THERMAL MANAGEMENT OF HIGH POWER MULTI CHIP MODULE BY DESIGN OPTIMIZATION OF SEGREGATED SERPENTINE FLOW COLD PLATE

by

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ABSTRACT

THERMAL MANAGEMENT OF HIGH POWER MULTI CHIP MODULE

BY DESIGN OPTIMIZATION OF SEGREGATED SERPENTINE

FLOW COLD PLATE

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Data center environment cooling requirements became a challenge with rapid increasing microprocessor power densities which leads to non-uniform distribution of temperature. A practical cooling solution which relies on the segregated flow of cooling resources based on power density for thermal management of high power equipment is introduced. This minimizes energy consumption of cooling infrastructure. Performance of existing cold plate is previewed and amount of savings possible is shown from numerical analysis of segregated model. Model is designed by considering manufacturing feasibility to make samples for proposed solution for future experimental study. A multi-chip module is chosen as a base for design of solution. Details of design and modelling of analysis was included.

The designed segregated model reported low Thermal impedance and less pumping power requirement and uniform temperature distribution across the MCM. Advantage of scalability for Various foot prints of multi-chip microprocessor.

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Chapter 1

INTRODUCTION

Microprocessors evolved to every field of day to day life from past decade. Drastic increase in power density changed the strategies of cooling system design for electronic components. Thermal analysis became the dominant element in design of electronic packaging and its maintenance. Failure to satisfy the thermal specifications and maintaining maximum temperature in operating range cause catastrophic failures.

It is necessary to measure max junction temperature in each component of large multi-chip module and make sure it is maintained in thermal specification required. Many techniques like air cooling, liquid cooling and Immersion cooling were practiced depending of feasibility and cost.

Due to varying power densities of functional units in high power multi-chip modules, using conventional cooling methods needs high thermal budget to design entire system for high maximum temperatures and reliability of these components is limited. These functional units work at high efficiency when used under full load conditions which leads to high temperature spots in specific locations of chips which are called hot spots. The primary requirement of future cooling solutions is to selective distribution of cooling resources to maintain uniform distribution of temperature with max temperature within thermal specifications at low cost.

Cold plate is a device which is similar to heat sink in which a fluid flows in channels of a metal block and carries the heat out of the system. Cold plates are made of copper materials with multiple layers brazed to prevent fluid leakages.

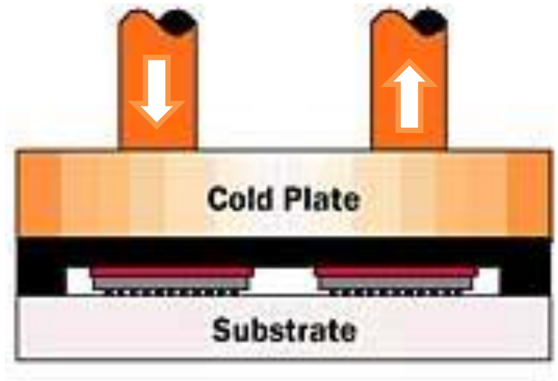


Figure 1-1[1] Example of a Basic cold plate layout in electronic cooling. .

1.1 THE CONCEPT

To obtain the above mentioned requirements the conventional cold plate is segregated into sections depending upon the power map below the cold plate base. Each section has independent inlet and outlet. Using the maximum power load underneath each section magnitude of flow that needs to be distributed is determined for cooling requirement. This segregation of cold plate can be scalable to any footprint and power load.

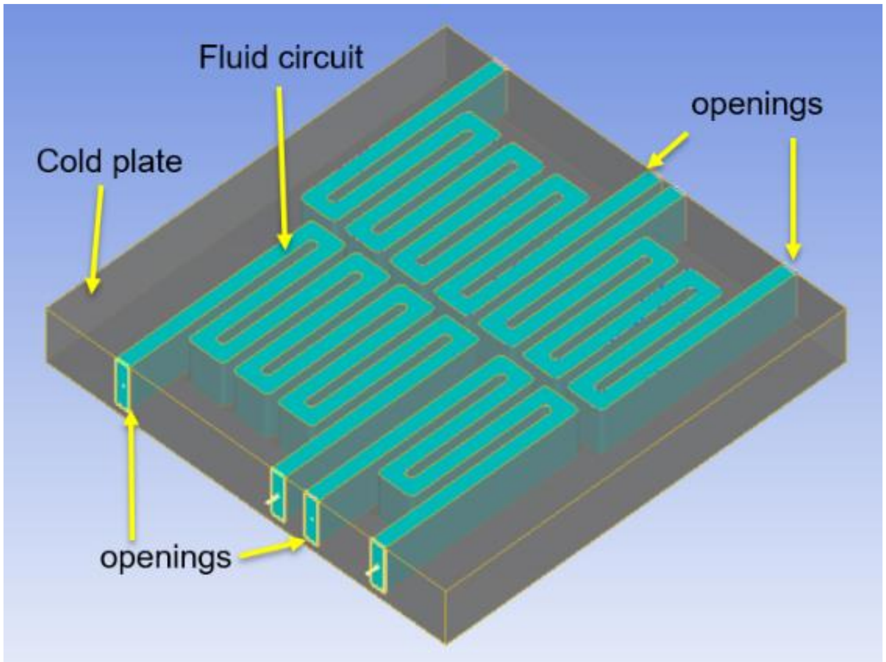


Figure 1-2 3D-Model of segregated cold plate.

1.2 REFERENCE PLATFORM

To base the segregation concept of cold plate, a reference high power multi-chip module is required. The Endicott Interconnect Technologies Inc.[2] provided MCM is used as a reference purpose. The module has thirteen surface mounted heat generating functional components with maximum power dissipation of 485watts over an area of 78mm x 78mm foot print. Description of components can be seen in table1. ASICs(Application Specific Integrated Circuits) and FPGA(Field-Programmable Gate Array) are only significant contributors of heat on given Module. The dimension of ASIC is 14.71mm x 13.31mm x 0.8mm and FPGA is 10.50mm x 12.70mm x 0.8mm. Other components which do not dissipate significant amount of heat are ignored for the study.

The cold plate used for study is a 92mm x 92mmx 12mm copper body with single point of ingress and egress of coolant. Serpentine flow Internal circuiting is been considered for study.

Table 1 Details of MCM components

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

1.3 LITERATURE REVIEW

High power electronic equipment is experiencing a shift from air cooling to liquid cooling over the last decade. Many complicated devices are having high power density which cannot be cooled by air due to complexity of shape and high cost to maintain specified working temperatures [3]. Liquid cooling has many advantages over air like high heat carrying capacity, recyclable resources and less space. Detailed review on management of high power devices using cold plates in [4]. A methodology for optimization of cold plate with multi variable parameters is discussed by Fernandes Et.al in [5], where he programmed a function to control flow rate of cooling liquid to maintain Maximum junction temperature in specific range. Fernandes et.al [6]discussed many designs to improve performance of cold plates. Remsburg [7] reported reduction in pumping power using impinging heat transfer due to reduced pressure drop.

The study reviewed are optimizing the flow rate and design of flow distribution to reduces the pumping power, In this solution we have serpentine internal flow segregated cold plate sectioned based on power map underneath the cold plate to obtain uniform temperature for avoiding hot spots in multichip microprocessors. Ansys Icepak a CFD tool is used to model a single serpentine flow cold plate and a segregated serpentine flow cold plate and analyzed to compare the performance parameters.

1.4 SEGREGATION OF COLD PLATE

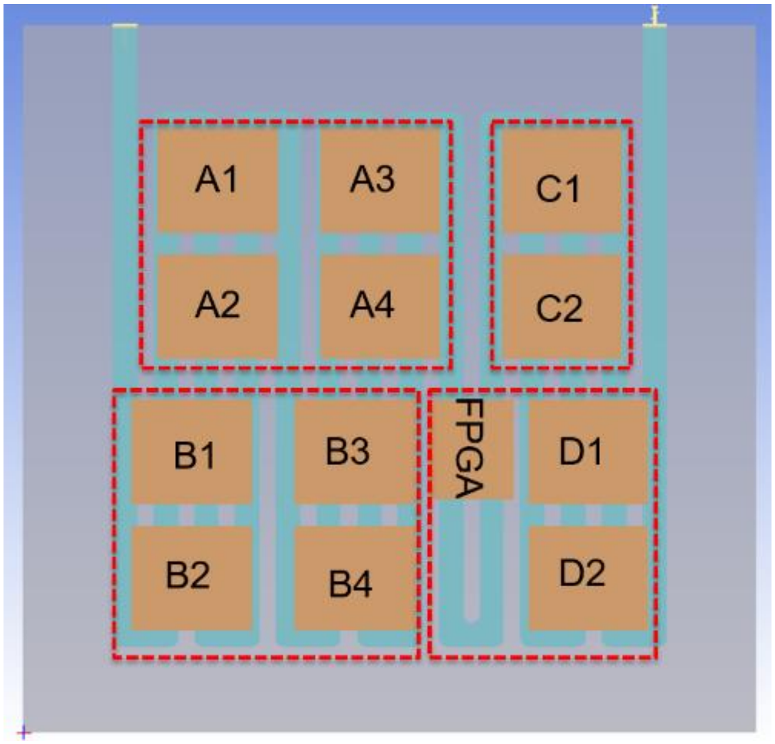


Figure 1-3 3D-model of Reference MCM showing sections

Based on heat dissipation of each component on the module the cold plate considered is segregated into four sections based on proximity as seen in Figure 1-4.

Sections are assigned as A to D and components in each section are named as shown above . Section A and B have each four Application-Specific Integrated Circuit (ASIC) each with 40Watts maximum heat dissipation accounting for 160W each. Section D additionally accommodates Field-Programmable Gate Array (FPGA) of 5 watts maximum power making it different from section C which has two ASIC's accounting for 80Watts.

This sectioning is considered as per the reference multi-chip module component dimensions and proximity. Sectioning can be considered in many ways which can satisfy the flow of cooling liquid distribution to maintain uniform temperature gradient.

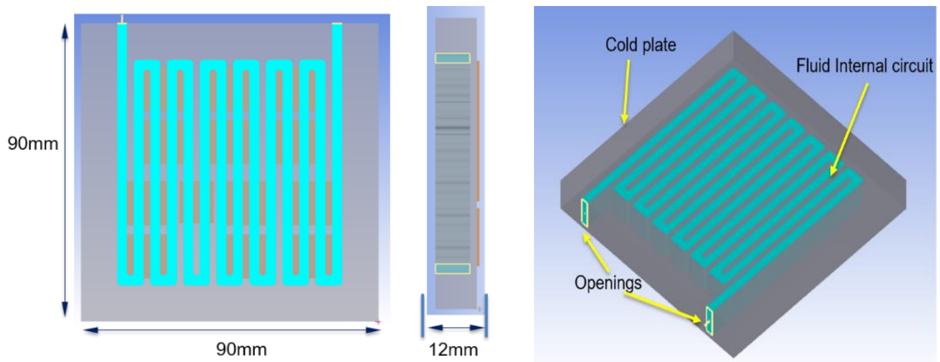
Chapter 2

MODELLING AND ANALYSIS

2.1 MODELLING THE BASE MODEL COLD PLATE

A numerical model is proposed and solved using commercial Computational Fluid Dynamics (CFD) software which uses finite element method for discretization For solving the set of governing equations for the problem using classical mathematics under the assumptions and boundary conditions.

As per reference module a cold plate base model design with serpentine flow can be seen in Figure 2-1.Channel width and height are designed considering manufacturing feasibility and from literature survey [6].There is a single inlet through which liquid at low temperatures enters the serpentine flow channel and passes through the conduit taking heat from the walls and base of cold plate. Liquid goes out from cold plate from an outlet at the end of serpentine flow channel . The cross section of channel is maintained constant throughout the flow including inlet and outlet. The overall dimension of cold plate is 90mm x 90mm x 12mm whereas height of channel was 10mm and a base of 1mm thick is in contact with the heat dissipating array of chips of MCM at the bottom of cold plate.



(a) (b) (c)

Figure 2-1 3D-model of Single serpentine flow cold plate(a) Top view, (b)side view, (c)Isometric view

The designed serpentine flow channel covers all the array of chips uniformly so no component is left uncovered by the Serpentine channel. Copper material is considered for the solid part of the model while water at initial temperature 32ºC is considered for cooling liquid flowing in the channel.

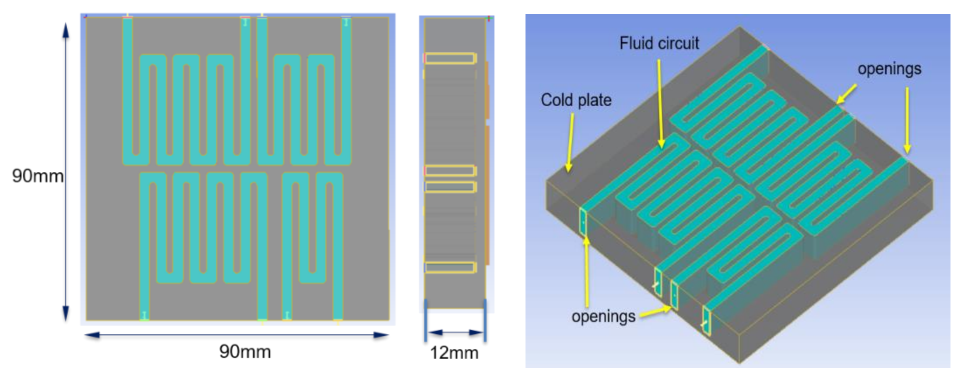
Table 2 Details of Cold plate and serpentine channel

Parameter	Value
Size	90 mm × 90 mm × 12mm
Channel width	3.0mm
Height	10.0mm

2.2 THE SEGREGATED COLD PLATE MODELLING

The suggested segregated model of cold plate is modeled with same overall dimensions as of base model and channel width and height are similar as shown in Table 2. The single serpentine flow in base model was now segregated into four sections as per the proximity of power map underneath the cold plate.

As per the reference MCM considered we have four independent sections. Each serpentine flow is independent of other and have one inlet and one outlet. The location of openings for each sections is designed so that cold water will be entering channel where the adjacent section hot water exits from outlet.



(a) (b) (c)

Figure 2-2 3D-model of segregated serpentine flow cold plate(a) Top view, (b)side view, (c)Isometric view

2.3 NUMERICAL AND CFD ANALYSIS

The above idea can be verified for its credibility using a CFD software which can solve continuity, Navier strokes and energy equations using control volume discretizing methodology and calculate the velocity, pressure and temperature of each component in the enclose. Ansys Icepak is efficient in time and more practical tool specifically designed for fluid flow in enclosures[8,9].This is very practical when used for multiple solutions of same model with varying input parameters.

Solver in Icepak is Fluent which is based on Finite element method[8]. The problem is solved step by step by Initial post processing and meshing, processing and obtaining the solution, post-processing the results.

Meshing is a method of generating set of finite elements by discretization. The finer the mesh, accurate the solution obtained. More the number of elements higher the processing time to solve the problem. To obtain a compromise between accuracy and in practical efficient time mesh sensitivity study is performed.

2.3.1 MESH SENSITIVITY ANALYSIS:

In every CFD study mesh sensitivity is essential factor to assure the results obtained are independent of grid count and density. Refining the grid, Increasing in number of cells gives 3% variation in results at 1.8 million grid count. This agrees with Linton and Agonafer [10] where they explained the conformal and non-conformal mesh to reduce the grid count without effecting the results. The slack of 1mm is used to create a bounding box around the cold plate and heat source assembly which is larger than assembly by 1mm on five sides. Bottom slack is zero as cabinet is in contact with bottom side. This box is then meshed separately with fine grid.

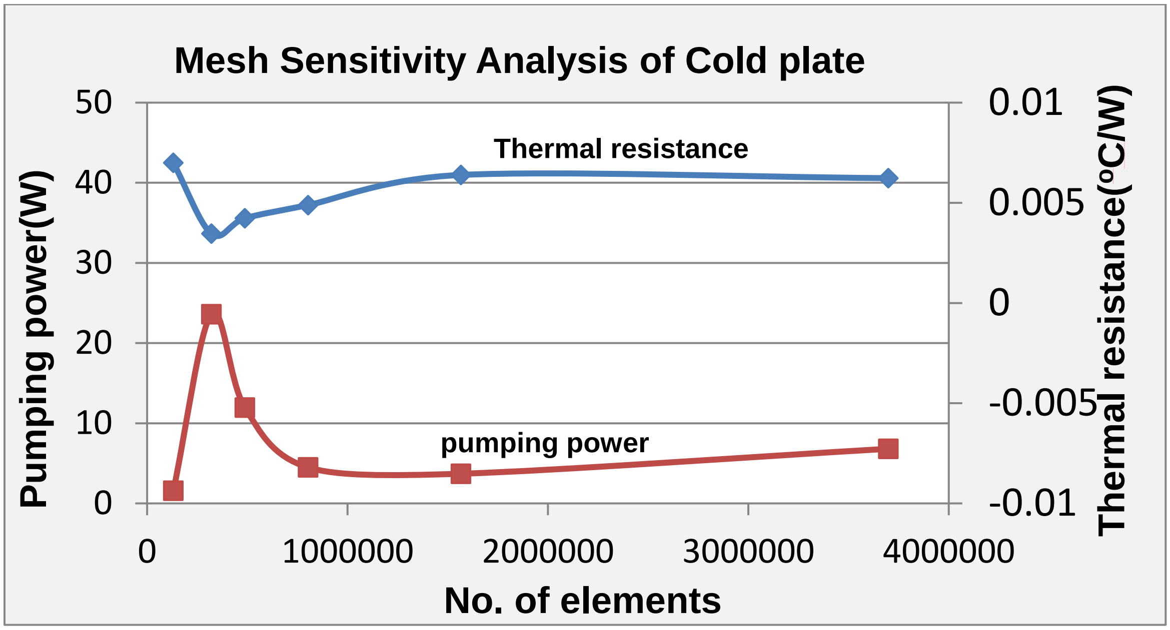


Figure 2-3 Graph of Grid elements to pumping power and Thermal resistance

Thermal resistance and pumping power are monitored for mesh sensitivity study. From the Graph It can be seen that both Pumping power and Thermal resistance converges at about 1.5million number of elements. For further analysis, the grid count of 1.8 million is considered for both the models.

2.3.2 BOUNDARY CONDITIONS AND ASSUMPTIONS:

To Simulate the experiment in a CFD software Boundary conditions are used to create an environment of the experiment. Boundary conditions are given in Icepak where we can create the material with user defined properties as original cold plate material. The solid regions which include all layers of cold plate and walls are assigned with tellurium copper material with thermal conductivity 354.8W/(m-k) and a density of 8940.6kg/m^3. Cooling liquid used for the study is water at 32^{o}C with a thermal conductivity of 0.6W/(m-k) and density of 998.2kg/m^3.

Table 3 Icepak Analysis material properties and boundary conditions

Component	Property or boundary condition	Assigned value
TeCu (solid regions)	Thermal conductivity (k_{Cu})	354.80 W/(m-K)
	Density (ρ_{Cu})	8940.61 kg/m^3
Water (fluid region)	Thermal conductivity (k_{Wa})	0.6 W/(m-K)
	Density (ρ_{Wa})	998.2 kg/m^3
	Dynamic Viscosity (μ_{Wa})	0.001003 kg/(m-s)
Inlet	Velocity@ 2lpm flow rate	1.13778 m/s (initial)
Outlet	Pressure	0 N/m^2

The boundary conditions for inlet is defined as velocity inlet which varies with case to case as per the flow rate and constant pressure outlet. Only one inlet and one outlet is defined for basic model while four velocity inlets and four pressure outlet are defined for segregated model. The direction of velocity is inwards serpentine channel for every section inlet.

Problem setting is to be defined in Icepak before solving the problem.
In basic parameters tab flow parameters, volume and pressure are solved along with temperature. An enhanced realizable two equation k-epsilon flow regime is considered as Reynolds number calculated by Icepak and suggests turbulent flow in the channel. Gravity vector is neglected for the study.

A default temperature of 32^{o}C is defined in defaults tab in basic parameters in problem settings. Defaults fluid is defined as water and solid material AL-extruded which is default. A New material is defined with properties of Tellurium copper to assign to Cold plate.

Steady state analysis is considered as no variable varies with time in any case. Flow is forced convection as initial velocity input for water is given as external source. Radiation and altitude affects are ignored throughout the study.

As the model and meshing is obtained for both basic and segregated model, boundary conditions are defined problem is ready for simulation.

In solution setting tab basic settings are modified as per convergence required. The convergence criteria for flow is 0.001 and energy is 10^{-7}.Finally number of iterations for each case is considered as 100 which gives uniform results for different trails.

Parallel settings tab is set to parallel configuration to reduce the solver time by parallel usage of cores available. In advanced settings setup pressure discretization scheme was selected as PRESTO as suggested by [9].Double precision is chosen for solution and remaining are left default.

Finally the Trails are defined for each model before solving the problem. Eight cases are defined for base model with flow rate at inlet ranging from 0.5lpm to 2.0lpm.

In segregated model the trails are defined by considering flow rate variable for independent channels. Total volume flow is shared among the four independent sections based on the power map below the section. The total flow rate is constant for every case in base and segregated model. Thermal Resistance and Pumping power is calculated to compare the performance of the models in each case.

Chapter 3

POST PROCESSING AND RESULTS

As the solution converges icepak generates results by default and verified solution satisfies basic conservation laws. Velocity, pressure difference and temperature contours are investigated using various postprocessing techniques available in Icepak.

For the study the value of most significance is the maximum operating temperature, also referred to as junction temperature which is used to calculate the Thermal resistance and pressure difference across the cold plate which is used to calculate pumping power.

Pumping power (P_p) is defined as

$$P_p = \Delta P \times Q = \Delta P \times A \times v_{avg}$$

Where ΔP is the pressure drop across the cold plate,

Q is the volumetric flow rate through the device which in turn calculated as a product of inlet cross sectional area and average velocity at inlet.

Thermal resistance (R_{cp}) is calculated as

$$R_{cp} = \frac{T_{avg,b} - T_{in}}{q}$$

Whereas q = Total power of module (Max 485W in our case), $T_{avg,b}$ is average temperature of base of cold plate and T_{in} is water inlet temperature. Both Thermal resistance and Pumping power is calculated for the models at eight trails with flow rates 2.0lpm to 0.5lpm with a increment of 0.2lpm volume flow rate.

A Summary report is defined for maximum temperature for all the heat dissipating chips in module and average temperature of cold plate at base. Average Pressure at both openings of serpentine channels is also obtained from summery report definition for all the trails in both the models. Results obtained from solution is visualized in various post processing techniques available in Icepak and compared.

3.1 BASE MODEL RESULTS

The relationship between the flow rate and maximum temperature in individual section at different flow rate is plotted as in Figure 3.1.

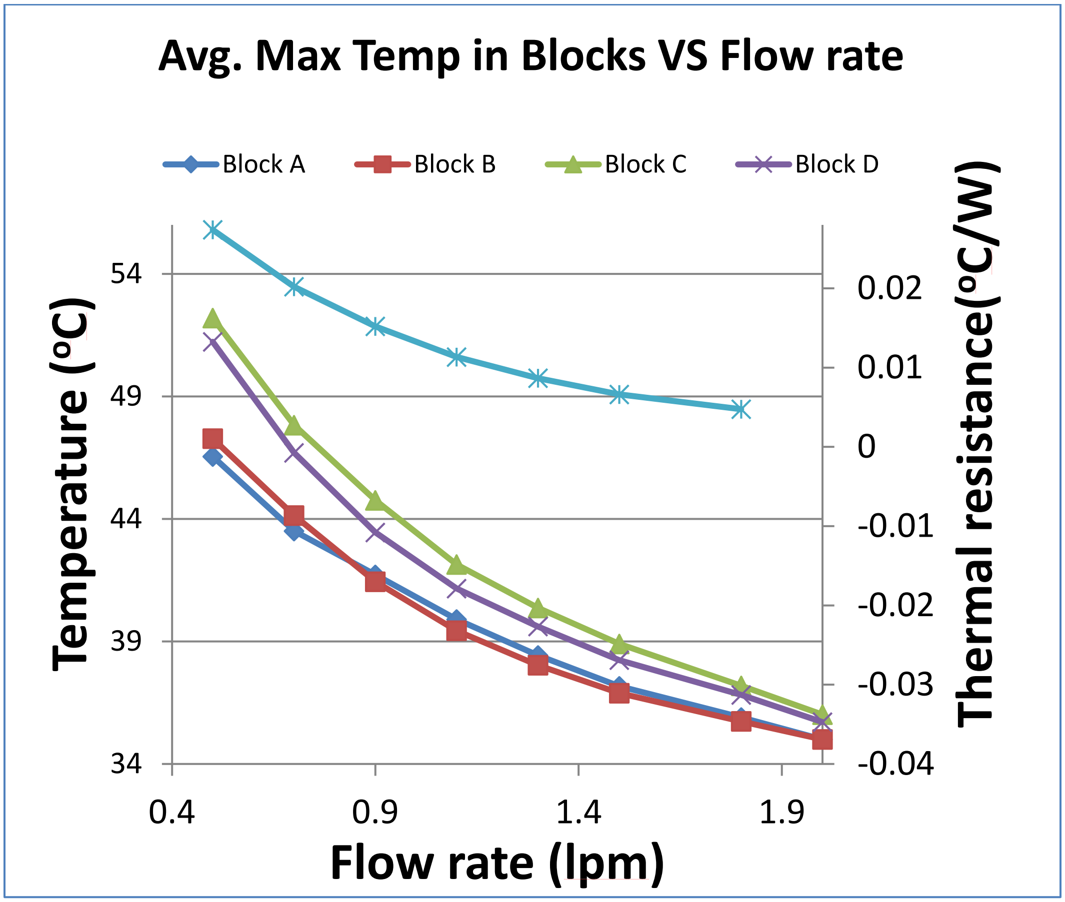


Figure 3-1 Graph showing maximum Temperature Vs flow rate in sections for base model

From the Above plotted graph Maximum temperatures in block A and block B are at similar range at all flow rates. The shift of maximum temperature in block C and D is obvious as in single serpentine flow water temperature is high as it reaches the blocks and thus temperature gradient reduces which leads to poor heat transfer rate in C and D blocks.

The graph between Thermal resistance and flow rates shows that as flow rate increases the resistance decreases and similar profile is followed by Temperature in each section as expected.

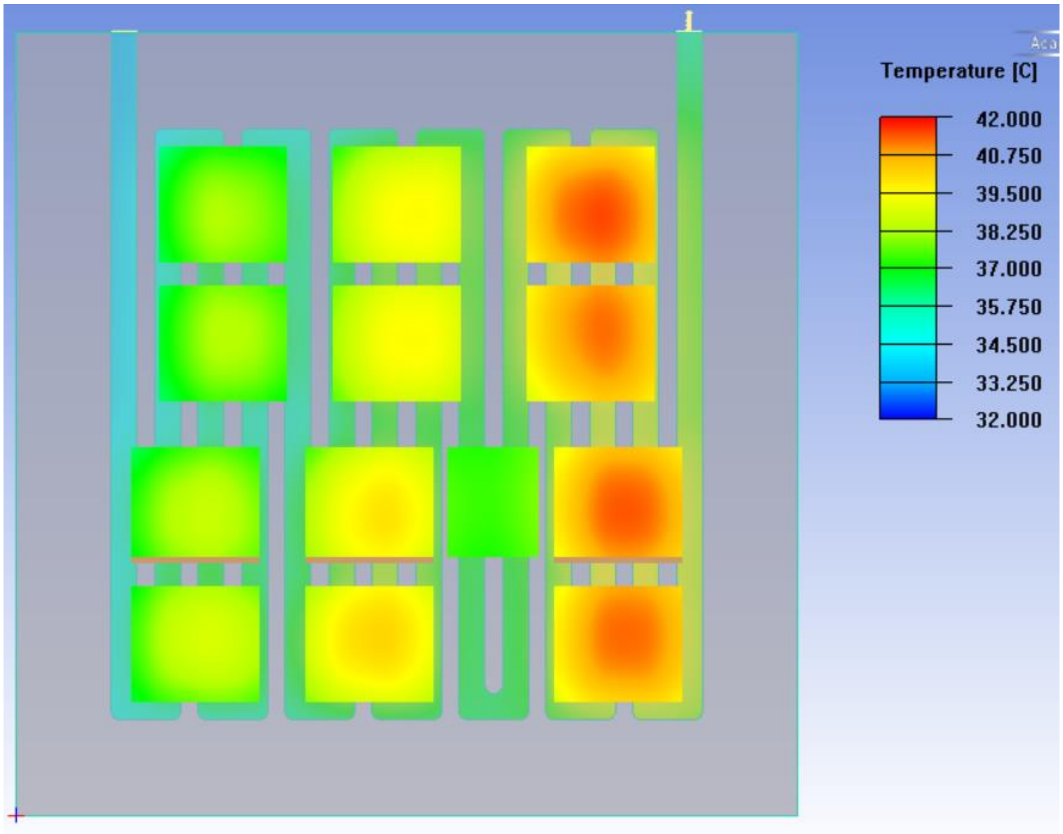


Figure 3-2 Temperature contours on MCM components for basic model

Icepak object face Temperature contours of basic model at 1.3 lpm flow above shows the temperature difference among the components of MCM. Temperature gradient is high at inlet thus the temperature is low when compared to chips close to outlet which leads to hot spots in the MCM .The temperature values trend in each component at same flow can be seen in bar graph as below.

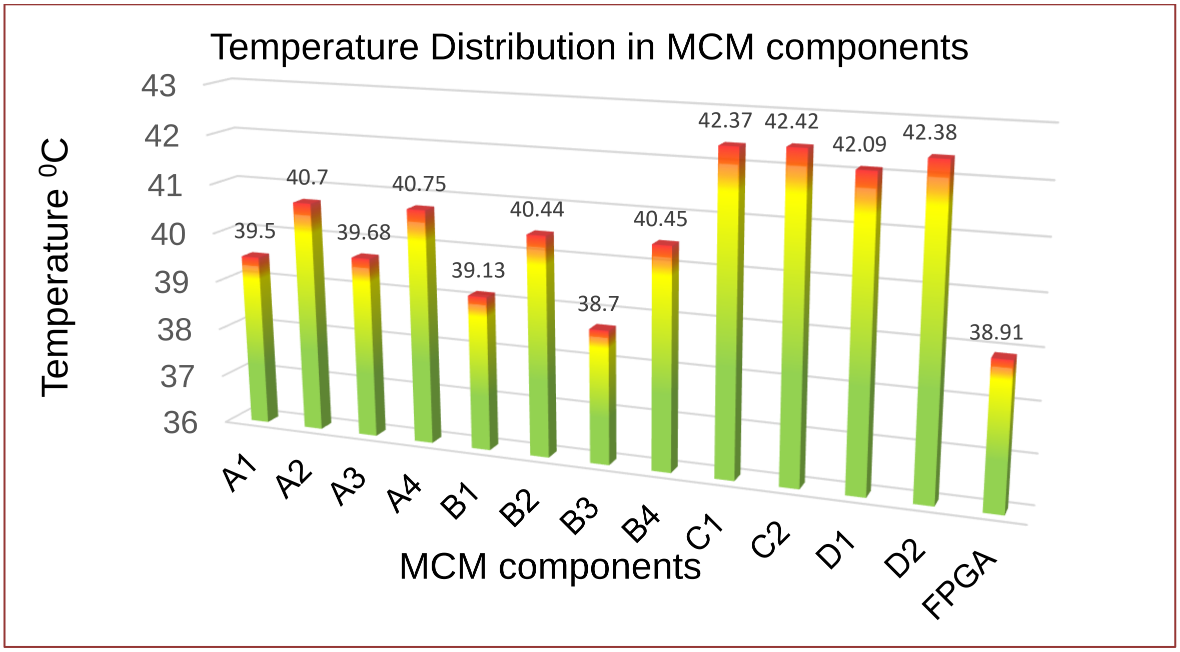


Figure 3-3 Temperature Distribution On MCM components for base model at 1.3 lpm flow rate

The lowest temperature at 1.3lpm flow rate among the chips is found in B3 which is 38.7ºC while the highest temperature is found in D2 which is 42.38ºC and the maximum difference between the temperatures is noted as 3.6ºC.

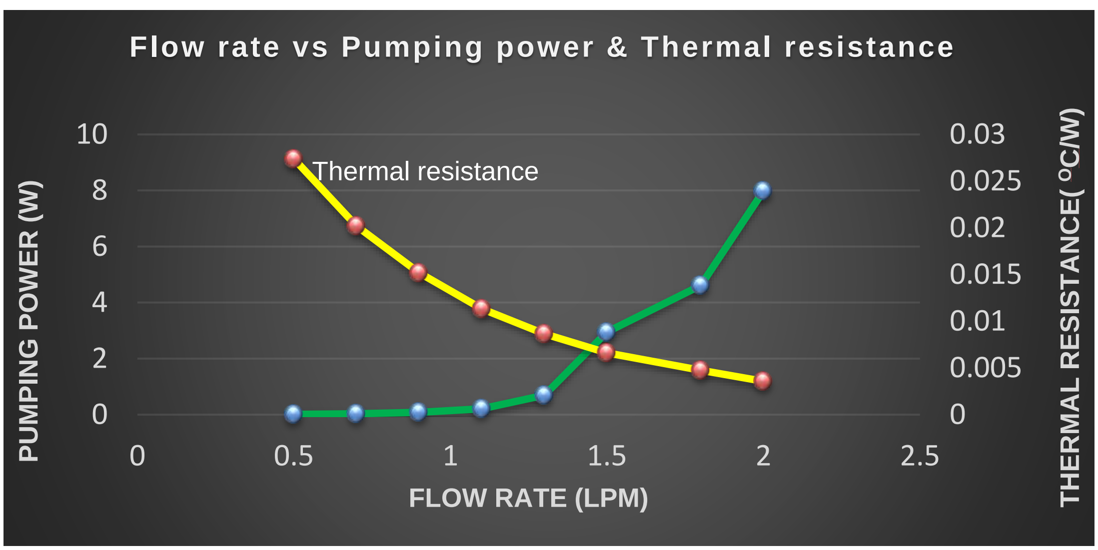


Figure 3-4 Flow rate Vs Thermal Resistance and Pumping power

Graph above implies increased flow rate is required to achieve lowered maximum temperatures in components which is leading to increased cooling cost as pumping is increases as flow rate increases. To maintain the low temperatures with less pumping power the segregated model is made.

3.2 SEGREGATED MODEL RESULTS

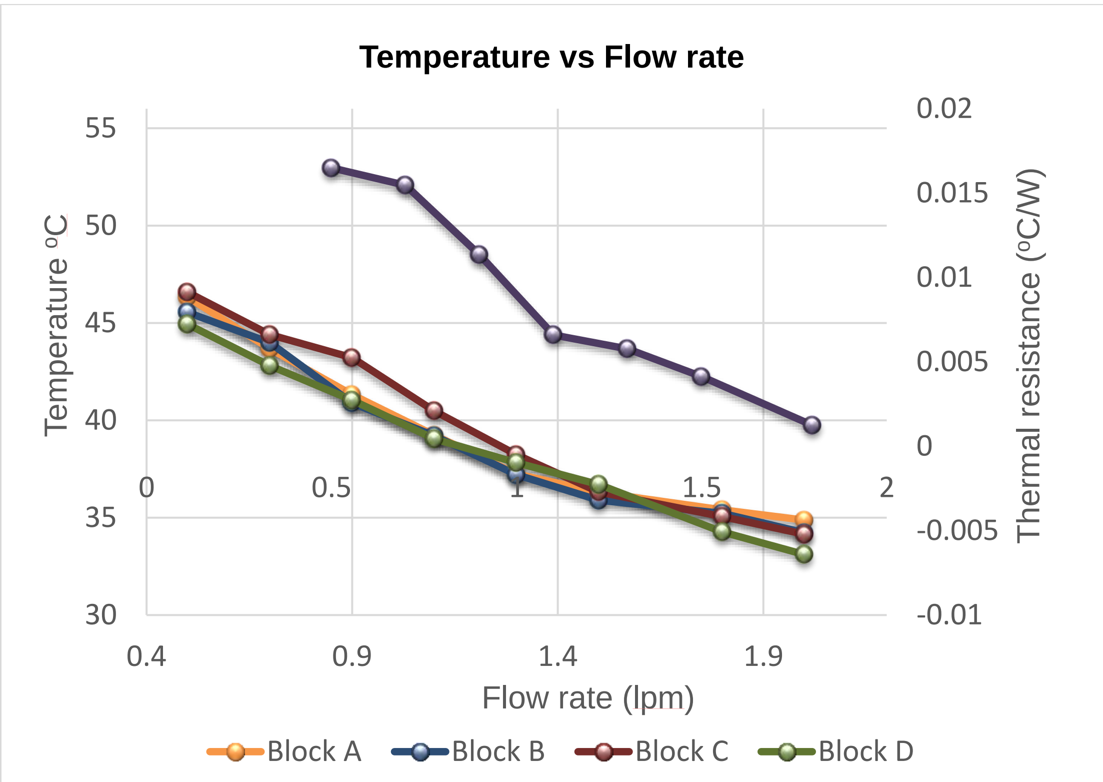


Figure 3-5 Flow rate Vs maximum temperature and Thermal resistance in segregated model

Relationship between flow rate and Maximum temperatures in sections of segregated model are characterized by the plot in Figure 3-5. For flow rate ranging from 0.5 lpm to 2.0 lpm the temperature in all sections overlap on each other. We can observe that Temperature shift that exist in the base model is not significant in segregated model which conforms the uniform distribution of temperature among all the components of module.

The Temperature contour in the components of MCM in segregated model is obtained from Post processing in Figure 3-6

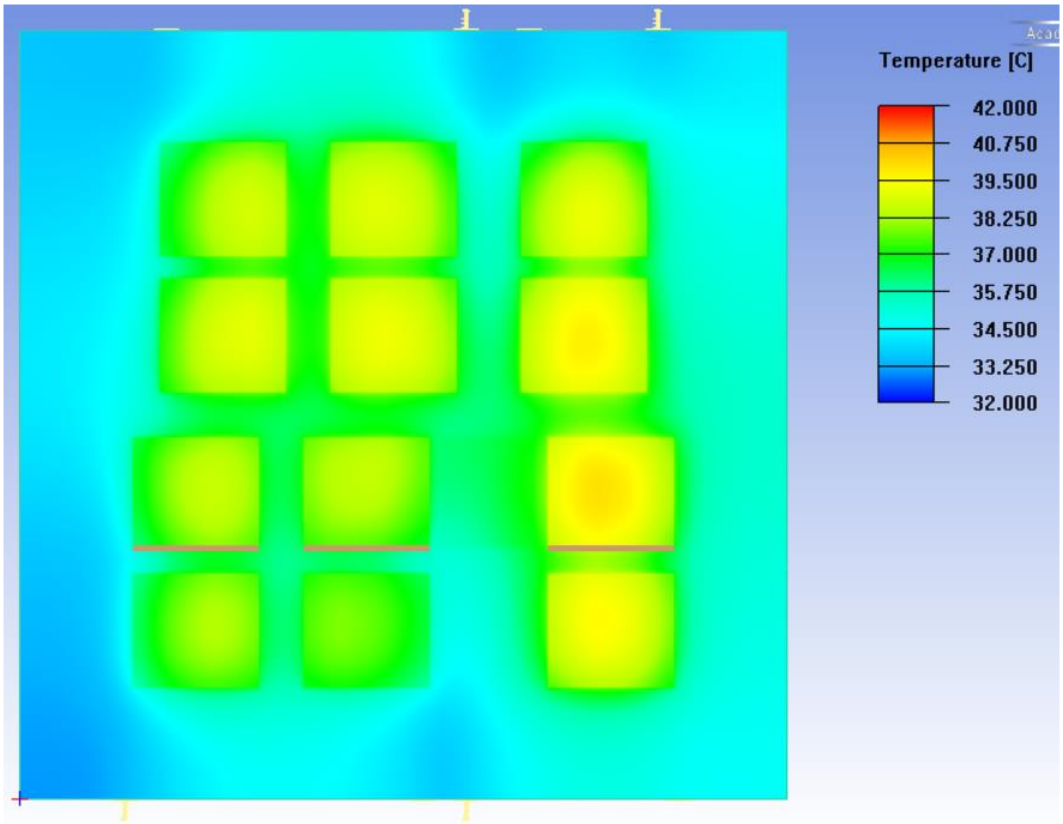


Figure 3-6 Temperature Distribution On MCM components for Segregated model at 1.3 lpm flow rate

The difference between the maximum temperature among all the components is less compared to base model which satisfies the uniform distribution of temperature among all the components in the module.

The maximum temperature in the components Is also reduced as the temperature gradient is maintained uniform for the all sections due to segregation of cold Plate.

Chapter 4

CONCLUSION AND FUTURE WORK

Segregated serpentine flow cold plate is compared with the base model In maximum temperature of individual components and overall Thermal resistance and pumping power calculated from the results obtained. The comparison is visualized from the Temperature counters and bar graphs.

The Temperature distribution contours show Distribution of Temperature is uniform in Segregated model as overall difference between the maximum temperature in components reduces significantly.

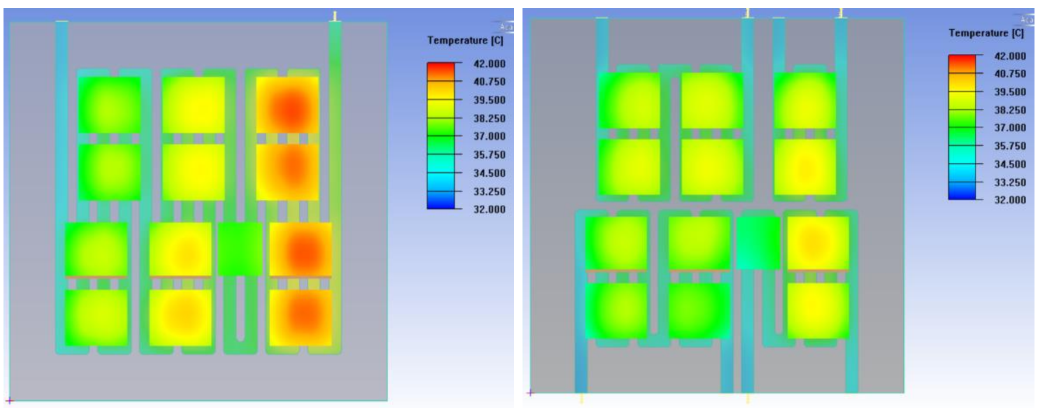


Figure 4-1 Temperatures contours on MCM components for base model and Segregated model

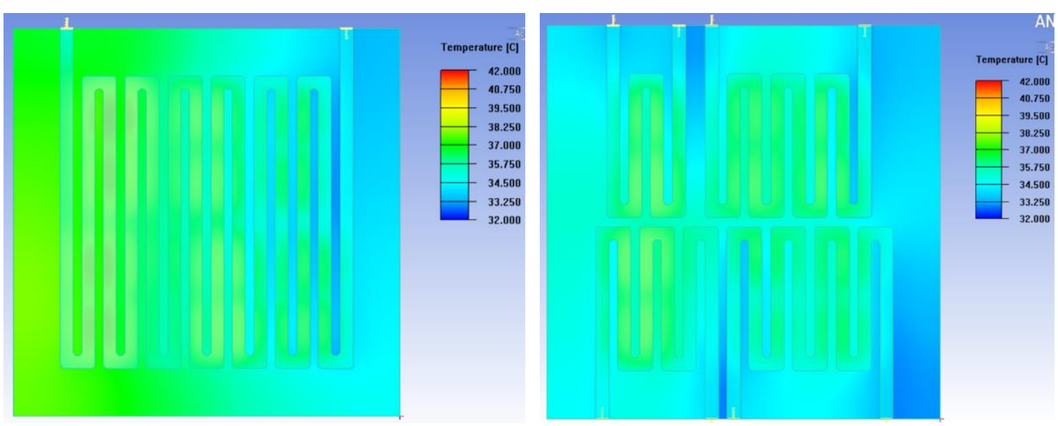


Figure 4-2 Temperatures contours on cold plate body for base model and Segregated model

Biased Temperature contours on cold plate body in base model and uniform distribution over the segregated model from the Figure 4-2 shows the effectiveness of segregation.

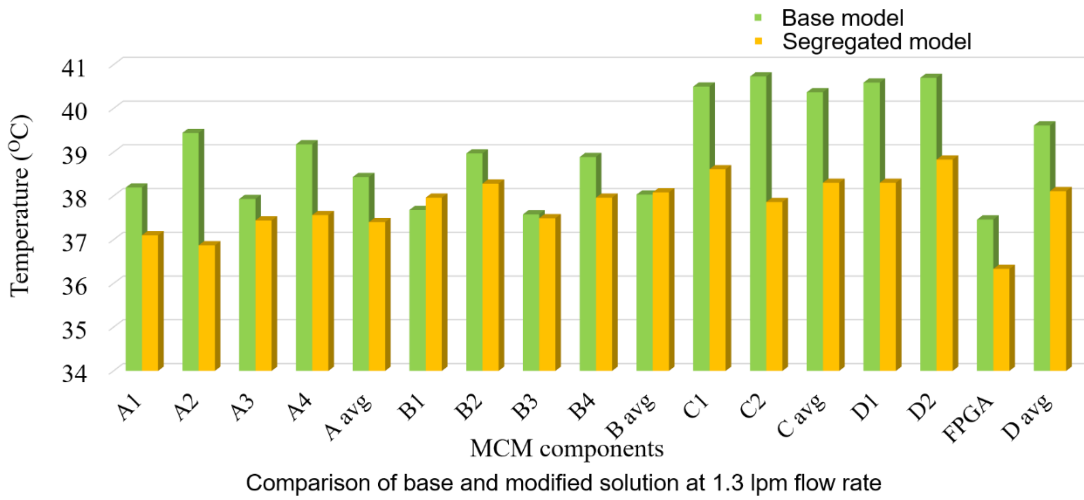


Figure 4-3 Maximum Temperatures on MCM components at 1.3 lpm flow rate for base model and Segregated model

Due to single serpentine flow in base model the blocks C and D have less heat transfer which leads to high temperature when compared to sections A and B. Segregation concept maintained uniform temperature gradient over all the sections with similar flow rate of cooling resource. Maximum temperature in segregated model is uniform in all sections. The reduction in maximum temperature over base model is envisioned in Comparison bar graph Figure 4-3,while the difference between component temperature was reduced by 20% in comparison to base model. As temperature gradient is maintained uniform the overall maximum temperature are lowered by 40%.

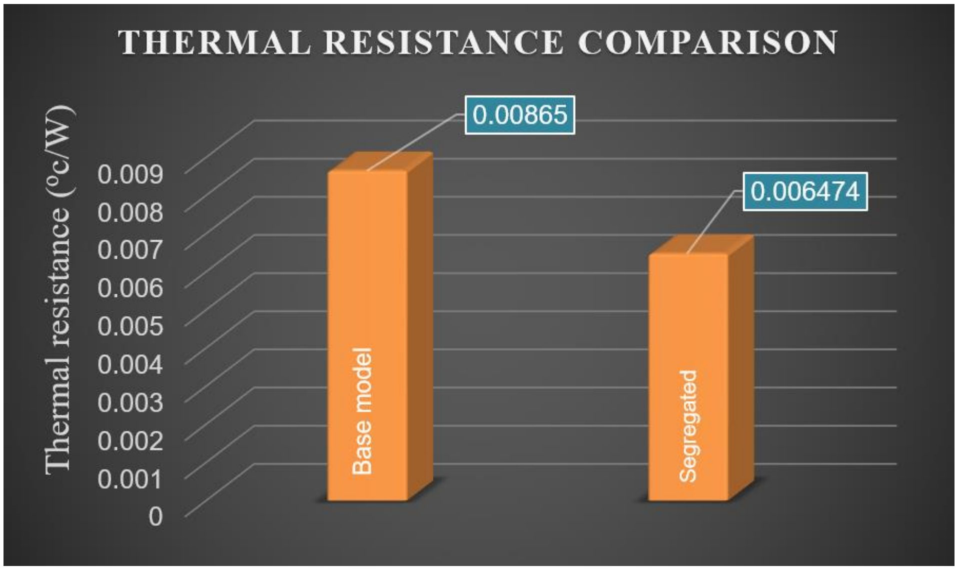


Figure 4-4 Thermal resistance of base and Segregated model at 1.3lpm flow rate

Maximum Temperature is the significant variable in thermal resistance, maximum component temperature is reduced and the Thermal resistance is reduced by 25% in comparison to basic model.

Figure 4-5 Pumping power of base and Segregated model at 1.3lpm flow rate

Flow rate is maintained constant for both the models in all cases and average pressure difference at the ends is used to calculate the Pumping power. Base model has only one serpentine so pressure difference between the inlet and outlet is used while four independent pumping powers are calculated for the segregated model and total pumping power is compared with the base model.

Pumping power is reduced by only 2%, but as Thermal resistance was very less to maintain Thermal specifications, Reliability levels are increased and Power density can be increased for same pumping power.

FUTURE SCOPE

The difference of maximum temperature in MCM Components is significantly less in segregated model over the base model.

Dynamic solutions are studied widely for High power density Chip scale packages. Experiments are to be designed combining segregated cold plate with flow control device to sense and dynamically supply cooling resource to individual sections. The scalability and cooling resources are to be explored to obtain Uniform temperature distribution and better thermal performance at low cost for large Multi-chip processors.

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