LIQUID COOLING OF A HIGH-POWER MULTI-CHIP MODULE USING A SECTIONED COLD PLATE

by

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Abstract

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With the advancement in micro-fabrication techniques and high performance chips, the heat flux generated through these electronics is reaching a point where air-cooling of these devices is not efficient enough. By definition, Multi-Chip Modules (MCMs) are specialized electronic packages where multiple Integrated-Circuits (ICs) and semiconductor dies are unified onto a single substrate. Increasing advancements in ICs enable MCMs as alternate packaging finding its application in high power electronics like power generation and cooling, medical devices, lasers and, military electronics etc. Hence, liquid cooling techniques are explored as possible solutions. In this study, a high power MCM is considered and, its cooling requirements are met with a sectioned cold plate with each chip in the arrangement having their own individual flow conduits. The dimensions of the cold plate were parameterized within the basic design constraints. An optimum design of the flow guide was used to address the mal-distribution of the flow for the present impingement of the flow arrangement. The design was also studied for

various dimensions of commercially available barb fittings at the inlet for various flow rates. The results calculated, using CFD, showed significant improvements over the conventional cold plate and the operating conditions of the MCM were efficiently maintained.

TABLE OF CONTENTS

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

1.1 Overview:

In this new millennium, power electronics are extensively used to efficiently generate, transmit and deliver power to homes, the appliances used at home, for transport and many other applications. Innumerable numbers of applications are now using power electronics to efficiently deliver energy, and given their higher reliability and control it is safe to say then in another 10-15 years, power electronics will find a part to play in all electronic applications.

The exponential growth of electronics and their use commercially since 1995, combined with the need for better power dissipation and system cooling, has in-turn caused the need to come up with better cooling technologies at affordable costs that are viable for commercial packing. Ever since the invention of Integrated Circuits (IC), there was a clear drift in the industry, where more and more of the electronic system would be integrated on to one tiny silicon chip. Moore's Law states that the number of transistor in an IC doubles every 18 months, and this goes to show what an incredible impact ICs have had in the electronics industry. ICs are now an integral part of virtually all the electronic equipment today, starting from computers to mobile phones and even the day-`to-day household appliances.

The high power electronics have huge high heat flux demands on the cooling system, making it imperative that they have an efficient cooling system. Although previously, air-cooling used to suffice for the low energy electronics, the new faster and more powerful system require a more advanced cooling system. With the advances in micro fabrication techniques and high performance chips, the heat flux from electronic components is reaching a point where air-cooling is unlikely to meet the cooling requirements for future generation computer chips.

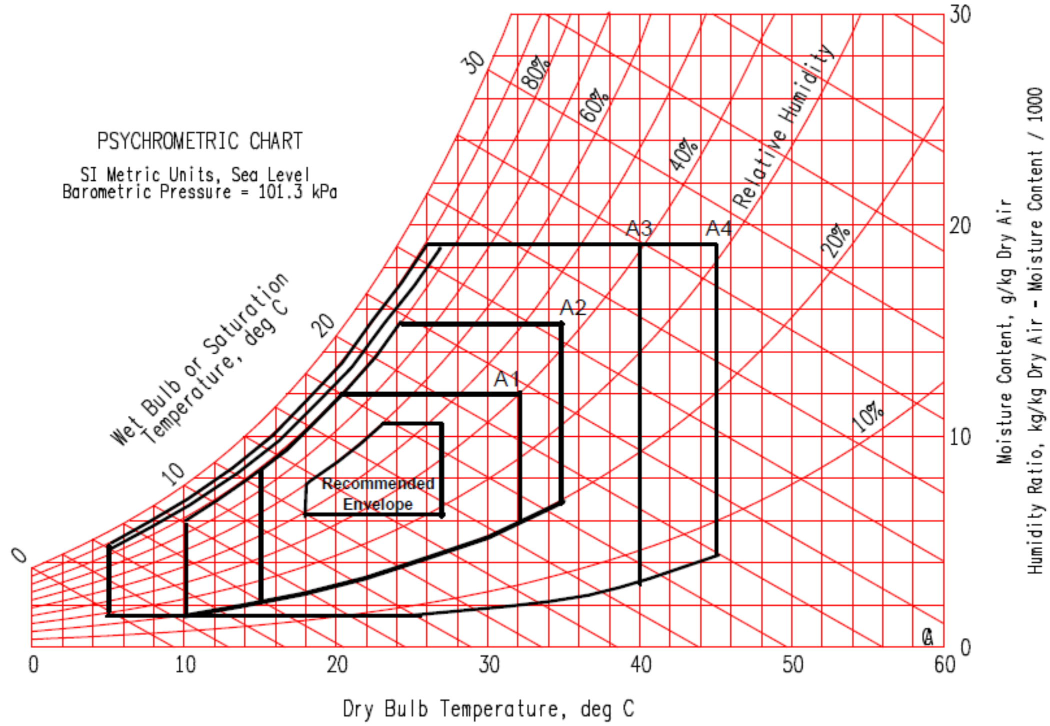


Figure 1.1 shows the functional limits of the electronic devices

1.2 Functional limits of Electronic Devices:

Any electronic package, irrespective of how they were packaged, have the following the limits as shown in the picture below fundamentally in terms of the component temperature. The reliability limit where, the package is optimized for the cooling technology installed and, the performance of the devices is not compromised. Then, there is the functional limit, within which the performance of the electronic device is peaked and, it is mandatory for a thermal engineer to bring it back to the reliability limit by efficient design of the cooling system. The third and, the last is the damage limit where the complete shutdown of the electronic device will take place damaging the components irrevocably. As mentioned earlier, this holds true for any electronic device and, it is rather important to understand these limits of each device before going ahead with its thermal management.

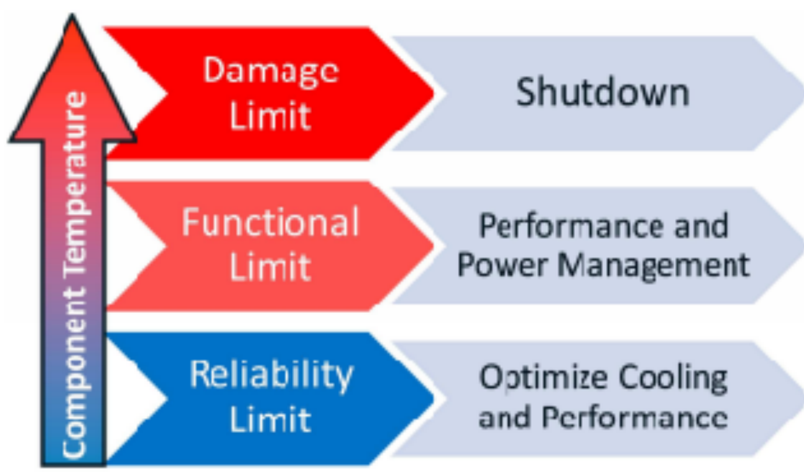


Figure 1.2 shows the component temperature limits

1.3 Evolution of Electronic Packaging:

With increasing functionality of the electronic devices increasing every day, the number of Input/output (I/O) connections increased and, thereby increasing the power associated. From the packaging stand out, it is imperative to design in such a way that the full potential of the semiconductors are met in its functionality. Through the history, the developing packaging techniques in it led a path of the efficient management of its functionality. The replacement of vacuum tubes by transistors at a point when the heat generated from the vacuum tubes were reaching the damage limit of the electronic devices. Later, CMOS technology replaced transistors and, the functional limit of the electronic devices increased. However, there was point when this limit was tested with the increasing power of the CMOS technology and, IBM came up with its Thermal Conduction Module (TCM). The picture of which is as shown below.

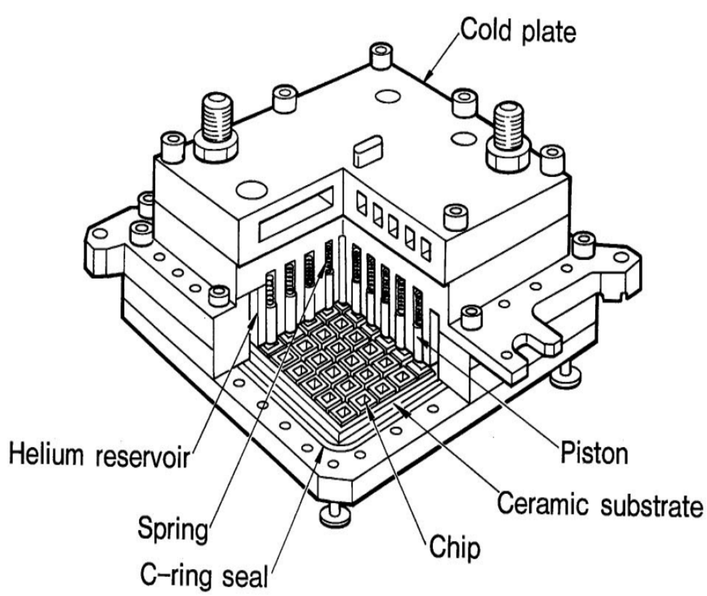


Figure 1.3 shows the IBM Thermal Conduction Module (TCM)

It was the earliest liquid cooled package. Also, the work was pioneering of sorts for the latest and, advanced liquid cooling technologies. Then, as the CMOS reached its damage limit, it led to the advent of Bi-polar devices and, air-cooling sufficed. The evolution of the CMOS and, the bi-polar devices with their modular heat fluxes are shown in the picture above.

Today, with all the intricate and, extreme applications of the electronic devices, these devices are at a point where, alternate ways to effectively keep the device in the functional limit is looked at which includes but not limited to spray cooling, multi-phase cooling and, liquid cooled cold plates. In this research, one such electronic package is considered and, effective ways to keep it in the operational limit are looked at and, optimum range is proposed using a water-cooled sectioned cold plate.

CHAPTER 2

LITERATURE REVIEW

With the increasing power of the bipolar devices in the 1980s, alternate and efficient cooling systems were looked at. One of the earliest and first applications of liquid cooled electronic package was IBM 3081 Main Frame computer introduced in the year 1982 with a water cooled Thermal Conduction Module (TCM). [1] This was around the time when the power packed into the bipolar devices was increasing exponentially. However, with the advent of CMOS in the early 1990s, air-cooling was considered to both energy and, cooling efficient. However, with the increasing demand of high-powered electronics, finding its feet in various applications, the CMOS technology couldn't prevent the increasing high power in the electronic devices and, alternate techniques of efficient cooling become imperative. [2]

Specifically, relevant to this research, some of the early foundations of Multi-Chip Module (MCM) thermal cooling system using liquid cooled cold plates were studied and implemented at IBM by Oktay and Kammerer [3] and Chu et al. [4]. Their works were breakthrough research in liquid cooling. It is also to be believed that this multichip module is still in use at IBM. Kishimoto and Ohsaki [5], in their paper designed a liquid cooled cold plate for VLSI Chips. In their work, they used twenty-nine 800 μm × 400 μm rectangular minichannels over an 85 mm × 105 mm substrate made of aluminum. Their design was to accommodate sixteen 25 W chips, combining to total heat dissipation of 400 W. This design was comparable to various immersion cooling techniques available at that time. Also, the package was assembled in stacks so as present a compact design for the MCM. Not only the liquid cooled cold plates configuration for this design proved to successful but also better than most liquid cooling design with significantly higher cooling rates. Further, the authors went on present an analytical solution to ensure the uniform distribution of flow through their channels. These two works, coupled with other developments over the course, form the basis for the present day cold plate design for high-powered electronic devices.

Further, at present, there are multiple techniques to efficiently manage the thermal systems of these high powered devices are in use such as single-phase liquid, air, jet impingement, pool boiling and flow boiling are employed. A detailed study of these techniques and, their comparisons are excellently presented by Anandan and Ramalingam [1] to better understand the cons and pros of each technique. In his research, Roux [2] studied the effects of different channel inserts, including copper fins and graphite foam, on the thermal performance of the heat sink. The authors carried out Computational Fluid Dynamics (CFD) analysis to provide the rank of order of these techniques. Also, they went on to show, for their design, that the smaller channel sizes yields much better thermal performance. Such design optimizations coupled with overall pressure drop are needed to effectively design the cold plate configuration for high-powered electronic devices.

Most of the modern day literature on using the water-cooled cold plates is focused on low power electronic-devices. As the power of these electronic devices increase, liquid cooling will be a cost-effective novel technique. Some of the other techniques that are studied include spray cooling, jet impingement, advanced single and two-phase micro-channel cooling, as shown in the papers. [8]

For high power applications, generally it is suggested that the cooler the devices, better the operating performance of the device, i.e., at higher operating temperatures, these devices will conspire power transients, triggering signals, noise and, localized heat effects leading to the failure of the devices. [9]. Generally, for the high-powered silicone devices, the rule of thumb is that beyond 50°C, with every 10-15°C increase the failure of the device doubles. [10]. Recent publications indicate the use of water-cooled cold plates for high power electronic devices provide sufficient savings in energy. [11]. Also, the use of CFD to effectively improve the design of existing cold plates is common.

Most of the literature around the high-powered electronics focused on effective cooling techniques using a single cold plate over the non-uniform distribution of heat flux. In the current study, ways and means to use a sectioned cold-plate over the non-uniform heat distribution and their design optimization are considered.

CHAPTER 3

DESIGN OPTMIZATION AND SECTIONED COLD-PLATE

3.1 Introduction to MCM:

A multi-chip module (MCM) is an electronic package is wherein multiple chips are populated onto a single substrate. Each chip will have it own heat flux and, combining together to a limit making an efficient cooling system in place to be mandatory. A classic MCM is as shown in the picture below. As seen in the picture, the colored parts on top of the substrate are the chips. The cooling system should be designed in a way to take away the heat from the package and, keep the device to its functional limits.

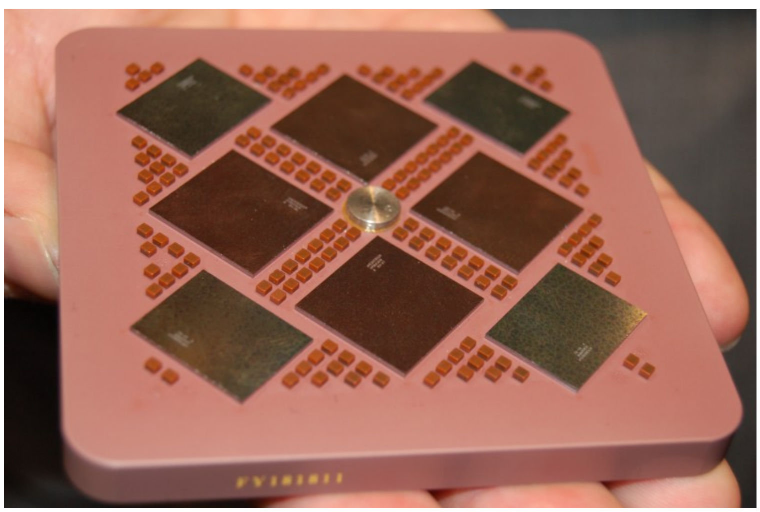
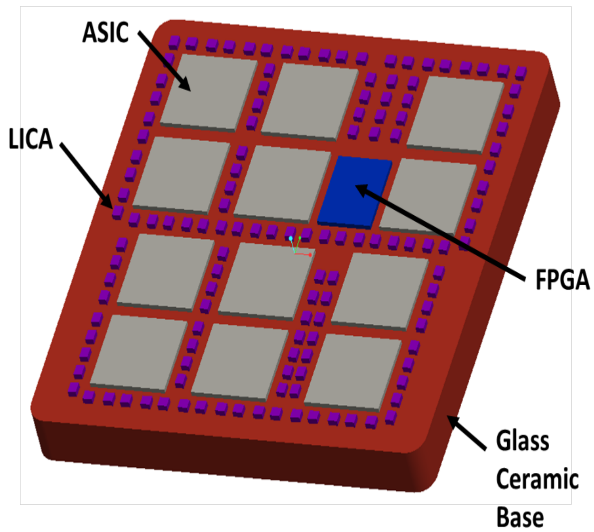


Figure 3.1 shows the basic structure of a Multi-Chip Module (MCM)

3.2 Reference MCM:

In the present study, a reference MCM is considered. The fundamental structure of the MCM used in the study is as below. The MCM has a total power dissipation of 480 W over a 78mm X 78 mm substrate. The power dissipating parts of the chips are listed in the table below.



Component	Quantity	Power (W)
Base	1	-
ASIC	12	40
FPGA	1	5
LICA	137	-

Dimensions (in mm)
ASICs – 14.71 × 13.31 × 0.8
FPGA – 10.5 × 12.7 × 0.8

Figure 3.2 shows the CAD model of the reference MCM used for this research with its specifications.

The effects of FPGA are small as compared to other power generating sources in the model and, hence not considered in this study. The design of the cold plate is one of the major studies in this research. For the proposed MCM, the power generating sources are non-uniform and, through the substrate. Hence, for this design, a concept of sectioned Cold-Plate is proposed. The sectioned cold-plate is placed over the top of the substrate such that, each section has its own and inlet and, outlet conduits. The dimensions of which are used from the commercially available barb fittings, keeping in mind the later experimental procedure. The design of the cold plate over each section is kept uniform with the same channel configuration through out. The sectioning of the cold plate is done as in the following image and, hence will be addressed using their section names.

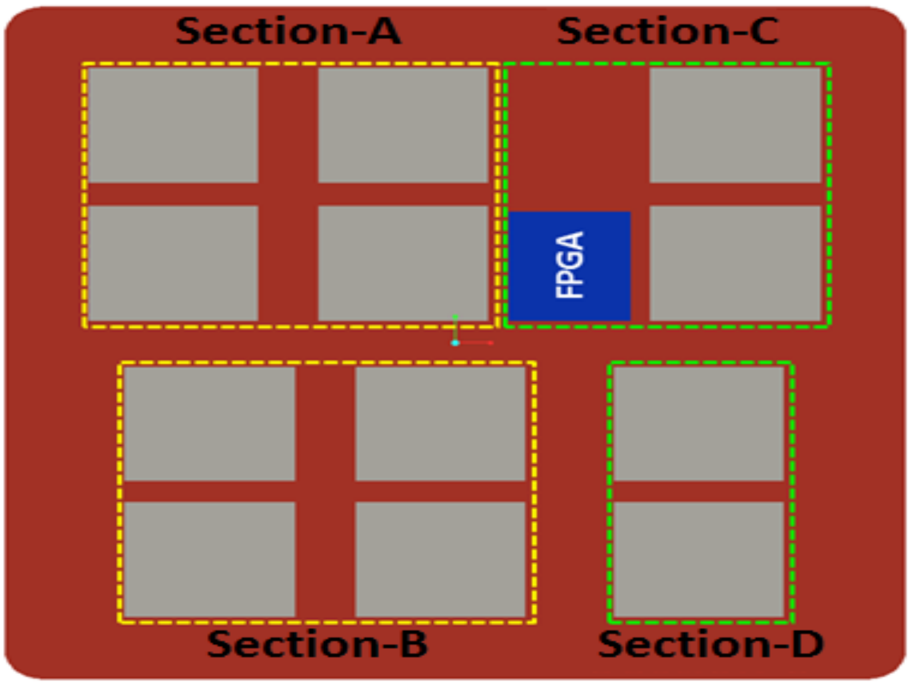


Figure 3.3 shows the sectioning of the base substrate

3.3 Flow Maldistribution:

To enhance the flow and, to avoid the flow maldistribution, a trapezoidal configuration is suggested through the center of each of the channels. The trapezoidal configuration is checked for various aspect ratios and, an optimum range of aspect ratio 1:2 is finalized.

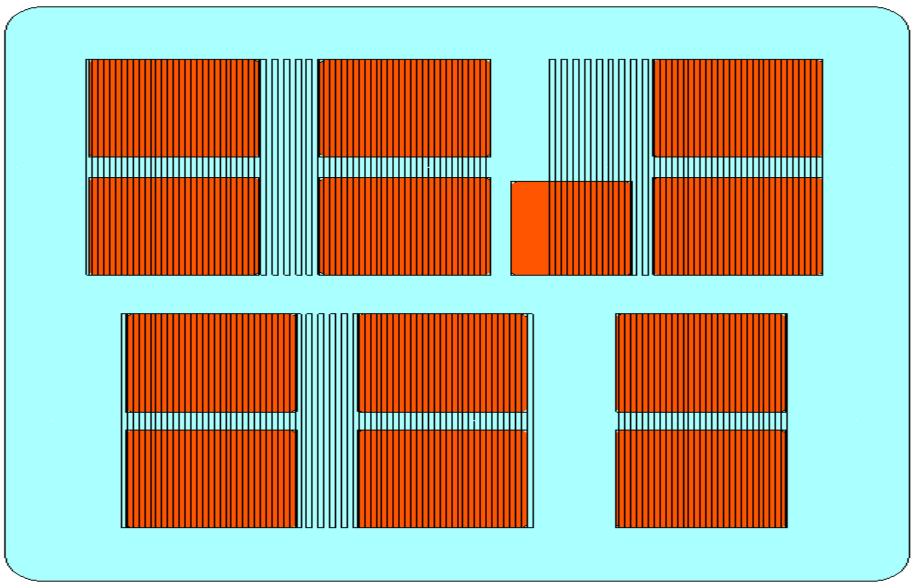


Figure 3.4 shows the sectioned cold-plate

It is important that for the effective performance of the proposed design, that flow is uniform through the channels. This is achieved through the trapezoidal configuration. This is indicated in the picture below with the trapezoidal section through which the flow is made to pass through. As seen in the image, each section has its own inlet and, outlet with the sectioned cold plate. The side view of the entire package is also shown in the Figure 3.5.

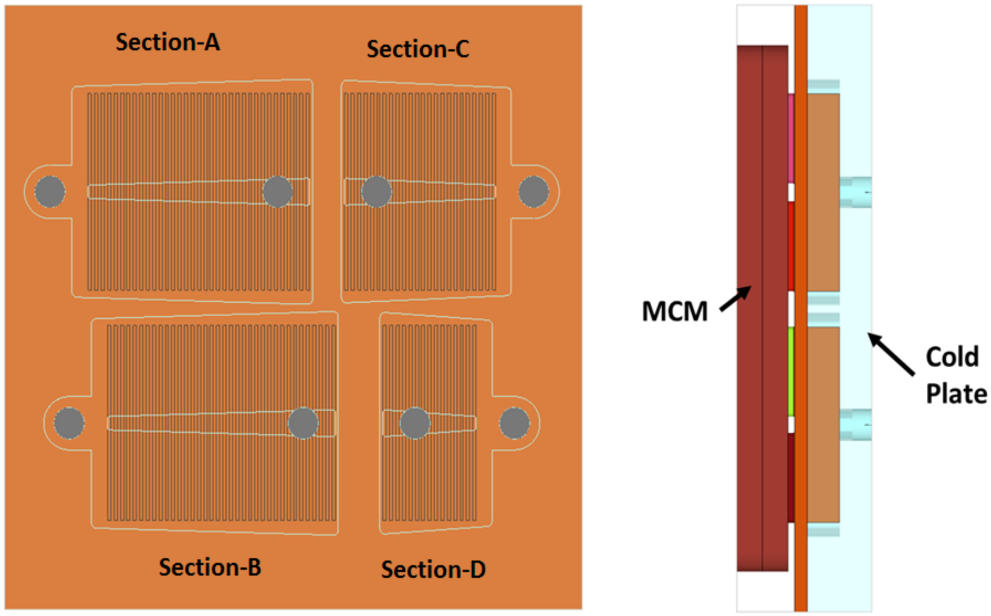


Figure 3.5 shows the trapezoidal flow guide and, the side view of assembly.

The design of the cold plate, in itself, was challenging. Given the design constraints of the MCM model, the cold plate is optimally design with so and so channel configuration over the model. Using the available literature, the design is finalized and, used for further study. As mentioned earlier, this configuration is kept uniform throughout the design. Varying dimensions of these are constrained and the thickness of the isolating wall.

The non-uniform distribution of the power is clearly seen. The challenge is to effectively model such a configuration. The CFD modeling should include all the necessities to be able to accurately predict the thermal performance of the design.

The complete assembled MCM is as shown in the figure. As seen in the picture, the bottom of the surface on the right is the substrate, which contains the power densities. The cold plate and the cover on the left form the rest of the assembly. The MCM was designed and, parameterized for various configurations using PTC Creo.

3.4 Meshing:

The meshing was carried out using Pointwise. The in-built Glyph scripting in Pointwise was used to do the meshing for the base model and, was later used for other design configurations too. The mesh was found to be grid-independent at around 1.9 million cells approximately for all the models used in the simulation with the maximum skewness ratio of 0.9, which is in the allowable limit.

3.5 Solver:

To accommodate for the non-uniform distribution of the power densities, ANSYS UDF was used to model it. UDF is a powerful tool, especially, to incorporate such non-unifrom boundary conditions. The pumping power of the model was also fixed at xxx using UDF. The simulation was carried out using Laminar-Viscous Model with standard pressure discretization using Fluent. The convergence criteria were set at 10e-6. To test and, validate the model, the simulation was carried for various flow rates.

CHAPTER 4

RESULTS AND ANALYSIS

4.1 Case 1- 0.5 in:

As mentioned earlier the simulations were carried for two different cases of the inlet and, outlet barb diameters. The following graphs are obtained for the inlet and outlet diameters of 0.5 in and, are as indicated.

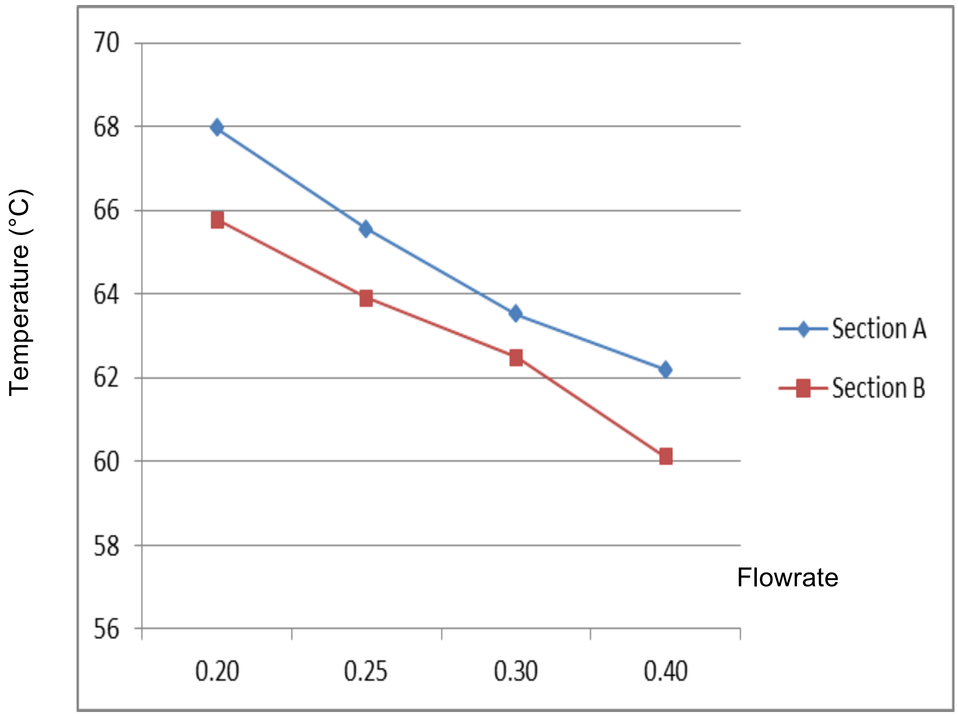


Figure 4.1 shows the graph for Flowrate Vs Temperature for Sections A and B.

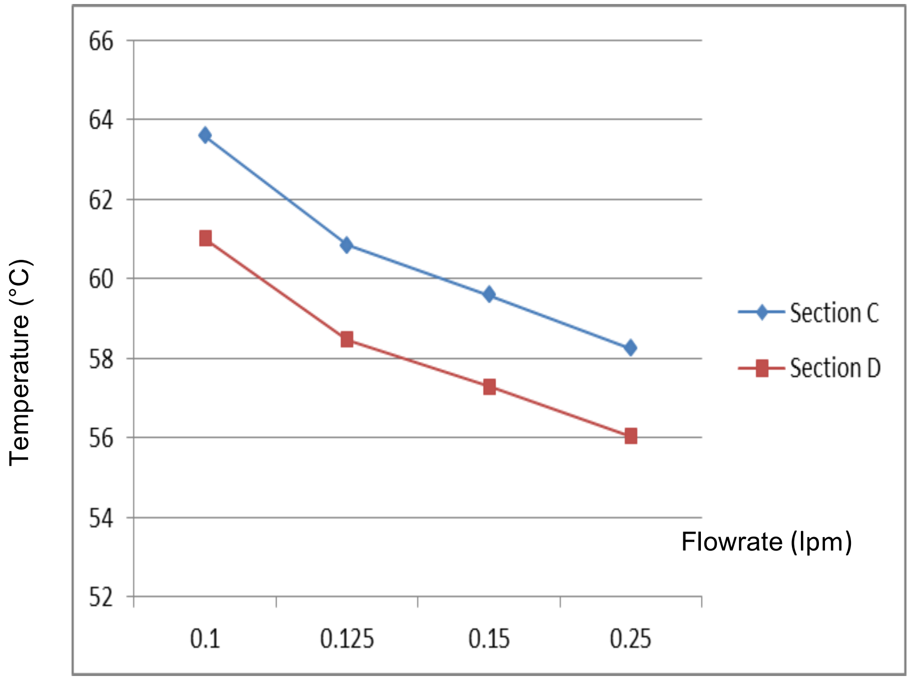


Figure 4.2 shows the graph for Flowrate Vs Temperature for Sections C and D.

The graphs show the maximum temperature within various sections for various flow rates. The flow rates were increased from 0.20 to 0.40. As seen in the graphs, the operational limits of the devices is effectively maintained through efficient design of the cooling system. The following graph shows the pressure drop vs flowrate through the complete pacakge for all the secitons. As expected, the pressure drop across the sectiones B and C are much lower than the Sections A and B. This can attributed to their smaller flow channels owing to their lower heat fluxes as compared to Sections A and B. The pressure drop across sections A and, B, as expected, higher pressure drop owing to their larger section with multiple heat generating units. This pattern is in excellent match with the literature confirming the effective design of the cold plate over these sections. As mentioned earlier, the pressure drop was also calcualted for various flow rated for this case and, the graph of which is as shown below.

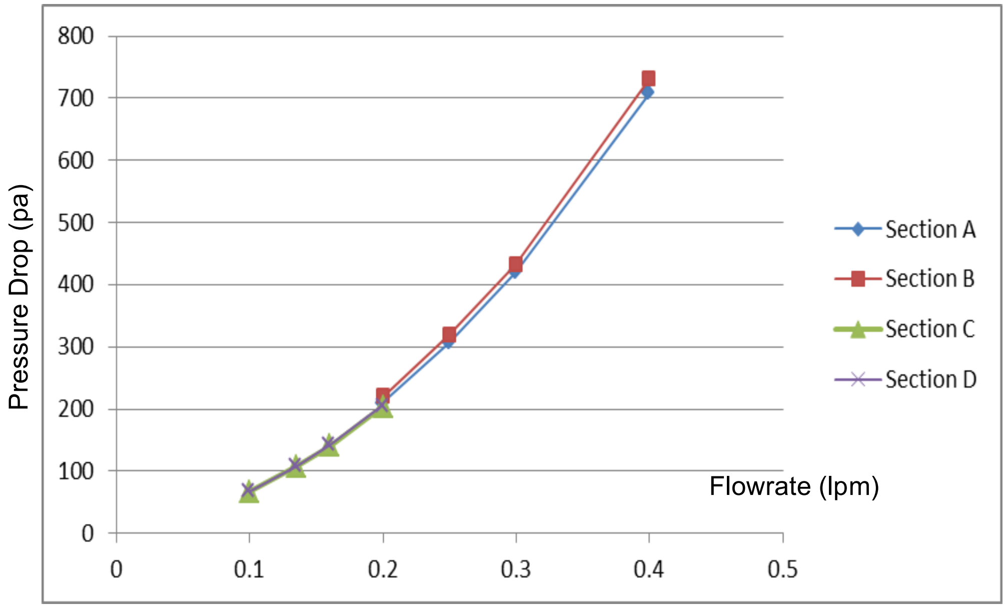


Figure 4.3 shows the graph for Flowrate Vs Pressure Drop for all sections.

4.2 Case 2- 0.3 in:

This case is simulated for the inlet and outlet diameter of 0.3 in and, the graphs obtained are as indicated on the next page:

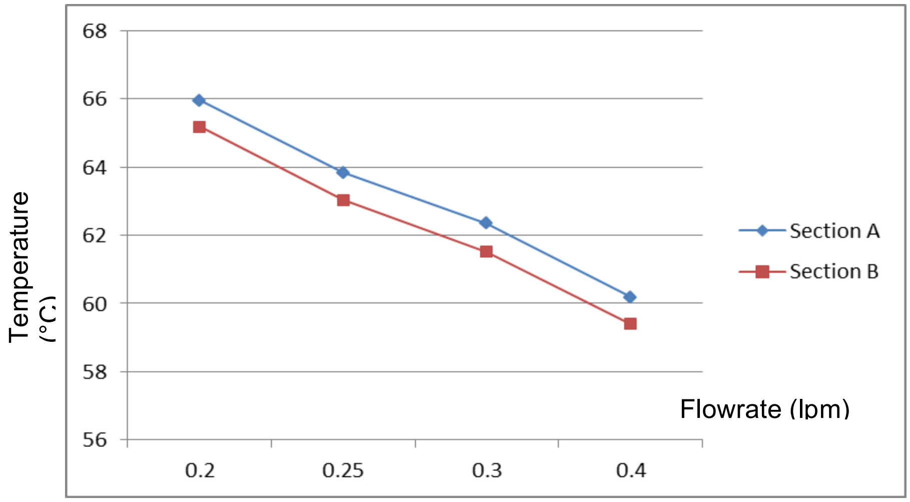


Figure 4.4 shows the graph for Flowrate Vs Temperature for Sections A and B.

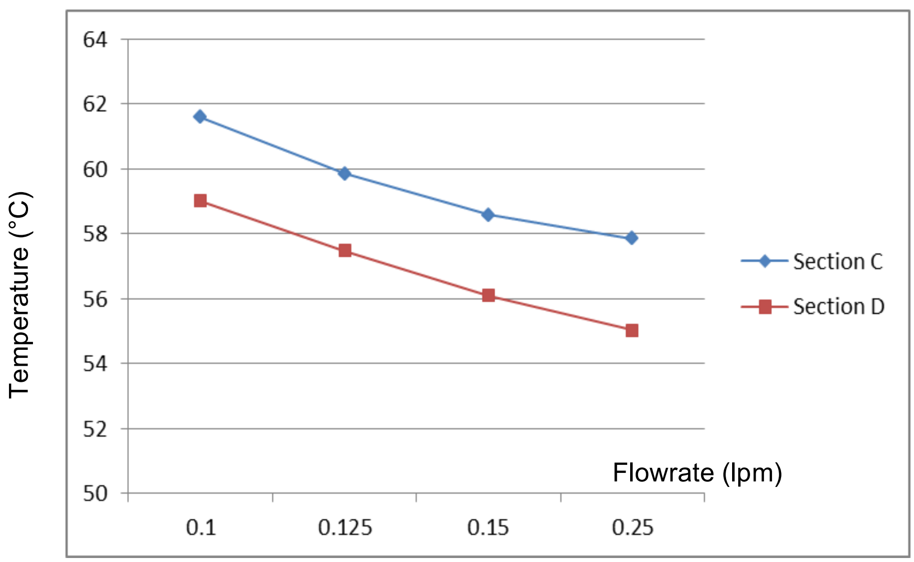


Figure 4.5 shows the graph for Flowrate Vs Temperature for Sections C and D.

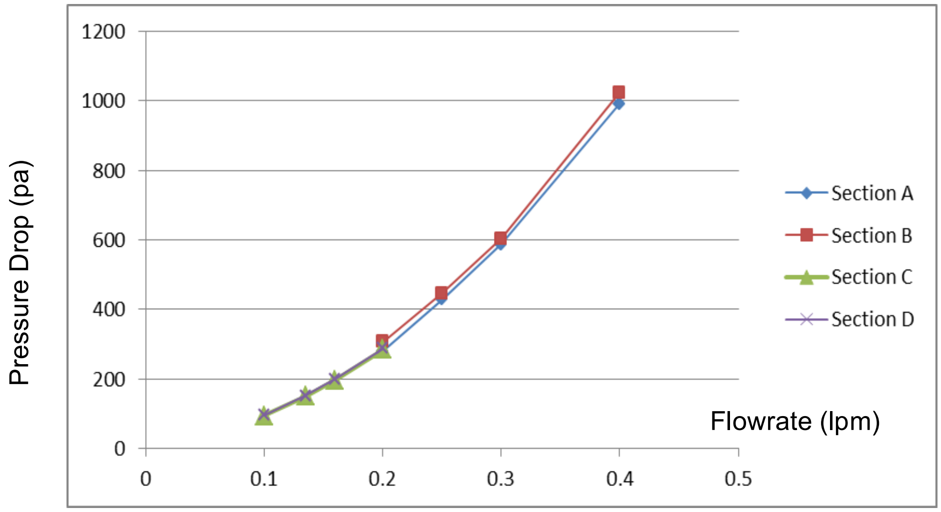


Figure 4.6 shows the graph for Flowrate Vs Pressure Drop for all sections.

As in the previous case, the maximum temperature and, the pressure drop for this case is well within the operational limits of the device. This design of the cold-plate for the MCM shows considerable improvement over the original cold-plate.

4.3 Discussion: The objective of this research was to efficiently manage the thermal aspects of a MCM. The reference MCM used in this research is commercially used and, managed with a single cold-plate through the substrate. This design was improved upon in this research with a sectioned cold-plate with individual inlet and outlet conduits through each cold plate. Further, to avoid the maldistribution of the flow through the channels of the cold-plate, a flow guide in trapezoidal form is introduced. The final design of which was optimized to an aspect ratio of 1:2 leading to equal distribution of the flow through the channels. This trapezoidal flow guide was used through all cold-plates with the similar aspect ratio. Also, the design was also tested for different inlet and outlet barb units showing significant improvement over the original cold-plate.

The design was successfully able to maintain the operating limits of the MCM efficiently and effectively. The segregated flow coupled with the flow guide ensured proper distribution of the flow and the fluid characteristics were significantly improved over the original cold plate. The design was tested for different barb fittings resulted in improved performance. The overall thermal performance and, the power saved is significant over the original cold plate design.

CHAPTER 6

FUTURE SCOPE AND RESEARCH

The current design had been tested and, solved computationally. In the future, carrying out experiments can support this research. Also, the design can be further enhanced and, improved by testing the design using other refrigerants. Further, the design of the cold-plate, in itself, can be optimized for other design constraints. The concept of sectioned cold plate can be extended to other electronic devices and, tested.

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BIOGRAPHICAL INFORMATION

Ananthavijayan Sridhar completed his under-graduation in Anna University, Chennai, India with Bachelors in Aeronautical Engineering. He then went on to pursue his Master's degree in Mechanical Engineering in 2013, at the University of Texas, Arlington, where he worked in Dr. Dereje Agnofer's team on several Computational Fluid Dynamics projects as well as some industrial projects. He has always been passionate about CFD and Electronics industry, and after completing advanced courses on CFD, Thermal Management and Electronic Packaging, he successfully completed his research and defended his graduate thesis in Liquid Cooling of a High Power Multi Chip Module using a Sectioned Cold Plate.