Thermal Design Considerations for Portable DLP™ Projectors

Scott P. Overmann
Texas Instruments Incorporated
Post Office Box 869305, MS 8477
Plano, TX 75086
Phone: (972)-575-0477, Fax: (972)-575-0457, E-mail: overmann@ti.com

Abstract

Portable DLP™ (Digital Light Processing™) projectors continue to lead the projector industry in terms of lumens/in³ and lumens/pound. Recently announced products break the 1.4 kg (3 lb.) barrier with brightness exceeding 1000 lumens. While the weight and volume of these products has decreased dramatically over the past several years, the power dissipation has remained unchanged or, at best, decreased only slightly. Trends in projector size and power are explored and compared to other types of portable equipment such as the laptop computer. Critical thermal design considerations are discussed including DMD™ (Digital Micromirror Device™) cooling, lamp cooling, touch temperature requirements, fan selection, fan temperature, vent design, and acoustic challenges. Testing and analysis methods used in the design process for the system and subsystem levels are also discussed.

Key words: thermal management, portable, projector, DLP™, DMD™

Introduction

Portable DLP™ (Digital Light Processing™) projectors continue to lead the industry in terms of smallest size and weight. There is a strong trend to decrease projector size and weight while increasing brightness. These goals must be achieved while maintaining or improving acoustic performance, lamp life, touch temperature, light leakage, and overall system reliability. This becomes increasingly challenging with each new generation of projectors, partially due to thermal design capabilities. This paper addresses the major system and subsystem level thermal design issues and offers analysis and testing techniques to achieve a satisfactory projector thermal design.

Historical Trends

The portable projector industry is a relatively new industry with 3.1 kg (6.8 lb.) products first becoming available in late 1997. Current products offer twice the brightness (1000 lumens) and less than half the weight 1.4 kg (3 lb.) of the lightest projector available in 1997. The strong demand for lighter and brighter projectors will continue in the foreseeable future, making portable projector thermal design more challenging. Figures 1 and 2 show historical trends in lumens/pound and lumens/in³. Both of these curves are increasing at more than a linear rate versus time. While these curves are very impressive and favorable to the consumer, the increase in power density (projector power/in³) places significant burden on the thermal design as shown in figure 3. Power density for 1.4 kg (3 lb.) projectors introduced in late 2000 approach 1.5 W/in³, which is roughly three times a laptop computer under maximum power dissipation or seven times a laptop under typical operating conditions.

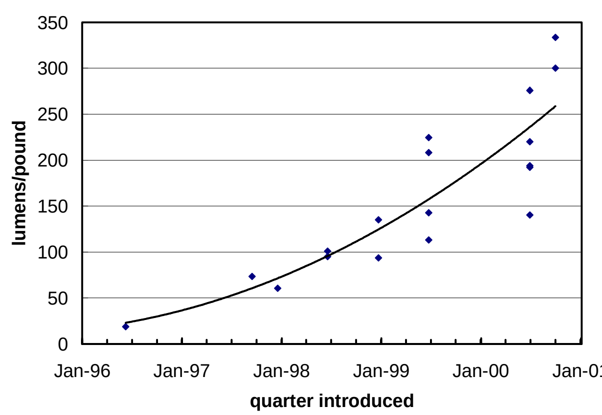

Figure 1: DLP™ projector lumens/pound versus time

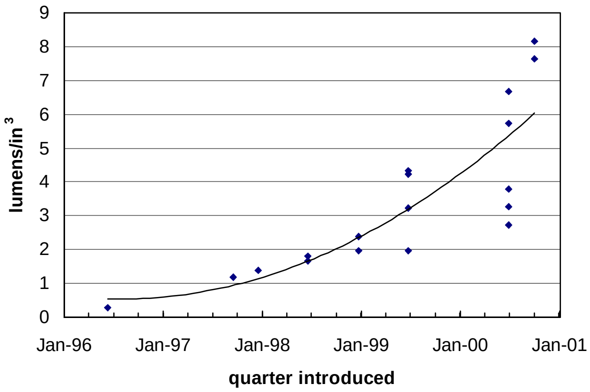

Figure 2: DLP™ projector lumens/in^3 versus time

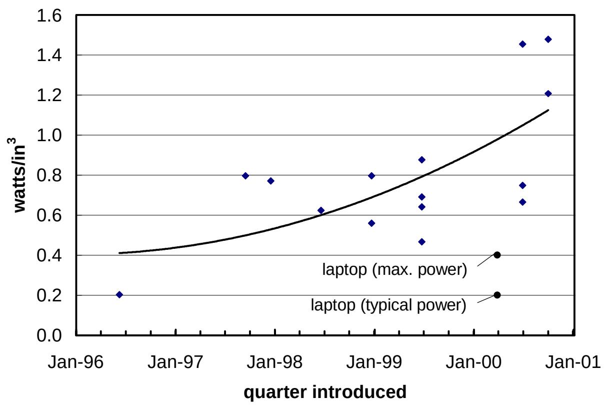

Figure 3: DLP™ projector power density versus time

Critical Thermal Design Issues

With projector power density increasing at a rapid rate, thermal design has become a vital part of overall projector design. Design engineers must consider thermal capabilities along with performance goals to achieve a successful product. The critical thermal design issues to be considered on the system and subsystem levels are discussed throughout the remainder of the paper.

System power dissipation

Total system power dissipation for portable projectors is dominated by the lamp power, which typically represents 75% of the total power. The lamp power supply is also a significant contributor to the total power dissipation and represents another 15% of the total system power. The remaining power is dissipated in the electronics, fans, and color wheel motor (figure 4).

Portable projectors all use fans to circulate ambient air through their chassis and cool the internal components convectively. Required volumetric airflow is based on total system power dissipation and allowable temperature rise from air inlet to exhaust. Assuming allowable temperature rise is fixed and fan speed is limited for acoustic reasons, then the primary method of dealing with increased system power is to select larger fans. Fans are becoming a significant contributor to the overall size and weight of portable projectors. For their size to decrease substantially, system power dissipation must be reduced.

Since most of the power dissipation is concentrated in a small area (around the lamp), projectors typically have a very non-uniform temperature distribution on their external surfaces. Projector housing temperatures are the hottest around the lamp and exhaust vents. UL (Underwriters Laboratories) requirements provide maximum touch temperatures that cannot be exceeded, however projectors which are significantly cooler than these limits are more acceptable to the user. Touch temperature requirements based on excerpts from UL 1950 are shown in table 1 [1]. Projector housing temperature has become more of an issue recently as projectors have become smaller and chassis are made from magnesium instead of plastic. Magnesium housings reduce weight and enhance structural integrity but have a substantial touch temperature disadvantage. As shown in table 1, the allowable touch temperature for metal is lower than plastic. A metal chassis will feel hotter than a plastic chassis at the same temperature due to its higher thermal conductivity, and therefore must be maintained at a lower temperature for comfort and safety.

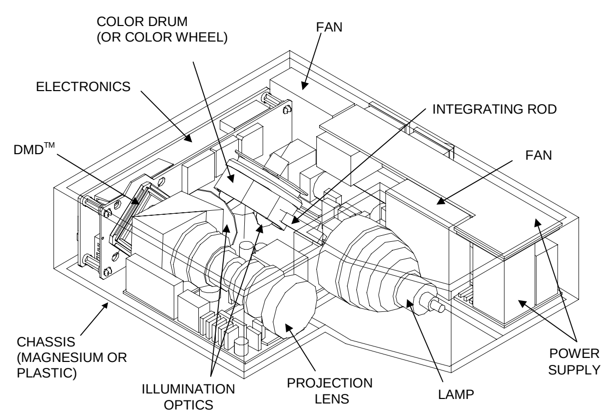

Figure 4: Example DLP™ projector layout

Table 1: Touch temperature requirements based on excerpts from UL 1950 [1]

	Maximum temperature rise (Kelvin)	
Part	Metal	Plastic
Handles, knobs, grips, etc. held or touched for short periods only	35	60
External surface of equipment which may be touched	45	70

DMD™ cooling

DLP™ projectors project light to the screen using the DMD™ (Digital Micromirror Device™). The DMD™ is a MEMS (Microelectromechanical System) device containing thousands of microscopic mirrors that tilt to direct light to the screen in the on-state and to a dump light absorber in the off-state as shown in figure 5. Each mirror represents one screen pixel.

Like most semiconductor devices, temperature control of the DMD™ is important to maximize performance and reliability. However, unlike most semiconductor devices which dissipate only electrically generated heat, the DMD™ must also dissipate heat that is absorbed from the illumination light source. Electrical load of the device is small but not insignificant at approximately 1W. Absorbed load is more significant and increases with higher screen lumen requirements since the device must be illuminated with more light to increase the brightness on the screen. For a 1000 lumen projector, typical absorbed light load is 3 to 4 watts depending on the optical design. Removing the combined electrical and absorbed load of 4 to 5 watts from a 30 mm x 40 mm DMD™ is not trivial. Most portable projector manufacturers design to maximum operating ambient conditions of 35 to 40 °C. The maximum operating limit of the DMD™ is specified at 65 °C, allowing an acceptable temperature rise from ambient of 25 to 30 °C. This poses a significant thermal challenge that usually requires a substantial air-cooled heatsink to solve.

With temperature rise from the room ambient to the DMD™ limited to around 25 to 30 °C, it is critical that the DMD™ heatsink and all other interfaces to the DMD™ (optics engine and printed circuit board) receive cooling air that is not preheated by other parts of the projector. The DMD™ is usually positioned far away from the hot lamp and very close to inlet air vents. This layout minimizes preheating of the air seen by the DMD™ and also minimizes parasitic loading effects caused by heat conduction from the hot lamp to the DMD™.

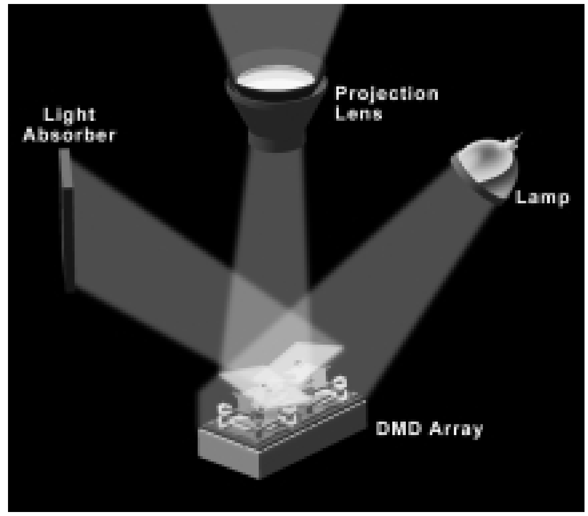

Figure 5: Mirrors in on-state and off-state

The DMD™ can effectively be cooled through its base ceramic material using a heatsink attached to an aluminum stud on the back of the ceramic. The stud offers flexibility to the designer since different shapes and sizes of heatsinks can be attached to meet each projector's thermal, weight, and shape requirements. As screen lumen levels increase, there will be a need for more effective heatsinking of the DMD™. One possible solution is the integrated fan and heatsink coolers used to cool PC processors. From a thermal standpoint, the DMD™ is similar to a processor in a PC. Both are the highest power dissipating chip in their respective system, and both have more stringent temperature limitations than most other chips in the system. Fortunately, the integrated fan and heatsink technology has matured for the PC industry and should be easily adaptable to the projector environment.

One main difference between a processor in a desktop computer and a DMD™ in a projector is the size and weight constraint. One may argue that DMD™ cooling in a 1.4 kg (3 lb.) projector is more like processor cooling in a laptop computer. Like today's laptop computers, there is simply no space for a large integrated fan heatsink cooler in the smallest portable projectors. In laptops, other cooling methods are used that spread the heat over a large area. This works well in a laptop since its surface temperature is somewhat uniform and it has low system power dissipation, but is more challenging in a projector since a large portion of the projector surface is heated by the lamp and is therefore unavailable for DMD™ cooling.

Lamp cooling

Metal halide lamps and high pressure mercury lamps are the most common lamp types in portable projectors. Over the past few years there has been a transition from metal halide to high pressure mercury lamps, especially in the smallest projectors. High pressure mercury lamps exhibit more stable operation and are not as sensitive to bulb cooling conditions. They also have excellent efficacy (lumens/watt), allowing lower total system power dissipation than metal halide lamps. High pressure mercury lamps typically operate at a higher voltage and lower current than metal halide lamps, allowing a smaller lamp ballast to be used.

There are several temperature related mechanisms that can contribute to lamp failure. First is oxidation of the metal foils in the glass to metal seals. The thin metal foils seal the atmosphere inside the bulb from the surrounding air (figure 6). The foils will oxidize over time, eventually compromising the seals and causing a lamp failure. The oxidation process is accelerated at high temperature, therefore it is important to provide proper cooling to both the front and back seals. A second failure mechanism is devitrification, which is a change in the crystalline structure of the quartz in the bulb area. Devitrification weakens the quartz bulb, eventually leading to a lamp failure. This failure mechanism is also accelerated at high temperature, therefore maintaining bulb temperature below a certain limit is important for long lamp life. Aside from catastrophic failures, there is another thermal consideration that affects lamp performance, overcooling. Excessive bulb cooling is undesirable since bulb temperatures that are too low can cause the fill materials to condense on the inner wall of the quartz resulting in an unstable arc, or a change in the lamp output spectrum.

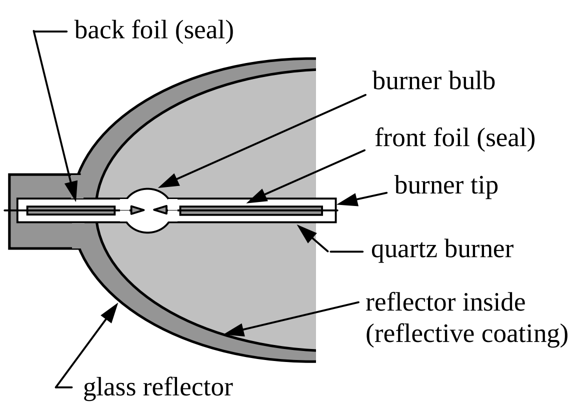

Figure 6: Cross-section of high pressure mercury lamp

As projector size decreases, the lamp reflector must also shrink to meet the size and weight constraints of the product. As a result, the power density of the lamp (power/volume) increases, requiring more airflow in a smaller volume to control the critical seal and bulb temperatures. Another effect associated with smaller reflectors is the tendency of the outgoing light to be obscured by the burner tip. The front foil can be shortened to reduce this effect, but shortening the foil can decrease the lamp life because a short front seal is not as robust. Seal integrity is proportional to the length of the seal.

For small high pressure mercury lamps, cooling air is usually required across the front electrode and possibly the bulb. Since more air is usually required across the front electrode than the bulb, directing the air into a channel or concentrated stream is often beneficial. This is very difficult to accomplish with an axial fan due to the large fan exhaust area, therefore small radial blowers are often used for this purpose. Axial fans are frequently used to ventilate the lamp housing and cool the reflector. Even with adequate cooling on the lamp, reflector surface temperatures are much higher than UL touch temperature limits for the projector chassis. Therefore, providing an insulating barrier from the reflector to the projector chassis is important to reduce localized hot spots that could cause safety hazards or discomfort. Thermal insulating materials are often placed on the insides of the chassis skin. They are usually covered with reflective foil to inhibit much of the radiation heat transfer that would otherwise occur.

Normally lamps are placed in lamp modules, which contain the lamp and connector. The lamp module allows easy lamp replacement by the user at end of life. Careful consideration of airflow around the reflector, front foil, and bulb are important for a good lamp module design. Features can be included in the lamp module to block stray light, guide air, and provide insulating barriers

Since the lamp dissipates about 75% of the total system power and can withstand higher temperatures than other parts of the projector, placing the lamp at the projector exhaust and as far away from critical components as possible is crucial. Care should be taken to thermally insulate the lamp from other parts of the projector and to ensure air ducting around the lamp is well sealed and does not allow exhaust air to recirculate into other parts of the projector.

Power supply cooling

Power supplies have traditionally been made using through hole technology, although there may be a shift to more surface mount and miniature through hole technology as size and weight requirements decrease. Through hole power supplies have the advantage of large surface area since many components "stand up" on the board. Heatsinks may be required on high power transistors and diodes, but in general the surface area of the components is sufficient for cooling provided there is flow between components. As power supply size shrinks, it is important to maintain some space between components for airflow. Consideration of the airflow direction is critical in the early design phases to ensure components are placed in their least restrictive arrangement.

Power supply components can usually withstand case temperatures higher than the DMD™ and other discrete electronics. Therefore, the power supply should be downstream of the DMD™ and other electronics.

Fans

While fans provide cooling for the projector, they also need to be maintained at an acceptable temperature. The operating temperature limit shown in fan catalogs is typically a maximum of approximately 70 °C. This limit is imposed to achieve a certain lifetime based on the manufacturer's reliability requirements. Fans can operate above the operating limit listed in the catalog, but with decreased life. It is important to understand the lifetime versus temperature relationship for each fan used in the design.

Fans can be placed before or after the lamp, which will make a difference in their operating air temperature. Placing fans downstream of the lamp can be done, provided there is sufficient airflow through the system to keep the air temperature reasonably low.

Axial fans and radial blowers have traditionally been used in the cooling of small projectors. Fans generally provide high volumetric airflow with relatively low pressure capability, while blowers can overcome higher backpressures, but with lower volumetric flow. Therefore, axial fans are often used to move air through more open channels and provide overall system flow, while blowers are more useful to force air though more restrictive channels such as a lamp assembly. Axial fan diameter is generally limited to the projector height or thickness, unless a bump in the packaging is provided. This limits the maximum size of the axial fans and may force the use of multiple fans to attain the required system flowrate. However, multiple fans allow flexibility to more evenly distribute the airflow through the projector. When using multiple fans, it is important to try to mix the hot and cold fan exhaust streams to reduce exhaust air temperature.

Acoustics

There are many factors that affect the acoustic performance of fans. Some are inherent to the fan design, while others can be controlled by the projector design. Factors that can be controlled include the fan speed and unrestricted areas at the fan inlet and exhaust. Fan speed will have the greatest impact on system noise, however obstructions very close to the exhaust and especially the inlet of the fan can produce significant noise as well. The compactness of DLP™ projectors leaves little room for open air space around fans, however a minimum of ¼ of a fan diameter unrestricted space at the fan intake and exhaust is recommended. Obstructions spaced closer than this cause more noise and significantly reduce air flowrates.

System restriction and vent area

Designing a projector with sufficient open internal volume and vent area becomes increasingly difficult as projector size shrinks. But low airflow restrictions are necessary so that fan speed can be minimized, resulting in a quiet projector. When designing inlet and exhaust vents, a good rule of thumb for portable projectors is 25.8 cm^2 (4 in^2) of open vent area at the inlet and 25.8 cm^2 (4 in^2) at the exhaust.

Testing and Analysis Methods

Mock-up thermal testing

A mock-up is a physical model of the projector and critical subassemblies used to experimentally determine critical temperatures and airflow before engineering prototypes are available. Mock-ups can be made by modifying a previous generation projector, or from scratch using materials such as sheet metal, plexiglass, and tape. The purpose of mock-up is to provide experimental data throughout the design cycle, before the final version of hardware is available.

Mock-up testing is very useful at all stages of the design cycle. Early on, simple mock-ups can be made to test and verify general cooling configurations to help choose the location of major subassemblies, select and locate fans, and determine vent location and size. Mock-up testing can be used to verify predictions from hand calculations and more sophisticated CFD (Computational Fluid Dynamics) models. Before the first prototype electronics and power supplies exist, resistive heaters can be used to simulate heat dissipation at various locations within the projector. Resistive heaters are available as blocks which can be attached to sheet metal plates to simulate power dissipation of electronics, or as thin foil patch heaters which are very useful in places where a larger block type resistor may not fit. Both types are available in many shapes, sizes, and maximum power dissipations.

As the design progresses, resistive heaters will be replaced with more realistic parts such as the correct lamp, power supply, and electronics. Thermal mock-up testing is important throughout the design to ensure the design starts with a feasible cooling scheme and ends by verifying all temperature sensitive components meet design goals.

CFD analysis

CFD analysis tools can effectively be used to simulate air flow and temperature for a projector design. These tools have the advantage of allowing temperature predictions in a system concept where no hardware is available, or in situations where mock-up testing is impractical. CFD analysis can also be used to isolate variables that are difficult to control in mock-up testing. However, building and solving complex models is often time consuming. Using CFD analysis together with mock-up testing will help identify problems with the thermal design, often before complex hardware is built and will assist in making engineering trades since data will be available to make an informed decision.

Lamp testing

Maintaining lamp temperatures within design goals leads to maximum lumen output and longer lamp life and is therefore an important part of projector design and verification. Type T thermocouples are very useful for measuring temperatures up to about 200 °C since they are very accurate up to this point. At higher temperatures seen in lamp measurements, type K thermocouples are more useful, since they are accurate up to about 1300 °C. Thermocouples attached to the lamp can experience temperatures from about 200 °C on the reflector to about 900 °C on the bulb. Since the temperatures are high, thermocouples must be held in place with a high temperature material. The same cement used to pot lamp burners in reflectors is commonly used to attach thermocouples to the lamp. This material can be applied and then cured fairly quickly with a hot air gun.

When lamp temperatures are measured, it is important to simulate the actual operating configuration of the lamp in the projector. Portable DLP™ projectors utilize elliptical lamp reflectors along with a color wheel. The color wheel reflects a large portion of the light back into the lamp since most cannot pass through the color filters. Depending on several factors including the location of the color wheel, the shape of the ellipse, and the length of the front electrode, the reflection of light from the color wheel may significantly affect the front electrode temperature. Comprehending the color wheel reflection is critical to obtaining accurate lamp temperatures in a mock-up test. Before a working color wheel is available, a polished aluminum plate can be used to simulate the color wheel reflection.

DLP™ electronics testing

Power dissipation of the DLP™ electronics is dependent on several factors, one of which is the DMD™ data rate. When measuring temperatures of the DMD™ and DLP™ electronics, it is important to operate the projector in a mode that exercises the parts and provides worst case power dissipation. Displaying a checkerboard pattern with every other pixel in the off state will produce a practical worst case power dissipation for the DLP™ electronics and is therefore a good pattern to display during thermal testing.

Summary

Portable DLP™ projectors continue to lead the projector industry in terms of size and weight. Successive shrinks over the past few years have resulted in projector power densities of 1.5 W/in^3, which exceed laptop computer power density by seven times under typical operating conditions. As these trends continue, projector thermal design will become an increasingly important part of the overall projector design.

Achieving an acceptable projector thermal design requires consideration of several critical thermal issues. These include cooling of the DMD™, lamp, and power supply, as well as fan selection, vent design, and acoustics. Thermal design goals can be achieved through a design process involving a combination of CFD analysis and thermal mock-up testing. CFD analysis can be used before testing hardware is available, while thermal mock-up testing can be used from the early design stages up to the final prototype to ensure thermal design goals are met.

References

[1] Underwriters Laboratories Standard for Safety, UL 1950, Safety of Information Technology Equipment, Including Electrical Business Equipment, Third Edition, 1995