Use of Flow Network Modeling for rapid thermal design of electronic cooling systems

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Since reliable operation of electronics systems is critically dependent on satisfactory thermal performance, thermal design has become an integral part of the product design process. Further, due to continuous increases in the complexity and power density of electronics systems, there is a constant need for improving the productivity of the design process. Thus, a good system design has to be developed early in the design process that meets thermal performance goals, while also satisfying mechanical, electromagnetic compatibility, and acoustic constraints.

Conventional techniques used for the analysis of the above design issues involve hand calculations, spreadsheets, and Computational Fluid Dynamics (CFD) analysis. However, hand calculations are very limited, spreadsheets are time consuming to construct and lack generality since they are system-specific, and CFD analysis is expensive in terms of model definition, solution, and post processing.

In this article, Tom and Kanchan describe Flow Network Modeling and its benefits for the design process.

Flow Network Modeling overview

The Flow Network Modeling (FNM) technique fills the gap between limited hand calculations/spreadsheets and detailed CFD analysis. It is a simple, fast, and accurate technique for a scientific examination of various design options at the Conceptual/System Design stage.

Traditional use of flow network analysis in the design of electronics cooling systems has been discussed by Ellison[1]. A generalization of this technique for the prediction of flow rate, pressure, and temperature distributions for network models of complex systems has been presented in detail by Belady et al[2].

This article describes the FNM technique and illustrates its use for the design of a real-life combined air- and liquid-cooling system for a television transmitter cabinet.

Flow Network Modeling technique

Network representation and component characteristics

A flow network of a practical electronic cooling system is constructed by graphically representing the paths followed by the coolant streams as a network of components such as ducts/tubes, heat sinks/cold plates, filters, orifices, card passages, fans/pumps, bends, and tee junctions.

The overall flow and thermal behavior of each component in the system is characterized by an empirical correlation that relates the pressure drop and heat transfer rate to the corresponding flow rate. Thus, the flow characteristics of a component are commonly represented in terms of the minor loss factor in the following equation:

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

where: K = loss coefficient
ρ = fluid density
Q = volumetric flow rate
A = flow area

The loss coefficients for various components can be obtained from handbooks (such as Idelchik[3], Blevins[4]). For components such as fans or pumps, supplier data can be used to determine the overall flow characteristics.

Calculation of the bulk temperature of the coolant requires specification of the heat dissipated in the individual components such as heat sinks and cold plates. The average surface temperatures of these components are determined from the surface heat transfer coefficients or thermal resistance. These, in turn, are determined from empirical correlations in dimensionless (Nusselt number as a function of Reynolds number) or dimensional form (thermal resistance as a function of flow rate).

It should be noted that there is no restriction on the functional behavior used to represent flow and thermal characteristics. Thus, curve fits to the experimental measurements, CFD analysis, and vendor-supplied data can also be used to specify the variation of the overall pressure drop with the volumetric flow rate.

Similarly, the thermal performance of cold plates or heat sinks can be represented in terms of any variation of the thermal resistance as a function of the flow rate of the coolant. Finally, the heat exchanger performance can be represented as a variation of the effectiveness (or the heat transferred per unit difference in the inlet temperatures) of the two fluids with flow rates of the two fluids participating in heat transfer.

Equation solutions and analysis results

The distribution of flow rates, pressure, and temperatures is determined by solving mass, momentum, and energy conservation equations over the flow network. The flow characteristics constitute the momentum equations while conservation of mass and energy is imposed at each junction in the network. A direct solution with a Netwon-Raphson linearization is used for the solution of the network equations. The resulting analysis procedure is very robust and efficient. A more detailed description of the solution method is provided by Belady et al[2].

Network analysis gives an overview of the flow and temperature distributions in the entire system. It predicts quantities that are of direct engineering relevance to the thermal engineer – total flow rate, pressure drop, and temperature change for each component, so that the system performance can be evaluated in a succinct manner.

Utility of FNM Analysis for Thermal Design

Benefits of FNM

The FNM technique is simple, fast, and accurate. Construction of a network model is simple due to the modular nature of the network representation, and the process takes less than an hour for a typical system. The analysis is very fast (approximately 20 seconds on a PC) because the behavior of each component utilizes a lumped-parameter representation so that the number of equations is small (and orders of magnitude smaller than CFD analysis).

The results of analysis are also accurate since the correlations are empirically determined. Thus, they accurately account for the effect of flow regimes (laminar, transitional, and turbulent), component geometry, and fluid properties (such as changes in density due to elevation or temperature).

Because of the inherent advantages of the FNM technique, it offers the following benefits for system-level thermal design.

- Evaluation of design alternatives – This technique can be used to evaluate designs with different component layouts, or perform parametric studies involving component characteristics in a very rapid manner (for instance, analysis of literally hundreds of competing designs within a day) for determining a good system design at the early design stage.
- Sizing of components – Components such as heat sinks/cold plates, fans/pumps, screens/filters, and heat exchangers can be sized in a rapid manner for achieving the desired flow and thermal performance.
- Identification of performance-limiting components – Components that constrain the system performance can be very quickly identified so as to obtain large improvements in the performance by incorporating a few critical design changes. Further, ideas for design improvements can be quickly devised and tested.
- "What If" studies – Evaluation of the performance of partially populated systems, and magnitude of the impact of contingency scenarios such as fan failure or increase in the ambient temperature can be quickly determined.

Improved design process productivity

Use of FNM significantly reduces the effort that is otherwise required for system-level analysis so that the number of design alternatives can then be quickly reduced in a scientific and cost-effective manner.

Further, due to speed of analysis, many more design options can be explored in the early design stage and the quality of the final product is improved. CFD analysis can then be used in a focused manner for detailed analysis of only the few good designs or the critical parts of a good design. This is followed by laboratory testing and refinement to determine the final design.

Such an approach utilizes the optimum tool at the each stage in the design process so that both the overall analysis time and the risk of having to make a change later in the design process are substantially reduced. The resulting optimum design cycle has been shown graphically in the study by Belady et al.[2] and is reproduced in Figure 1.

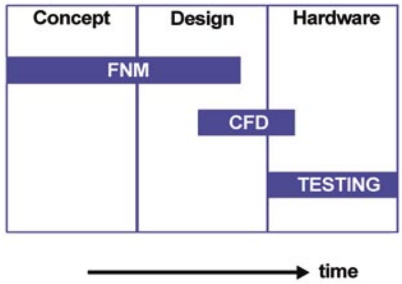

Figure 1

Illustrative application

The FNM methodology has been applied to the design of the combined liquid- and air-cooling system of the Atlas Analogue solid-state UHF television transmitter from the Harris Corporation Broadcast Communications Division[5]. The commercially available software program MacroFlow from Innovative Research was used for this purpose.

The physical system

The television transmitter cabinet (Figure 2) consists of Power Amplifier (PA) modules (up to eight in number), Radio Frequency (RF) absorption loads (up to seven in number), a transformer, several custom 19 inch rack-mount electronic chassis, and various circuit boards and other electronic components.

Figure 2

Each PA module dissipates up to 3 kW, while the heat load for each RF load can range from 1kW to 4 kW. Because of the high power densities within the cabinet, a water-glycol liquid cooling system is used to remove the majority of the dissipated heat. Forced-air cooling is used to augment liquid-cooling to remove additional heat that is not feasible for absorption using liquid cooling. Following is a description of the important features of the liquid- and the air-cooling systems.

Liquid-cooling system

The liquid cooling system uses custom designed cold plates to remove heat dissipated by the PA modules and six of the RF loads, and a water jacket for the main RF load. A copper pipe network containing supply and collection manifolds is used to distribute the water-glycol mixture in the coolant loop. A pump module and an air-to-water heat exchanger external to the cabinet are used to circulate the coolant and to maintain its temperature at a desired level.

A schematic diagram of the liquid cooling system within the transmitter cabinet is shown in Figure 3. The PA modules are located in the front of the transmitter cabinet, and the RF loads are located in the back of the transmitter cabinet.

Network representations

The flow network models of the liquid and air-cooling systems were created by representing the flow paths of the coolants through the various components in the respective systems. Following is a brief overview of these models.

Liquid-cooling system

The network model of the liquid-cooling system is shown in Figure 5. The three branches of main supply tube feed the RF load cold plates, the main RF load, and the PA modules.

The cold plates for the individual RF loads and the PA modules are configured in parallel flow manifold arrangements that are represented using Tube, Tee Junction, Area Change, Cold Plate, and User-Defined Resistance elements.

The flow behavior for each component is determined by using empirical correlation based on the component geometry (such as Moody's chart for tubes, and loss factors for contractions, area changes, and tee junctions), vendor data (such as pressure drop vs. flow rate relationship for the

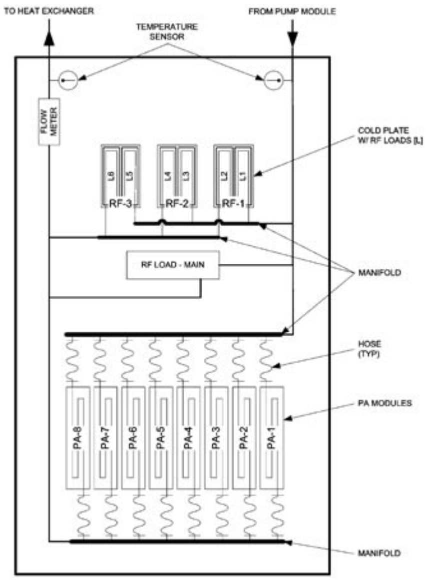

Figure 3

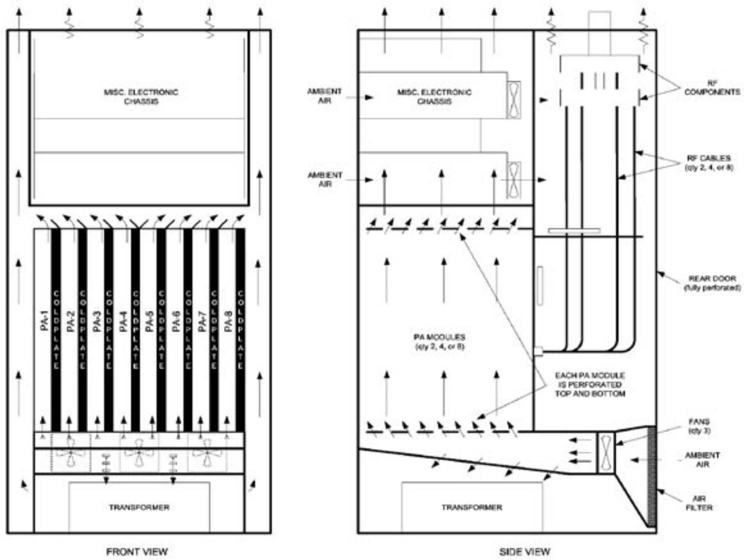

Figure 4

Air-cooling system

The primary air-cooling system is used to cool the transformer located at the bottom of the cabinet and to augment the cooling of the PA modules (Figure 4).

Axial fans located at the rear of the cabinet draw air through a filter and push it into a plenum from which it is distributed to individual PA modules and to the transformer. The air stream cooling the transformer is directed to ducts at the sides of the transmitter. The air streams flowing through the PA modules merge in the space above the amplifier module and are also directed to the sides of the cabinet where they combine with the transformer stream.

The combined air streams on the side of the cabinet are then ducted up to the top of the cabinet where they exit into the ambient. Secondary air cooling of the transmitter cabinet involves self-contained fan-cooled electronic chassis and natural-convection-cooled components that are isolated from the primary air-cooling system.

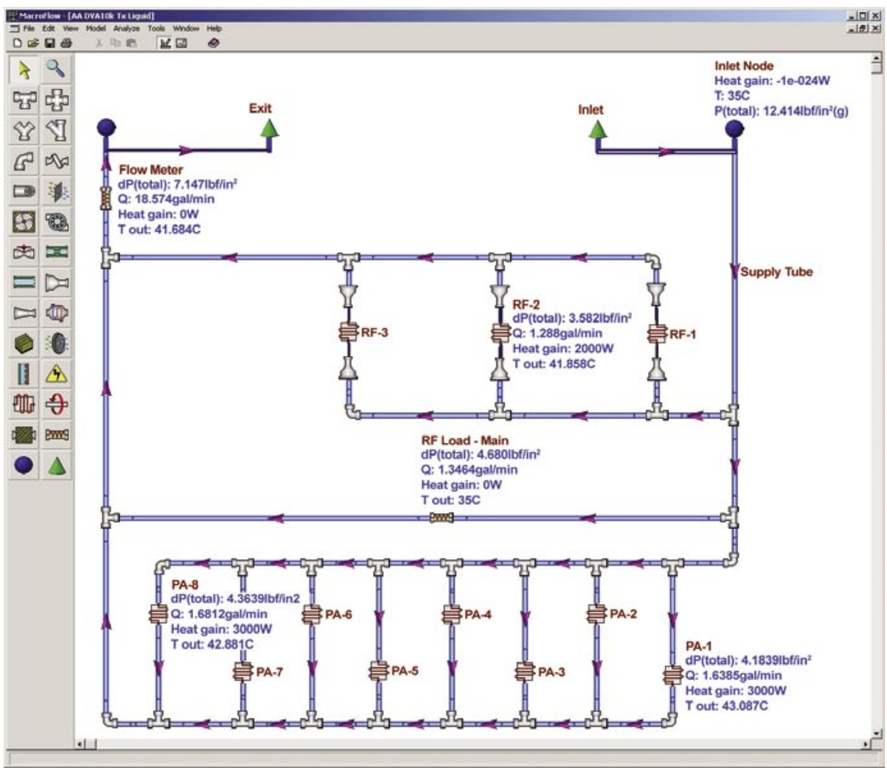

Figure 5

main RF load and flow meter), and laboratory testing (for the nonstandard cold plates used for cooling the PA modules and RF loads).

Note that the loss correlations for the tee junctions account for the flow inertia, and therefore enable the accurate prediction of the flow maldistribution that may occur among the cold plates in the parallel flow paths.

Thermal analysis requires specification of the heat dissipated by the individual components and the thermal resistance characteristics for the cold plates and the main RF load. The flow characteristics of the cold plate used in the PA modules are shown in Figure 6. The thermal characteristics are shown in Figure 7.

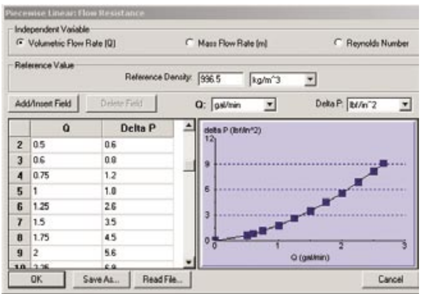

Figure 6

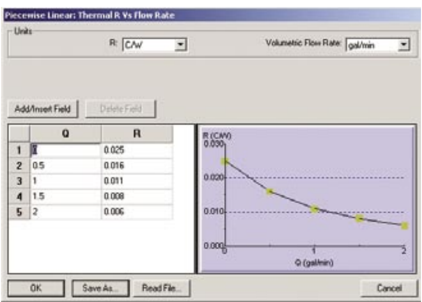

Figure 7

Air-cooling system

The network model of the primary air-cooling system is shown in Figure 8. Various components within this system include Fan, Filter, Duct, Screen, Card Passage, Tee Junction, and Bend elements.

The air filter at the inlet represents the flow resistance offered by the filter and, if desired, MacroFlow has the ability to account for the effect of filter dust loading on the pressure drop.

The airflow through each PA module is represented by a Card Passage component

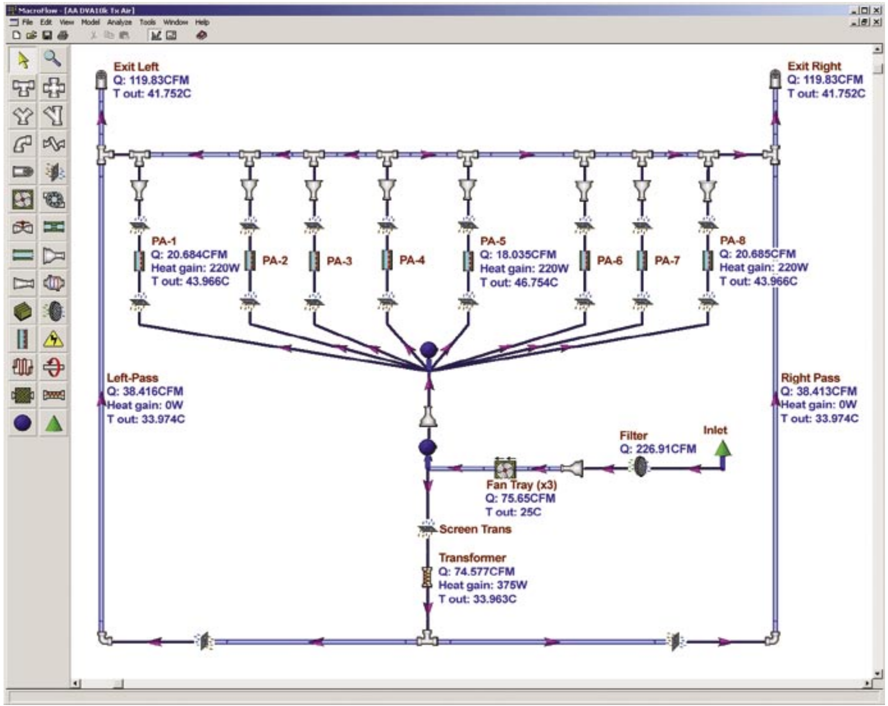

Figure 8

to represent the flow resistance created by the electronic component within each PA module. Also, the Screen components on either side of the Card Passages account for the flow resistance of the perforated plates present at the inlet and the exit of the PA module assembly. Tee junction components are used to represent merging of the individual flow streams exiting from the individual PA modules, and of the PA module and Transformer air streams.

Flow characteristics for most components are determined from corresponding empirical correlations that specify the loss factor as a function of the Reynolds number of the flow and the component geometry. The characteristics for the filter and the fan are specified using vendor data. The fan curve used to represent each fan is shown in Figure 9. A multiplier of three is used to represent the fan tray that contains three fans.

System-level design using network analysis results

Network analysis of the liquid- and air-cooling systems predict the total induced flow, and the distribution of flow rates, pressures, coolant temperatures, and the average surface temperature of the components throughout the system.

Analysis of the model for one system configuration took less than a minute on a PC. Thus, effects of various design

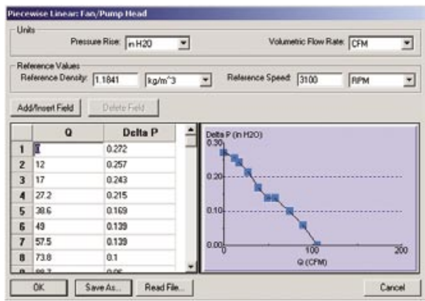

Figure 9

changes were examined in a rapid manner to decide on design of the individual systems that satisfy the desired thermal performance requirements. Following are the important details of the analysis.

Liquid-cooling system

The design goals for the liquid-cooling system were to deliver the flow rates of the water-glycol mixture to each PA module and RF load cold plate, and to the cooling jacket of the main RF load that are adequate to remove the dissipated heat under the highest heat dissipation scenarios.

Further, it was desired that the flow balancing be achieved without the use of orifices in individual branches. This was accomplished in two stages.

First, analysis was carried out by adjusting the locations, lengths, and diameters of the tubes that feed the three main branches so that the desired total flow was delivered to the set of RF load cold plates, PA module cold plates, and the main RF load.

Next, the lengths and sizes of flexible hoses and tubes in the branches containing the individual PA modules and the RF load cold plates were adjusted so as to deliver the flow uniformly to each component. A plot of the flow rates in the various branches of the fully populated system is shown in Figure 10.

The flow impedance curve of the system, determined from the network analysis, was then used in sizing the systems pump. The heat exchanger was also sized and its air-cooling operation determined so that the temperature of the coolant entering the transmitter was at the desired level. Finally, by running the network model under various depopulated modes of operation (fewer than eight PA modules), a flow table was constructed for use in the control system software that monitors the overall cabinet flow rate.

Air-cooling system

The design goal for the air-cooling system was to induce sufficient flow over the transformer and through the PA modules to remove dissipated heat and maintain component temperatures within manufacturer's specifications.

This involved the use of the model for the air-cooling system with a prescribed overall flow rate. The characteristics of the perforated screens at the bottom and top of each PA module were determined to ensure that each PA module in the parallel manifold arrangement received nearly the same airflow for flushing the heat not removed by the liquid-cooling system.

Then, several different percentage open areas of the screen leading to the transformer were examined to provide the desired flow split into the PA modules and the transformer space. The fans were then chosen from commercially available options so that the desired airflow was created through the cabinet with the filter at the inlet of the system. The pressure drops through various components in the air-cooling system are shown in Figure 11.

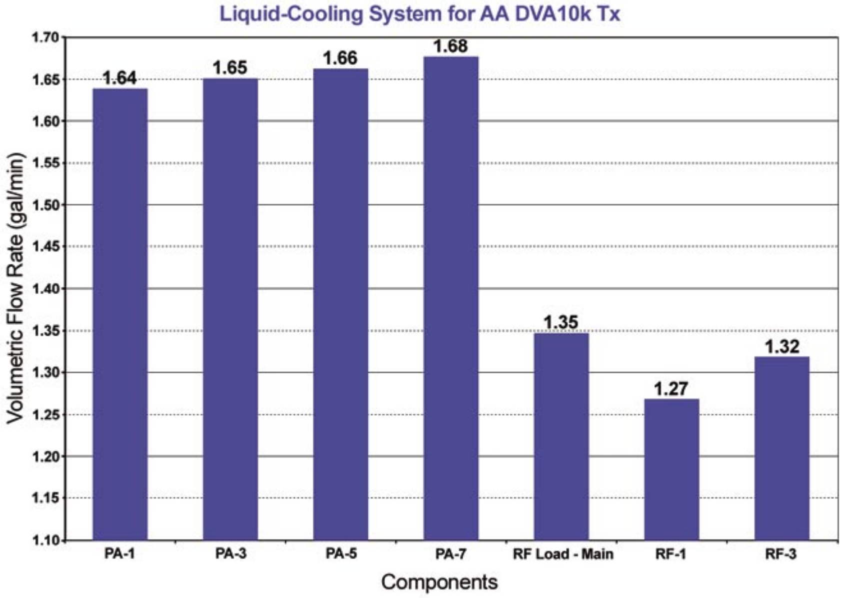

Figure 10

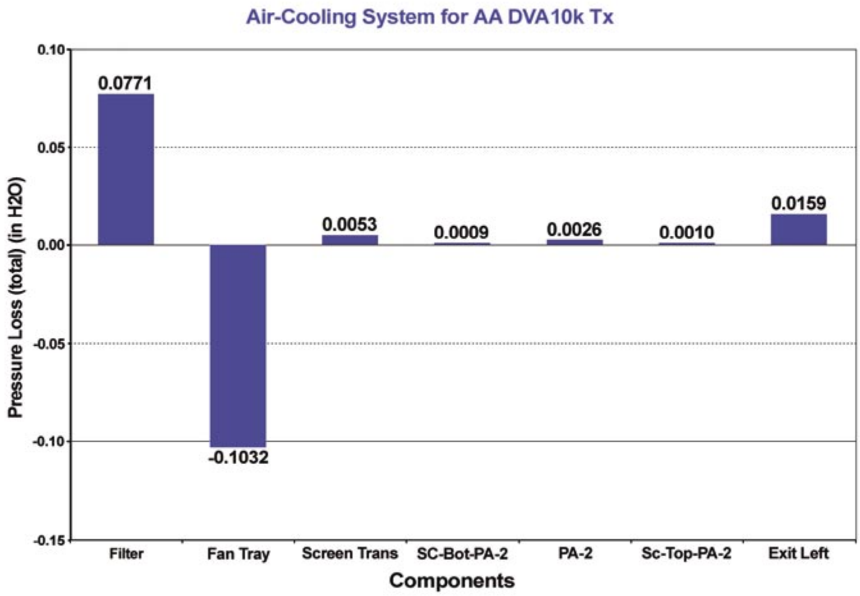

Figure 11

Finally, the model was run for worst case ambient conditions (high temperature and elevation) to ensure that the air-cooling system provided sufficient cooling at the lower air density.

Utility of the FNM analysis

The use of FNM-based analysis enabled accurate sizing of the individual components, and provided a scientific method for the evaluation of the system performance under standard and nonstandard operating conditions. Thus, a reliable design of the entire cooling system was developed in the early design stage.

Subsequent testing proved that the basic design of the cooling system met the thermal performance requirements, and only a few refinements were necessary for finalizing the design. Up-front use of network analysis was, therefore, extremely useful in determining a good system configuration in a rapid and scientific manner early in the design process.

Summary

Flow Network Modeling involves a network representation of a flow system in which each flow path and component is characterized by empirical flow and heat transfer characteristics. Then, the mass, momentum, and energy conservation equations are solved to determine system wide distribution of the pressures, flow rates, and local bulk temperatures of the coolant.

FNM fulfills the need for a simple, fast, and accurate system-level thermal design analysis between spreadsheets and CFD. FNM-based analysis can significantly improve the productivity of the design process, and substantially mitigate the risk of design changes in the later stages of the design process. This technique is applicable for the design and analysis of open and closed air-cooled and liquid-cooled systems in avionics, marine electronics, telecom, and computer applications. Ω

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