Flow Network Modeling: A Case Study in Expedient System Prototyping

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ABSTRACT

Fortunately for engineers responsible for thermal management of today's electronic systems, many tools exist that provide for efficient, comprehensive thermal design. These tools, including heat transfer correlations, Computational Fluid Dynamics (CFD) solvers, and Flow Network Modeling (FNM) techniques, assist engineers in answering complex layout questions and proposing thermally feasible design alternatives quickly. This paper presents the use of FNM, as proposed by G. Ellison, to perform a first order thermal analysis on a next-generation mid-range computer design. Ellison's method is used to predict system level pressure drops and air-mover performance in the complex computer system prior to building hardware, performing sub-system flow measurements or completing system level CFD analyses. In this application, the use of FNM allowed a small design team to sufficiently validate the system layout early in the product's design cycle, enabling continued sub-system layout, detailed design, and prototype production within the constraints of the project's aggressive schedule. Results of the Ellison based approach are compared with those of a comercially available FNM software package and with data taken from a system prototype. Comparison shows that the results agree well, validating the use of FNM as an aid in developing thermally feasible computer designs.

KEY WORDS: thermal design, system analysis, electronics cooling

NOMENCLATURE

Q	Volumetric Flow Rate
P	Power
R	Flow Resistance

Greek symbols

ΔT	Temperature Change
ρ	Fluid Density

Subscripts

Sys	System

INTRODUCTION

Thermal designers of current computer systems find they have reached the crossroads of speed, flexibility, and accuracy: all are required to make today's computer products marketable, feasible, and reliable. Rapidly changing electronics technology force computer companies to demand speedy, efficient design practices as product cycles are tightened. Emerging architectures and the need for platform conformity well into the future necessitate the ability to weigh alternatives and create novel approaches to removing increasingly larger amounts of thermal energy from increasingly smaller, more densely populated spaces. Technology performance enhancements that produce faster, more powerful electronics seemingly everyday require detailed design calculations and extensive risk management appraisals to insure product functionality and reliability.

Fortunately, today's thermal engineers have a plethora of design tools available to them [1]. Heat transfer correlations are well established and published in the literature. Spreadsheet based design tools, such as those used to aid in heatsink design, are available both commercially and, in many instances, within private company organizations. Finite Element Analysis (FEA) and Computational Fluid Dynamics (CFD) software packages exist to aid in chip package through system level thermal analysis by bringing extensive computational power to bear in solving the complex equations of energy and fluid particle motion. Additionally, Flow Network Modeling (FNM) is fast becoming a popular methodology for estimating air distribution in electronics systems. These tools vary in complexity, ease of use, accuracy, and resolution. It appears clear that, in order to optimize resources such as time, personnel, and money, thermal designers will naturally progress through many or all of these tools as a product's design cycle matures.

This case study presents the use of FNM methodology presented by Ellison [2,3] to perform a first order thermal analysis on a next generation computer design. The use of FNM early in the product design cycle enabled a small mechanical design team to validate its system layout and proceed with more detailed subsystem layout and design. Further thermal analysis and prototype testing validate FNM modeling results and support the use of this methodology for expedient thermal design of complex electronic systems.

FNM: A SUMMARY OF ELLISON'S METHODOLOGY

According to Ellison [2], a typical first order flow network of a forced convection system consists of a circuit representation of the major fluid flow paths within a system. In the case of an air-cooled electronics system, flow can be either through components such as power supplies, heat sinks, and card cages, or through the channels existing between them. Flow is analogous to current; flow paths are represented as resistors in the circuit model. Flow resistance correlations (based upon sea level system operation) are available in the literature [2,3,4], or can be determined from empirical methods if hardware is available for testing. Gage pressure, the primary driver of the flow, is analogous to voltage and can be determined at nodal points located throughout the circuit.

Once the system flow paths are identified and the individual flow resistance values are calculated, resistances are combined into a single flow resistance for the entire system (R_{Sys}) using the appropriate rules for adding series and parallel elements in a circuit as shown in Table 1.

Series Elements	$R = R_1 + R_2$
Parallel Elements	$\frac{1}{\sqrt{R}} = \frac{1}{\sqrt{R_1}} + \frac{1}{\sqrt{R_2}}$
Flowrate of Parallel Elements	$\frac{Q_2}{Q} = \frac{1}{1+\sqrt{\frac{R_2}{R_1}}} = \sqrt{\frac{R}{R_2}}$

Table 1: Turbulent Flow Resistance Rules

In deriving these rules, it is assumed that the flow through the system is predominantly turbulent (a typical first approximation for a forced convection cooled computer) and obeys Equation 1. Ellison presents the derivation of these rules based upon the turbulent assumption in [3].

$$\Delta P_{Sys} = R_{Sys} Q_{Sys}^{\ 2}$$

Equation 1

It should be noted the user may derive and use similar rules for systems that are estimated to be other than turbulent using the expression:

$$\Delta P_{Sys} = R_{Sys} Q_{Sys}^{\ N}$$

Equation 2

where N is a flow constant varying between 1 (completely laminar flow) and 2 (completely turbulent flow) [3,5].

Finally, the system impedance curve for fully turbulent flow is calculated and plotted from Equation 1. The total volume flow rate through the system is determined by the intersection of the fan performance curve and the system impedance curve. This point is known as the system operating point and is shown in Figure 1.

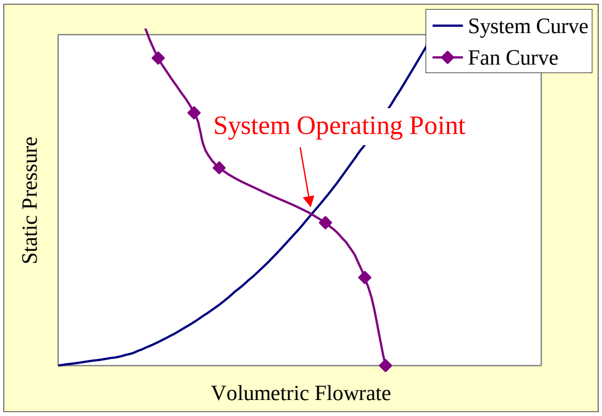

Figure 1: System Operating Point

Fan performance curves may be adjusted to represent multiple fan systems (series and parallel orientations) as discussed in [5], and to represent blower, intermediate, or exhaust style orientations as discussed in [3]. Flow rates through the individual branches can be estimated using the appropriate relationship (Table 1). Ambient air temperature rises (sea level) through the entire system or specific sub-systems can be determined using Equation 3 as discussed in [2]:

$$\Delta T[^oC] = \frac{1.76P[W]}{Q[Ft^3/Min]}$$

Equation 3

Ambient air temperature rises can be adjusted for high altitude effects as discussed in [6].

With this information, the designer can assess the thermal feasibility of the product layout. Predicted flow rates can be used in spreadsheets to predict heat sink and chip case temperatures as required; estimated ambient air temperature rises through subsystems can be checked against component air temperature specifications and design parameters.

Notably, flow resistance correlations proposed in the literature [2,3,4] typically represent the pressure drop through a flow component as a function of the cross sectional area of the flow. (Ellison notes the inverse square dependence of a flow's pressure drop to its free cross-sectional area [2].) Thus, Ellison's approach can truly be a first approach: it enables the thermal designer to analyze a system as soon as system and sub-system area dimensions (height, width, and pitch) and layout orientations are known. This feature makes the FNM method a valuable tool for early system level thermal analysis.

FUTURE COMPUTER SYSTEM: THE FNM APPROACH APPLIED

Conceptual models of the future computer system described by this study are shown in Figures 2 and 3. The inherent complexity of this computer system, combined with the magnitude of its power dissipation, made it clear that a system level thermal analysis was necessary to validate the feasibility of the design. Because the small design team faced an aggressive schedule and a product development objective of remaining cost focused, it was required that the thermal evaluation sustain minimum schedule (prototype design/ build time) and budget (prototyping cost, manpower) impacts.

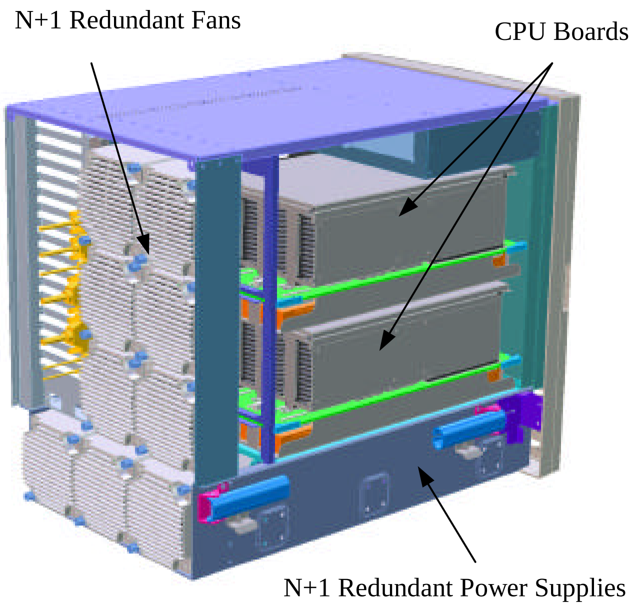

Figure 2: Computer System CPU/Power Section

To accomplish these tasks it was clear that a mathematical thermal model was required. Time and resources to design, build, and measure the airflow characteristics of sub-systems and product mock-ups could not be afforded at this stage: the mechanical design had to proceed in order to meet first prototyping schedules. Additionally, the thermal evaluation was required to proceed quickly but remain flexible in order to stay on schedule and to accomodate changes to the still "fluid" design. For these reasons, Ellison's FNM methodology was chosen to assess the thermal feasibility of the design.

It should be noted that the Ellison approach to FNM was particularly suited to the analysis of this design due to the layout's 1) the front-to-back airflow scheme, 2) largely straight and predictable airflow paths, and 3) "simple" fan orientation schemes (series and parallel). These factors significantly affect the accuracy of the flow network model and should weigh heavily into the decision to use this approach.

FNM Development

The computer system represented in this study consists of two distinct airflow compartments with separate fan arrangements: the CPU/Power section Figure 1) and the PCI/Memory section (Figure 2). The CPU/Power section contains two multi-processor printed circuit boards (PCBs), an active back-plane board, and N+1 redundant bulk power supplies. ("N+1" redundancy implies that any one redundant component can fail and the system will continue to operate unaffected.) These components are cooled through a common air plenum by an array of N+1 redundant fans mounted in a parallel orientation to the external rear face of the chassis. The PCI/Memory section contains four memory carrier PCBs and the PCI card cage. These components are cooled via two columns of N+1 redundant fans, mounted in series. Because the air does not mix between these compartments, the complete system level representation consists of two separate flow network models: one for the CPU/Power section and another for the PCI/Memory section. The flow network representation of the entire computer system is shown in Figure 4.

The application of Ellison's methodology was straightforward. First, the major flow paths through the system were identified and flow resistances along each path were placed into their respective circuits. Sea level resistance values using formulae from [2,3,4] were calculated using flow path dimensions taken from available CAD models of the system. In some instances where components were leveraged from previous products (e.g. Memory PCBs, Mass Storage Bay, PCI Card Cage), available empirical data was used. The airflow circuits were simplified to the form of Equation 2 using the rules presented in Table 1. Detailed flow network representations of the CPU/Power section and the PCI/Memory section are shown in Figures 5 and 6, respectively. Calculated flow resistance values for the CPU/Power section and the PCI/Memory section are shown in Tables 2 and 3.

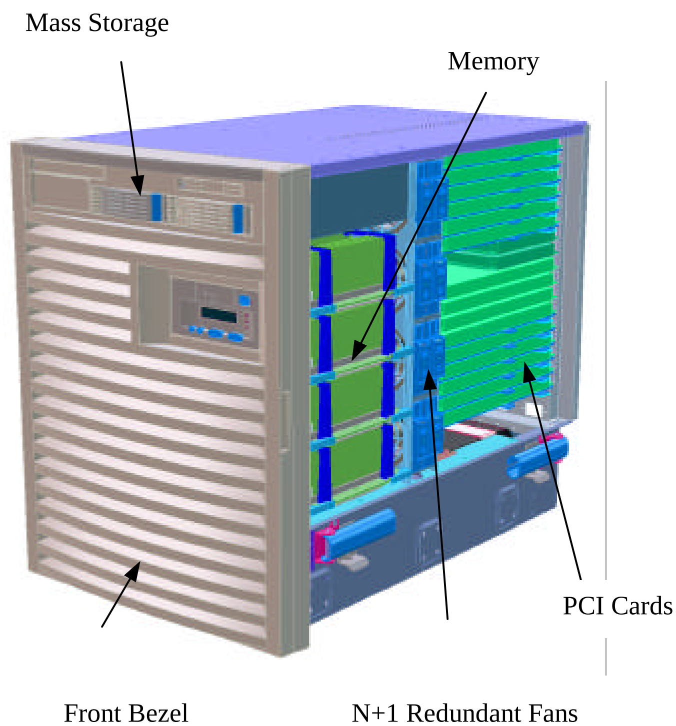

Figure 3: Computer System PCI/Memory Section

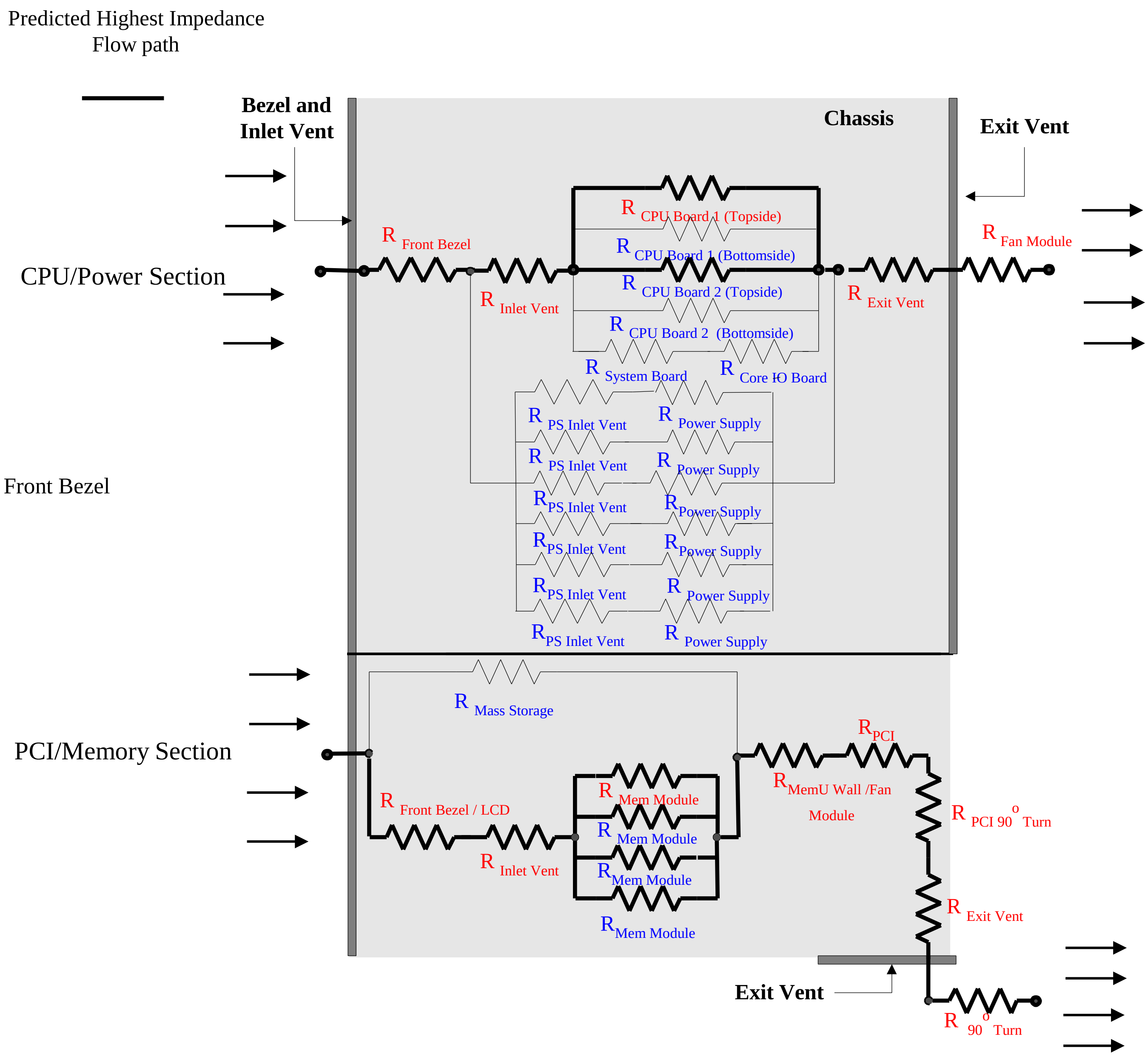

Figure 4: Flow Network Representation of a Future Computer System

Initial construction of the Ellison based FNM was the most time consuming task, requiring aproximately 5 man-days to complete. This time included initial investigation into the methodology as well as selection of sub-system resistance correlations. Once the intial model was constructed, subsequent iterations were completed more rapidly. Iteration solution can be semi-automated and, thus, quickly accomplished (on the order of minutes).

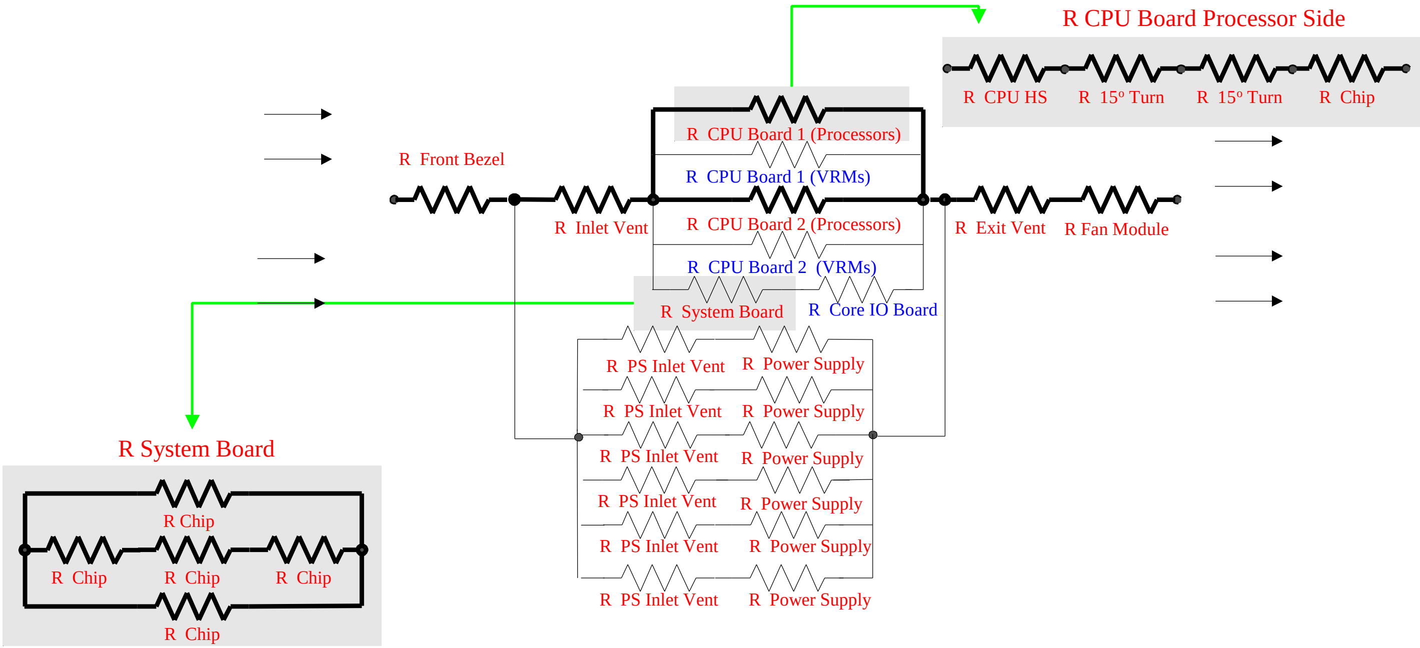

Figure 5: Detailed CPU/Power Section Flow Network

Component	Function	Resistance Formula	R esistance [in H_20 / CFM^2]	Assumptions	Source
Front Bezel	Perforated Plate	2.4×10^{-3} /A^2[in^2]	1.84×10^{-7}	50% open	[2], [3]
Inlet Vent	Perforated Plate	2.4×10^{-3} /A^2[in^2]	1.28×10^{-7}	60% open	[2], [3]
CPU Board (Top)			5.52×10^{-5}		
CPU Heat sink	Extruded Heatsink	$[1.29 \times 10^{-3}]$ /N_p^2 A_c^2[in^2][K_c+K_e+$4f_{app}L/D$]	1.17×10^{-3}	Turbulent Flow	[3]
15^0 Turn	Contraction	1.2×10^{-3} /A^2[in^2]	2.00×10^{-5}		[3], [4]
Chip Heat sink	Extruded Heatsink	$[1.29 \times 10^{-3}]$ /N_p^2 A_c^2[in^2][K_c+K_e+$4f_{app}L/D$]	2.32×10^{-3}	Turbulent Flow	[3]
CPU Board (Bottom)			1.02×10^{-4}		
VRM Channels	Contraction	0.63×10^{-3} /A^2[in^2]	Various		[3]
	Sudden Expansion	$1.29 \times 10^{-3}[1/A_1(1-A_1/A_2)]^2$	Various		[3]
System Board			4.70×10^{-4}		
Chip Heat sink	Extruded Heatsink	$[1.29 \times 10^{-3}]$ /N_p^2 A_c^2[in^2][K_c+K_e+$4f_{app}L/D$]	3.12×10^{-3}	Turbulent Flow	[3]
Core IO Board			NA	Negligible (No Heat sinks)	
Exit Vent	Perforated Plate	2.4×10^{-3} /A^2[in^2]	1.41×10^{-7}	60% open	[2], [3]
Fan Modules	Perforated Plate	2.4×10^{-3} /A^2[in^2]	8.98×10^{-8}	75% open	[2], [3]
Power Supply Inlet Vent	Perforated Plate	2.4×10^{-3} /A^2[in^2]	4.63×10^{-5}	60% open	[2], [3]
Power Supply	Card Cage	3.1 x 10-4 L[in] /A^2[in^2]	4.30×10^{-5}	50% open	[2]
				components on a 1" pitch	
Total	CPU/Power Section	Table 1 Rules	1.31×10^{-6}	Turbulent Flow	[2], [3]

Table 2: CPU/Power Section Resistance Values

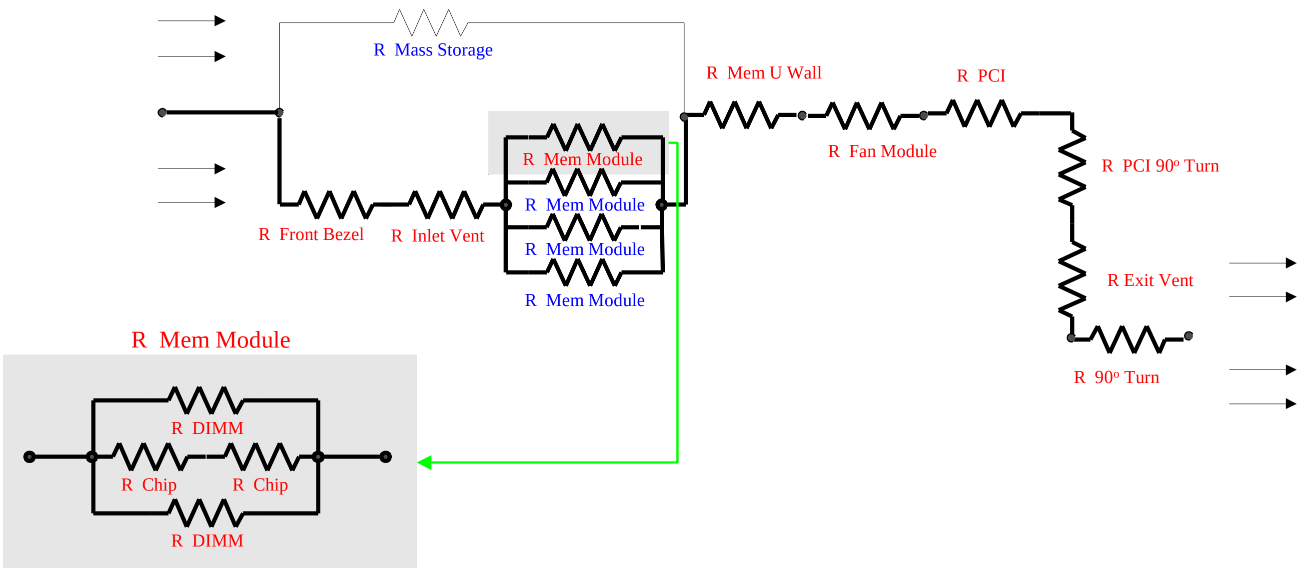

Figure 6: Detailed PCI/Memory Section Flow Network

Component	Function	Resistance Formula	R esistance [in H_20 / CFM^2]	Assumptions	Source
Front Bezel	Perforated Plate	2.4 x 10^{-3} /A^2[in^2]	3.13 x 10^{-6}	50% open	[2], [3]
Inlet Vent	Perforated Plate	2.4 x 10^{-3} /A^2[in^2]	4.78 x 10^{-7}	60% open	[2], [3]
Memory Module (Carrier Board)	Measurement		1.80 x 10^{-5}	Leveraged from past product	
Mass Storage Bay	Measurement		3.3 x 10^{-5}	Leveraged from past product	
Memory "U" Wall	Perforated Plate	2.4 x 10^{-3} /A^2[in^2]	1.08 x 10^{-6}	50% open	[2], [3]
Fan Modules			NA	Negligible (finger guards only)	[2]
PCI Card Cage	Card Cage	3.1 x 10^{-4}L[in]/A^2[in^2]	1.67 x 10^{-6}	modified by 1.5 to match data	[2]
				Leveraged from past product	
Exit Vent	Perforated Plate	2.4 x 10^{-3} /A^2[in^2]	5.74 x 10^{-7}	60% open	[2], [3]
90^0 Turn	Sharp Cornered Turn	1.81 x 10^{-3} /A^2[in^2]	4.71 x 10^{-7}		[3]
Total	PCI/Memory Section	Table 1 Rules	6.67 x 10^{-6}	Turbulent Flow	[2], [3]

Table 3: PCI/Memory Resistance Values

Each system curve (CPU/Power section and PCI/memory section) was plotted against manufacturer fan curves, modified for number and arrangement as discussed in [5], to determine the system operating points of the two airflow sections (Figure 6). Because the PCI/Memory section fans function as intermediate fans, fan velocity discharge losses were added to the appropriate fan curves as described in [3]. Because the CPU/Power fans function as exhaust fans, they do not require this adjustment. It is important to note that the curve that results from "adding" fans, whether in series or parallel, is a best case aggregate fan performance curve. Typically, aggregate fan performance will be less than the best case curve predicts due to losses caused by mechanical attachment method and, if applicable, an arrangement in which fans pull from a shared air plenum [9]. To compensate for any potential degradation of fan performance in this analysis, several fans of different performance levels (speeds) were considered in order to validate the fan size, number, and arrangement.

Flow rates for each airflow section were extracted from these plots and used to predict individual sub-system flow rates using the relation given in Table 1. Based upon the assumption of turbulent flow and the knowledge that tube-axial fans are constant speed devices, the volumetric flow rates of air through identified flow paths remain constant with increasing altitude [10]. Thus, volumetric flow rates estimated at sea level conditions were used to predict heat sink temperature and ambient air temperature rises at worst case design conditions (5,000 feet altitude and 35^0C inlet air temperature) as discussed in [6]. This information was used to validate the design feasibility, identify potential problem areas, and justify the continuation of prototype production.

FNM Verification

Upon receipt of the first prototype chassis, a complete system " airflow mock up" was constructed using prototyped PCBs, heat sinks, power supplies, and cosmetic grills. Injection-molded plastic parts, such as the front bezel and fan modules,

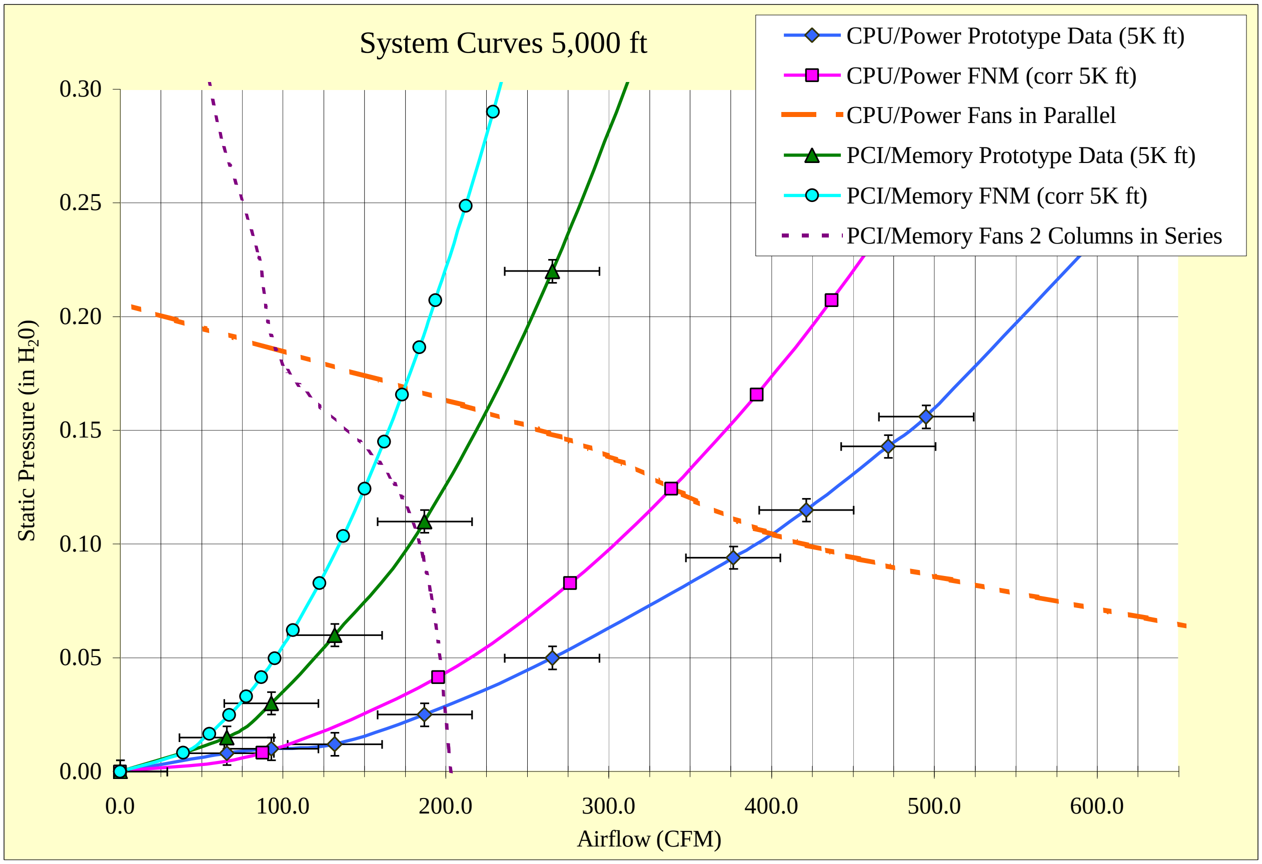

Figure 6: Experimental Results

were created from stereo lithography techniques in order to accurately replicate their flow effects. The airflow mockup was measured in a metered air source, as described in [7,9], to attain the system curves and system operating points of both airflow sections. Experimental measurement error is based upon manometer accuracy is determined to be +/- 0.005 in H_20 for static pressure measurements and 29 CFM for volumetric flow rate measurements (+/- 0.02 in H_20 for a 3 inch nozzle). Measured curves for the CPU/Power and the PCI/Memory sections are plotted against representative fans curves (adjusted for number and parallel or series orientation) and predicted curves, as shown in Figure 6. Measured curves are found to be within 14-18% of the Ellison FNM predicted curves for the PCI/Memory and CPU/Power sections, respectively. Additionally, it is important to note that both system predictions using the Ellison method were conservative.

The growing popularity of FNM has led to the availability of a commercial software package, *MacroFlow* [11], which incorporates this technique. Once this tool became available, additional flow network models of the computer system were constructed to further assess the system's feasibility as well as to compare results with the Ellison based model. This tool incorporates a generalized flow network methodology for prediction of flow distribution within complex flow systems [1]. It does not necessitate the construction of overall system impedance values. Instead, the interaction among system impedances and fan curves is handled automatically within the software. Similarly, this generalized methodology does not restrict the form of the impedance characteristic of individual components and, thus, does not require an upfront estimate of the system flow regime (laminar, transitional, or turbulent). Furthermore, experimental data, such as pressure drop vs. flow rate measurements, can be specified for accurate modeling a systems' flow distribution. Flow rates predicted by the Ellison and *MacroFlow* based models and measured data are compared in Table 4.

FNM Results

Ellison based system level FNM results were conservative, yet matched prototype data and *MacroFlow* results within 14-18% for the PCI/memory and CPU/Power sections. Ellison based sub-system FNM results also compared favorably to *MacroFlow* results (3-29% difference). The worst case discrepancy of sub-system flow rates occurred in the division of flow between the Mass Storage Bay and the Memory Carrier PCBs. This difference is attributed to fitting turbulent based resistance curves (of the form $\Delta P=RQ^2$) to experimental data which was transitional in nature (of the form $\Delta P=RQ^{1.5}$).

Furthermore, although the Ellison based FNM results diverged from the *MacroFlow* results by 16% in the area of

Component	Ellison FNM [CFM]	Macroflow FNM [CFM]	% Difference Ellison vs MacroFlow	Exp Data [CFM]	% Difference Ellison vs Exp Data
CPU/Power Section	338	398	17.8	398	17.8
CPU Heatsink	5	6	20.0		
System Board	14	16.8	20.0		
System Board Heatsink	4.6	5.5	19.6		
Power Supply	31	26	16.1		
PCI/Memory Section	158	163	3.2	180	13.9
Mass Storage	38	27	28.9		
Memory Carrier PCB	30	34	13.3		
PCI Card	9.6	10.2	6.3		

Table 4: Flow Rate Estimate Comparison

the power supplies, the results did point to a potential problem concerning the balance of airflow between the CPU boards and the power supplies. *MacroFlow* results substantiated the existence of this problem, although indicated the problem to be less severe. The most likely cause of this discrepancy is an underestimation of the power supply resistance, caused by the choice of resistance correlation, in the Ellison based FNM. Regardless, early predictions enabled the design team to anticipate the problem and develop potential solutions prior to building system prototypes.

CONCLUSIONS

This study presents the use of Flow Network Modeling, as proposed by Ellison [2,3], as an aid in estimating system pressure drops and predicting air mover performance during the early development stage of complex computer system design. The advantages of the Ellison FNM methodology as seen in this study are:

- Quick Solution Time
- Ease of Iteration
- Requires no experimental data (although data can be used if available)
- Requires no special software (although enhanced FNM software is available)

Regarding the constraints of this approach, Ellison suggests that this analysis may not resolve all thermal issues within a system but, with enough care, can provide for accurate results [2]. Care should be taken to insure that 2D system flow paths are dominant and predictable, as FNM techniques cannot resolve 3D flow paths. Ellison's method assumes that component placement is defined and requires an upfront prediction of the system flow regime. Iteration may be necessary. Time and accuracy must be optimized to attain results that are beneficial yet expedient.

In conclusion, this study has shown FNM to be an effective means to validate system level thermal design prior to performing prototype builds, sub-system airflow testing, and detailed CFD analyses. Using Ellison's FNM method, designers can rapidly develop system operating point estimates and predict sub-system airflow rates with enough accuracy to assess system layout characteristics and identify potential problem areas with confidence. The true benefit of this method is its ability to be applied early in the design process in order to converge quickly on a thermally feasible layout. Detailed design and higher order thermal problems can then be solved using more refined analysis techniques.

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