Thermal Design for Sustainability of Air Cooled Heat Sinks

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1. Introduction

Extended surfaces of fins, or so-called heat sinks, are in common use in the electronic industry and serve to extend the thermal capability of convective cooling with air. The use of passive, natural convection cooled heat sinks offers substantial advantages in cost and reliability, but is often accompanied by relatively low heat transfer rates, and significant added mass. The use of fan driven forced air cooling facilitates high performance, compact, and lighter heat sink designs, but at the increased burden of pumping power. Thus, the substantial material stream and energy consumption rate associated with the cooling of electronic equipment using air cooled heat sinks, lends urgency and importance to the "perfection" of these fin arrays. The financial constraints at work in the electronic industry make it essential that specific cooling requirements be achieved with the lowest cost solution. It is anticipated that in large volume production, as worldwide energy costs escalate, the “least-energy” solution will nearly always provide the lowest cost solution.

The least-energy optimization of natural and forced-convection plate-fin heat sinks is described. Emphasis is placed on the use of a Coefficient of Performance, COP_T, relating cooling capability to the energy invested in the formation, fabrication, and operation of the heat sink. It is shown possible to determine the heat sink geometry, which maximizes the value of COP_T, for each operating condition and cooling mode. For forced convection cooling, the most favorable distribution of invested energy - between heat sink formation/fabrication and operation - can also be found. Although optimum natural convection heat sinks can deliver highly reliable, noise-free, operation, the COP_T values for forced convection cooled heat sinks are found to far exceed the values associated with passive cooling. The thermal analysis of the natural convection rectangular plate-fin array has been carried out using a previously developed model by Iyengar and Bar-Cohen [1], which utilizes the composite Nusselt number correlation developed by Bar-Cohen and Rohsenow [2] to calculate the fin average heat transfer coefficient. The forced convection results are obtained using a well-validated, semi-analytical model developed by Holahan et al. [3]. In order to concretize the benefits of such "least-energy" heat sink designs, the proposed modeling and optimization techniques will be applied to an advanced heat sink configuration, considered suitable for the cooling of a high-end microprocessor. Thus, many of the results are derived for an aluminum plate-fin heat sink on a 10cm × 10cm base, and 5cm fin height, operating at an excess temperature of 25 K.

2. Key Features

Fig. 1 displays the range of the COP_T for forced and natural convection cooling of the 10×10×5 cm heat sink, for an invested work of 10 kWh and a life of 6000 hours. Each line in Fig. 1 represents a specific value of ξ_{PP}, and displays the variation of COP_T with the fin density. Each ξ_{PP} relates to a specific combination of fin mass, M, and pumping power, IP. A closer examination of the finned forced convection results, yields trends showing each forced convection curve to rise steeply with fin density towards a peak value, and then decreases gradually. In addition, the existence of an optimal ξ_{PP} value can also be seen, which would suggest the most favorable distribution of existing energy resources between heat sink manufacturing and operation, over a fixed product life cycle. For the design space explored in Fig. 1, COP_T for an input of 10 kWh for 6000 hours operation, is maximized to yield a value of 92 for a ξ_{PP} of 0.25, representing 88g of fin material and 0.42W of pumping power.

A special case where the given 10 kWh has been entirely utilized for pumping air over the bare base surface, in the absence of any fin material, shows COP_T values comparable to that for finned natural convection. Finned forced convection arrays substantially outperform the natural convection and unfinned channels in terms of “cooling returns” on invested work, thus demonstrating the important benefits of so called ‘energy intensive’ forced air solutions. It must be noted, however, that under certain circumstances including remote locations, high noise, or expensive power; passive cooling will remain the technique

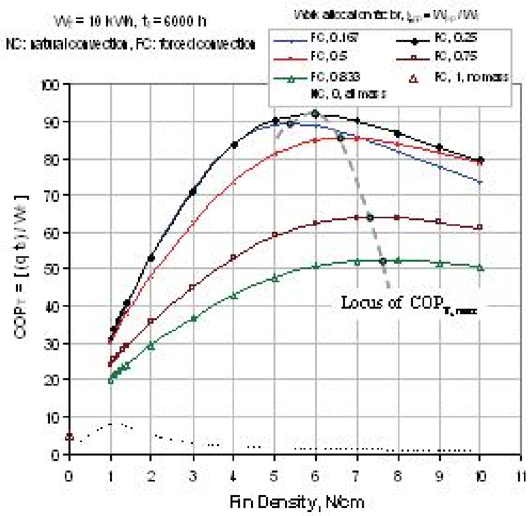

Fig. 1. COP_T for rectangular plate-fin arrays. W_T = 10 kWh, regular duty cycle, t_l = 6000 h {3 years, 50 wk., 5 days/wk., 8 h/day}, L = 0.1m, W = 0.1m, H = 0.05m, θ_B = 25K, aluminum.

of choice. It must also be noted that in this study, the fluid pumping power does not account for the efficiency of the fan, which when introduced may be expected to moderately diminish the present finding.

3. Conclusions

This study demonstrates the usefulness of the COP_T metric to enable the least-energy optimization of plate-fin convective heat sinks, resulting in the maximization of the cooling capability that can be achieved in a specified volume, while minimizing the material and energy consumed in the fabrication and operation of the specified heat sink. Counter intuitively, despite the absence of any investment in pumping work in the natural convection arrays, the analysis shows the forced convection arrays substantially outperform the natural convection designs, for a fixed available input cooling energy and life cycle of duration. For forced convection configurations, an optimal resource allocation ratio, was identified, that provides the most favorable distribution of existing energy resources between heat sink manufacturing and operation, over a fixed product life cycle.

4. References and Bibliography

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Author Biographies

Avram Bar Cohen is Distinguished University Professor and Chair of Mechanical Engineering at the University of Maryland, where he continues his research in the thermal management of Micro/Nano systems. Bar-Cohen was a founding member and currently serves on the Advisory Board of ASME's Nanotechnology Institute and represents ASME on the Assembly for International Heat Transfer Conferences (2002-2006). Prior to accepting his current position, he served as the Director of the Center for the Development of Technological Leadership and held the Sweatt Chair at the University of Minnesota, where he earlier served as Professor of Mechanical Engineering and Director of the Thermodynamics and Heat Transfer Division.

Madhusudan Iyengar received his B.E. degree in Mechanical Engineering from the University of Pune, India, and his M.S. and Ph.D. degrees in Mechanical Engineering from the University of Minnesota in 1998 and 2003, respectively. After a short stint as a post-doc at Purdue University, Madhusudan Iyengar has worked at IBM is Poughkeepsie, New York, as an Advisory Engineer in the Advanced Thermal Labs in the Systems and Technology Group. He has thirty-nine papers, 2 US Patents, and 28 patents pending.