ANALYSIS OF FLOW DISTRIBUTION IN A POWER SUPPLY USING FLOW NETWORK MODELING (FNM)

Gamal Refai-Ahmed
ASTEC APS
185 Corkstown Road, Nepean
Ontario, Canada K2H 8V4
gamal@nortelnetworks.com

Amir Radmehr, Kanchan M. Kelkar
Innovative research, Inc.
3025 Harbor Lane North, Suite 300
Plymouth, MN 55447
radmehr@inres.com, kelkar@inres.com

ABSTRACT

This paper presents an analysis of flow distribution in a new-generation power supply used in telecommunication applications. The power supply involves several boards, each containing several magnetic components, EMI screens, and heat sinks, arranged in a rack. The flow in each passage is driven by four suitably placed fans.

The study utilizes the technique of Flow Network Modeling (FNM) for efficient prediction of the flow distribution in the power supply system. The novelty of the study lies in the use of a two-level flow network approach to achieve modularity and gain further efficiencies in the analysis of flow distribution. A flow network model of a passage formed by two successive boards is first constructed to determine the characteristics that describe the behavior of the flow in and out of an individual power supply. Two types of flow characteristics, namely resistive and pumping, are outlined and used for constructing these equivalent compact characteristics of the power supply. Network model for the overall system is then constructed by arranging the compact models for each passage in a manifold arrangement corresponding to the physical arrangement in the rack. Analysis is carried out for three placements of cabinets, namely a isolated cabinet, two cabinets side by side, and three or more cabinets side by side. Results of analysis show that for a single cabinet, the flow is uniformly distributed among the passages because of the presence of side vents. However, with multiple cabinets placed side-by-side, the forward flow streams from individual passages are forced to merge in the header passage at the back of the cabinet. The resulting combining manifold gives rise to a maldistribution of flow among the passages with lower flow rate in the bottom passages. The two-level network modeling approach outlined in this study is very efficient in terms of the time required for model definition, analysis, and examination of results. The modularity of the approach is well suited for a top-down design and packaging of large scale electronics systems for achieving the desired thermal performance.

KEY WORDS: Power Supply, Thermal Design, Flow Distribution, Flow Network Modeling,

INTRODUCTION

The ever-increasing demand for bandwidth has resulted in rapid advances in telecommunications technology and its large-scale deployment for improving the telecommunications infrastructure. An important element in the development of the new generation of the telecommunication equipment is the power supply system. Traditionally, thermal design of power supply equipment has not received sufficient attention. However, it is anticipated that the new generation of power equipment will be smaller in size and will dissipate 5-10 times the heat as compared to the existing equipment. Therefore, thermal design becomes an important aspect in the packaging of such equipment for ensuring reliable performance.

Power supply equipment is typically cooled using forced flow. Packaging of such equipment should be carried out in a manner, which ensures that sufficient cooling flow is provided for critical components such as diodes. Typically, thermal designers use either hand calculations or spreadsheets, and Computational Fluid Dynamics (CFD) analysis to predict flow and temperature distributions for providing 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. Although CFD analysis provides detailed information about the flow and temperature distribution throughout the system, such analysis for an entire system is time-intensive in terms of model definition, computation, and visualization of results. More importantly, 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 prediction of system wide 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]. A generalization of this technique has been proposed by Belady et al. [2]. The FNM technique is particularly well-suited for conceptual system design where different system layouts are explored. The simplicity, speed, and accuracy of the FNM technique allow intelligent selection of the feasible system-level designs in a rapid fashion. (Steinbrecher et al. [3]).

The power supply cabinet analyzed in the present study involves boards with electronic components mounted in a rack arrangement. The resulting system is large and involves complex flow patterns. The present study proposes the use of a two-level FNM approach for the analysis of airflow distribution in the power supply cabinet. This cabinet has 20 identical boards arranged in a stacked manner forming 20 identical flow passages. Detailed flow network model of a single passage is first constructed. The model includes multiple air movers and multiple air passage resistances and interconnects. The detailed model is then used to formulate an equivalent compact model of the flow passage. The compact models are then assembled to construct a model of the complete rack. Therefore, the use of a two-level approach enables further efficiency during the analysis and is consistent with a modular approach for the packaging of the power supply system.

THE TECHNIQUE OF FLOW NETWORK MODELING (FNM)

A brief description of the FNM technique is provided in this section for completeness. More details of this methodology are described by Belady et al. [2] and Steinbrecher et al. [3].

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. 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. The set of discrete equations for the network is solved using the SIMPLE algorithm of Patankar [4]. The resulting algorithm for the prediction of flow rates, pressures, and temperatures over a flow network is fast and robust.

Overall flow characteristics of standard components such as ducts, screens, and bends can be obtained from handbooks by Idelchik [5] and Blevins [6]. For nonstandard components supplier data, CFD analysis, or test data can be used to get the flow characteristics. Empirical correlations are also used for heat transfer coefficients needed in determining the heat losses or surface temperatures. 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 assures that predictions of the system performance obtained from FNM analysis are accurate over wide range of operating conditions. The strength of FNM

Detailed analysis and testing can then be carried out only for a few design alternatives. Thus, use of FNM in the early design cycle significantly shortens the overall design cycle

is its ability to analyze system-wide interaction of the individual components in a rapid and accurate manner.

PHYSICAL SYSTEM CONSIDERED

The present study analyzes a power supply used in telecommunications applications. The proposed system is expected to occupy less foot print space in the telecommunication room in comparison to the existing system. It consists of twenty boards arranged in a rack fashion. Each board contains several magnetic components, EMI screens, heat sinks. The flow through each passage is driven by four fans placed in front of the heat sinks. The flow enters each passage through the fans and is discharged at the back of the passage. Merging flow streams from individual cards form a combining manifold arrangement at the back of the cabinet. Note that the flow can also come out from the openings between the fans at the front of the passage. The dimensions of the system cabinet are 20×12×65 inches and the total power dissipation is approximately 6 kW. This system is designed to be installed about 2 inches away from the wall. Figure 1 shows the schematic diagram of a single board and Fig. 2 shows arrangement of multiple power supply in the cabinet. The three different placements of the cabinets analyzed in the present study are shown in Figure 3. Case A shows an isolated cabinet, Case B shows two cabinets placed adjacent to each other, while in Case C, a large number of cabinets are placed adjacent to each other. Note that Cases A and C represent the extreme configurations in terms of the flow distribution in the cabinets.

The flow through each passage is affected by the flow impedances within the passage and the interaction of the flow streams from the individual passages. The packaging of the cabinet involves design issues such as placement of the components on the individual boards, separation between the boards, and sizing of the fans to ensure sufficient overall flow through each passage and through the individual heat sinks in each passage.

In the present study, a commercially available program MacroFlow [7], that incorporates the FNM technique described in the previous section is used for analysis of the flow distribution within the cabinet.

DETAILS OF THE FLOW NETWORK MODEL

Motivation for the Use of a Two-Level Network Model Approach

As described before, the power supply consists of several passages in a stack arrangement. Further, the flow in each passage of the rack involves multiple streams and is complex. A single flow network model of the entire system involving detailed models of each passage can be constructed and there is no inherent difficulty in its solution for determining the flow distribution over the entire system. However, for a system with many passages, such a model can be large in size and involve unnecessary details for evaluation of system-level design changes. Instead, a two-level approach is used to achieve computational efficiency. First, an equivalent condensed model of a typical passage containing multiple fans, heat sinks, and outlets is constructed. Such a model describes the flow characteristics of the passage succinctly in terms of the relationships between the net pressure change across the passage and the flow rates of outflow streams through the front and back of the passage. The network model of the entire system is then constructed by using the compact models to represent the behavior of the individual passages. Note that the two-level approach will provide results identical to an analysis that involves use of a single flow network of the entire system containing a detailed network representation of the individual passages.

The two-level approach is very modular in nature and results in a system-model that is succinct. It offers several advantages over a single detailed model for the entire system. This approach allows the use of a top-down design methodology where larger scale design issues, e.g. relative arrangement of the racks, constraints on the performance of individual racks, or ducting for the system, can be first tackled. Also, construction of the network models for alternative overall arrangements and their solution is very efficient since such models involve fewer components. Further, using the network model for a single passage alone, the arrangement of components on an individual board can be optimized to obtain the desired cooling. The two-level approach proposed in this study is very general and is applicable to modeling of any large system.

<u>Network Model and Characterization of a Single Passage</u>. The network model of a passage has two purposes - to predict the flow distribution through various parts of the passage and to determine the flow characteristics of the power supply for use in the global system model.

The network model for the passage between successive boards is constructed by graphically describing the paths followed by the air as it travels from the front to the back of the board. Figure 4 shows the flow network model for the passage between the successive boards. The air is pushed into the passage by four fans. The fans are in-line with the downstream heat sinks. The base of Heat Sink 1 is horizontal and the flow created by Fan 1 goes entirely through the heat sink. Therefore, there is no bypass area for the incoming flow stream. However, bases of heat sinks 2,3 and 4 are vertical and flow jets issuing from the fans can bypass these heat sinks. Therefore, there are bypass passages around these heat sinks. Note that the flow can enter into or exit from the large volume between the heat sinks 3 and 4. The corresponding network description in this region allows for the possibility of forward or reverse flow. The flow streams going through and around the heat sinks pass through screens and discharge into the header passage at the back of the stack. The pressure in this passage is assumed to be uniform and is represented by a specified pressure node.

For a given pressure at the inlet, the fan characteristics, and the back pressure, the network model predicts the flow distribution throughout the passage. In order to determine the overall flow characteristics of a passage, it is necessary to identify the form (resistive or pumping) of characteristics, and the pressure drop and flow rates that go into determining these relationships. For an individual passage, there are two output flow streams – the flow that discharges into the back of the passage (forward flow streams) and the flow that exits from the front of the passage (reverse flow streams). These flow rates depend upon the pressure at the back of the passage and the corresponding overall flow characteristics are constructed in the following manner.

- Forward Flow Characteristics – The forward flow rate results from the interaction of the pumping provided by the fan, the pressure change between the inlet ambient pressure and the back pressure, and the resistances encountered by the forward flow streams. Because of the presence of the fan, the forward flow is present even when the back pressure is higher than the ambient pressure. Thus, the forward flow characteristics are similar to a fan or a pumping characteristics in which the pressure head across the channel decreases with the forward flow rate and they represent the pumping actions of all the fans in the passage in a lumped manner. The resulting forward flow characteristics are determined by running the network model for different values of the back pressure and is shown in Fig. 5.
- Reverse Flow Characteristics – The reverse flow results due to the difference between the back pressure and the ambient pressure. Thus, the resulting flow characteristics are resistive in nature and are shown in Fig. 6. The reverse flow characteristics represent the lumped behavior of the outflow streams that issue from the openings between the fans in the front plane of the passages.

In summary, a single passage is represented by two independent flow characteristics – the forward flow characteristics that behaves like a fan curve and the reverse flow characteristics that is effectively a flow impedance.

<u>Global Network Model of the System</u>. A network model of the complete system is constructed by using the overall characteristics for each passage in the rack and representing the merging of the forward flow streams at the back of the system using a manifold arrangement. Note that the design of the power supply rack is such that each passage also has opening on lateral surfaces. Therefore, for a power supply cabinet placed in isolation, the air flow can discharge into the back of the passage or vent directly to the atmosphere through these openings. The network model for such a system is shown in Figure 7. Note that each passage is represented by two parallel flow paths, one containing a fan possessing the forward flow characteristics and the other containing the resistance characteristics for the reverse flow stream. The tee-junctions represent the merging of the flow streams in the header passage at the back of the system. The flow from the header passage exits to the environment at the top of the system.

In the present study, three placements of the cabinets have also been analyzed – single cabinet in isolation, two cabinets placed adjacent to each other, and a large number of cabinets placed next to each other. When two cabinets are placed next to each other, a passage in each cabinet has only one lateral vent instead of the two vents shown in Fig. 7. If a large number of cabinets are adjacent to each other, impedance for lateral flow is very large. Such a system is modeled by eliminating the side flow paths and the cooling air exits through the top of the system after merging at the back of the cabinet.

The two-level network modeling approach is used to predict the flow distribution throughout the system. First, the overall network model predicts the total forward and backward flows, and the back pressure for each passage. The details of the flow distribution within any passage is then obtained by using the back pressure for that passage as a boundary condition in the network model of a single passage. The two-level flow network analysis of the power supply is very efficient in terms of model construction and analysis. Construction of the model for a passage and determination of the overall characteristics required less than 2 hours. Network model for the entire system is very simple and required only a few minutes for its construction and less than a minute for solution.

Figures 8, 9, and 10 show the flow rates of the forward and reverse flow respectively in all the modules for the three placements of the cabinet. For the single cabinet, presence of side vents reduces the overall impedance for forward flow. Further, although not reported in the paper, a large portion of the flow entering each passage leaves through the side vents because it is the path of least resistance. Thus, the effect of the combining manifold at the rear of the cabinet is very weak and all passages have about the same amount of flow rate for the forward stream. Note that the static pressure in the back header decreases from the bottom to the top of cabinet because of the gradual merging of the flow streams. Since the back flow is proportional to the static pressure at the back of the cabinet, it decreases from the bottom to the top of the cabinet.

For the two-cabinet arrangement, a smaller portion of the forward flow escapes through the vent on the lateral surface and the effect of combining of the streams from the individual passages is discernible. Thus, the forward flow increases and the reverse flow decreases from the bottom to the top of the cabinet. With several cabinets placed adjacent to each other, the forward flow streams cannot escape sideways and have to combine in the header at the back of the cabinet before exiting from the top. Thus, the effect of this combining manifold at the back governs the forward and reverse flow distributions. Thus, the forward flow is smallest and the reverse flow is highest at the bottom because the back pressure is the highest at the bottom. Further, relative to the single or two-cabinet arrangement, the amount of the forward flow is smaller due to an increase in the overall impedance caused by the absence of the vents. Although detailed measurements have not been performed for the flow distribution in the cabinets, the qualitative behavior of the forward and reverse airflow rates and the effect of cabinet placement on these distributions predicted from the model are consistent with empirical observations.

Figure 11 shows the flow rates through the four heat sinks for the bottom passage for a single cabinet arrangement. Based on the knowledge of the flow rate through each heat sink in combination with the heat sink geometry, material, and the heat supplied allows determination of the heat transfer coefficient and hence the base temperature of the heat sink. However, in the present study the focus is on the prediction of the flow distribution within the system and prediction of the temperature field is not attempted.

CONCLUSION

This paper uses the technique of Flow Network Modeling (FNM) for the prediction of the flow distribution in a large power supply system used in telecommunications. The power supply consists of a large number of identical boards arranged in a rack with flow in each passage driven by four fans. A two-level approach is proposed for efficient modeling of the flow distribution in this system. A combination of two qualitatively distinct flow characteristics, namely pumping and resistive, are utilized for the construction of the overall characteristics of a flow passage. These characteristics are, in turn, used to construct the network model of the entire system. Analysis is carried out for two extreme placement scenarios of the cabinets – an isolated cabinet, and two or several cabinets placed adjacent to each other. Flow network analysis, in combination with the two-level approach, is computationally very efficient in terms of model definition and computational time.

Results of analysis show that for an isolated cabinet, the cooling flow is almost the same for all passages. However, with a large number of cabinets, the combining manifold situation created at the back of the cabinet gives rise to a significant variation in the cooling flow in the passages, with the bottom passage having the least flow through it. The trends predicted in the variation of the flow rate among the passages and the effects of cabinet placement on this variation are consistent with qualitative behavior observed in initial laboratory testing. The two-level network modeling approach presented in this study is very general in nature and is very useful for efficient and modular design of cooling strategies for of complex electronics systems.

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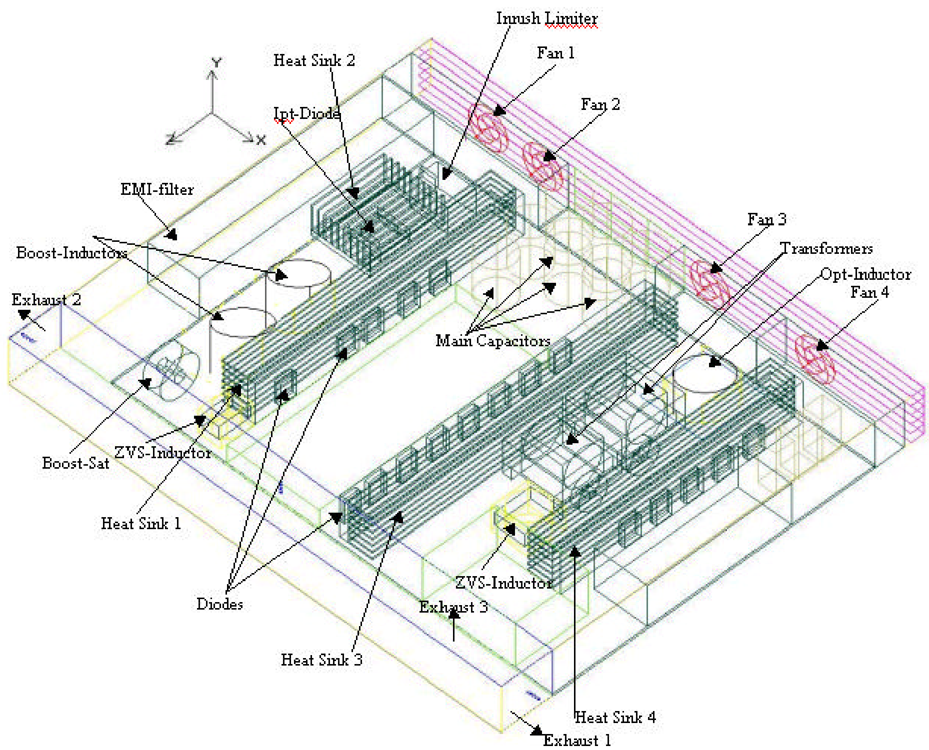


Figure 1. Schematic diagram showing the arrangements of components on a single board

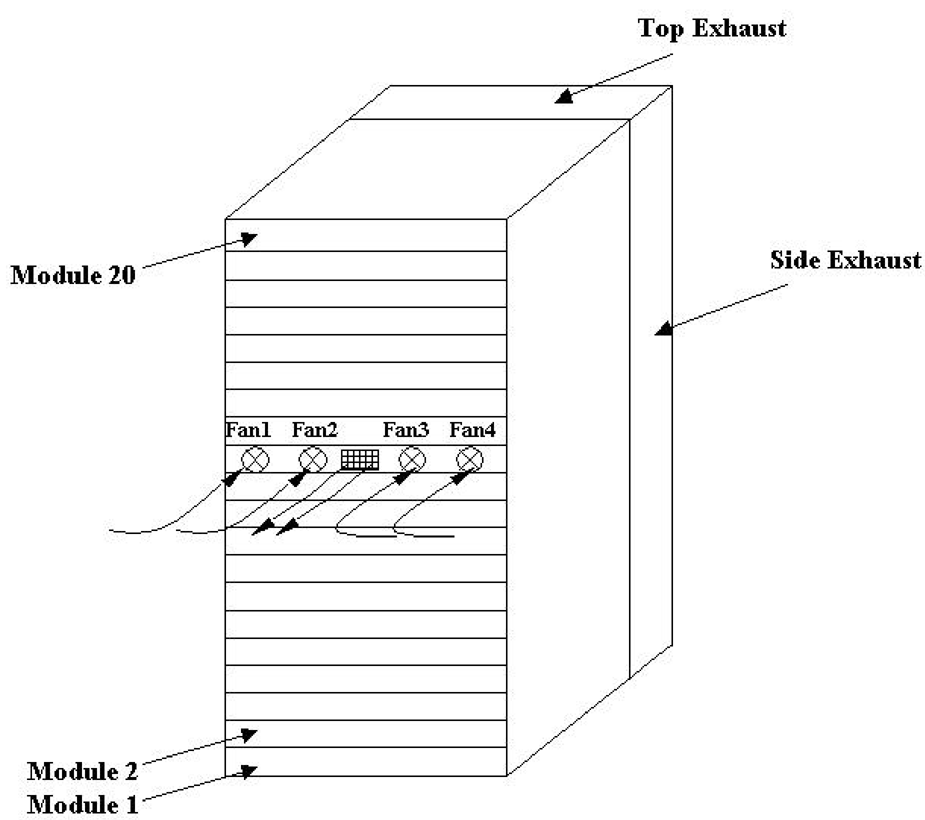
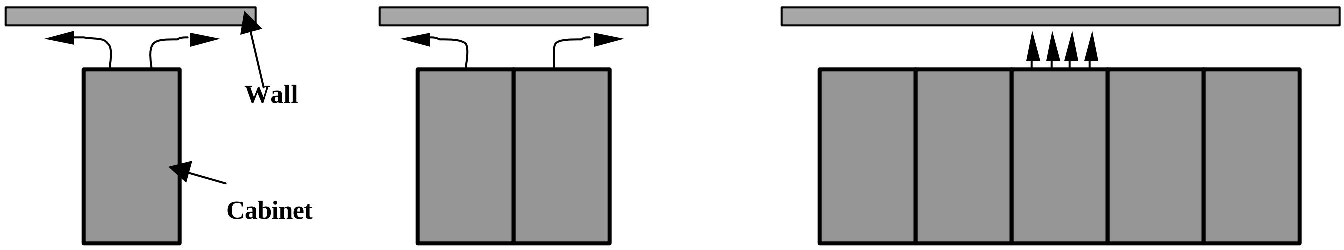


Figure 2. Schematic diagram showing the arrangements of the boards in the power system cabinet.



(A) (B) (C)

Figure 3. Three different placements of the power system cabinets analyzed in the present study
(A) Single cabinet (B) Two cabinets (C) Several cabinets

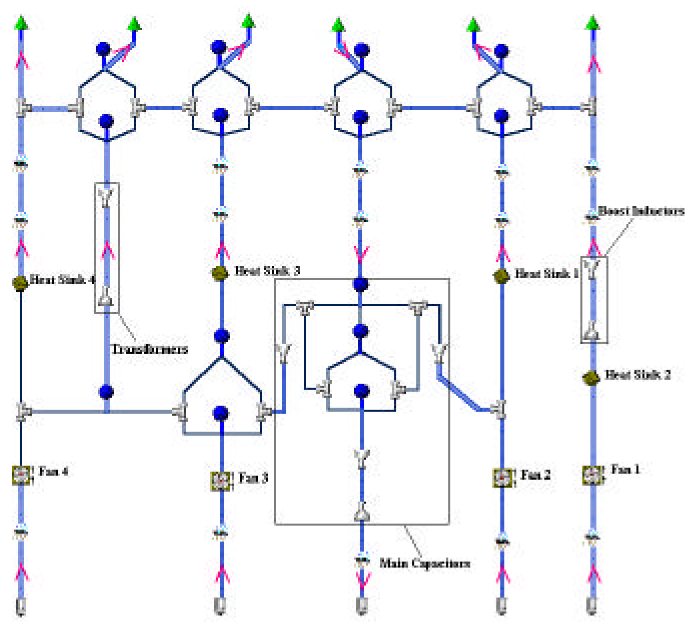


Figure 4. Flow network model for a single passage

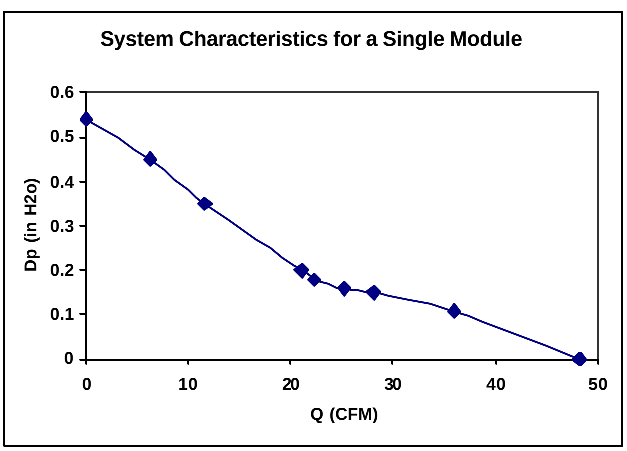


Figure 5. Pumping-type overall characteristics for the forward flow through a passage

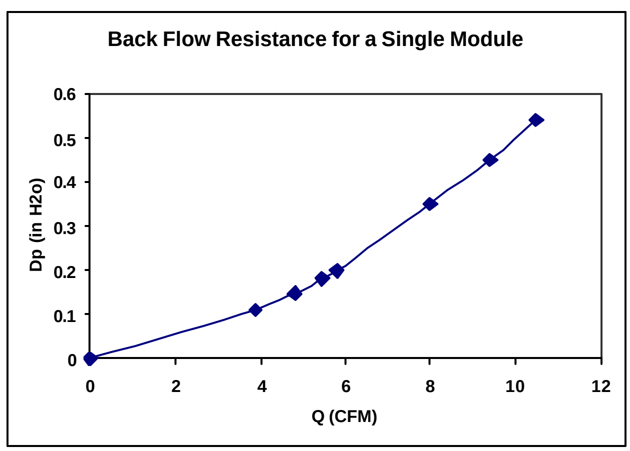


Figure 6. Resistive-type overall characteristics for the reverse flow.

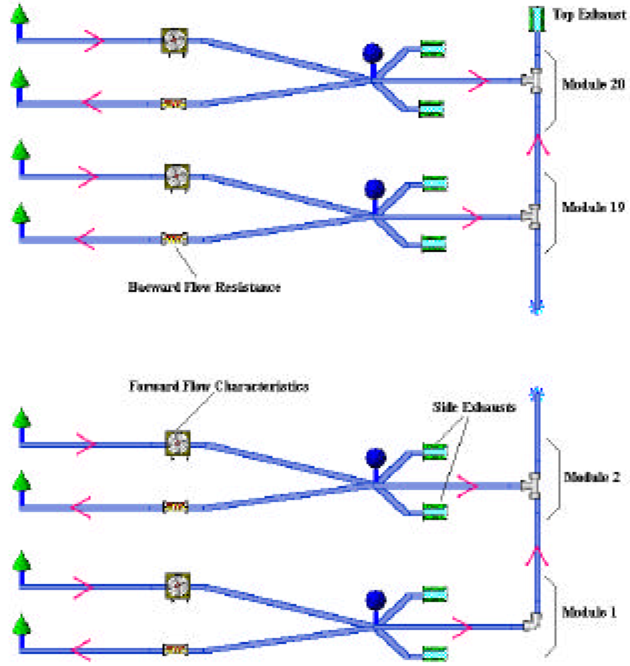
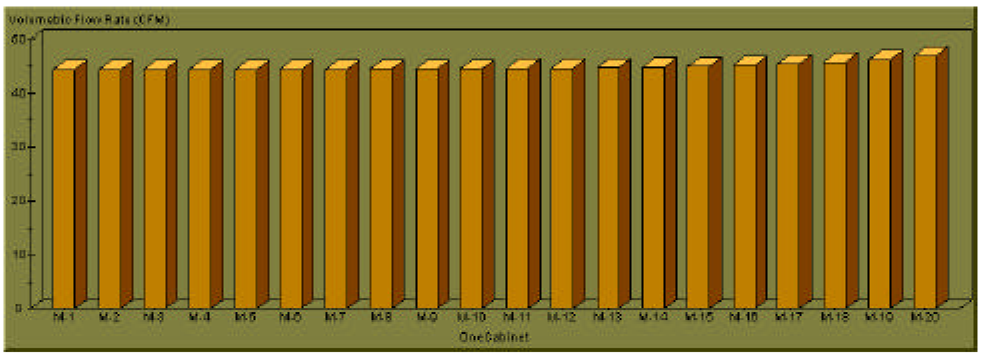
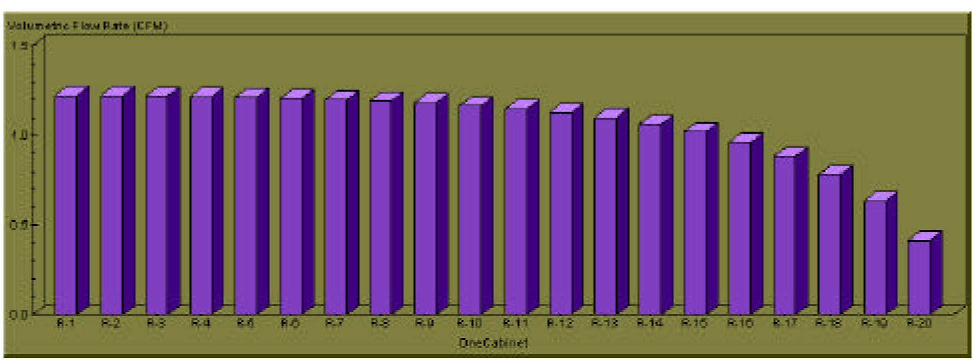


Figure 7. Flow network model for the entire system.

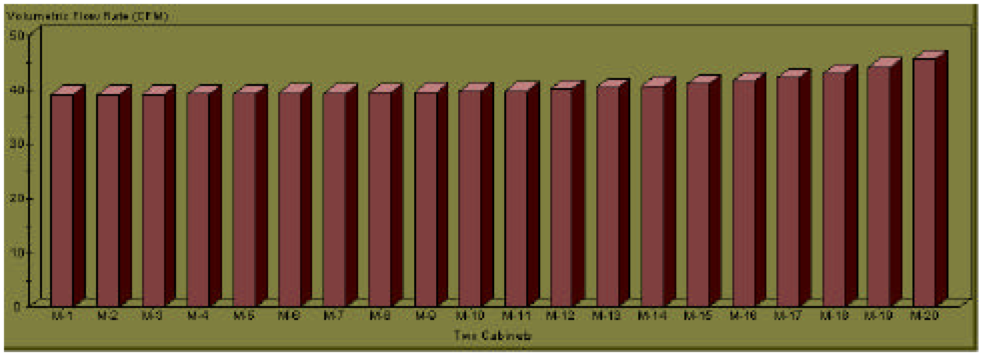


(a)

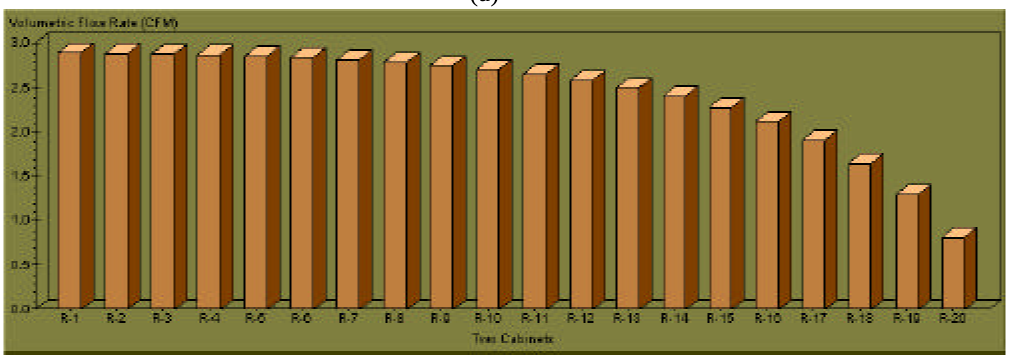


(b)

Figure 8. Variation of the (a) forward and (b) reverse flow through individual passages in a single cabinet.

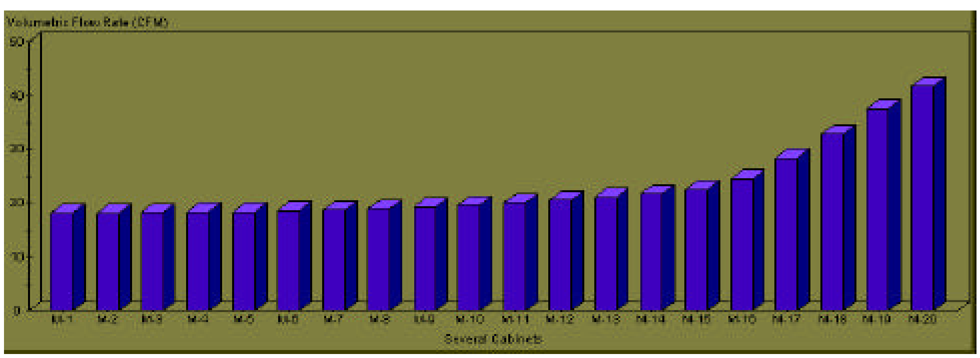


(a)

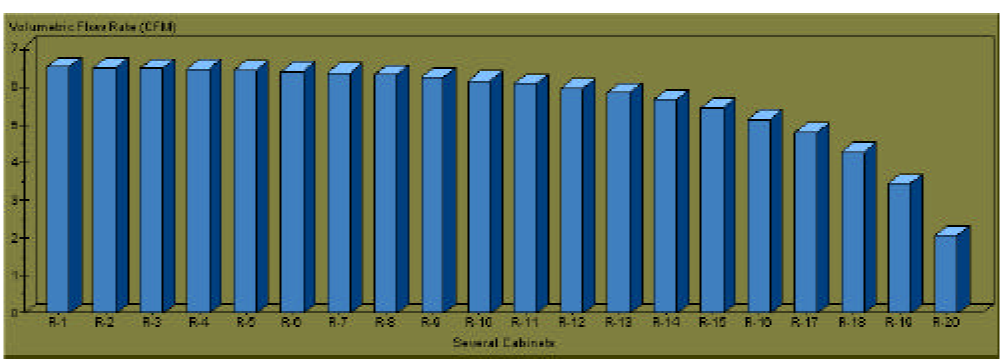


(b)

Figure 9. Variation of the (a) forward and (b) reverse flow through individual passages for two cabinets placed adjacent to each other.



(a)



(b)

Figure 10. Variation of the forward and reverse flow through individual passages for several cabinets placed adjacent to each other.

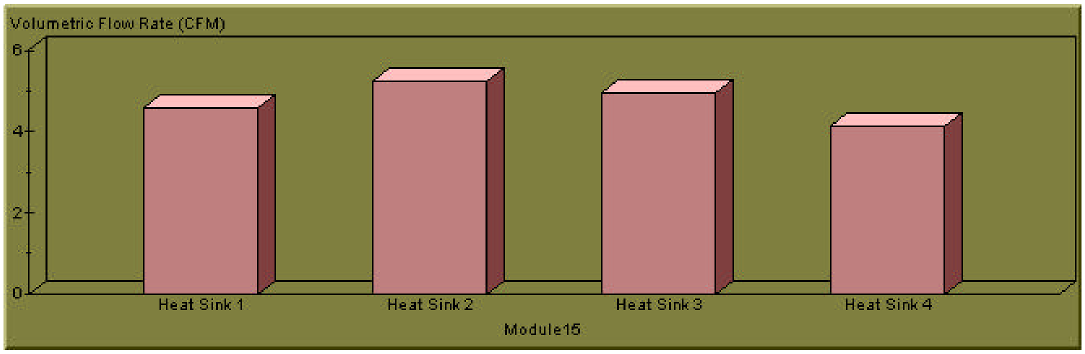


Figure 11. Flow rates through the heat sinks in 15th passage (out of 20) for an isolated cabinet.