case study of thermal management, involving temperature reduction using electrical and mechanical means, for a typical MMM product. Several simulations using FLOTHERM and experiments are performed to quantify the effects of venting, power reduction and solar loading on temperatures inside the console of a roof-mounted DVD player. The following conclusions are drawn from the results of experiments and simulations.

- The existing design, with all linear regulators, is unacceptable. The DVD optics and the regulators exceed rated maximum temperatures, when subjected to high voltage and high ambient temperature.
- By using a switcher in the electrical circuit and venting the plastic console, substantial reduction in operating temperatures is demonstrated using experiments and simulations.
- Venting the console helps cool the DVD optics further. Small vents on the rear and right side of the console, with cutouts in the wraparound, provide an additional temperature drop of 5 °C.
- With the changes, the unit is validated to pass continuous operation at high voltage (16 V) and 57 °C ambient temperature.

References

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