Use of Flow Network Modeling (FNM) for Enhancing the Design Process of Electronic Cooling Systems

Kanchan M. Kelkar, Amir Radmehr, Patrick J. Kelly, Suhas V. Patankar
Innovative Research, Inc.
Minneapolis, MN 55413
Phone: (612) 378-0320, Fax: (612) 378-0535, Email: kelkar@inres.com

Christian Belady
Hewlett-Packard
Richardson, TX 75080
Phone: (972) 497-4049, Fax: (972) 497-4245, Email: belady@rsn.hp.com

Abstract

This paper outlines the technique of Flow Network Modeling (FNM) for system-level thermal design of electronic devices. FNM is a generalized methodology involving representation of a cooling system as a network of components and flow paths for predicting systemwide distribution of flow rates, pressures, and temperatures. Performance of the individual components in the network is specified by overall flow and thermal characteristics. FNM analysis constitutes a simple, fast, and accurate technique for system-level thermal design because of it determines system performance based on overall component characteristics. Use of FNM has been illustrated for the prediction of the flow distribution in a fan-cooled cabinet with a centrally located card array. The case study demonstrates the simplicity and speed with which FNM allows investigation of the base design and its modification for obtaining uniform flow distribution in the passages within the card array.

Benefits of FNM include rapid and scientific evaluation of competing designs, generation of ideas for design improvements, performing "What If" studies, and complementary use with CFD. An enhanced design cycle that is significantly shorter than the conventional design process is proposed. It uses FNM for intelligent narrowing of the design options during system-level design, focused use of CFD for detailed design, and testing for refinement of the final design. It results in an optimum design process that improves the productivity of the thermal engineer and the quality of the final design.

Key Words: Flow Network Modeling, System-Level Thermal Design, Manifold Distribution

Introduction

With increasing power density and complexity of the electronic devices, appropriate cooling of the heat dissipating components is critical for reliable operation. Typically, thermal designers use either hand calculations or spreadsheets, and Computational Fluid Dynamics (CFD) analysis to predict flow and temperature distributions in the cooling systems to provide design guidance. Hand calculations are prone to error and their use is very limited. Spreadsheets are system-specific and are therefore inflexible for use in a generalized manner for system-level design. CFD analysis provides valuable information about the flow and temperature distribution throughout the system. Further, such analysis for an entire system can be time-intensive in terms of model definition, computation, and visualization of results. Further, such detail is not necessary for system-level thermal design and conceptual design during the early part of the design cycle.

A valuable technique for quick and accurate prediction systemwide flow distribution for use in the system-level thermal design is Flow Network Modeling (FNM). Traditional use of flow network analysis in the design of electronics cooling systems has been discussed by Ellison [1]. Detailed description of a generalized FNM methodology for the prediction of flow, pressure, and bulk temperature distributions in arbitrarily complex networks has been provided by Belady et al. [2]. This paper outlines the theory, illustrates the application of FNM for the design of an electronic cabinet, and discusses the productivity benefits obtained by incorporating FNM in the product design cycle.

An Overview of the FNM Technique

FNM is a generalized methodology for calculating systemwide distributions of flow rates, pressures, and temperatures in 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. Each constituent of the system is represented by overall flow and thermal characteristics. Solution of the mass, momentum, and energy conservation over the flow network provides the distribution of the flow rates, pressures, and temperatures throughout the system. Note that FNM employs overall component characteristics instead of attempting to calculate detailed flow and temperature distributions of within the component. As a result, it is very fast in terms model definition, solution, and data analysis.

Theoretical Basis of FNM

Components Characteristics

FNM requires specification of the overall flow and heat transfer characteristics of all the components in the network representation of the system for the prediction of the systemwide distributions of the flow rate and the bulk temperature of the coolant. The flow characteristics can be represented by the following equation:

$$\Delta p = K \frac{1}{2} r (Q / A)^{n} + \frac{B}{Re} \qquad (1)$$

The first and second terms on the right hand side account for the losses in the laminar and turbulent regimes respectively. The typical value of the exponent n for turbulent flow is 2. The minor loss coefficients for standard components (screens, ducts, piping system components, etc.) are available in handbooks such as Idelchik [3] and Blevins [4]. For card arrays, the loss coefficient can be determined using the Moody chart [3, 4] with corrections applied to account for the blockage effects of heat sinks and electronic components. For components such as power supplies and heat exchangers, component characteristics can be obtained from supplier data, CFD analysis, or laboratory testing.

Change in the bulk temperature across a component is calculated by specifying the heat dissipated in that component. Further, the average surface temperature of the component is determined from the surface heat transfer coefficient. The following form of empirical correlations that relate Nusselt number (dimensionless heat transfer coefficient) to the Reynolds number and the Prandtl number are used for this purpose.

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

Discretization and Solution of the Conservation Equations

Prediction of the flow rates, pressures, and temperatures over the system require solution of the mass, momentum, and energy conservation equations. The flow characteristics represented in Eq. (1) constitute the momentum equations for each flow path. Mass conservation is imposed at each junction in the flow network. It has the following form with the sum carried out over all the flow paths that meet at the junction under consideration.

$$\sum_{l=1}^{n} r Q = 0 \qquad (3)$$

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 discretized momentum, mass, and energy conservation equations are solved using the SIMPLE algorithm of Patankar [5]. The resulting algorithm is fast and robust. Further details of the discretization technique and the solution algorithm are provided by Belady et al. [2].

Illustrative Application for an Electronic Cabinet

The FNM methodology has been applied for the prediction of flow distribution in an air-cooled cabinet. Analysis has been carried out using a commercially available program MacroFlow [6].

The Physical System

The electronic cabinet analyzed in the present study is shown in Fig. 1. The physical layout of the cards is representative of card rack systems. It involves a manifold flow distribution encountered in a variety of industrial applications such as industrial VME-based microcomputers and avionics systems. The physical system consists of a box with a centrally located card array and a fan tray located at the bottom left face for creating flow the throughflow of air. The flow through the screened inlet is in a direction perpendicular to the passages between the cards. After flowing through the card rack, the air leaves through the top surface of the cabinet. For simplicity, the cards are assumed to be equally spaced. The relevant geometrical dimensions are indicated in Fig. 1 in centimeters. The fan is assumed to be Rotron-MajorAC-MR2B3. This fan provides a maximum head of 0.8 inches of water and a maximum flow rate of 240 CFM. The screened inlet and exit have 50% open area. Flow distribution has been calculated for air with atmospheric conditions of 1 atm and 27°C.

It is well known that a manifold design gives rise to a very nonuniform flow distribution in the card array. Therefore, design modifications are often sought to improve the flow distribution. For this purpose, two variations of the physical system are considered in this study. In the first design (Design I), the bottom passage has a constant cross-section while the second design (Design II) includes a taper to the bottom wall (angle of 18°) to create a bottom passage that has a decreasing cross section. The focus of the application is to illustrate the calculation of the flow distribution. Therefore, calculation of the temperature distribution is not considered in this study.

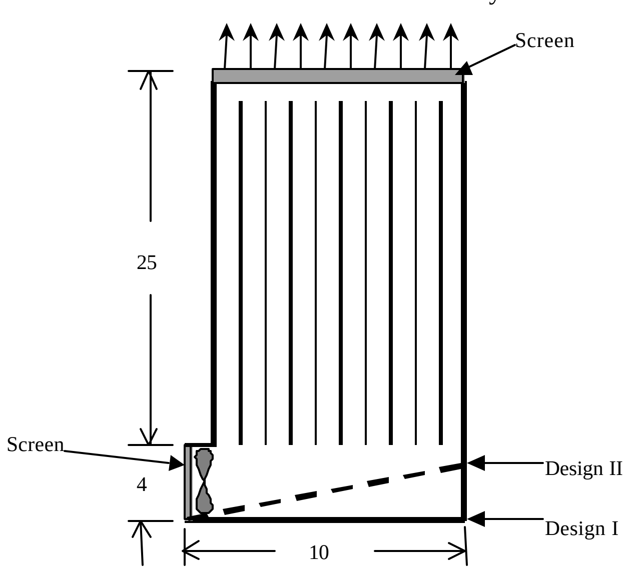

Figure 1 – Layout of the electronic cabinet

Network Representation

The network representation of the physical system is shown in Fig. 2. The flow network directly corresponds to the physical layout of the system. Each card passage is represented by a duct of appropriate rectangular cross-section and flow length. The tee junctions at the bottom of each of the card passage account for the flow inertia in predicting the bifurcation of the flow stream in the bottom passage. These flow streams meet in a plenum above the card array and exit through the screen. The topology of the network distribution is the same for both designs. The only difference for the second design corresponds to the specification of a progressively decreasing cross-section of the duct segments between the tee junctions. The losses in the various ducts (bottom duct segments and card passages) are calculated using the Moody chart while the losses in screened inlet and exhaust and the tee junction are calculated from appropriate correlation in various handbooks (e.g. [3],[4]).

Results

The predicted flow directions are shown by arrows on the network in Figure 2. The direction of the flow in various passages is the same in two designs. Figures 3 and 4 show volumetric flow rate in the card passages for the two designs. For Design I, majority of the flow goes through the farthest three passages because of the inertia of the inlet flow. Note that, for this situation, the static pressure at the bottom of the card passage increases continuously away from main inlet. When the bottom wall is tapered, the decrease in the flow rate (increase in the pressure) caused by the bleeding of the main flow into the successive card passages is compensated by the decrease in the area of the bottom channel. This keeps the velocity (and hence static pressure) at the bottom of each card passage to be approximately the same. Since the flow in a card passage is governed by the drop of static pressure across it, the distribution of the flow in the card passages is relatively uniform. The maldistribution of flow in a manifold design and the corresponding improvement in the flow distribution are consistent with the analysis of simple manifolds presented by Blevins [4]. Note that, the solution of the conservation equations in the FNM analysis allows characterization of the system impedence. Thus, the overall flow rate in the system is determined by the balance between the system impedence and the fan characteristics.

It is of interest to note that the FNM analysis of the cabinet for Design I required only 1 hour for model setup, 30 seconds for calculation, and 10

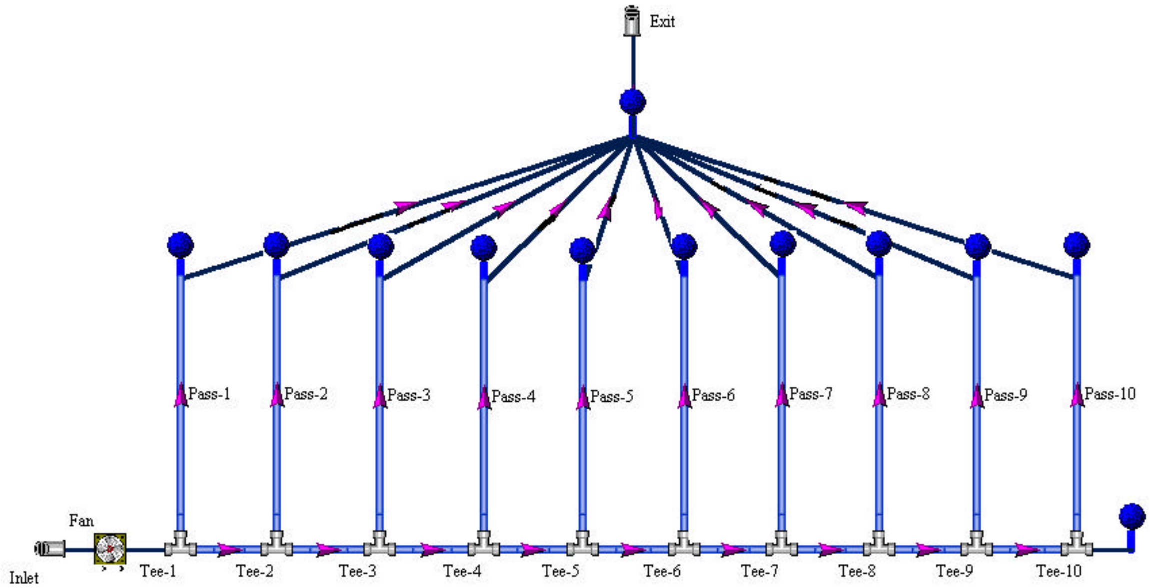

Figure 2 – Flow network representation of the electronic cabinet

minutes for examination of the results. Further, investigation of the modification of the base required an additional 15 minutes. Thus, FNM analysis is extremely efficient. It is also accurate because of the correlations used in the analysis are empirically determined. This example illustrates the simplicity, speed, and utility of FNM technique for system-level thermal design.

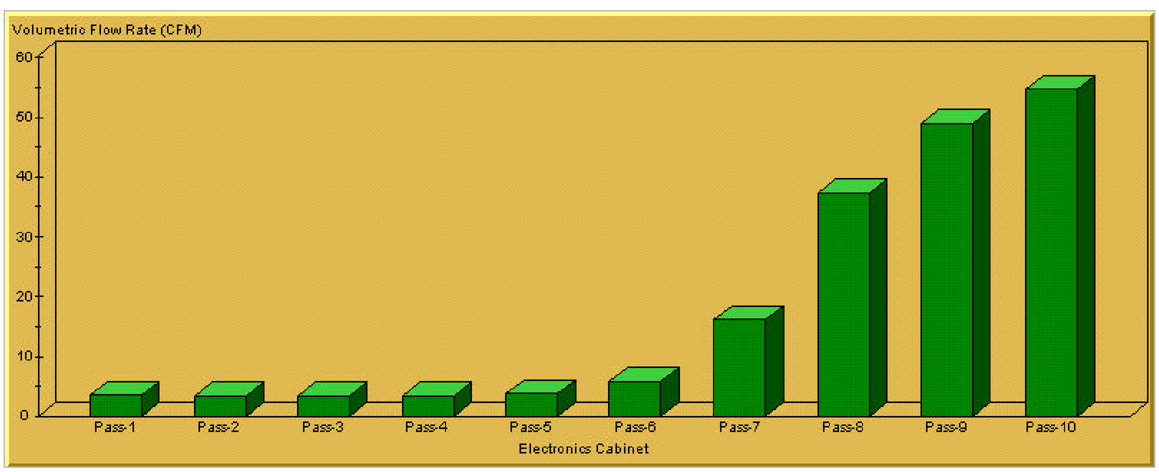

Figure 3. Volumetric flow rate through card passages for Design I

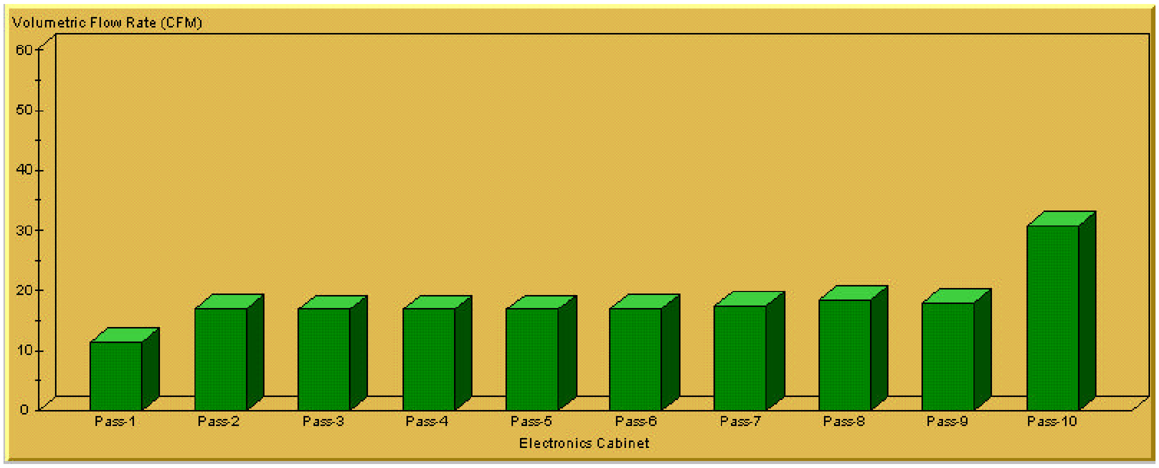

Figure 4. Volumetric flow rate through card passages for Design II

The Enhanced Design Cycle

The design of electronics cooling systems is an evolutionary process that proceeds through three discernible stages – Conceptual and System Design, Detailed Design, and Design Verification as described by Kang [8]. A good layout of the system package needs to be developed at the end of the system-level design stage because any changes in the design later in the cycle are very costly. Therefore, a quick and simple analysis procedure that allows evaluation of the airflow performance of various design options in a scientific manner is necessary to support the rapid evolution of the system. FNM fulfills this need for quick and scientific analysis required for system-level thermal design.

The benefits of FNM for system-level design include rapid and accurate evaluation of thermal feasibility of a large number of design options, identification of performance limiting areas of the system and development of strategies for design improvement, investigation of contingency scenarios and "what If" studies, and complementary use with CFD. Based on these benefits, an enhanced design cycle has been proposed by Belady et al. [2] which is reproduced in Fig. 5. Use of FNM for system-level and conceptual 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 fewer systems. The proposed design cycle significantly shortens the time required for arriving at the final design and improves the quality of the product by enabling 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.

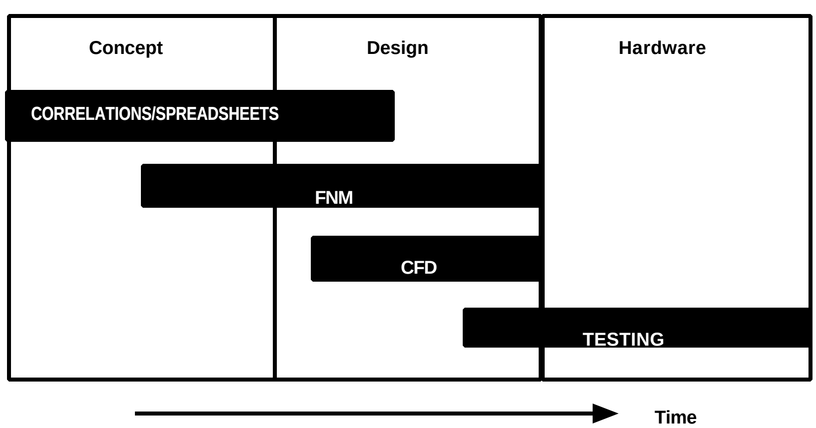

Figure 5. An enhanced Design Cycle

Conclusions

This paper outlines the theory and the use of Flow Network Modeling (FNM) technique for the system-level thermal design electronics systems. FNM involves representation of a cooling system as a flow network consisting of flow paths through various components of the system. It uses flow and thermal characteristics of the individual components and applies momentum, mass, and energy conservation to predict the flow, pressure, and temperature distribution over the entire system. Because of the use of accurate overall component characteristics, FNM analysis is simple, fast, and accurate. The paper illustrates the use of FNM for the analysis of flow distribution in an air-cooled electronic cabinet containing a card rack. Two designs have been studies – a base design and its modification that includes the tapering of the bottom wall. FNM allows efficient analysis of the flow distribution in the two designs for rapid and scientific investigation of the effect of a design modification on the flow performance of the system.

The FNM approach offers significant benefits for system-level and conceptual design of the electronics systems. These include rapid evaluation of various system layouts for intelligent narrowing of design choices, investigation of "what if" scenarios, identification of performance limiting components or parts of the system and ideas for design improvements, and focused use of Computational Fluid Dynamics analysis during thermal design. These benefits suggest the adoption of an enhanced design cycle - FNM for system-level and conceptual thermal design, CFD for detailed design, and laboratory testing for design refinement to arrive at a final design. The use of FNM significantly shortens the design cycle, allows the designer to investigate wider design options, and thereby optimizes the design process through improved productivity and product quality.

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