IMPROVED PRODUCTIVITY WITH USE OF FLOW NETWORK MODELING (FNM) IN ELECTRONIC PACKAGING

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Introduction

As the complexity and power density of electronics systems increase, there is an ever-increasing demand for tools to improve the quality of the product and the productivity of the designers. This is especially true for thermal designers who now routinely use Computational Fluid Dynamics (CFD) tools for their thermal designs. Several important factors have been driving this trend:

1. The complexity of systems has increased significantly to the point that each part of the system can no longer be designed independently. Changing one part of the system has an impact on the flow distribution throughout the system.
2. CFD tools allow designers to complete parametric studies for optimizing the design.
3. Availability of application specific CFD tools has made such analysis accessible to the general design community.

However, due to its detailed nature, CFD analysis can be time-intensive in terms of model definition and computation especially for large systems. For this reason, the use of CFD in the early part of the design cycle may be premature and impractical due to the "fluid" state of the design.

This paper describes the technique of Flow Network Modeling (FNM) and discusses the productivity benefits it provides in the design of electronics cooling systems. Traditional use of flow network analysis in the design of electronics cooling systems has been discussed by Ellison [1, 2]. The FNM methodology described in the present paper incorporates a completely general method for the solution of the mass, momentum, and energy conservation equations in arbitrarily complex networks to enable efficient analysis of real systems. This paper also outlines an enhanced product development cycle that incorporates FNM in the early design stage. Finally, application of FNM for a computer system is illustrated.

The Development Cycle

Thermal design has become an integral part of the product design cycle as a result of critical role of satisfactory thermal performance and the high cost of modifications later in the design process. Figure 1 shows the conventional development cycle as presented by Biber & Belady [3]. In the current design process, benefits obtained from empirical correlations are limited because of their use in hand calculations or spreadsheets. FNM expands the use of correlations by utilizing them in a flow resistance network that represents the system. During the conceptual and system-level design phase, the number of design alternatives can then be quickly reduced in a scientific and cost-effective manner. This allows focused and economical use of CFD for detailed analysis of the chosen alternatives for the system or parts of the system. The resulting enhanced development cycle is shown in Fig. 2.

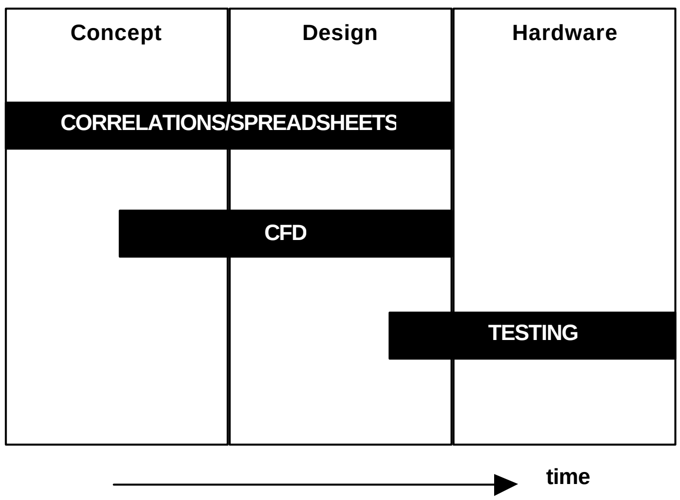

Figure 1. Product Development Cycle

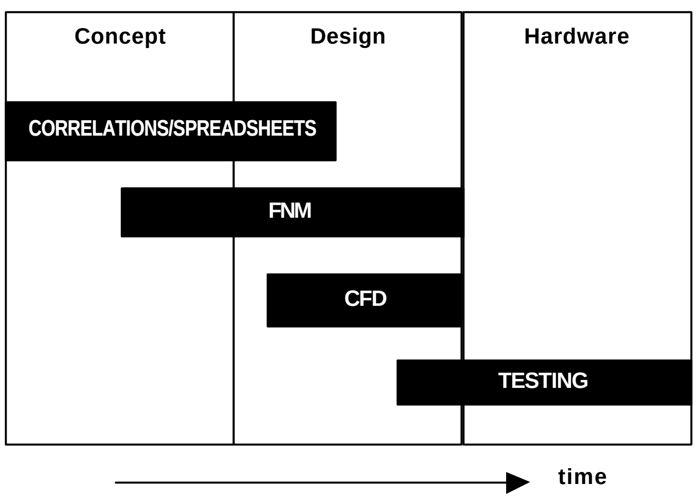

Figure 2. Enhanced Product Development Cycle

What is FNM?

FNM is a generalized methodology involving representation of a cooling system as a network of components and flow paths for the purpose of predicting systemwide distribution of coolant flow rates and temperatures. Figures 3 and 4 show an example of a computer system and its network representation, respectively. Each component in the network is represented by an empirical correlation that relates pressure drop and heat transfer rate to the corresponding coolant flow. Therefore, the results of the analysis are accurate to the same level as the empirical correlations used in the model and automatically account for the effect of the flow regime (laminar or turbulent flow), geometry of the component, fluid density and viscosity, and other parameters. Furthermore, FNM is cost-effective in terms of model definition (~ 1hour) and computation time (~10 seconds on a PC) due to the compact representation of the components. Thus, the following advantages of FNM make a compelling case for its use as a system-level design tool:

- *Evaluation of Competing Designs* - Quick and accurate evaluation of the thermal performance of competing physical layouts.
- *New Concepts for Design Improvements* - Generation of ideas for design improvements (e.g. incorporation of flow balancing elements, addition of backup fans) and evaluation of their benefits.
- "*What If" Studies* - Investigation of "what if" and contingency scenarios (e.g. fan failure and rise in ambient temperature).
- *Use with CFD* - Construction of boundary conditions for accurate and focused CFD analysis for subsystems during the detailed design stage.

The user should also be aware of the following limitations of this approach and use CFD where applicable:

- *Component Temperatures* – FNM cannot predict the temperatures at the component level. To do this would require a detailed thermal network, which increases the complexity to the level of a CFD analysis.
- *Network Representation* – Construction of a flow network for a physical system requires the user to have insight into the flow paths that the fluid follows as it moves through the system. In addition, flow network representations may not be accurate or even possible for systems in which the flow paths are not well defined.
- *Flow Resistances* – The accuracy of FNM results depends upon the validity of the flow resistance correlations employed.
- *Passively Cooled Sealed Enclosures* – The FNM methodology is applicable for open enclosures that are cooled using natural convection. However, in its form described in this paper, it may not be applicable to sealed enclosures in which the cooling occurs purely by natural convection, unless the flow paths can be clearly identified. In both situations, the buoyancy force provides the pumping action analogous to a fan in forced air systems.

Theoretical Basis of FNM

Network Representation and Component Characteristics

The flow network of an electronic cooling system is constructed by graphically representing the paths followed by the flow streams as they pass through different components of the system. There are no restrictions placed on the interconnections of the components in the network and the size of the network.

Prediction of the systemwide flow and temperature distributions requires specification of the flow and heat transfer characteristics of the components used in the network model. The pressure loss in a component can be represented as a function of flow rate with the following equation:

$$\Delta p = K \frac{1}{2} r \, (Q / A)^2 \tag{1}$$

where: K = loss coefficient
r = fluid density
Q = volumetric flow rate
A = flow area

The loss coefficients for standard components (screens, ducts, bends, etc.) are available from handbooks such as Idelchik [4] and Blevins[5]. For card arrays, the loss coefficient can be determined using the Moody chart [4, 5] with corrections to account for the blockage effects of heat sinks and electronic components. For nonstandard components, supplier data, CFD analysis, or testing can be used to get the flow characteristics. The performance characteristics of fans and pumps are specified in terms of pressure rise as a function of the flow rate.

The bulk temperatures in the different cooling streams are determined from the heat dissipated into these paths as well as mixing of the streams in different parts of the system. The average surface temperatures are determined from the surface heat transfer coefficients. Empirical correlations for the Nusselt number (dimensionless heat transfer coefficient) have the following form.

$$Nu = A \, \mathrm{Re}^m \, \mathrm{Pr}^n \tag{2}$$

where: A = constant
Re = Reynolds number
Pr = Prandtl number
m = constant
n = constant

Solution of the Conservation Equations

Each component in the system is represented by a combination of links and nodes. Pressure and temperature are calculated at each node while the flow rates are associated with links. The flow characteristics of each link, given by Eq. (1), constitute the momentum equations. Mass conservation is imposed at each node of the network. The forms of the discretized momentum and continuity equations are given below.

Momentum Equation for a Link

$$p_1 - p_2 = S_{CR} + RQ \tag{3}$$

The quantities S_{CR} and R are determined by linearizing Eq. (1). Thus, R is the slope of Δp-Q curve while S_{CR} represents the departure of this curve from a linear variation.

Mass Conservation at a Node

$$\sum_{l=1}^{n} rQ = 0 \tag{4}$$

Here n denotes the total number of links at that node.

The calculation of the heat loss/gain in each link in combination with the imposition of energy balance at each node determines the temperature distribution in the network.

An efficient method to solve momentum and mass conservation equations is to use the "SIMPLE" algorithm of Patankar[6]. It involves the following steps.

1. Assume a distribution of flow rates over the links and pressures at the nodes.
2. Calculate the flow rates for the links from the momentum equation with the existing nodal pressures.
3. Construct a pressure correction equation by combining the corrected momentum and continuity equations. Solve the matrix of the pressure correction equations using a direct method and update the pressures and the flow rates.
4. Solve the discretized energy equations at all nodes using a direct solution to determine the temperatures at all nodes.
5. Repeat steps 2 to 4 till convergence.

The resulting algorithm is fast and robust.

Example

The FNM methodology has been applied for analyzing the air flow distribution in a typical air cooled computer. A commercially available FNM program [7] was used for this purpose.

The Physical System

The physical layout of the computer system is shown in Fig. 3. The air flow through the system is provided by two fans. The air flows through the DASDs, through the gap between the DASDs, and through the clearance above the Tape Drive and the CD-ROM. These flow streams meet in the Central Plenum. The fan located in the Central Plenum

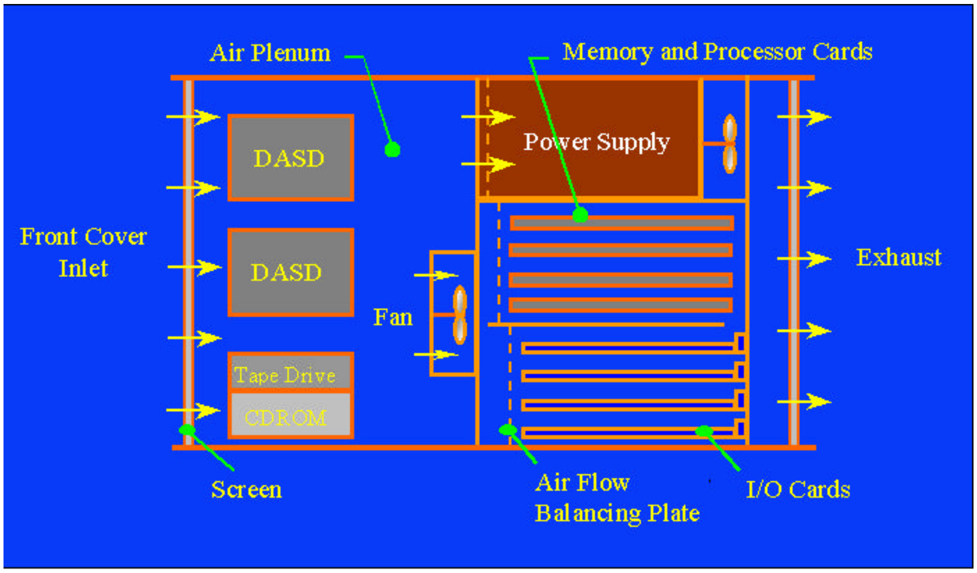

Figure 3 – Layout of a typical computer system

forces the flow through the I/O and the Memory and Processor Card stacks. The Power Supply Fan draws some of the air through the Power Supply.

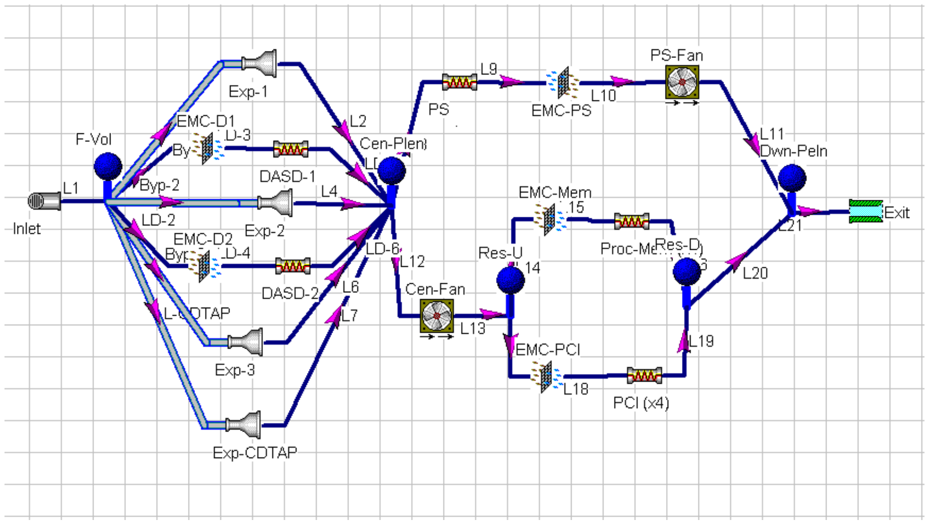

Figure 4 – Flow network representation of the computer system

Network Representation

The network representation of the computer system is shown in Fig. 4. In general, there is a one-to-one correspondence between the network layout and the components of the physical system. However, the following features of the network model require special attention.

- The area expansion components (Exp-1, Exp-2, and Exp-CDTAP), account for the pressure losses that occur when the streams from the clearances between the DASDs and above the Tape/CD-ROM drives discharge into the central plenum.
- Note that air flows through the I/O and Processor/Memory Card arrays through four flow channels formed by the cards. Accordingly, a multiplier of four is applied to each of these components to represent a set of four resistances in parallel.

Component Characteristics

The loss coefficients for standard components such as screens, ducts, and area expansions are available in handbooks [2, 3]. The flow characteristics and heat dissipation rates for the remaining components are listed in Table 1 and 2.

Table 1 – Flow characteristics and heat dissipation rates of individual components

Component	*Loss coefficient B* $Pa/(m^3/s)^2$ *in* $Dp=BQ^2$	*Heat Dissipation (Watts)*
DASD	$1.0\text{x}10^{-4}$	2.5
Processor and Power Supply	$2.0\text{x}10^{-5}$	150
Memory	$5.0\text{x}10^{-6}$	60
I/O Cards	$1.0\text{x}10^{-5}$	20

Table 2 – Maximum head and flow rate provided by the fans

Fan	*Maximum Head (In of Water)*	*Maximum Flow Rate (SCFM)*
Main Fan	0.15	66
Power Supply Fan	0.28	74

Results

The predicted flow directions are shown by arrows on the network in Figure 4. Figure 5 shows the volumetric flow rate through various parts of the system. The flow in the front part of the system bypasses the disk drives due to their large flow resistance. For Processor/Memory and I/O card arrays, the flow rates reported in Figure 5 pertain to one representative channel within them. The results show that the system is well balanced and provides air flow to the PCI, Processor, and Power Supply components according to their heat flux requirements. Figure 6 shows the bulk temperature of the air streams exiting the heat dissipating components.

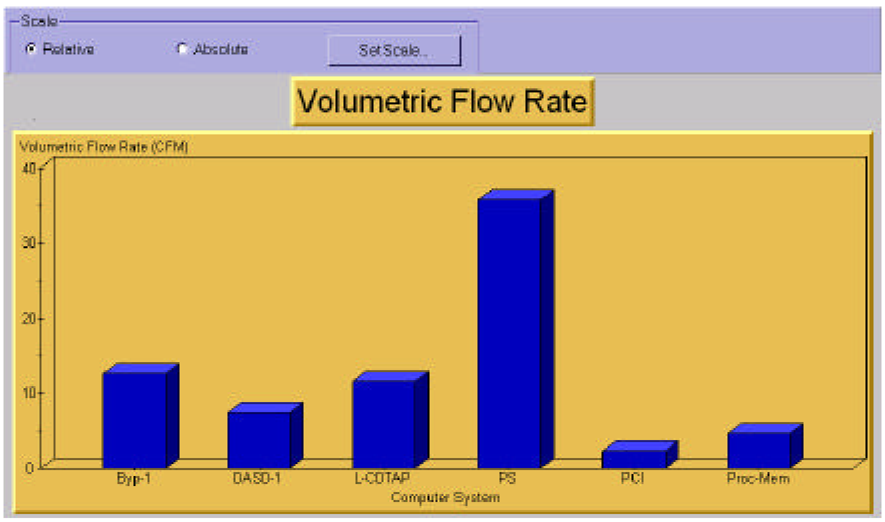

Figure 5. Volumetric flow rate through various parts of the system

Although not reported here due to space limitations, examination of the component pressure losses reveal that only the losses through the Inlet and the Power Supply are significant. Incorporation of a separate and more powerful fan downstream of the Power Supply is necessary to overcome the impedence and provide sufficient flow for cooling.

It is of interest to note that the construction of the flow network model required 1.5 hours while the calculation of the flow and temperature distribution required 10 seconds on a Pentium 133 PC. Thus, the case study presented here illustrates the utility of FNM for rapid and accurate evaluation of the coolant flow distribution and thermal performance for system-level design.

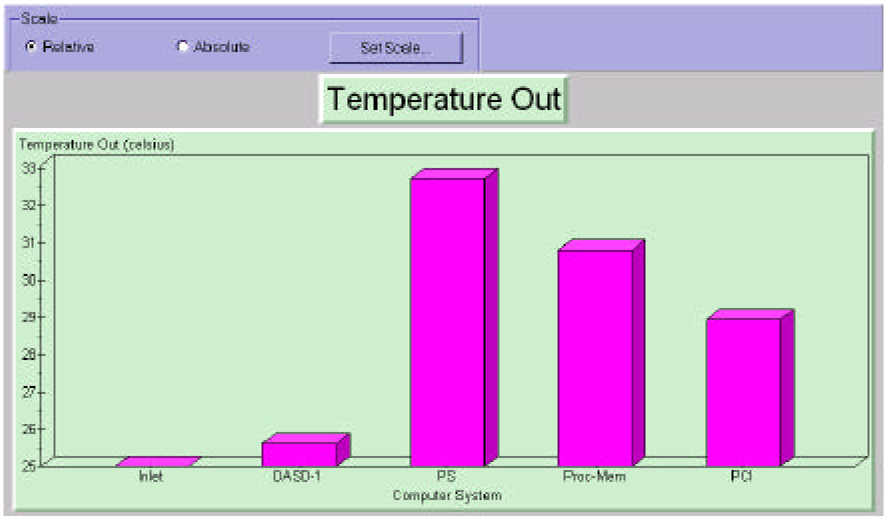

Figure 6. Bulk temperature of the air streams

Conclusions

This paper introduces the concept of Flow Network Modeling (FNM) and its application in the design of electronics cooling systems. FNM enhances the productivity of the thermal designer by fulfilling the need for a technique between spreadsheets and CFD for system-level design.

A generalized FNM methodology has been described that involves network representation of a flow system by tracing the paths followed by the cooling streams. Each flow path and component in the network is assigned flow and heat transfer characteristics. Then, the mass, momentum, and energy conservation equations are solved to determine systemwide distribution of the flow rate and the local bulk temperature of the coolant. Although the use of FNM approach has been illustrated for the design of an air cooled computer system, a liquid cooled system would be analyzed similarly.

The FNM approach offers the following benefits in the design of electronics cooling systems:

- Rapid and accurate evaluation of competing system configurations during the conceptual design stage.
- Developing ideas for design improvements and analysis of “what if” scenarios.
- Focused, selective, and efficient use of CFD analysis for later detailed design.

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Authors' Bio-Data

Christian Belady received a B.S. from Cornell University in 1983 and and M.S.from Rensselaer Polytechnic Institute in 1986 both in Mechanical Engineering. In 1990, he received an M.A. in International Business from the University of Texas at Dallas. He is currently a Technology Specialist for the High Performance Systems Division of Hewlett Packard where he is responsible for developing the cooling requirements for its computers as well as identifying and developing strategic technologies for HP.

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