Analysis of the Effect of Bypass on the Performance of Heat Sinks Using Flow Network Modeling (FNM)

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Abstract

Heat sinks are used in electronics cooling systems to provide extra area for transfer of the heat dissipated by semiconductor devices. However, in presence of clearance regions around the heat sink, flow that would otherwise go through the heat sink bypasses it. The present study uses the technique of Flow Network Modeling (FNM) to analyze the effect of flow bypass on the heat transfer performance of a plate fin heat sink. The physical situation analyzed corresponds to a typical wind tunnel test cell used for the characterization of the heat sink performance. Results of network analysis predict that increasing the bypass region has a strong effect on decreasing the flow rate through the heat sink. Therefore, the effectiveness of the heat sink is reduced when large clearance regions are present around it. The network analysis is shown to be very easy, quick, and accurate. It can be used for analyzing the placement of heat sinks in practical cooling systems.

Nomenclature

A_b	heat sink base area
A_f	heat sink fin area
c_p	specific heat
h	heat transfer coefficient
k	heat sink thermal conductivity
$\dot{M}$	mass flow rate
T_b	heat sink base temperature
T_{in}	inlet fluid temperature
Q	heat flow
δ_b	heat sink base thickness
η	fin effictiveness

I. Introduction

Heat sinks are widely used for maintaining the temperature of semiconductor devices in electronics systems. Heat sinks are directly mounted on the cases that enclose the semiconductor devices to provide extra surface area for transfer of heat from the device to the cooling fluid, which is typically air. Heat sinks use a variety of fin arrangements to provide the extra surface area for heat transfer. Presence of closely spaced fins also creates an extra resistance for cross flow through the heat sink. In most practical applications, heat sinks are mounted on circuit boards such that there are significant clearances around them. Because of the higher resistance for flow through the heat sink, the cooling fluid tends to bypass the heat sink and flow through the clearances around it. Since the temperature rise across the heat sink and the heat transfer coefficient (especially for transitional or turbulent flow) depend on the velocity of the flow through the heat sink, the bypassing of the flow adversely affects the heat transfer performance of the heat sink. Note that the clearance areas around a heat sink are specific to each electronic system being designed. Therefore, accurate system-specific analysis of the effect of bypass is necessary to obtain the best pressure drop-heat transfer performance of the system utilizing heat sinks.

In the present study, the effect of bypass on the performance of a heat sink is analyzed in a system that is used to characterize the heat sink performance. The novelty of the study lies in the use of the technique of Flow Network Modeling (FNM) (Belady et al. [1] and Kelkar et al. [2]) for the analysis of the heat sink performance. The study illustrates the suitability and benefits of the FNM technique in the analysis of electronics cooling system during the design process. A simplified version of the model proposed by Butterbaugh and Kang [3] is used for the network representation of the heat sink in presence of bypass. The network model of the system with the heat sink is extremely easy to construct, it runs very quickly, and it accurately predicts heat sink performance. Results show the effect of clearances around the heat sink on pressure drop and heat transfer performance.

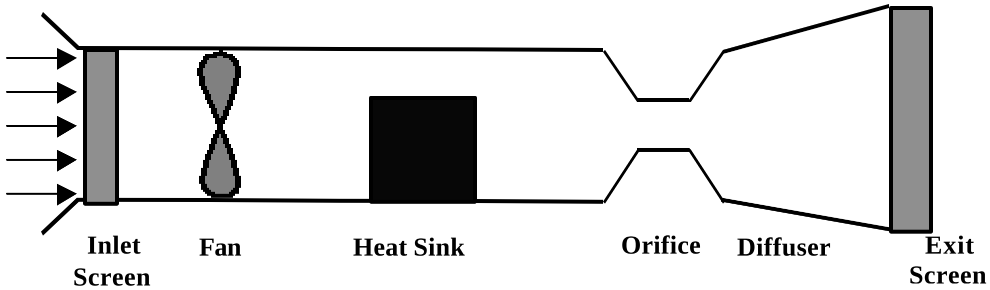

Figure 1 – The wind tunnel test cell for characterizing heat sink performance

II. Physical System

The physical system analyzed in the present study is shown in Fig. 1. It corresponds to a wind tunnel test cell used for characterizing the pressure drop and heat transfer performance of cross-flow heat sinks (Belady [4]). The heat sink is situated inside a duct (wind tunnel). Screens or perforated plates may cover the inlet and the exit of the duct. The flow is driven by a fan situated near the inlet. The flow rate is varied by controlling the opening of the orifice. Further, the size of the duct cross-section can be varied (by moving the walls or using different sized ducts) to study the effect of bypass on the performance of the heat sink. A diffuser is incorporated in the duct to recover the velocity head before the flow exits the system. The cross-sectional view of the duct with the fin sink is shown in Fig. 2.

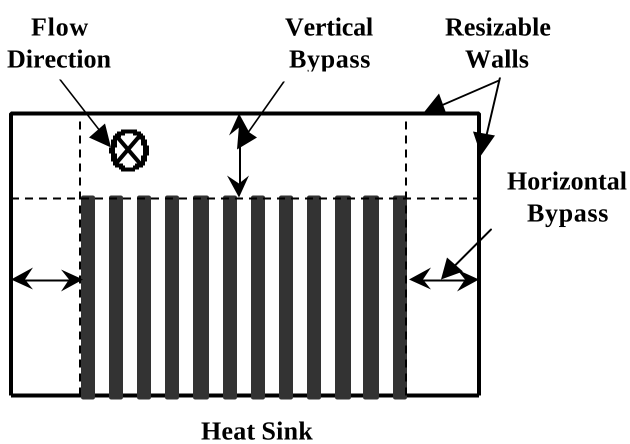

Figure 2- Cross-sectional view of the heat sink with bypass

The physical system has all the characteristics of a passage between cards on which a heat sink is mounted. Thus, the orifice corresponds to flow balancing elements often used in at the exit of card passages and the exit screen corresponds to the screens used on the surfaces of computer enclosures.

The plat-fin heat sink used for analysis in the present study is manufactured by Wakefield Engineering [5] and has the following characteristics.

Table 1- Geometry of the fin sink manufactured by Wakefield Engineering.

Dimension	*Value in inches*
Length	2.2
Width	4.6
Fin Height	0.75
Fin Pitch	0.1
Fin Thickness	0.012

III. Flow Network Analysis

A. *Theoretical Basis of Flow Network Modeling (FNM)*

FNM is a generalized methodology for calculating systemwide distributions of flow rates, pressures, and temperatures using a network representation of a cooling system. Practical electronics cooling systems can be represented as a network of flow paths through components such as ducts, heat sinks, screens, filters, passages with card arrays, fans, bends, and junctions. There is no restriction placed on the interconnections among the components and flow paths.

Note that, in the FNM technique, each constituent of the system is represented by overall flow and thermal characteristics and a detailed prediction of the flow and the temperature fields is not attempted. As a result, it is very fast in terms of model definition, solution, and data analysis. A detailed exposition of the technique of the FNM technique is provided in the studies by Belady et al. [1] and Kelkar et al. [2]. Only the important features are described below.

The flow characteristics of a component relate the pressure loss in the component to the velocity or the flow rate through it over the laminar and turbulent flow regimes. Compilation of loss coefficients for a variety of standard flow components is available in Idelchik [6]. For nonstandard components, the component characteristics can be obtained from supplier data, CFD analysis, or laboratory testing. Heat transfer characteristics of a component are necessary to determine the component temperature for a specified heat dissipation or for determining the heat exchanged for a specified component temperature. These characteristics involve specification of the dependence of the heat transfer coefficient (Nusselt number) on the flow rate/velocity (Reynolds number) and fluid properties (Prandtl number).

Prediction of the flow rates, pressures, and temperatures over the system require solution of the mass, momentum, and energy conservation equations. The flow characteristics constitute the momentum equations for each flow path. Mass conservation is imposed at each junction in the flow network. The calculation of the heat loss/gain in each link in combination with the imposition of energy balance at each junction enables prediction of temperature distribution in the system. The momentum, mass, and energy conservation equations are solved using the SIMPLE algorithm of Patankar [7]. The resulting algorithm is fast and robust.

B. *Network Representation of the Physical System*

The network representation of the flow passage with the heat sink is shown in Fig. 3. A commercially available FNM software [8] was used for this purpose. The important features of the model are as follows:

- The inlet and exit sections of the duct are represented using a screened inlet with a screen. The screen is characterized by appropriate specification of the fractional open area and the geometry of a representative orifice.

- The network representation of the physical system needs incorporation of a fan as shown in Fig. 3. The flow rate through the system is determined by the balance between the fan and the system impedance characteristics. As the bypass region around the heat sink is changed, the flow resistance of the system changes. This causes not only the flow split between the heat sink and the clearance region but also the total flow through the system to change. Therefore, in order to illustrate the effect of the bypass on the heat sink performance in a clear manner, analysis was performed for a constant value of 10 SCFM of the flow rate through the system.

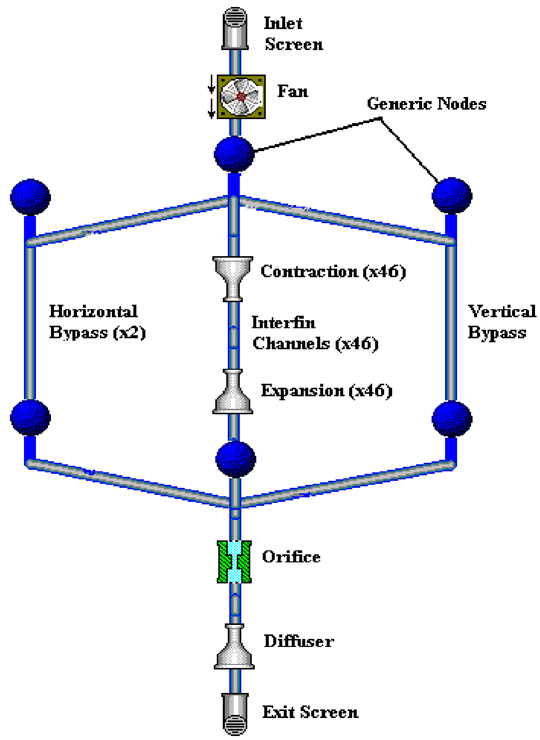

Figure 3 – Network representation of the test cell used characterizing the heat sink performance

- The plate-fin geometry of the heat sink allows representation of the flow paths using standard flow components. Thus, the interfin spaces (a total of forty-six) are represented as channels of a rectangular cross-section. Note that as the flow enters each interfin space, it goes through an area contraction. Similarly, the flow goes through an area expansion when it exits an interfin space. Correspondingly, the flow network contains Contraction and Expansion components upstream and downstream of each interfin space. During the calculation of the effective resistance, forty-six of such channels are assumed to be in parallel. For a more complex heat sink such as an interrupted plate-fin or pin-fin heat sink, an empirical correlation needs to be used to represent the flow and heat transfer characteristics.

- The two horizontal bypasses on the two sides of the sink are represented as passages of the same length as the fin sink, but with appropriate cross-sectional dimensions and wetted perimeters corresponding to the clearance between the fin wall and the duct wall. Two such bypasses are assumed to be in parallel during the calculation of the flow resistance. A single rectangular channel is specified corresponding to the vertical bypass. The no bypass configuration is simulated by simply specifying the clearance dimension in these passages to be very small.
- The Orifice downstream of the sink is a flow control element. The flow through the channel is controlled by the opening of the orifice.
- The portions of the duct before and after the sink are represented as rectangular passages with appropriate dimensions.
- The Diffuser enables pressure recovery before the flow leaves the system.
- The Generic Nodes used in the network represent the junctions where the flow streams meet or from which flow streams divide. Thus, a Generic Node represents junctions in which no losses take place.
- Calculations have been done with ambient air (25 degrees C, 1 atm) flowing through the duct.

The flow characteristics are valid over the entire range of the Reynolds numbers for incompressible flow. For example, Moody chart is used to characterize the pressure losses in the interfin passages. Similarly, correlations for laminar and turbulent forced convection through rectangular ducts, with appropriate interpolation for the transitional regime, are used to determine the corresponding heat transfer coefficient. Thus, the FNM technique accurately predicts the system performance in laminar, transitional, and turbulent regimes.

IV. Results

Figure 4 shows the variation of the fraction of the flow through the heat sink as a function of the fractional clearance area around the heat sink for a fixed orifice opening. The fractional clear area is defined as the ratio of the clearance area around the heat sink and the total cross-sectional area of the duct. As the clearance region around the heat sink increases, the resistance to flow through it decreases and the fraction of the flow going through the heat sink decreases.

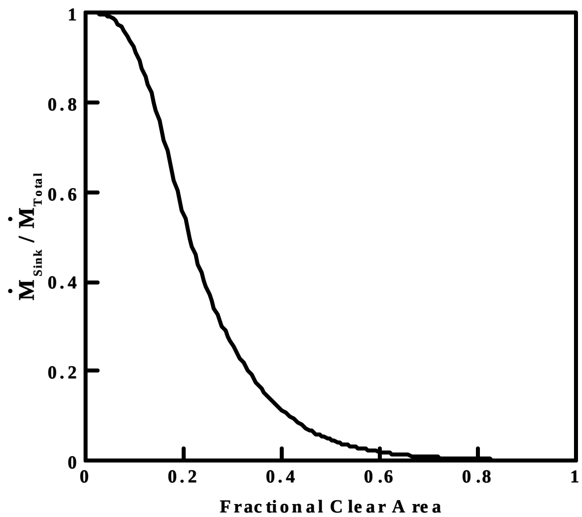

Figure 4 – Variation of the fraction of the total flow through the heat sink as a function of the fractional clearance area around the heat sink.

Figure 5 shows the corresponding variation of the dimensionless pressure drop through the heat sink as a function of the clearance around the heat sink. As expected, the total pressure loss across the heat sink decreases with increasing clearance since the effective resistance for the flow decreases.

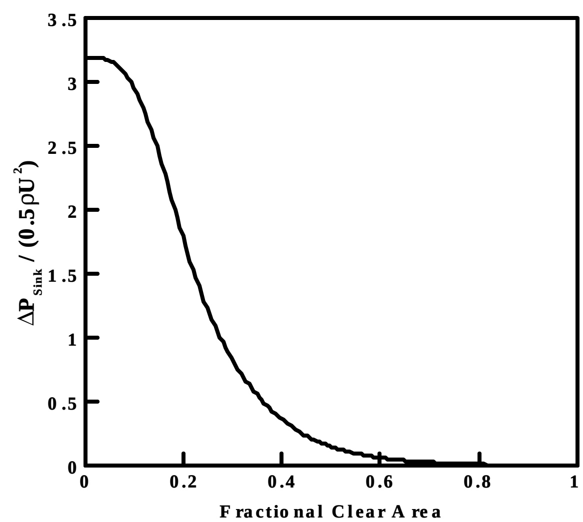

Figure 5 – Variation of the pressure drop through the heat sink as a function of the fractional clearance area around the heat sink.

The network model assumes the heat transfer in the interfin passages to be fully developed, an assumption that is valid for heat sinks with sufficiently large length relative to the fin spacing. For the conditions analyzed, the flow is predicted to be laminar and the heat transfer coefficient is predicted to be a constant value of 36.6 (W/m^{2}K).

Since heat sinks are made of metals (which have a high thermal conductivity), the variation of the temperature within the heat sink is very small in comparison to the possible change in the temperature of the fluid. The primary thermal resistances within the heat sink are across the thickness of the base of the heat sink and along the length of the fins (which is characterized by the fin efficiency). With these assumptions, the following equation can be derived that relates the temperatures of the base of the heat sink to the inlet fluid temperature, flow rate, heat supplied, and heat sink parameters.

$$T_b = T_{in} + (R_b + R_f)Q$$

$$R_b = \frac{\delta_b}{kA_b}$$

$$R_f = \frac{1}{\dot{M}c_p\left(1 - \exp(-\frac{\eta h A_f}{\dot{M}c_p})\right)}$$

Assuming a relatively negligible resistance of the base, the temperature of the base of the heat sink for a specified heat dissipation can be calculated using the above

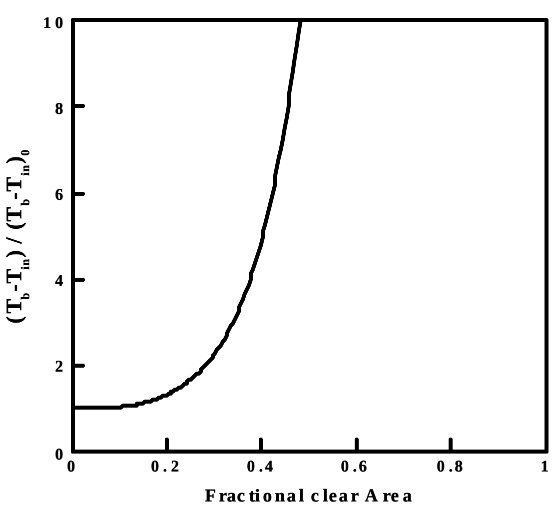

Figure 6 – Variation of the base temperature of the heat sink as a function of the fractional clearance area around the heat sink.

equation. Figure 6 shows the variation of the dimensionless base temperature as a function of the fractional clearance area. The base temperature is nondimensionalized by normalizing the difference between the base and the inlet fluid temperatures with the value of this difference at zero clearance. Note that for zero clearance, the entire flow goes through the heat sink and the corresponding base temperature is at its minimum. Thus, the dimensionless temperature shown in Fig. 6 is a direct measure of the deterioration of the heat sink performance due to the presence of bypass regions around it. Figure 6 shows that for the flow rate through the system considered, there is a significant degradation of the heat sink performance as the extent of the bypass region around the heat sink increases.

V. Conclusions

This study presents an analysis of the effect of bypass on the heat transfer performance of a plate-fin heat sink. The physical situation corresponds to a typical wind tunnel test cell used for characterizing heat sink performance. The technique of Flow Network Modeling (FNM) is used to analyze the flow and pressure distribution in various parts of the system including the heat sink and the clearances around it. The special geometry of the plate-fin heat sink allows a first-principles-based network representation of the heat sink using standard flow components such as expansion, contraction, and channels. For complex heat sinks, empirical correlations for no-bypass condition are used for characterizing the heat sink in the flow network representation of the system. The network model is very easy to construct and allows rapid analysis of the flow and heat transfer performance of the heat sink. Results show that the presence of large clearance regions around the heat sink significantly reduce the flow through the heat sink. This adversely affects the operating temperature of the base of the heat sink that transfers a specified amount of dissipated heat. Therefore, analysis of the effect of bypass on the heat sink performance need to be performed during the placement of heat sinks for effective removal of the heat dissipated by semiconductor components.

VI. References

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