Getting the Most Out of Your Heat Sink Design:

An Overview of the Parameters Which Influence Your Design

The design of a heat sink needs to be based upon a holistic approach to derive the most satisfactory result possible. Heat sinks are widely used as the primary means of heat transfer from a component to the environmental air. It is, relatively, one of the cheapest cooling methods available on the market, has a high reliability and can be easy to implement. In the past, the heat flux limit achievable with liquid cooled system could be achieved with air cooled systems though advancements in the design of heat sinks [1].

Some of the thermal resistances in the design of a heat sink are shown in Figure 1, which are, namely, the thermal resistance of the heat sink to the air, R_{hs}, the spreading resistance in the base, R_{sp}, and the thermal interface resistance, R_{TIM}. Each of these resistances have to be considered during the design process.

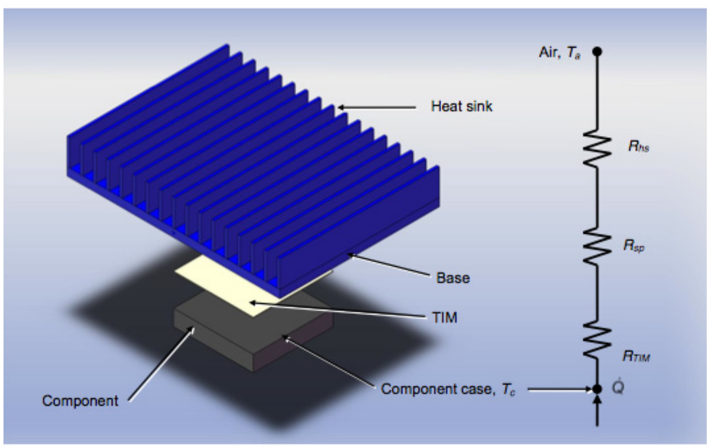


Figure 1. Exploded View of a Straight Fin Heat Sink and Equivalent Thermal Resistance Diagram

One also needs to look beyond the heat sink, to inside the component (if possible) and to the system level. Depending on the application, chassis or room level also needs to be looked at. The two aforementioned are shown graphically in Figure 2.

Figure 2. Thermal Analysis Chain of an Electronic System, From IC to Data Centre [2].

Apart from heat sink convective and radiative heat transfer optimization, key issues in advancing the effectiveness of air-cooling solutions include:

- Integrated circuit (IC) design and layout
- Package material development
- Die-to-die carrier and component-to-heat sink interface thermal contact resistance minimization, which can be comparable to the actual heat sink thermal resistance
- Integration of heat spreading technologies, such as heat pipes and high thermal conductivity materials, to minimize heat sink base temperature rise
- Aerodynamic fan performance improvement
- Integration of hybrid cooling solutions, such as phase change materials (PCMs) to manage peak transient heat loads
- Airflow optimization
- Minimization of heat sink surface fouling, whose impact on thermal resistance is becoming a major warrantee issue in both notebook and desktop computer products

- System architecture-based thermal management techniques
- Thermal load monitoring
- Sustainability
- Standardization of thermal management hardware performance characterization.

Heat Sink Manufacturing Technologies

Heat sinks function by extending the surface area of heat dissipating surfaces through the use of fins. Their design and analysis is one of the most extensive research areas in electronics cooling. Advances in heat sink cooling performance have been achieved through progress in manufacturing technology (Figure 3 and Table 1) and to a lesser extent, fan design, thereby resulting in more efficient heat removal from a given volume. Heat sink manufacturing technologies have been discussed in detail in past Qpedia articles [3].

Parameter	Extruded	Die-casting	Bonding	Folding	Modified Die-casting	Forging	Skiving	Machining
Min. t [mm]	1	0.175	0.75	0.25	0.2	0.4	0.3	0.5
Max. H/s	8:1	6:1	60:1	40:1	--	50:1	25:1	50:1
Min. s [mm]	6.6	8.3	0.8	1.25	0.2	1	2	1
Material	Al	Al, Zn-alloy	Al, Cu, Mg	Al, Cu	Al, Zn-alloy	Al	Al, Cu	Al, Cu, Mg

Table 1. Manufacturability Constraints: Innovative Versus Conventional Manufacturing Technologies, Compiled For A Range Of Heat Sink Suppliers [4].

Figure 3 (a) shows two types of extruded heat sinks, namely, straight fin and maxiFLOW™ heat sink types. Figure 3 (c) shows a copper skived heat sink with an integrated fan and spring loaded stand-offs.

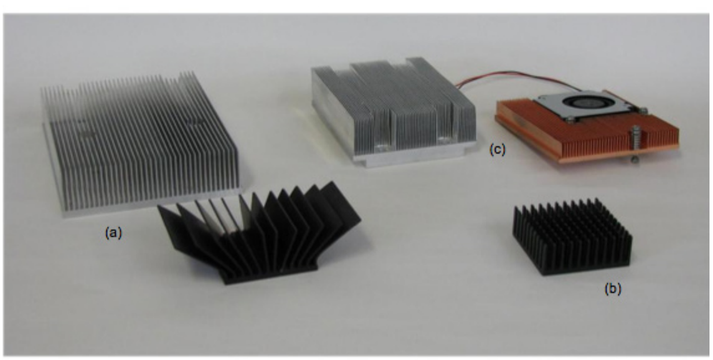


Figure 3. Some Heat Sink Manufacturing Technologies, Showing Extruded Heat Sinks (A), Forged Pin Fin (B) And Skived Aluminium And Copper Heat Sinks (C).

Heat Sink Fin Field Optimization

In the past, publications have focused on the parametric optimization of a heat sink thermal and hydraulic performance for a given application [1]. Despite the value of the publications, the optimization is limited to the case studied. For natural convection, Elenbaas [5] developed convective analysis using parallel plate Nusselt-Rayleigh number correlations. This work was extended to U-channel geometries representative of fin array heat sinks by Starner and McManus [6], Van de Pol and Tierney [7] and Aihara and Maruyama [8]. Ellison [9] derived a gray body radiative heat transfer analysis for these geometries.

Least energy optimization of a heat sink is a methodology that minimizes the energy consumed during manufacture and the operating costs while maximizing the thermal energy that can be extracted from the heat sink given the physical constraints. The physical constraints include the overall heat sink dissipation, heat sink material, manufacturing process and heat sink volume. The least energy optimization is presented by Kern and Kraus [10] to the optimization of a passively and actively cooled fin array heat sink design for manufacturability.

The least energy optimization method was followed by the minimization of entropy generation associated with the heat transfer and fluid friction [11], [12] and [13]. The least energy optimization and entropy have combined to form a phenomenological understanding of heat sink design optimization, in terms of cooling capability versus energy invested in the fabrication and operation of the heat sink.

Interface Thermal Resistance Minimization

In current high-performance air-cooled heat sink applications, the component-to-heat sink interfacial contact thermal resistance can be comparable to that of the actual heat sink [13]. Consequently, improved thermal interface materials are now the focus of much on-going research [13] [14] [15]. Thermal interface material (TIM) applications are categorized as TIM 1 and TIM 2, as shown in Figure 4. The aforementioned encompass a variety of adhesives, greases, gels, pads and PCMs. Recent advances in thermal interface technology include high-performance die attach materials and solder-based TIMs. A past Qpedia article [16] discussed the different types of TIM available, their specific applications and relative performance.

The bulk thermal conductivities of newly developed silver-filled or carbon fiber-loaded epoxy resin die attach adhesives, which are intended for high-performance/power ICs, are claimed to exceed those of eutectic solders. However, to fully exploit the potential of such materials, the die attach assembly process (adhesive deposition, curing) requires careful optimization to ensure good structural integrity of the bulk adhesive (maximum surface area coverage, minimum voiding) and optimum bondline thickness [14].

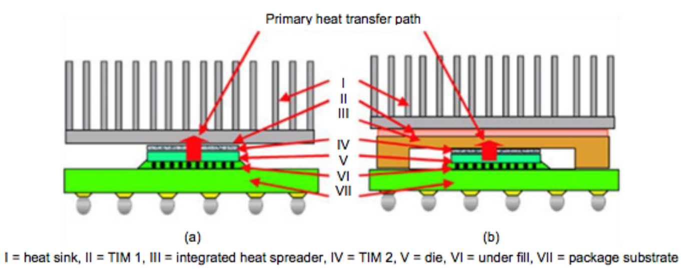


Figure 4. Thermal Architecture Typically Used (a) Laptop Applications, (b) Desktop And Server Applications [15].

Mechanical attachment

Mechanical attachment of a heat sink is not only used for the attachment of the heat sink to the component or system, but it is also an integral part of the heat sink design. This is because of the interface pressure required for the proper application of the interface materials. Attachment methods include thermally conductive tapes, epoxy, z-clips, component clip-ons, push pins with compression springs, spring load push pins and standoffs. Each has its own advantages and disadvantages, which have been discussed in detail in a Qpedia article [18].

Heat Spreading

A localized heat source acting on a heat sink base can generate significant spatial temperature gradients, as illustrated in Figure 5. The definition and control of thermal resistance has been discussed in detail in previous Qpedia articles [19] and [20]. Heat sink base thermal spreading resistance can be reduced through the use of highly thermally conductive materials, such as graphite or two-phase passive heat pipe heat spreading technology [21].

The two-phase heat transfer mechanism results in heat transfer capabilities from ten to several thousand times that of an equivalent piece of copper. Such as in heat pipes and vapour chambers shown in figure 6 [22]. A prior Qpedia article [23] discusses a comparison of thermal resistance of copper, silicon and heat pipes.

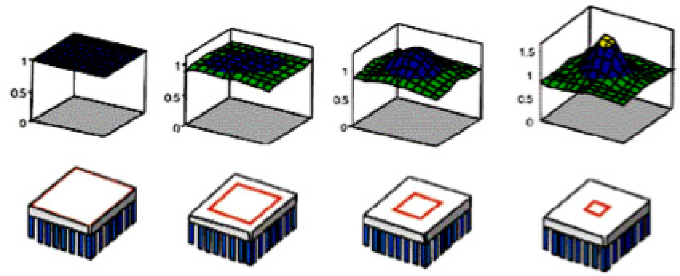


Figure 5. Heat Spreading On A Heat Sink Base: Normalized Local Temperature Rise With Heat Sources Of Different Size; From Left To Right, Source Area = 100%, 56%, 25%, 6% Of Heat-Sink Area [24].

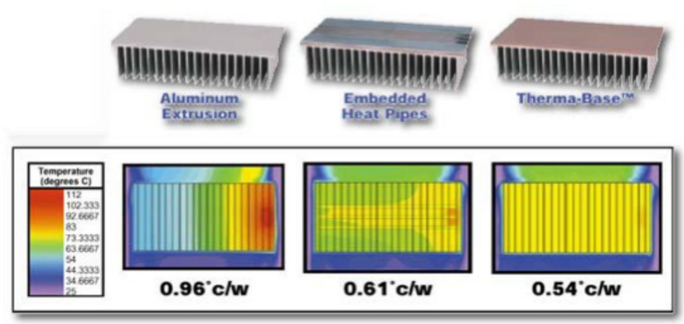


Figure 6. Heat Pipe Versus Vapor Chamber Thermal Performance Comparison [Thermacore].

Fan Performance

When selecting a fan for the cooling of a heat sink, it is essential to keep in mind that the system curve of the fan was determined in an idealised situation. When applied in an electronics cooling environment, the system can significantly differ from that is specified by the manufacturer. This has been previously discussed in a Qpedia article [25], where Figure 7 and Figure 8 show the reduced system curve for specific applications.

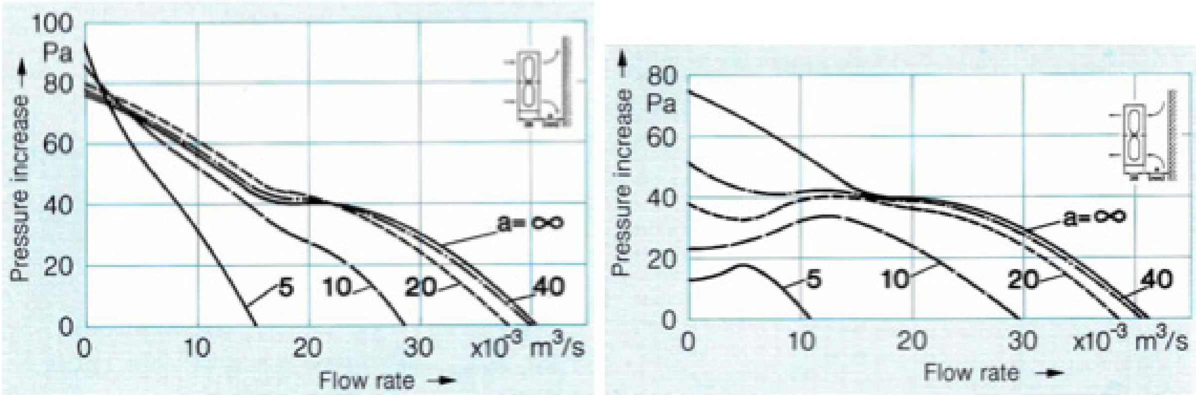


Figure 7. Change In The Characteristic Curve Of An Axial Fan Caused By A Square Plate On The Pressure Or Suction Side [26].

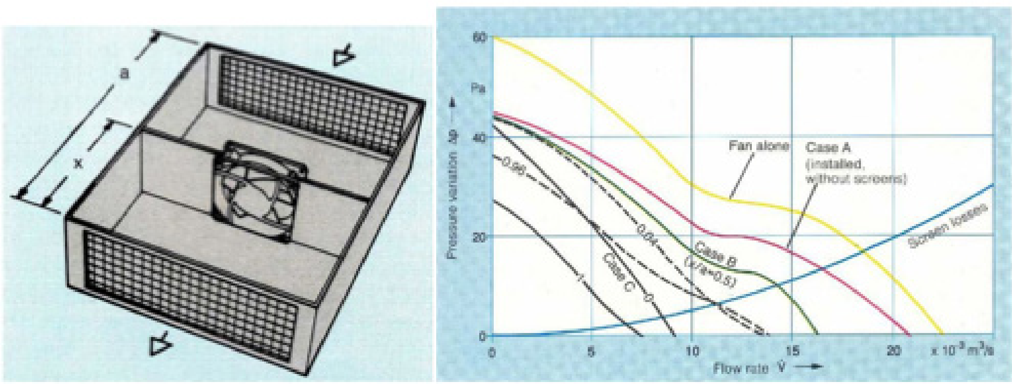


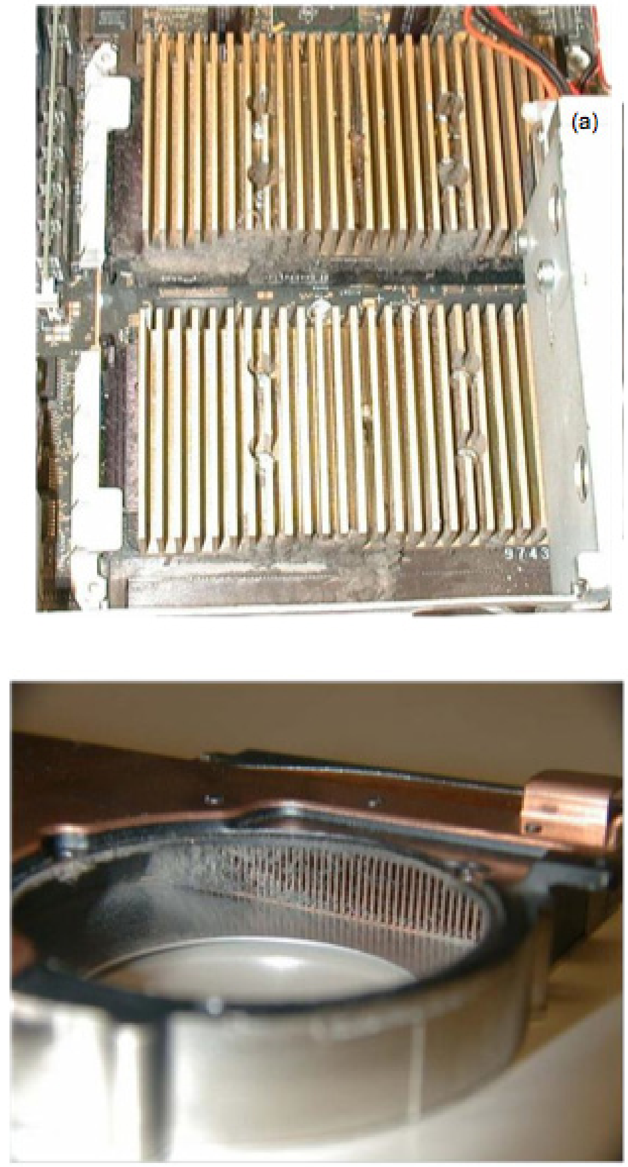
Figure 8. Fan Curve Performance As A Function Of Fan Placement [26]

Phase Change Materials (PCMs)

Thermal designs are typically focused on getting the absolute temperature below a certain maximum value for a design's continuous operation [27], based on worst-case assumptions [28]. In the peak loads, the temperature will rise towards the maximum allowed temperature. How rapidly will it rise depends on the thermal capacitance of thermal design. The thermal capacitance of a system can be increased by changing materials or by increasing the material available. Changing from an aluminium heat sink to a copper heat sink is an example of changing materials to increase the thermal capacitance of a heat sink. Both of the previously mentioned methods have direct cost implications. Copper is more expensive than aluminium and heavier. An alternative might be the use of phase change materials.
Going over an absolute maximum temperature is not the only means of failure for an electronics product. Thermally induced stress can cause cracking or delamination near the interface area of composites having different thermal expansion coefficients material properties. A means of reducing the temperature cycles can also be achieved by employing phase change materials in the design.

Surface Fouling

With the reduction of heat sink thermal design margins, which has resulted from rising processor heat dissipation, system miniaturization and fan acoustic noise constraints, the impact of fouling (9) on heat sink thermal resistance (thermal and hydraulic performance) has become much more critical than in the past. This impact is most pronounced for fine- pitch heat sinks, which are commonly employed for computer cooling. The resulting loss of heat sink cooling makes air-cooled desktop computers prone to self-protection shutdown, even in standard office environments. To maintain product performance and reliability, methods of minimizing heat sink fouling, such as anti-dust accumulating heat sink design features and filter design, require investigation. This will require an understanding of the mechanisms of heat sink fouling and its impact on thermal performance, as a function of contaminant and application environment, for a range of fine-pitched heat sinks.



(b)

Figure 9. Heat Sink Fouling [Courtesy Of David Moore, HP]. (A) Desktop Application And Notebook Computer Application (B)

The article has discussed the various design parameters which will influence the effectiveness of the end heat sink design, ranging from heat spreading, fan performance to heat sink surface fouling. Even though a heat sink looks like a simple piece of metal, its implementation in a real application requires the information and knowledge of many different parameters in order to fully utilize the advantage of a heat sink.

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