Use of Flow Network Modeling for the Design of an Intricate Cooling Manifold

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ABSTRACT

The automatic test equipment designed at Teradyne requires various cooling systems to prevent the internal circuit boards from overheating. One of the water-based cooling systems includes the use of an intricate manifold. The manifold serves as the base for the mounting of the numerous liquid cooling modules spaced between circuit boards. The efficient circulation of water through this manifold is critical for the proper operation of the liquid cooling modules.

The following study uses the technique of Flow Network Modeling (FNM) for a comparative study of the flow distribution in a variety of cooling manifold designs. Each of the manifold designs is modeled as a network of links and components. The FNM technique allows for the prediction of pressure differentials and volumetric flow rates at critical locations in the manifold. In the optimal design, pressure differentials between elements in the system should be at a minimum. However, due to the complexity of the manifold, this task is difficult. FNM technique allowed rapid and accurate comparison of the relative performance of different designs and suggested different design improvements. Thus, the results of the simulation aided in achieving an optimal design. Incorporation of the FNM-based analysis improved the efficiency of the manifold design process by reducing prototype design time, and design and experimental testing costs.

Keywords: flow network modeling, cooling manifold, liquid cooling module, manifold

INTRODUCTION

Automatic test equipment has become more complex, requiring extremely reliable and efficient cooling systems. The complexity of the system requires an elaborate structure that is capable of distributing coolant to all extremities of the system. The structure, known as the manifold, helps guide the coolant through the many cooling modules. The performance of the manifold will be dependent on the pressure differentials and volumetric flow rates inherent to the design. This paper describes the use of the FNM approach for the design of the manifold. In order to understand the evolution of the design, a summary of the design process and requirements are given. The FNM results obtained, comparison with conventional techniques and FNM limitations are also explained prior to the concluding remarks.

Manifold Design for Mechanical Packaging

Initial prototypes of the manifold required an extensive use of experimental testing to aid the evolution of the design. With the use of FNM-based analysis, the design process life-cycle has been shortened. The design process is now composed of the following stages: Conceptual Design, Conceptual Design Verification, Detailed CAD design and Detailed Design Verification (derived from Kang et al. [1]). At the conceptual design stage, the manifold design is very dynamic. Design constraints are applied to the design in an iterative manner. Many iterations of the conceptual design are then analyzed using the FNM technique. At the same time, the detailed CAD design is started. The results of the analysis are then used to finalize the CAD design. The final design must meet the cost, material and timing goals allocated for the manifold. The final design is obtained after thorough experimental prototype testing is done in the Detailed Design Verification stage.

FLOW NETWORK MODELING (FNM)

FNM is a generalized methodology involving representation of a flow system as a network of components and flow paths, which allows for the prediction of system-wide distribution of flow rates and temperatures. Practical liquid cooled electronics systems can be represented as a network of components such as ducts, bends, tee junctions, orifices, filters, and pumps. 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. A detailed description of this technique is provided in the papers by Belady et al. [2] and Steinbrecher et al.[3].

MANIFOLD DESIGN

The manifold has been designed using a commercial software package MacroFlow™ [4] which incorporates the FNM technique and a Computer-Aided Design tool. After several iterations between the FNM and the CAD design, an optimal design was obtained. The actual design problem encompassed a variety of system requirements and constraints that guided and shaped the manifold design. An overview of the physical design is illustrated in Figure 1. A section of the FNM is illustrated in Figure 2 below.

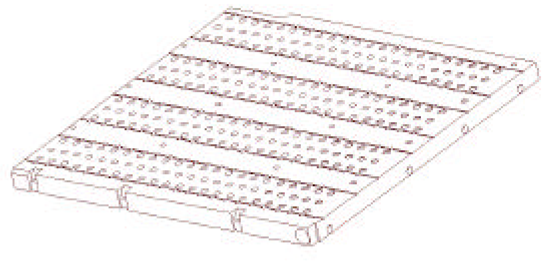

Figure 1. Physical Design of Manifold

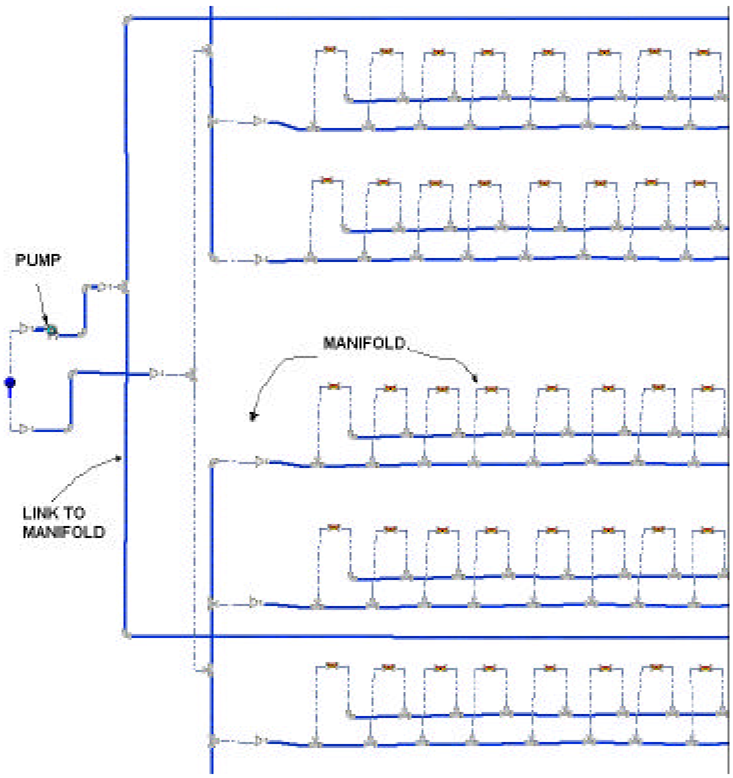

Figure 2. Section of Overall FNM of System

The manifold interfaces with liquid cooling modules (LCM) and coolant inlet/outlet hoses. The LCM is a u-shaped device that is mounted to the manifold and spaced between warm components/boards in the system. It contains the coolant, which helps remove heat from the components/boards. The manifold is also connected to a tank and a pump through a system of hoses. These elements of the design have also been modeled using the FNM technique.

System Requirements/Constraints

The overall design requirements and constraints consist of:

- A Minimum/Maximum pressure level and flow rate requirement,
- Structural integrity,
- Maximum size/shape requirement,
- Specific features required to interface to other components.

These requirements are briefly described below.

Pressure Level Requirements

A variety of pressure differentials in the manifold are required to prevent damage to interfacing components, as well as support an adequate water supply to all areas of the system. In order to provide proper circulation of water to the liquid cooling module (LCM), pressure drops between the manifold and LCM interface must remain relatively high.

Structural Integrity

The manifold material must support the pressure and fluid flow requirements within the confines of the allocated space for the manifold.

Maximum size/shape requirement

The manifold is contained within a larger structure, the testhead. It is designed in synergy with other structural components in the system. Therefore, its maximum size and shape are somewhat predetermined and, therefore, limited.

Specific features required to interface to other components

As described earlier, the cooling system contains a variety of components. The manifold must interface to each of these efficiently. In addition to maintaining the pressure level and water flow requirements, the interfacing features must be reliable and space efficient.

FNM MODEL OF THE MANIFOLD

The manifold system contains a large number of liquid cooling modules and associated flow components. Therefore, a single network model of the system that is constructed by a detailed representation of all components in the system may become computationally inefficient and too detailed for convenient analysis. In the present study, a two-level approach is used for the construction of the network model. It involves use of a stand-alone network model of the LCM for determining its flow characteristics. These characteristics are then used to represent the overall behavior of each LCM in the network of the individual branches of the system or the entire systems. This approach is computationally very efficient because it exploits the repetitive use of the same subassembly in the entire system. Further, such an approach is consistent with a modular and top-down design methodology.

Thus, the network analysis is divided into the following stages:

- Single LCM
- Row of LCMs
- Complete system

Single LCM

The single liquid cooling module, modeled in Figure 3 consists of an inlet, a straight large flow area, a bend and flow constriction, another bend, another straight large flow area and finally the outlet. These elements and geometries were easily represented using the node, tee, pipe, elbow and orifice components (see Figure 4).

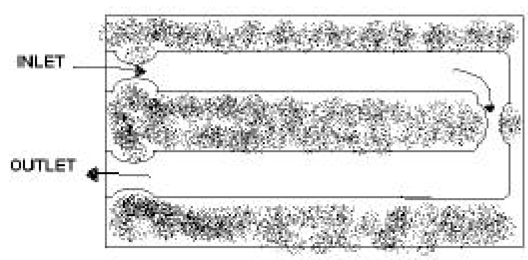

Figure 3. A liquid cooling module

Many assumptions were made in order to model the LCM in this manner. These included:

- ❑ A long 'zero-resistance' pipe connection represents a region that is at atmospheric pressure with little resistance to flow.
- ❑ The change in cross-sectional area across the LCM inlet/outlet can be represented as an orifice.

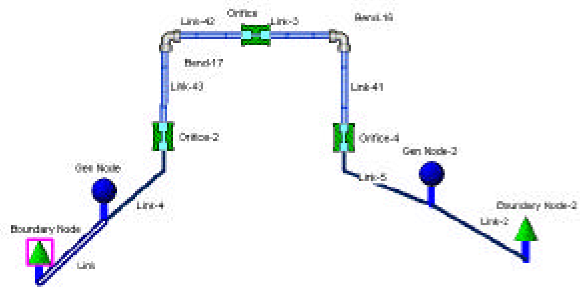

Figure 4. One Branch of the FNM, analogous to one LCM

- Each branch of the FNM (Figure 5) can be represented as a single resistance element (Figure 6). The Pressure-flow curve for the element is a piecewise linear correlation derived from the original FNM in Figure 5. A sample curve is illustrated in Figure 6.

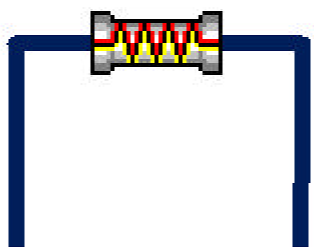

Figure 5. Resistance element

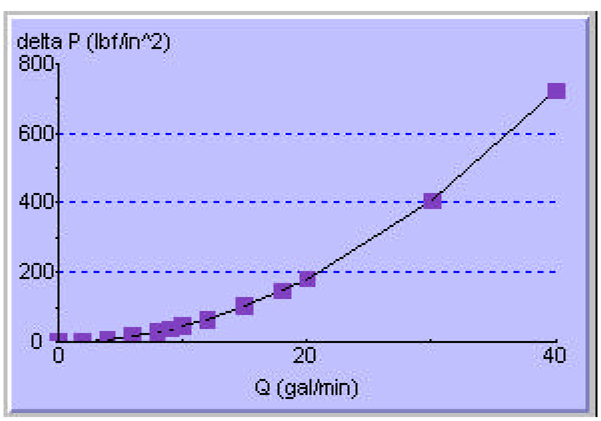

Figure 6. Pressure-Flow Piecewise Linear Correlation for Resistance Element

Row of LCMs

The row of LCMs involved connecting a series of single resistance elements. This represents a single section of the manifold. A part of one row is illustrated in Figure 7.

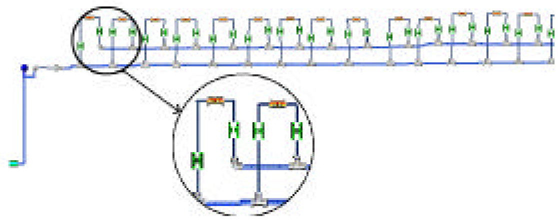

Figure 7. One Row of the FNM, analogous to a section of one row of the manifold

Complete System

The complete system consists of several rows of LCMs connected to a single inlet and four separate outlets. A section of the complete system is illustrated below in Figure 8.

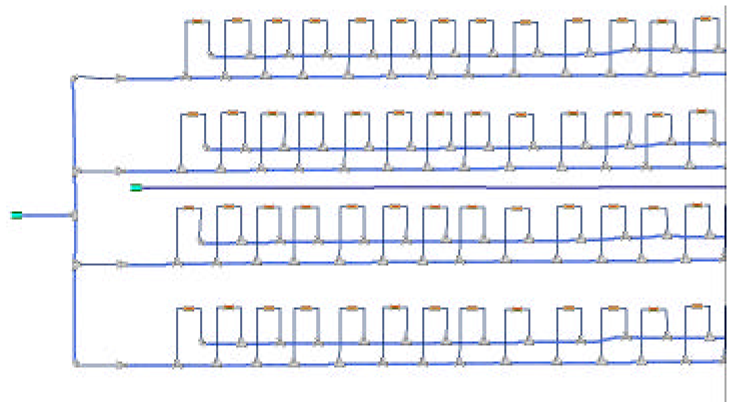

Figure 8. A Section of the Complete System

RESULTS

Prediction from the FNM Model

Once the model was developed, the simulation was run. The volumetric flow rates and pressure drops obtained from the simulation are tabulated below. The range in values is an averaged result of the variety of configurations that were examined. These included:

- system orientated horizontally (entire system is at the same height)
- system placed vertically (parts of the system are at different heights, so gravity is included in the model)
- system placed vertically (gravity) and higher friction coefficients allocated in each of the LCMs (sharp vs. smooth corners increases frictional resistance to flow)

- system with different diameter flow paths

System Type	Volumetric Flow Rate (gal/min)	Pressure Drop across inlet/outlet (psig)
1 LCM	0.12±0.01	3.50±.0.30
1 Row	3.40±0.05	3.00±0.50
Complete System	13.60±0.50	2.00±1.1

Table 1. Flow Rate and Pressure Drop Results

The graph in Figure 10 illustrates the volumetric flow rate curve obtained across a row of LCMs. The flow rates obtained from this particular configuration of the complete system are optimal.

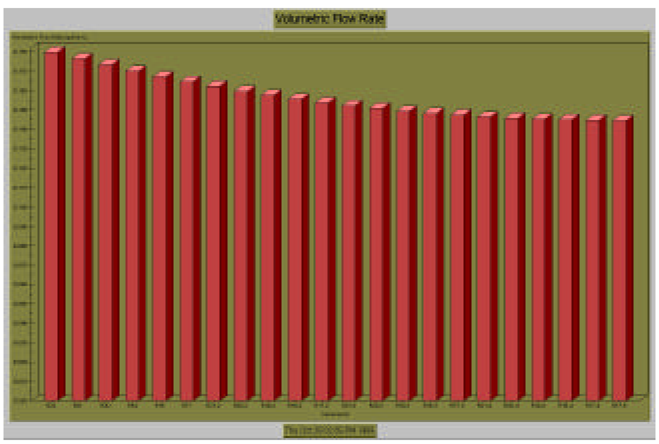

Figure 10. Absolute Volumetric Flow Rate across a section of the manifold

The pressure drop across the LCM inlet/outlet and the manifold/LCM inlet are approximately 0.5 psig.

<u>Comparison with Experimental Testing</u>

The FNM technique-based manifold design has been validated with the following experimental testing:

- Pressure readings on a completely assembled cooling system

- Pressure drops/Flow rates across single LCMs

The pressure readings across the assembled cooling structure were within 10% of readings obtained from the FNM based design.

The pressure drop across one LCM was also within 10% of values obtained from the FNM based design.

<u>Benefits and Limitations for the Use of the FNM Technique</u>

The FNM approach used in the present study offers several benefits in the design of liquid cooled electronics systems. First, it allows quick and accurate evaluation of the performance of alternate designs. Secondly, in a given design, performance-limiting components can be quickly identified. New design ideas can then be developed and evaluated rapidly. Finally, use of FNM analysis enables a top-down and modular design approach that minimizes the experimental trial-and-error. Use of this technique significantly shortens the design cycle and enables development of designs of better quality at lower costs.

Along with the benefits, the user needs to be aware of the limitations of the FNM approach in the design of electronics cooling systems. Firstly, the FNM analysis is based on accurate characteristics of the individual components that constitute the system. Therefore, if practical systems contain nonstandard components, their flow and heat transfer performance has to be accurately characterized for obtaining reliable predictions of the system behavior. Secondly, the FNM analysis provides average quantities and does not provide detailed predictions of the flow and heat transfer behavior within a component.

CONCLUSIONS

The FNM method provides a good basis for the design and development of the manifold. It allows the designer to shorten the design cycle process for the manifold, by reducing engineering experimental costs and prototype costs. In addition, many variations of the design can be analyzed and compared before any prototypes are built. The result is a valuable saving to engineering time.

The Flow Network Modeling technique has proven to be a solid design tool for the manifold. Not only has it enhanced the excellence of the design, but it has also provided an efficient design tool to the engineer.

ACKNOWLEDGEMENTS

Dr. Amir Radmehr of Innovative Research Inc. provided very useful suggestions in developing the network model of the manifold. Manish Bedekar of the design team at Teradyne, Inc. also provided valuable suggestions during the evolution of the FN model of the manifold. These efforts are gratefully acknowledged.

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