USE OF FLOW NETWORK MODELING (FNM) FOR THE DESIGN OF AIR-COOLED SERVERS

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ABSTRACT

The present study describes the technique of Flow Network Modeling (FNM) and its application for the design of an air-cooled server. The technique of FNM involves representation of the flow system as a network of flow paths and components for the prediction of system-wide flow and bulk temperature distribution. The FNM technique is very efficient in terms of the effort required for model definition, solution, and examination of results because it employs overall component characteristics for analyzing their system-wide interaction. Further, use of empirically measured component characteristics ensures good accuracy of the predicted flow distribution. Application of this technique for the design of an air-cooled server involved investigation of the flow distribution in different system layouts, generation of ideas for performance improvements based on predicted system-wide flow distribution, and evaluation of these modifications on the air-flow performance of the system. Use of FNM is shown to significantly reduce the time required for a comparative performance evaluation of different system configurations. Such rapid analysis enabled development of a good system design during the Conceptual Design Stage, before the design proceeded to a stage where changes are very costly to implement. An enhanced design cycle is outlined that uses FNM analysis during the early design stage for shortening the overall design process, enhancing the quality of the final design, and improving the productivity of the thermal design engineer in a significant manner.

INTRODUCTION

With increasing power density of electronic systems, their reliable operation is critically dependent on satisfactory thermal performance. Therefore, thermal design plays an integral role during the packaging of electronic systems. Fluid flow and heat transfer analysis, involving mainly the Computational Fluid Dynamics (CFD) technique, is increasingly used to guide the thermal engineer in devising effective cooling strategies. This paper advocates the use of the technique of Flow Network Modeling (FNM), prior to CFD analysis, for deriving significant productivity gains during the packaging of electronic systems. It is, therefore, useful to discuss the system design process and conventional methods of thermal analysis, before introducing the FNM technique.

System Design for Electronic Packaging

The design of electronics cooling systems is an evolutionary process that proceeds through three discernible stages – *Conceptual System Design, Detailed Design*, and *Design Verification* as described by Kang (1998). The Conceptual System Design stage is the most dynamic phase of the design cycle due to its interdisciplinary nature and the corresponding rapid pace of evolution of the system layout. Thus, at the concept stage, a system architect proposes component and board configurations based on the following constraints:

- Routing and transmission line length considerations and electromagnetic compatibility
- Mechanical integration into a system
- Cooling of the system components

The order shown is normally the priority given to each of these considerations.

The responsibility of the thermal engineer is to quantify how these concepts can be packaged while meeting system goals for component placement, component temperatures, thermal system cost, system availability and acoustical output. A good layout of the system package needs to be developed at the end of the Conceptual System Design stage because any changes in the design later in the cycle are very costly. Then, the later steps, namely Detailed Design and Design Verification, involve refinement of the system layout developed during the concept stage and experimental validation of the performance of the final design.

Conventional Analysis Methods for Thermal Design and Their Limitations

The primary purpose of analysis during the Conceptual System Design stage is to help the thermal engineer in quickly identifying, from the numerous possible system layouts, the packaging concepts that meet the system goals. In the conventional design process, hand calculations/spreadsheets and CFD are used for quantitative evaluation of various cooling concepts. Hand calculations and spreadsheets attempt to use the available empirical correlations for pressure loss and heat transfer through various parts of the system for a quick evaluation of thermal performance. However, hand calculations are tedious and very simplistic while spreadsheets are time consuming to construct and are system specific and therefore inflexible. On the other hand, use of CFD analysis is impractical for examination of a large number of design alternatives in the early design stage. This is because it is time-intensive in terms of model setup, computation, and interpretation of the large amount of data. Thus, a quick and simple analysis procedure that allows evaluation of the airflow performance of various design options in a scientific manner is necessary for Conceptual System Design.

FNM expands the use of empirical correlations by generalizing their use in complex flow network representations of cooling systems. The FNM technique is simple, fast, and accurate and is ideally suited for use during the Conceptual Design Stage. Detailed analysis then needs to be performed only for the feasible system configurations.

The Technique of Flow Network Modeling (FNM)

FNM is a generalized methodology involving representation of a flow system as a network of components and flow paths for the purpose of predicting system-wide distribution of flow rates and temperatures. Practical electronics cooling systems can be represented as a network of components such as ducts, heat sinks, screens, filters, passages within card arrays, fans, bends, and tee junctions. The emphasis of FNM is the analysis of the interaction among the components for determining the system performance. Therefore, prediction of the details of flow and heat transfer within a component is not attempted. Instead, each component in the flow network is represented by empirical correlations that relate pressure drop and heat transfer rate to the corresponding flow rate. The flow and thermal performance of the system is predicted by imposition of the conservation of mass, momentum, and energy over the flow network.

Because of the use of overall component characteristics, FNM-based analysis is very quick in terms of model definition and computational time. Further, use of empirical characteristics that are valid over laminar, transitional, and turbulent flow regimes assures that predictions of the system performance obtained from FNM analysis are accurate over wide range of operating conditions. The strength of FNM is its ability to analyze system-wide interaction of the individual components in a rapid and accurate manner.

Theoretical Basis of FNM

Component Characteristics, Prediction of the system-wide flow and temperature distributions requires specification of the flow and heat transfer characteristics of the components used in the network model. The flow characteristics involve specifying the variation of the pressure loss in a component as a function of flow rate. Typically, the following equation describes this variation:

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

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

The loss factor is given by the following relations:

$$K = \frac{B}{Re} \qquad \text{for} \qquad Re \le Re_{Lam}$$

$$K = \text{constant} \qquad \text{for} \qquad Re \le Re_{Turb}$$

The loss factor K is appropriately interpolated in the transitional range. The loss coefficients for standard components (screens, ducts, bends, etc.) are available from handbooks such as Idelchik (1994) and Blevins (1992). For card arrays, the loss coefficient can be determined using the Moody chart with corrections to account for the blockage effects of heat sinks and electronic components. For nonstandard components supplier data, CFD analysis, or test data can be used to get the flow characteristics. It should be noted that, whereas Eq. (1) is the most common method of specifying the flow characteristics, any functional variation relating the pressure loss to the flow rate can be used in the FNM methodology. 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 transferred to the streams from the components and mixing of the streams in different parts of the system. If the heat dissipation is known, the component temperature is determined from the surface heat transfer coefficient. On the other hand, for a component exposed to an external environment, the heat transfer within a component is determined from the overall heat transfer coefficient. The following form of empirical correlations are used to determine the Nusselt number (dimensionless heat transfer coefficient) for each component that participates in heat transfer.

$$Nu = A\,Re^{m}\,Pr^{n} \qquad (2)$$

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. This storage scheme is similar to the staggered grid used in the control volume based CFD technique of Patankar (1980) for detailed analysis of flow and heat transfer in a region of interest. 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 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. The SIMPLE algorithm of Patankar (1980) is used to solve the discretized mass, momentum, and energy equations. The resulting algorithm for the prediction of flow rates, pressures, and temperatures over a flow network is fast and robust. More details on the construction and the solution of the discretization equations over a flow network are provided by Belady et al. (1999).

DESIGN OF AN AIR-COOLED SERVER

The FNM technique described above has been applied for the system-level design of an air-cooled server. A commercially available software package, MacroFlow (1999) was used for this purpose. The details of the physical system, flow network analysis, and the corresponding design iterations are now discussed. A comparison of the predictions of FNM and CFD analysis for a specific system configuration are also presented to demonstrate the accuracy of this technique. The study clearly demonstrates the power of the FNM technique in allowing quick and accurate evaluation of alternate packaging concepts and the resulting productivity gains.

The Physical Design Problem

System Components, A server typically includes multiple printed circuit boards (PCBs) with the following functions:

- CPU – support for processors, memory and IO control
- IO - PCI bus and peripheral device logic support and connections
- Power and signal distribution – interconnects all system boards and distributes power from the supplies
- Peripheral device back-plane – provides an organized PCB for connection of removable and non-removable media such as floppy, CDROM, and hard disk drives.

Rack Packaging, Most servers are packaged for use in rack furniture and must be integrated with other rack-mount components such as disk arrays. To achieve integration with other components normally requires design of a front-to-back cooling configuration to prevent recirculation within the rack. The rack furniture itself must be designed to enable unencumbered venting to the room environment. Effects of the rack furniture on airflow performance are not included in this study although they could easily be included using the described techniques.

Redundancy/High Availability, The need for high server availability drives the requirement for cooling redundancy and the capability of replacing air-moving device (AMD) failures without server downtime. As a result, AMDs must be accessible and their replacement must not disrupt server operation.

The Purpose of the FNM Analysis, In order to guide the thermal engineer in the system-level design of the server, the analysis must allow quick and accurate prediction of the airflow performance of the system features and operating conditions:

- Impact of the characteristics and placement of each component on system thermal performance

- Different rack furniture and AMDs
- Peripheral devices with empirically-determined flow impedance
- Incorporation of different types of perforated plates for flow balancing
- Failure scenarios involving fan malfunction and environmental conditions

Network Representation of the Air-Cooled Server

Figure 1 shows an exploded isometric view of the system layout. Air enters through the front of the system at the fan side of the chassis and takes parallel paths through three sets of fans. The air exhausts from the fans through the four processors and parallel bypass paths into the PCI card area. Air exhausts between and above the PCI cards.

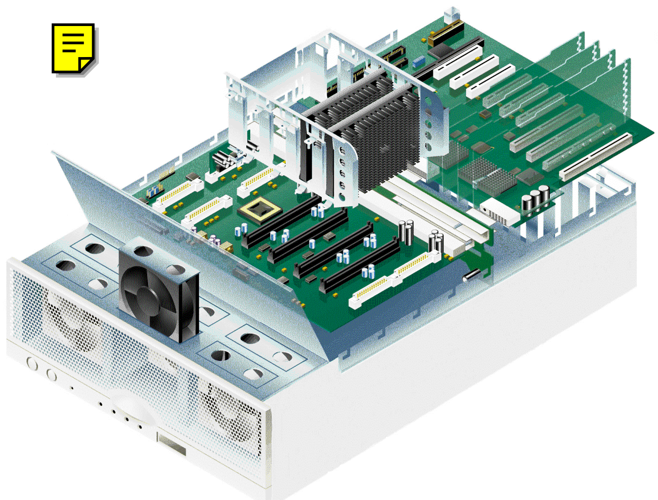

Figure 1 – A CAD diagram of a feasible system configuration

The important components and their characteristics used in the network analysis of the physical system are described below. Unless otherwise stated, correlations from handbooks (Idelchik, 1994, Blevins, 1992) are utilized for characterizing the components.

- Perforated plates – On the external surfaces of the system, perforated plates are used at air inlets and exhausts for safety requirements. Internally, perforated plates are used for flow balancing and to meet safety requirements for user accessible areas.
- PCI cards – The regions between PCI cards were modeled as ducts with rough surfaces. PCI cards vary in length, component placement, size and quantity. An extreme case was considered assuming full-length cards with maximum-height components on a 1.25" card pitch. This gives a conservative estimate of the system performance.
- System chassis – The flow impedance of the system chassis were modeled by representing the system chassis geometry through ducts and area expansions and contractions.
- Fans – Vendor fan performance curves were used in this analysis. Alternatively, performance as measured on an airflow measurement system could be used.
- Processor cards with heat sinks – Each processor card used a heat sink that covered most of its surface. This processor/heat sink combination had been used previously on another system design, consequently a processor CFD model based on the Flotherm program (Flomerics, 1998) existed and had been characterized. The flow impedance characteristics as quantified through the CFD model were, therefore, used in the FNM analysis.

Figure 2 shows the flow network of the system model with the key components shown.

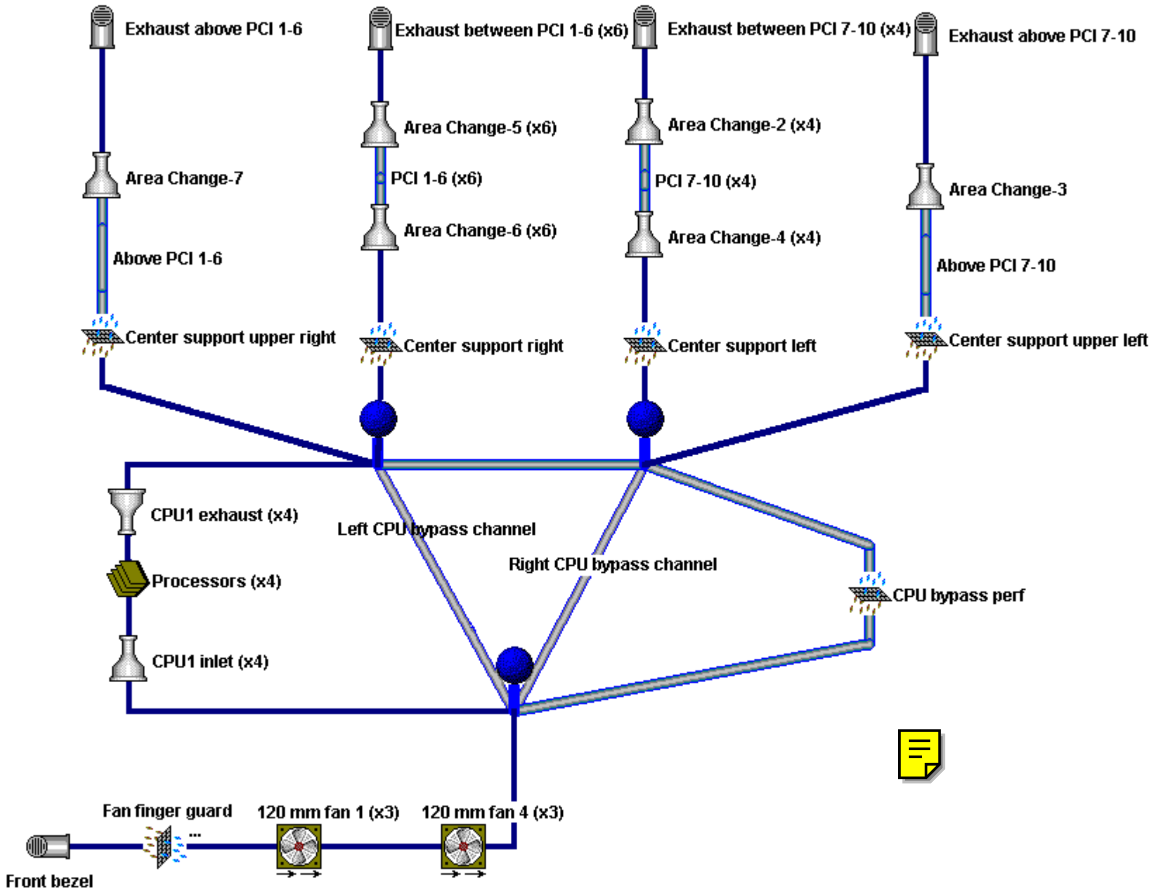

Figure 2 – Flow network representation of the air-cooled server

Results

Design Goals, The critical components in the subject design were the processors and the PCI cards. As mentioned earlier, the processor and the PCI cards have been used in previous systems. Therefore, the thermal requirements of each individual processor and PCI card passage were well understood from prior thermal testing and analysis. Accordingly, the design goals are listed below:

- Volumetric airflow rates
- Processor - 14 CFM for each processor based on its size and bypass
- PCI Cards - 6 CFM between adjacent PCI cards for a fully populated system
- Minimum flow resistance of remaining parts of the system for reliable operation

Design Iterations, The initial analysis, Case A, showed a large flow imbalance between the four processors and the adjacent area reserved for upgrades. Figure 3 shows this by comparing volumetric flow from the system fans through the processors, processor upgrade area and other processor bypasses. To correct this imbalance the bypass flow was restricted by using a perforated plate with the plate properties varied to attain the proper flow through the processors while balancing the flow to the PCI cards. By changing the perforated plate in the bypass region to 36% open (designated as Case B), flow requirements for the processors and PCI cards were met.

Further FNM analysis of the system showed that the system exhaust vents were severely restrictive thereby reducing overall system flow. Figure 4 illustrates this constriction by comparing pressure loss through the system components. As expected the processor flow impedance is significant relative to the AMD operating point pressure but the flow impedance of the exhaust area between and above the PCI cards was significantly higher severely reducing total system flow. Ideally the most critical components should drive the AMD sizing rather than chassis vent area restrictions.

Based on this finding, Case C was performed whereby additional side venting (16 in^2 near the rear of the chassis) was included to determine its effect on total system flow. The increase in total system flow was substantial, 22 percent, and the change was recommended.

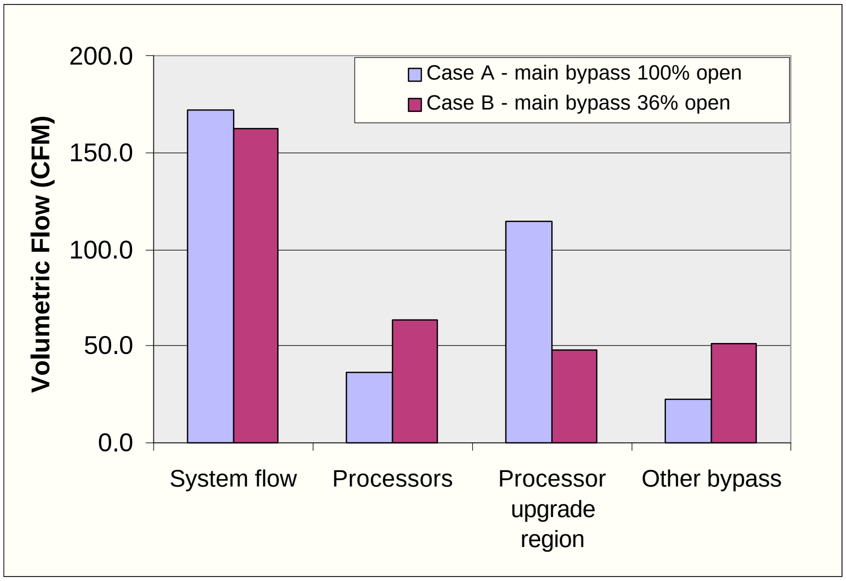

Figure 3 – Correction of flow imbalance between processors and the main bypass region

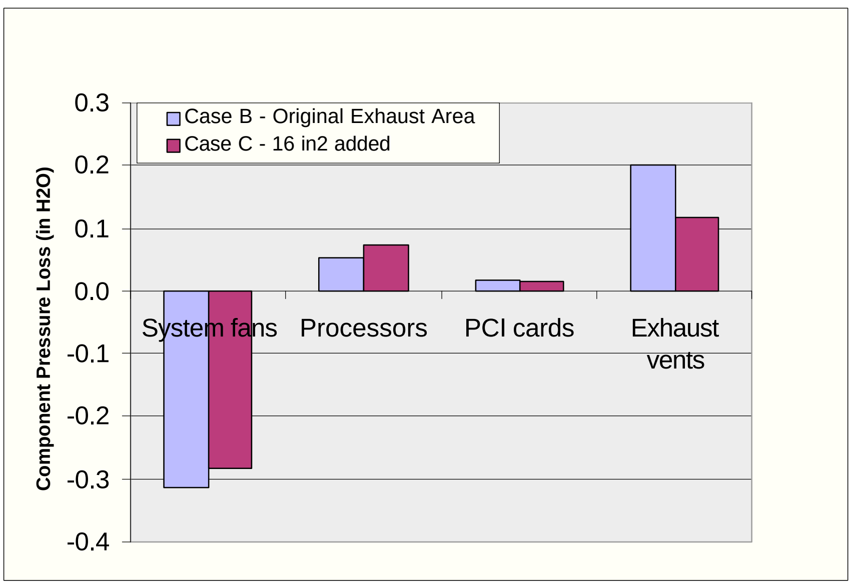

Figure 4 – Effect of the reduction of the flow impedance at system exhaust

As seen in Table 1, the processor flow improvement is dramatic and provides a compelling reason to make the modeled system changes.

Table 1 – Comparison of the processor and PCI-card flow rates for the three system modifications

Case	Description	Processor average (CFM)	PCI card 1 through 6 average (CFM)	PCI card 7 through 10 average (CFM)	Total System Flow (CFM)
A	100% open CPU bypass	9.0	9.2	9.6	172
B	36% open CPU bypass	15.8	8.8	8.9	162
C	36% open CPU bypass and 16 in^2 additional exhaust area	19.5	7.6	7.7	197

Selection of Air Moving Device (AMD), Although it appears that the subject server system provides more than adequate flow to all components, the analysis presented was for a redundant cooling configuration (six fans). The product was designed to provide the required flow under a single fan failure condition. Had this not been the case, smaller fans, which delivered less airflow (and less noise), could be used. Further the FNM analysis was repeated for five operating fans to ensure that all components received sufficient flow.

This highlights another benefit of the FNM model. System flow impedance can be characterized by using either fixed flow or fixed pressure sources at various input levels. Thereafter, proposed AMDs can be integrated in the model to characterize operating points and make an appropriate AMD selection. Unstable AMD operating regions or inappropriate AMD selections due to acoustic effects can easily be recognized and avoided.

Comparison with CFD Results, A CFD model of the server was created for comparing its predictions with the results of the FNM analysis. The CFD analysis required four hours for model construction, 5 hours for solution, and 3 hours for the intrepretation of the calculated results. Note that FNM analysis predicts only the total flow rate in each passage modeled while CFD analysis predicts the variation of the velocity in the various passages. Therefore, the CFD results were integrated to obtain the total flow rates calculated in the FNM analysis for a direct comparison of the results of the two analyses. Table 2 summarizes the comparison for the key system elements and shows that average FNM processor volumetric airflow is within 12 percent of that determined using the CFD model while average PCI volumetric flow is within 10 percent of that determined by the CFD model. Thus, the FNM analysis is seen to predict the average flow distributions at the same level of accuracy as that of the CFD analysis but, as seen in the next section, with an effort that is orders of magnitude smaller especially when multiple designs have to be analyzed.

Table 2 – Comparison of the flow distribution predicted using FNM and CFD for Case B

Model type	Processor average (CFM)	PCI card 1 through 6 average (CFM)	PCI card 7 through 10 average (CFM)	Total System Flow (CFM)
FNM model	15.8	8.8	8.9	162
CFD model	18.0	9.8	9.6	151

Productivity Gains due to FNM in the Design of the Air-Cooled Server, It is very important to note that the FNM analysis of the server system was quick. Specifically, the network construction for the base case required thirty minutes, solution for each case required less than one minute on a Pentium 2 200 and examination of results took fifteen minutes. Further, due to the component-oriented nature of the network representation, incorporation of changes in the system configuration and evaluation of their effects took minutes to perform.

The impact of the use of FNM early in the design cycle can be summarized as follows:

- Analysis time for each design was reduced dramatically relative to conventional CFD-based approach, thereby allowing comparative evaluation of many design changes in a rapid fashion.
- The server design was directed in the right direction through incorporation of beneficial system changes early in the design cycle. This prevented the possibility of allowing an undesirable system design to proceed to a stage where implementation of any changes would have been prohibitively costly.

USE OF FNM FOR THE DESIGN OF ELECTRONICS COOLING SYSTEMS

Benefits and Limitations of FNM

FNM offers a simple, quick, and accurate method for flow and thermal performance of electronics systems. Some of the benefits it offers for system-level thermal design are described below.

- *Evaluation of Competing Designs* – The strength of FNM is the analysis of system-wide interaction of individual components. Thus, thermal performance of competing physical layouts of the system can be evaluated very quickly and accurately through FNM analysis of corresponding flow networks involving different interconnections of the same set of system components.
- *New Concepts for Design Improvements* – FNM analysis of a system provides a clear overview of the flow and temperature distribution in the system. This is very useful not only in identifying the problem areas in the system but also in generating ideas for design improvements (e.g. incorporation of flow balancing elements, addition of backup fans). Further, benefits of these improvements can also be quickly evaluated.
- "*What If*" *Studies* – FNM analysis is ideally suited for determining the magnitude of the impact on system performance under "what if" and contingency scenarios (e.g. fan failure and rise in ambient temperature).
- *Complementary Use with CFD* – FNM and CFD complement and enhance each other. Thus, CFD can be used for accurate determination of characteristics of nonstandard components (e.g. complex heat sinks) for use in FNM analysis. Similarly, results of the FNM analysis of an entire system can be used to provide boundary conditions for a detailed analysis of part of a system (e.g. card array) using CFD. FNM also enables focused use of CFD for the analysis of the most feasible system layouts.

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. A detailed board-level thermal network or CFD analysis is necessary for this purpose.
- *Flow Resistances* – The accuracy of FNM results depends upon the validity of the flow resistance correlations employed.
- *Network Representation* – Flow network representations may not be accurate or even possible for systems in which the flow paths are not well defined. An example of such a system would be an externally cooled sealed cabinet that has large open spaces inside it. A network representation for the buoyancy driven flow inside such a system would be difficult to construct. Therefore, FNM analysis cannot be used when the flow system cannot be represented as a network of identifiable flow paths.

The Enhanced Produced Design Cycle

An enhanced design cycle that incorporates FNM in the early design stage, is shown in Figure 5 (Belady et al., 1999 and Kelkar et al., 1999). Use of FNM for Conceptual System Design significantly reduces the effort that is otherwise required for system-level thermal analysis. CFD can then be used in a focused manner for detailed analysis of flow distribution and component temperatures in critical parts of a system or in specific competing system designs. The proposed design cycle significantly shortens the time required for arriving at the final design and improves the quality of the product by enabling the thermal engineer to explore more design options. Thus, use of FNM improves the productivity in the thermal design process and results in an optimum design cycle.

CONCLUSIONS

The present study describes the technique of Flow Network Modeling (FNM) and its application for the design of an air-cooled server. The technique of FNM involves representation of the flow system as a network of flow paths and components for the prediction of system-wide flow and bulk temperature distribution. The FNM technique is very efficient in terms of the effort required for model definition, solution, and examination of results because it employs overall component characteristics for analyzing their system-wide interaction. Further, use of empirically measured component characteristics ensures good accuracy of the predicted flow distribution. Application of this technique for the design of an air-cooled server involved investigation of the flow distribution in different system layouts, generation of ideas for performance improvements based on predicted system-wide flow distribution, and evaluation of these modifications on the air-flow performance of the system. Use of FNM is shown to significantly reduce the time required for a comparative performance evaluation of different system configurations. Such rapid analysis enabled development of a good system design during the Conceptual Design Stage, before the design proceeded to a stage where changes are very costly to implement. An enhanced design cycle is outlined that uses FNM analysis during the early design stage for shortening the overall design process, enhancing the quality of the final design, and improving the productivity of the thermal design engineer in a significant manner.

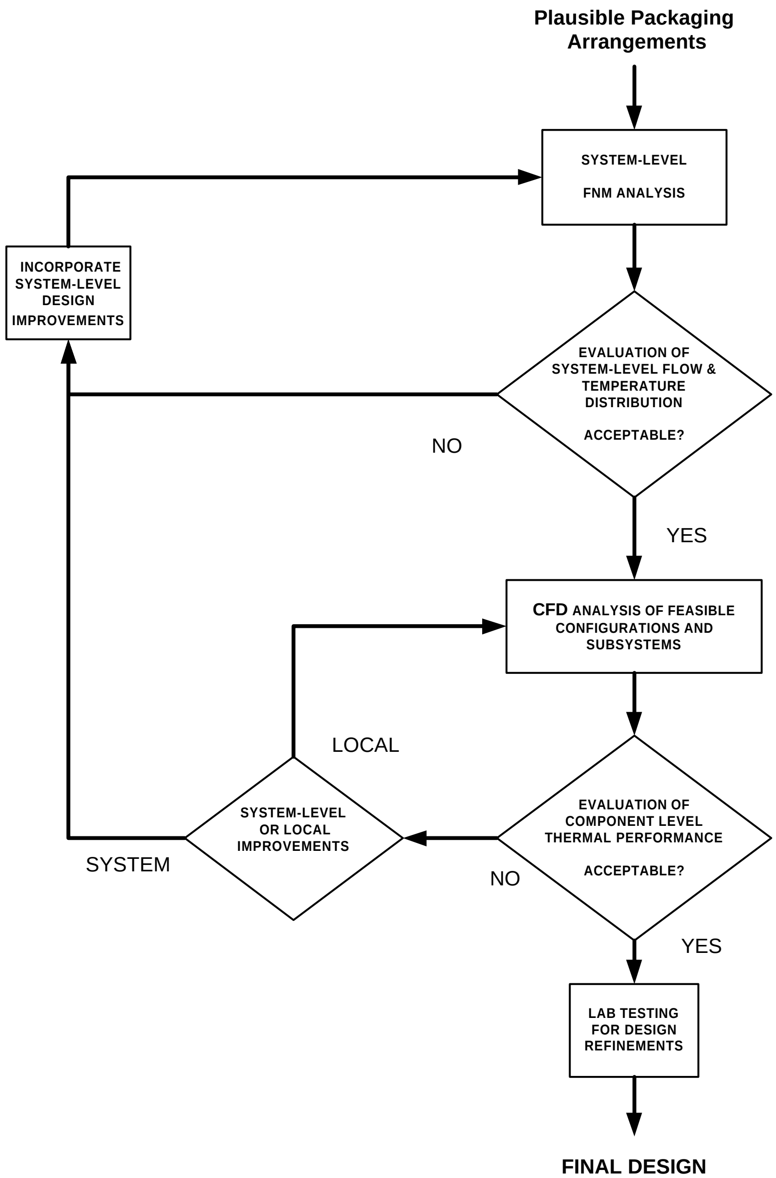

Figure 5 – The enhanced design cycle incorporating Flow Network Modeling (FNM) for system-level design

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