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ANALYSIS AND DESIGN OF LIQUID-COOLING SYSTEMS USING FLOW NETWORK MODELING (FNM)

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ABSTRACT

Liquid cooling is used for thermal management of electronics in defense, power, medical, and computer applications due to the increasing power density and the desire for compact packaging. The objectives in the design of these systems are to create a sufficient amount of total flow and to appropriately distribute the flow so as to maintain the electronic component temperatures at the desired level.

The technique of Flow Network Modeling (FNM) is ideally suited for the analysis of flow distribution and heat transfer in liquid-cooling systems. The FNM technique uses overall flow and thermal characteristics to represent the behavior of individual components. Therefore, solution of conservation equations over the network enables efficient prediction of the flow rates, pressures, and temperatures in a complete liquid-cooling system.

This article describes the technical basis of the FNM technique and illustrates its application in the design of a distributed-flow cold plate and of a complete water-cooled system. The study demonstrates the utility of the FNM technique for rapid and accurate evaluation of different design options and the ensuing productivity benefits in the design of liquid cooling systems.

INTRODUCTION

Liquid cooling is increasingly used for thermal management of electronics because of the several advantages it offers in the cooling of high-power devices. First, in applications where power densities exceed the limits of air-cooling, liquid cooling is the only practical heat removal mechanism. Second, liquid cooling offers a high-performance cooling solution and results in a compact design. Further, liquid cooling also offers better control over changes in the heat load and higher reliability. Liquid cooling has conventionally been used in defense, power, and medical laser and diagnostic equipment. It is now being considered for the cooling of high-end servers, telecommunication equipment, and automatic test equipment.

Design of a liquid-cooling system requires sizing of individual components so that the desired flow is delivered to the cold plates and heat sinks on which the electronics components are mounted. The individual cold plates and heat sinks also need to be designed so as to achieve effective and uniform cooling over the entire surface.

This article discusses the utility of the technique of Flow Network Modeling (FNM) for the analysis of flow and heat transfer in liquid-cooling systems and illustrates the productivity benefits that the thermal engineer can derive from its use in the design process.

DESIGN OF LIQUID-COOLING SYSTEMS

Liquid-cooling systems involve circulation of a coolant through a closed loop that contains components for *flow distribution* (tubes, quick disconnects, three-way and four-way valves, and pumps), *flow control* (valves and orifices), *heat absorption* (cold plates and fin stock), and *heat removal* (heat exchanger). A liquid *reservoir* is used to maintain the system pressure and compensate for any small leakage that may occur. The coolant loop may also use a *filter* to remove particulates from the circulating coolant.

The design of the liquid cooling system involves Component-level and System-level design as discussed below:

Component-Level Design – A critical component in a liquid-cooling system is the cold plate or the heat sink. The flow distribution within the passages of a cold plate should provide uniform cooling over the entire surface of the cold plate. Similarly, the fin thickness and fin spacing of a heat sink need to be chosen appropriately for obtaining the desired flow rate and heat transfer performance.

System-Level Design – Most practical cooling systems involve various components arranged in a *complex manifold*. Therefore, primary objectives of the system-level design are to achieve the total *overall flow* and to *appropriately distribute* that flow to *individual cold plates* so that the temperature of the electronic components is maintained at the desired level.

The FNM technique addresses the interaction among the individual parts of a flow system in an efficient manner for determining the resulting flow distribution and thermal performance. Therefore, it is ideally suited for both component-level and system-level design and analysis.

ANALYSIS USING FLOW NETWORK MODELING

The details of the FNM technique have been described in the earlier articles (Belady et al. [1]). The steps involved in the use of this technique for the analysis of liquid-cooling systems are as follows.

Network Representation - The flow system is represented as a network of components (e.g. Orifices, Valves, Tee-junctions, Pumps, Reservoirs, Cold Plates, and Heat Sinks) and flow paths (tubes).

Component Characteristics - Each component is characterized by an empirical correlation that relates the pressure drop and heat transfer rate to the corresponding flow rate. The flow characteristics are typically described by the following equation.

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

The loss coefficients for various components can be obtained from handbooks (e.g. Idelchik [2], Blevins [3]), experimental measurements, or a detailed CFD analysis. For example, flow characteristics of a *tube* is represented using Moody's chart. The minor loss factor for an *orifice* is calculated from the ratio of the minimum and the inlet/exit areas. Flow performance of *cold plates* can be characterized in terms of the variation of the overall pressure drop with the flow rate. The thermal performance of a *cold plate* or a *heat sink* is characterized in terms of the variation of thermal resistance with the flow rate. Thermal resistance, in turn, is defined as the difference between the temperature of the electronic component and the inlet coolant temperature required to transfer one unit of power. Another component that is important in the analysis of liquid cooling systems is the *Tee-junction*. Its loss factors account for the flow inertia so that accurate predictions can be made of the flow distributions in the flow manifolds encountered in liquid-cooling systems.

Solution of the 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 the links. The flow characteristics of each link, given by Eq. (1), constitute the momentum equations. Mass and energy conservation is imposed at each node of the network. The forms of the discretized momentum and continuity equations are given below.

Momentum Equation for a Link

$$p_1 - p_2 = S_{CR} + RQ \qquad (3)$$

The quantities S_{CR} and R are determined by linearizing Eq. (1). Thus, R is the slope of Δp-Q curve.

Mass Conservation at a Node

$$\sum_{l=1}^{n} \rho Q = 0 \qquad (4)$$

Here n denotes the total number of links at that node. 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.

An efficient method to solve the momentum and mass conservation equations is to use a pressure-based solution algorithm. It involves the following steps.

1. Assume a distribution of flow rates over the links and pressures at the nodes.
2. Calculate the flow rates for the links from the momentum equation using existing nodal pressures.
3. Construct a pressure correction equation by combining the corrected momentum and continuity equations. Solve the matrix of the pressure correction equations using a direct method and update the pressures and the flow rates.
4. Solve the discretized energy equations at all nodes using a direct solution to determine the temperatures at all nodes.
5. Repeat steps 2 to 4 till convergence.

The resulting algorithm is fast and robust. It allows determination of the pressures, flow rates, and temperatures throughout the system.

Benefits - The FNM method outlined above constitutes a simple, fast, and accurate technique for the analysis of flow and temperature distributions in liquid-cooling systems. The analysis proceeds very rapidly (less than a minute on a PC) due to the use of overall characteristics. The results are accurate because the empirical correlations that characterize the components are valid over the laminar, transitional, and turbulent regimes. This analysis can therefore be used to perform the following tasks for improving the productivity of the thermal design process:

- Evaluating the thermal performance of different flow configurations
- Sizing of individual components so that the desired total flow as well as flow balance is achieved
- Performing "What-if" and contingency studies

ILLUSTRATIVE APPLICATIONS

In this section, the FNM technique is applied for the design of a distributed-flow cold plate and a complete water-cooled system to demonstrate its utility for component-level and system-level design. A commercial software program MacroFlow™ [4] is used for this purpose.

Design of a Distributed-Flow Cold Plate

Physical System and Network Representation - In a *distributed-flow* cold plate, the flow is distributed within the cold plate using interconnected passages. A common method for achieving this is to embed tubes or to extrude passages

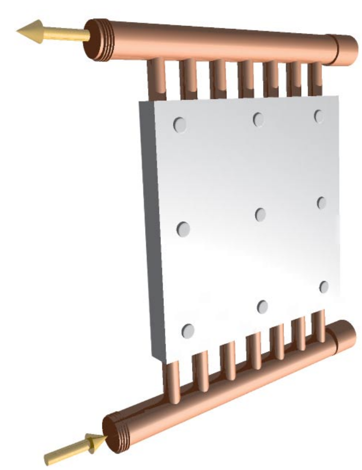


Figure 1 – A distributed-flow cold plate with a U-configuration

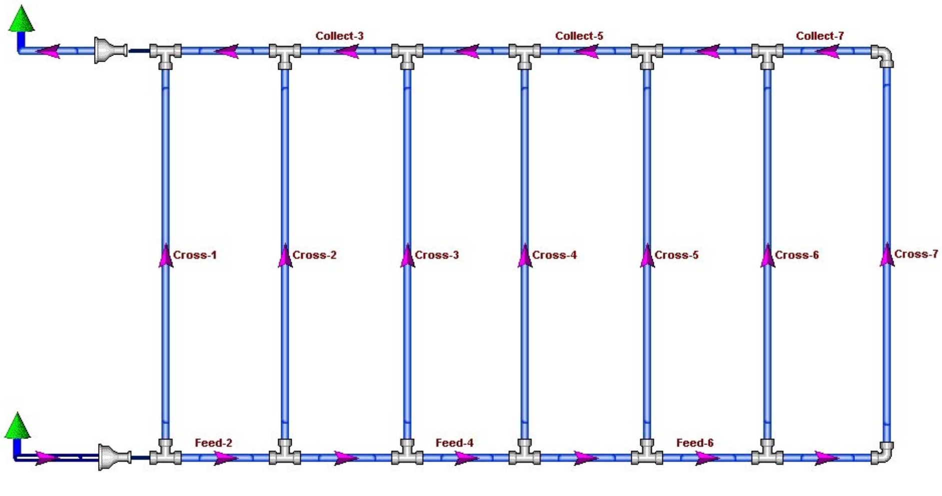


Figure 2 – Network model of the distributed-flow cold plate

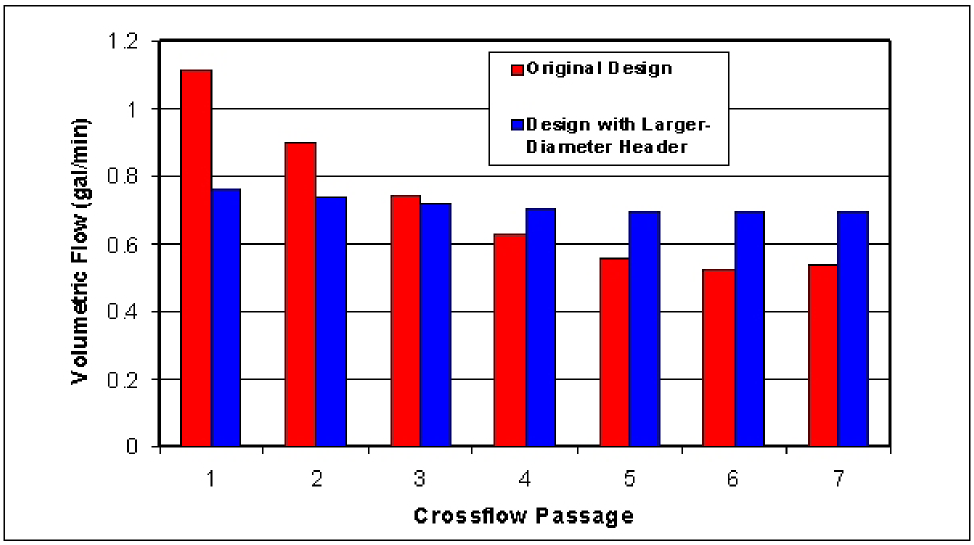


Figure 3 – Variation of the flow rates in the crossflow tubes for original (7/16” diameter header) and modified designs (7/8” diameter header) of the cold plate

within the solid block of the cold plate. The crossflow tubes are joined to the main tubes to form a U- or a Z-configuration of the flow path. The thermal performance is dependent on the uniformity of the flow distribution within the cold plate.

The cold plate considered for analysis is shown in Fig. 1. The two header tubes feed flow to and collect flow from the seven cross tubes that are placed along the width of the plate. The original design consists of crossflow tubes that are 1/4” in diameter, 7” in length and are spaced with a pitch of 1”, while the feeder tubes are 7/16” in diameter. Figure 2 shows the network model of the flow system. It is important to note that Tee-junctions are used to represent the division or merging of the flow from the main branch to the side branches.

Design Iterations - Figure 3 shows the variation of the flow rate in the crossflow branches for a total flow of 5 gal/min of water. For the original design (light/red-colored bars), there is significant nonuniformity in the flow distribution with the highest flow in the first branch.

The flow maldistribution within the cold plate can be reduced if the change in the static pressure in the main tube is made small in comparison to the pressure drop required to drive the flow through the crossflow tubes. This can be achieved by either increasing the cross-sectional area of the feeder tubes or decreasing cross-sectional area of the crossflow tubes. Figure 3 shows the flow rates in the crossflow tubes when the diameter of the feeder tubes is increased to 7/8”. The resulting flow distribution is very uniform (dark/blue-colored bars) and is expected to result in a cold plate that provides uniform cooling over its surface.

Design of a Water-Cooled System

Physical System and Network Representation - The liquid-cooling system considered in this study is shown in Fig. 4. It consists of five cold plates, chosen from the products offered by Lytron [5], arranged in a U-shaped manifold. The main orifice controls the total flow while orifices in each of the

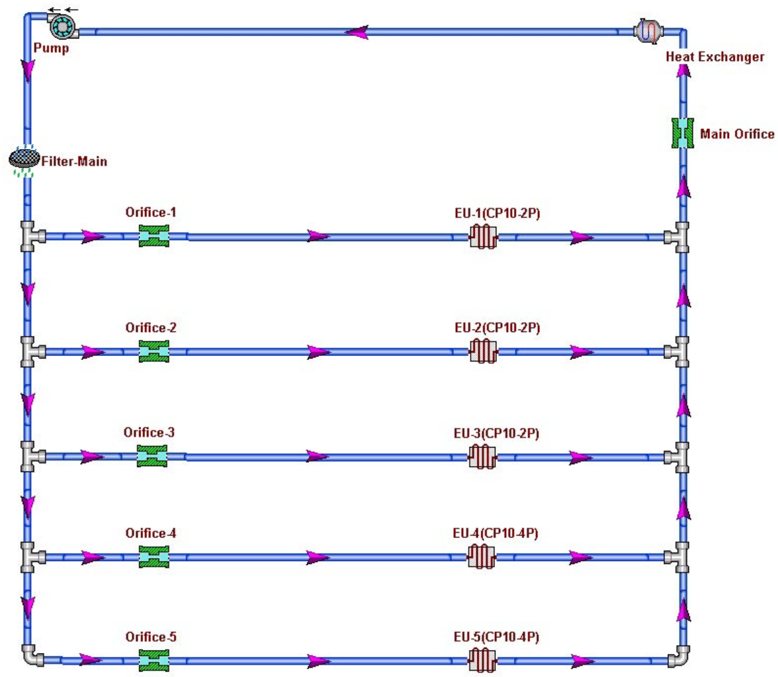
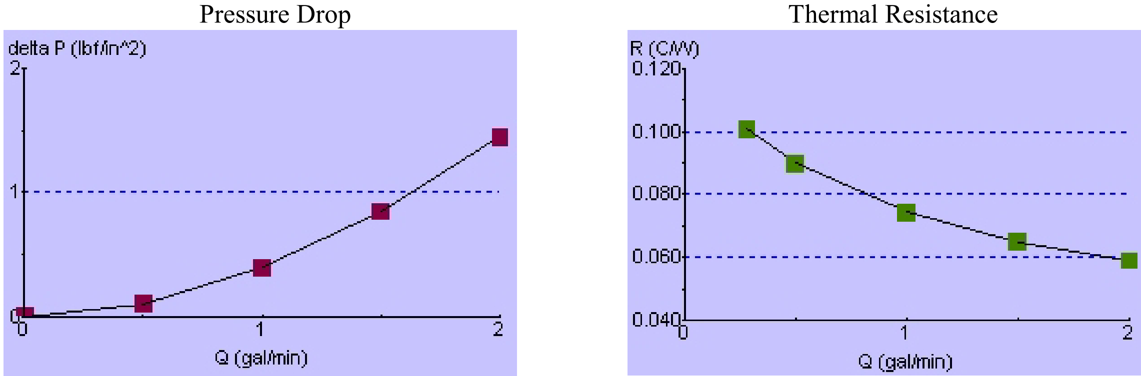
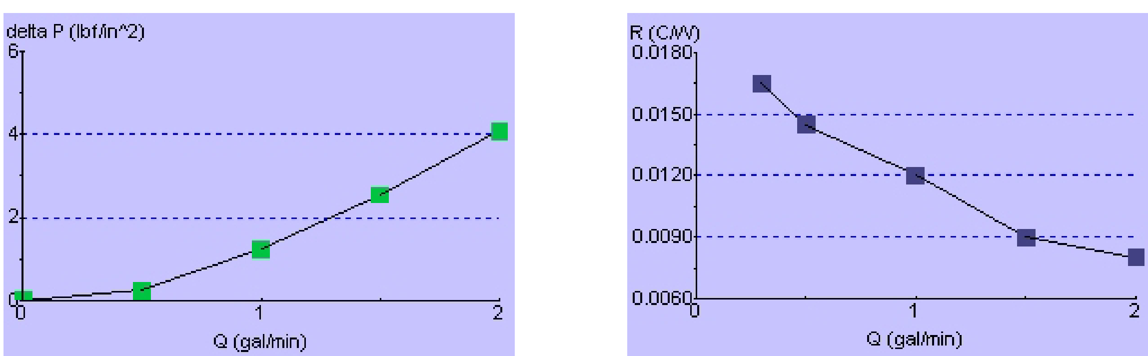


Figure 4 – Flow network representation of the closed-loop water-cooling system

Pressure Drop Thermal Resistance

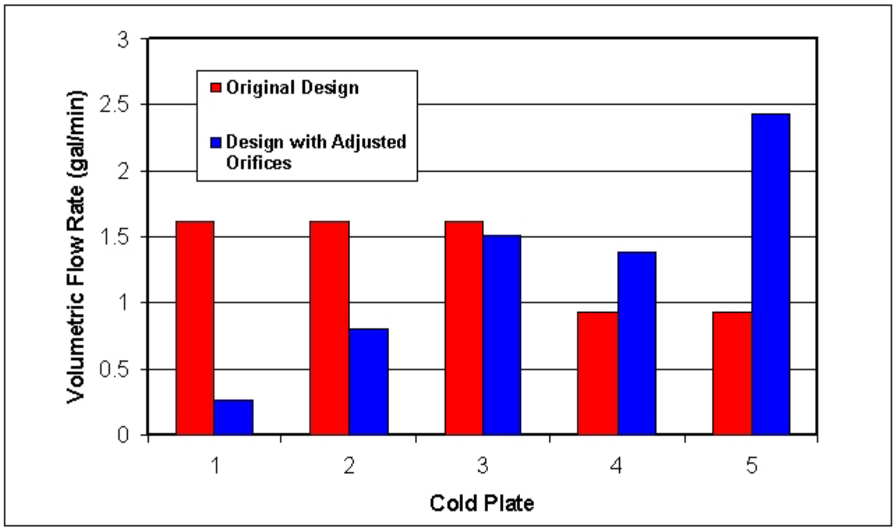


(a) CP-10 6" Double Pass

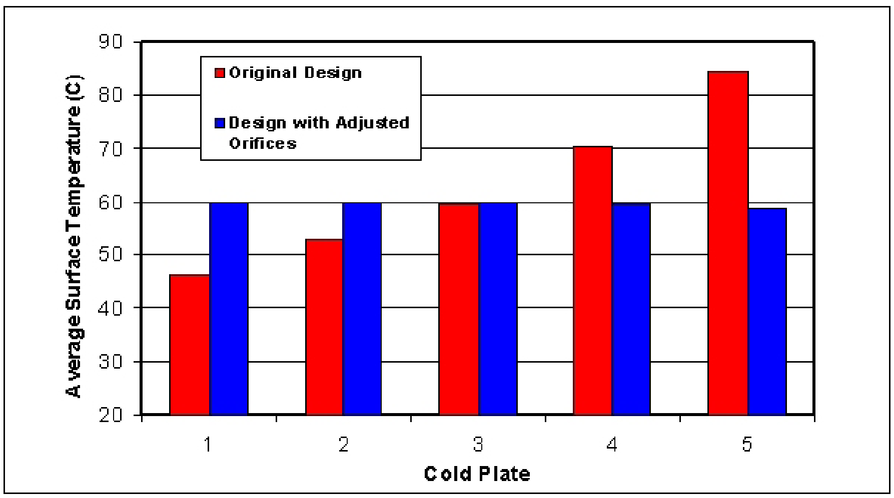


(b) CP-10 12" Quadruple Pass

Figure 5- Flow and thermal resistance characteristics of the Lytron cold plates [5]



(a) Volumetric Flow Rate



(b) Average Surface Temperature

Figure 6 – Flow rates and average surface temperatures for the cold plates in the original and revised designs

flow branches control the flow to the individual cold plates based on their cooling requirements.

As listed in Table 1, a small cost-effective cold plate is used for removing heat from EUs 1-3 while a high-performance cold plate is used to cool EUs 4 and 5. The flow and thermal characteristics of these cold plate designs are shown in Fig. 5.

Table 1 – Heat dissipation in the electronic units and the corresponding cold plates

Electronic Unit	Heat Dissipated (kW)	Cold Plate Type Lytron [6]
EU-1	0.3	CP-10 6” 2 Pass
EU-2	0.4	CP-10 6” 2 Pass
EU-3	0.5	CP-10 6” 2 Pass
EU-4	3.0	CP-10 12” 4 Pass
EU-5	4.0	CP-10 12” 4 Pass

Design Iterations - The objective of the design process is to keep the average temperature of the surface of each cold plate below 60°C so that the electronic components operate in a reliable fashion. Important steps in the design of the cooling system are now described.

Sizing of the Main Orifice, Pump, and Heat Exchanger – The first step in the design process is to size the components in the main flow paths based on the total flow rate requirement and to ensure that the system is scalable for accommodating additional electronic units. Network model is used for different combinations of the pump, heat exchanger, main orifice, and filter to determine a scalable configuration that provides the desired flow rate of 6.8 gpm at a temperature of 25°C at the exit of the heat exchanger.

Sizing the Orifices in the Branches – As seen in Fig. 6, in the original design that uses identical orifices in the side branches, Units 1 and 2 are cooled excessively while Units 3 and 4 are operating well beyond the permissible temperature of 60^{o}C (light/red-colored bars). Therefore, using the network model, sizes of the branch orifices are adjusted to achieve the desired flow distribution based on either the *forward analysis approach* or the *inverse design method* (Kang et al. [6]). Figure 6 shows that the flow distribution in the revised design (dark/blue-colored bars) ensures that each cold plate is operating below the maximum allowable temperature.

CONCLUSIONS

Liquid cooling is now being increasingly utilized for the cooling of electronics systems due to a rapid increase in the power density and the desire for compactness. Effective functioning of such systems requires careful design of the individual cold plates or heat sinks that remove the heat from the electronic components and proper distribution of the coolant flow to the heat removing components in the overall system. The technique of Flow Network Modeling (FNM) is ideally suited for component-level and system-level analysis and design. The analysis proceeds in a very rapid fashion because of the use of overall flow and thermal characteristics. Therefore, various design options can be evaluated in a simple, rapid, and accurate fashion. The productivity benefits of this technique are illustrated through its application for the design of a distributed-flow cold plate and of a practical closed-loop water-cooled system.

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