DESIGN AND PARAMETRIC ANALYSIS OF FLOW CONTROL DEVICE FOR DYNAMIC COLD PLATE TO OPTIMIZE THE TEMPERATURE FLUCTUATIONS OF THE MULTI-CHIP MODULE

By

AVINASH VELUTURLA

Presented to the Faculty of the Graduate School of

The University of Texas at Arlington in Partial Fulfillment

Of the Requirements

For the Degree of

MASTER OF SCIENCE IN MECHANICAL ENGINEERING

THE UNIVERSITY OF TEXAS AT ARLINGTON

May 2016

ACKNOWLEDGEMENTS

I might want to take this chance to express my profound appreciation to my overseeing teacher Dr. Dereje Agonafer for his consolation, backing and direction over the span of my exploration at The University of Texas at Arlington. He gave me chance to chip away at industry-supported tasks and go to meetings and workshops which helped me for systems administration and enhancing my delicate abilities.

I would truly express gratitude toward Dr. Haji-Sheikh, Dr. Miguel Amaya and Dr. Ratan Kumar to serve on my theory board of trustees additionally for their significant remarks on my postulation and the work I put in. I am likewise grateful to Kunal Shah, Parth Soni, Shivang Desai and other EMNSPC colleagues for their backing.

I am especially obliged to Ms. Sally Thompson for helping me with authoritative matters and other instructive matters at all times. Our discussions dependably served as an anxiety reliever and her sympathy toward my prosperity was certifiable.

I might likewise want to thank mechanical designing division workforce and staff that upheld me all through my graduate studies and helped me get past it all. Last yet not the minimum, my family and companions without whose enthusiastic and budgetary bolster none of this would have been conceivable.

ABSTRACT

Design and parametric analysis of flow control device for dynamic cold plate to optimize the temperature fluctuations of the Multi-chip module

Avinash Veluturla, MS

The University of Texas at Arlington 2016

Supervising Professor: Dr.Dereje Agonafer

Continuing trends of increasing microprocessor power densities and non-uniform temperature distribution pose a significant challenge to the data center cooling. The most usual approach to data center cooling is air cooling but there are certain limitations to that approach. Major limitation is heat transfer coefficient so in order to overcome those limitations, we came up with liquid cooling using water as coolant. To minimize energy consumption of cooling system the objective is to design a dynamic energy efficient and practical cooling solution for high power equipment. Multi-chip module is used as the base for the liquid cooling solution.

The main objective of this thesis is Designing flow control devices, find the performance characteristics and reliability of the bimetallic strip in order to increase the efficiency of the system. The reason why we have to use flow control device in liquid cooling is to Control the flow of water from the dynamic cold plate in order to control the temperature fluctuations by using a bimetallic strip as a temperature sensor and using different approaches to control the flow.

CONTENTS

List of Illustrations

List of Tables

CHAPTER 1

1.1 Data center cooling

Current server farms are amazingly innovatively mind boggling, and keeping them running securely and productively requires consistent close checking and administration. Among the most imperative different errands confronting server farm supervisors is keeping up the right temperature. Should the temperature and mugginess ascend to intemperate levels inside the server farm, buildup can begin to frame - in this manner harming the machines inside. It ought to abandon saying this can bring about enormous harm and disturbance, and that it in this manner must be dodged no matter what. Luckily, there are different innovations close by which can keep server farm temperatures at the right level.

Data center encompasses the management of a range of different factors - particularly temperature and humidity - to ensure that data center equipment runs efficiently and safely. In addition, hot air expelled from IT equipment can be recycled to improve data center cooling efficiency. Efficiency can also be improved by reducing bypass airflow - the amount of time it takes for air to flow through a device. This is known as air flow management

Data centers are home to very complex and advanced technology. Ensuring that this machinery ticks over safely and avoiding any potential problems is crucial. Of course, as the technology deployed in data centers evolves, so the challenges facing data center manager’s change. New techniques must continually be developed in order to deal with new risks - after all, IT refreshes tend to occur every one-and-a-half to two-and-a-half years, which should give you some idea just how rapid the pace of change tends to be.

1.2 Different trends in cooling

Why Air? It's shoddy, for one thing. Regardless of the fact that you need to run with a secondary selling cooler for your CPU or GPU, will be paying far short of what you would for a fluid cooling setup. The same goes for case fans. You can absolutely buy greater, better, more effective fans in the event that you need a calmer apparatus, or even fans that light up in case you're into that kind of thing. Of course, you'll need to pay for them, however regardless you'll spend far less money overhauling or fabricating a decent air-cooling setup than you will on a run of the mill water-cooling circle.

Customary air cooling has three noteworthy drawbacks, however. In the first place, fans aren't as effective as water cooling, which can represent an issue with seriously overclocked processors or in especially meaty apparatuses loaded with various design cards. Second, the warmth sinks on capable CPU coolers can get enormous. At last, fans are boisterous

One of the key advantages of a solid fluid cooling setup is that it permits you to cool particular framework segments to a more prominent degree than if were you to utilize fans—not the most appropriate setup for somebody running a normal stock-clock processor, yet one that is certainly important to anybody looking to overclock their chips a bit (or a ton).

.One major drawback of water cooling is its nearly high cost, particularly in case you're hoping to fabricate a custom setup. While most customary upper-end CPU coolers cost some place in the middle of $50 and $100, building a fluid cooling setup can cost much more. For instance, EKWaterBlocks' top-level H3O 360 HFX water cooling pack costs an incredible $360. (The cost is changed over from euros, so the 360 in the name might be unintentional

These days, there are two fundamental reasons why individuals swing to fluid cooling. The first is execution and the other is style. There is likewise a third reason, calm operation, which is not generally fundamentally included. That conveys us to the decision of parts for fluid cooling. In the event that you pick quality parts, pumps and fans, you can accomplish superior and noiseless operation. EKWB gives the fluid cooling market with top quality segments for verging on each part in your PC

The branch of style is exceptionally expansive and subjective. It extends from a basic, clean form to expound mods with different realistic cards, hard tubing, and so forth. The utilization of fluid cooling gives innumerable choices to altering, which leaves the end client with a remarkable setup. We could straightforwardly associate certain water cooled works to „art". Nothing gives more delight than owning or building your own one of a kind fluid cooled setup

Fluid cooling comes with a sticker price, such as everything that is great. There are no alternate routes in life and in this way, there are no easy routes in cooling either. In the event that you need the best execution and best visual impact, it will cost more. There are two ways you can begin your first fluid cooling enterprise. You can purchase a pre-amassed and pre-filled All-In-One or AIO arrangement or you can purchase every individual part yourself and gather a custom circle all alone

CHAPTER 2

2.1 Need for dynamic cold plate

The requirement for vitality effectiveness in server farms has agreed with proceeding with patterns of expanding chip power densities and non-uniform temperature circulations, which represent a noteworthy test to the cooling prerequisites of high power gadgets. Post-Pentium III period of chip presented non-uniform force dispersion at the bite the dust with fluctuating force densities doled out to various utilitarian units. This offered ascend to restricted areas of high temperature known as 'Hot spots'. In this manner, a significantly huge temperature distinction can be seen over the surface of a gadget which is inconvenient to its execution and unwavering quality. Thus, routine static cooling arrangements must be intended to cool these high temperature districts which expand the warm spending plan and thus cost of cooling these gadgets. What's more, rackmount servers are the most vitality proficient when they work near greatest use. In this way, the essential necessities of cutting edge arrangements are high power cooling and specific appropriation of assets for advancement of uniform gadget temperatures. This requires a nitty gritty comprehension and incorporation of chip design, electronic bundling, and control frameworks to deliver a strong arrangement.

2.2 Working of dynamic cold plate

To meet previously stated necessities, ordinary static frosty plate plans require combination of control gadgets and plans to empower focused on conveyance of cooling assets in view of prerequisite. The design and operation of the dynamic icy plate can be effectively pictured as found in Figure

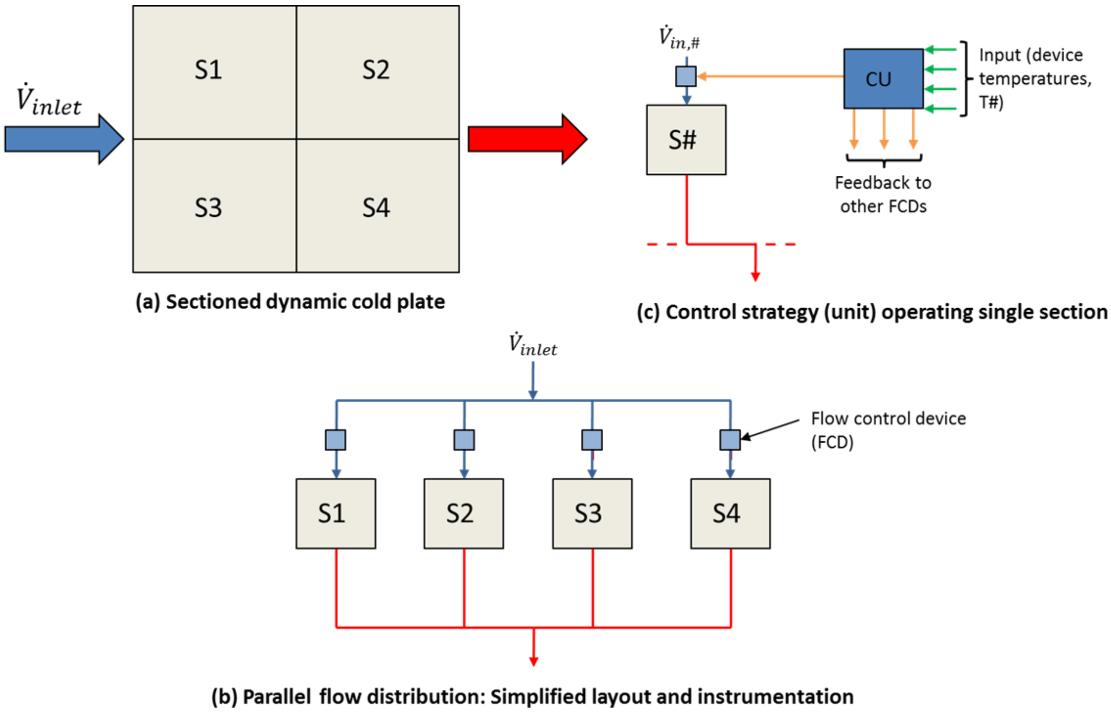


Figure 1: Conceptual layout for a cold plate with segregated flow control

Contingent upon the multifaceted nature of the gadget and its energy delineate, impression of the cool plate is separated into individual channel segments, as appeared in Figure 1(a). Every segment has an alternate delta conductor (see Figure1 (b)) that is encouraged by the principle purpose of entrance to the icy plate, making every free from the others. Keeping in mind the end goal to counter distinctive force disseminations underneath the dynamic locale of every segment, the presentation of detecting and control is fundamental. By using readings from temperature diodes incorporated into the passes on, or inserted thermocouples inside the frosty plate body, a sign of force scattering variety might be built up between various segments. These agent readings are then sustained into a control unit (appeared in Figure 1(c)) wherein a preset calculation decides the greatness/extent of stream that should be appropriated to every segment in view of cooling necessity. This sign is then bolstered into a FCD that directs stream according to necessity. Along these lines stream to every area is controlled continuously relying upon delegate temperature readings to advance lower temperature contrasts between individual segments. It is basic that the proposed configuration be adaptable to guarantee application for high power gadgets with various impressions.

Table 1: Details of MCM components

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

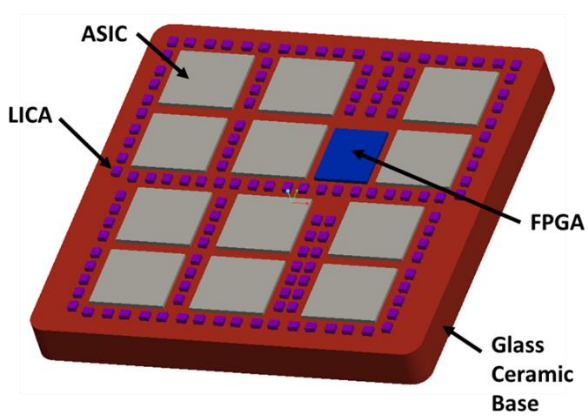


Figure 2: Multi-chip module and its components

So as to apply the previous idea, a reference stage is required for configuration of such a dynamic arrangement. Figure 2 demonstrates a high-control multi-chip module (MCM), gave by Endicott

Interconnect Technologies Inc. that fills this need. The module is populated with a variety of surface mounted segments (ASICs, LICAs and a FPGA) and setup to have a most extreme force dispersal of 485 watts over a 78mm by 78mm impression. A rundown of part power details can be found in Table. It is obvious that the main warmth creating segments of hobby are the ASICs (application-particular coordinated circuit) and FPGA (field-programmable entryway cluster). The previous is 14.71mm x 13.31mm x 0.8mm in size and the last is 10.50mm x 12.70mm x 0.8mm in measurement. The LICAs, while much more noteworthy in number, don't disperse (critical) warm and are hence ignored with the end goal of this study. A copper heat spreader, intended to represent divergence in part statures and spreading of warmth, is not considered in this study to exploit different spatially-isolated warmth sources on the module.

Table 2: Specifications of the original cold plate

Parameter	Value
Size	92mm × 92mm × 12mm
Thermal Resistance	0.0152°C/W
Flow Rate	2lpm (3.33E-5m^3/s)
Pressure Drop	2.5psi (17236.89Pa)
Pumping Power	0.575W

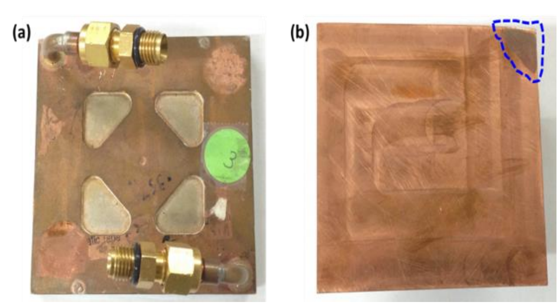


Figure 3: (a) Top and (b) bottom views of original cold plate

CHAPTER 3

3.1 Introduction to flow control device

A disentangled delineation of the test seat setup to assess both cool plates is portrayed in Figure. A Kinetics RS33AO11 recycling chiller drives course through the outer circle and cools the plate heat exchanger (HEX) highlighted by the specked green line. The chiller is outfitted with a positive removal pump fit for pumping up to 1.6gpm of coolant at 100psi and a temperature scope of -15°C to 75°C. As these units are known not (variety in temperature), the HEX gives generous warm capacitance to avert transmission to ensuing circles. A DC 4-wire pump [66], highlighted by the red dabbed line, drives course through the two HEXs in the middle of the road circle. So also, a different pump (highlighted by the blue spotted line) controls stream of refined water through all parts in the interior circle. Turbine flowmeters orchestrated in parallel measure the stream rate of water cooled by the plate HEX. Temperature and weight contrasts over the cool plate are measured utilizing K-sort thermocouple tests and weight transducers. The pump in the inside circle is essentially in charge of keeping up an altered stream rate amid testing. The pump in the middle of the road circle controls the bay temperature of water to the icy plate by balancing stream rate between the two warmth exchangers. Temperature and stream rate readings are data to the LabVIEW code that thusly controls both pumps. Gulf temperatures to the chilly plate as low as 15°C are focused amid testing. Water and glycol blend (50/50) is utilized in both transitional and outer circles to empower close to zero temperatures to represent heat misfortune.

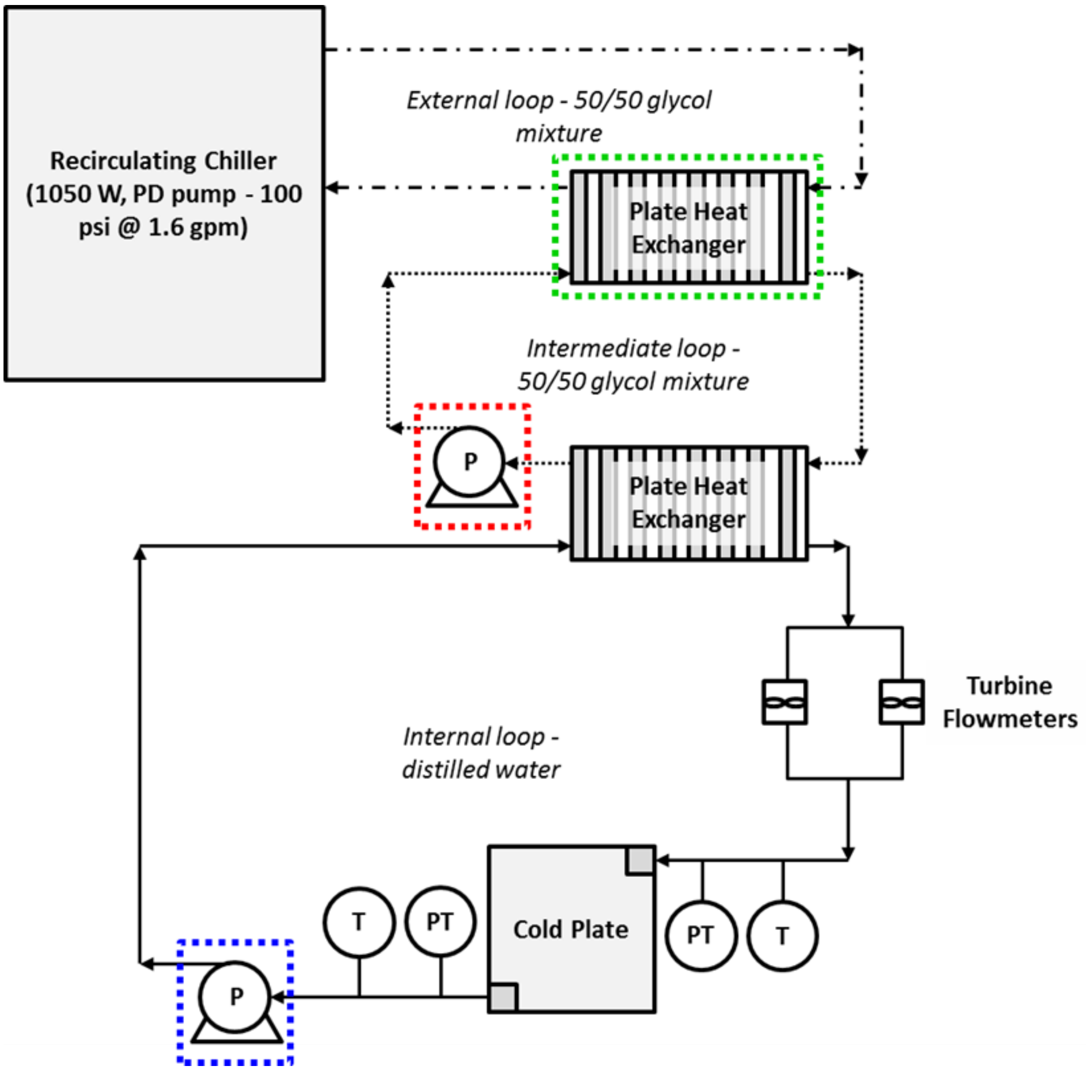


Figure 4: Coolant circuit for testing both original and dynamic cold plates

Once the delta to water is settled we thought of stream control gadget for the surge of water from the dynamic cold plate. As there are such a large number of hotspots furthermore part of temperature varieties inside the chip, by keeping up only the bay temperature and by not managing the water outside the dynamic cold plate we can't decrease the problem areas and keep up the uniform temperature, so we need a stream control gadget outside the dynamic cold plate with a specific end goal to diminish the warmth misfortune furthermore to keep up uniform temperature.

3.2 Disadvantages of traditional flow control devices

1. A stream control gadgets need's a solid valve, actuator, control framework and a sensor.
2. All these parts ought to work absolutely and dependably for quite a while so the expense for outlining and assembling such a gadgets are high.
3. These gadgets additionally takes longer get together time and if there should be an occurrence of a disappointment, the hardware downtime is more.
4. The expense to setup and keep up these control frameworks over the long haul is high.
5. Thus we require a reduced, dependable and shabby stream control gadget

3.3 Bimetallic strip as flow control device

This gadget fluctuates stream in a channel with change in temperature of the liquid stream. Can be controlled by applying current through the gadget or intended to fluctuate as per the temperature of the stream. Temperature of the liquid can roughly figure by change in resistance of the gadget. Straightforward configuration, simple to fabricate, control and collect. As the temperature of these strips transforms it can be composed in both approaches to open and close. In this way it can go about as actuator, sensor, valve and in few cases it can be planned as a dynamic control framework

CHAPTER 4

4.1 General physics of bimetallic strip

At the point when a segment made up of two distinct materials reinforced together is warmed or cooled, change in temperature can set up burdens. Then again, the impact can be abused by utilizing such a couple to quantify temperature changes. An illustration of such a sensor is the basic bimetallic strip, which has for some time been utilized as a part of indoor regulators and other warm gadgets.

As appeared in the accompanying chart, if the materials are not joined the free lengths of every material would be diverse after a temperature change. Whenever fortified, in any case, the distinction in unconstrained lengths offers ascend to inner hassles inside the strip, making it twist

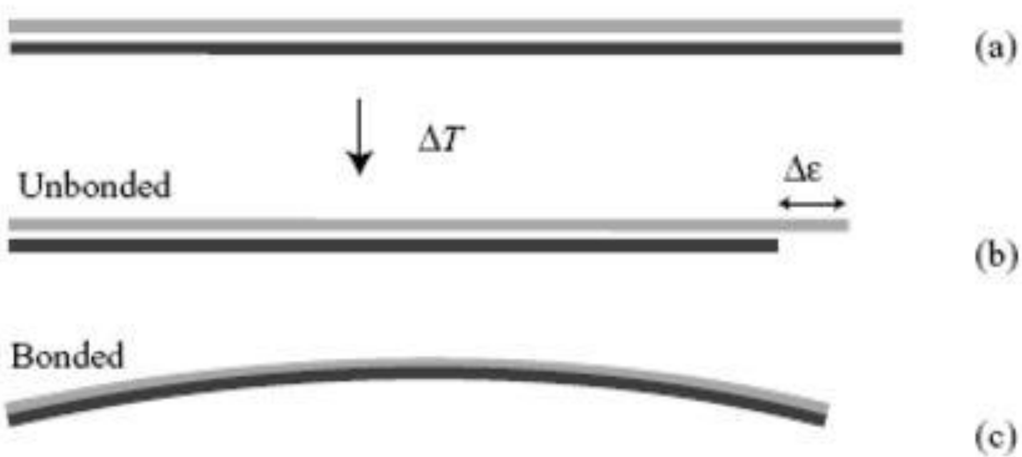


Figure 5: (a) Bimetallic strip (b) unbounded bimetallic strip (c) Bonded Bimetallic strip

The bimetallic strip consists of two strips of equal initial length undergo a temperature change ΔT, such that the relative difference in their unconstrained lengths is $\Delta\varepsilon$ ($= \Delta\alpha\ \Delta T$). Since the two strips are in fact bonded together, the resulting internal stresses generate a uniform curvature.

4.2 Equations

1) **Radius of Curvature** : $$\frac{1}{R_T} - \frac{1}{R_O} = \frac{6(\alpha_2 - \alpha_1)(1+m)^2}{3(1+m)^2 + (1 + m \cdot n)\left(m^2 + \frac{1}{m \cdot n}\right)} \cdot \frac{T - T_O}{s}$$

2) **Flexivity** : $$k = \frac{\left(\frac{1}{R_T} - \frac{1}{R_O}\right) s}{T - T_O}$$

3) **Deflection** : $$A = \frac{aL^2}{4s} \cdot \Delta T$$

4) **Force** : $$P = \frac{aEBs^2}{L} \cdot \Delta T$$

Nomenclature

R_T = Radius of curvature at temperature T

R_0 = Radius of curvature at some other temperature T0.

α_1 = Thermal expansion coefficient of material 1

α_2 = Thermal expansion coefficient of material 2

M = t1/t2, ratio of the thicknesses of the materials

N = E1/E2, ratio of the elastic moduli of the materials.

S = Total thickness of the Bimetallic strip (t1 + t2)

A = Deflection

E = Young's modulus

B = Width

P = Force

4.3 Different materials of bimetallic strip

Table 3: List of materials and its properties

Material	Density (g/cm^3)	Thermal Expansion Coefficient (C^-1)	Young's Modulus (Mpa)	Poison Ratio
Aluminum	2.77	2.30E-05	71000	0.33
Copper	8.3	1.80E-05	110000	0.34
Iron	7.87	1.20E-05	211000	0.29
Nitinol (Ni-Ti)	6.45	6.60E-06	35000	0.33
Titanium	1.32	9.40E-06	3600	0.4
PEEK (Poly Ether Ether Ketone)	4.6	2.60E-05	96000	0.36
Brass	8.49	1.90E-05	97000	0.31

The criteria of material choice depends on the warm extension coefficient of the individual material. In the aforementioned table we can watch that Nitinol has slightest warm development coefficient and PEEK has the most astounding warm extension coefficient. As bimetallic strip comprises of two materials as per our required bend we select the mix of materials. In this study according to our prerequisite we utilized PEEK as inward interface material and Nitinol as external interface material.

CHAPTER 5

5.1 Deflection vs length

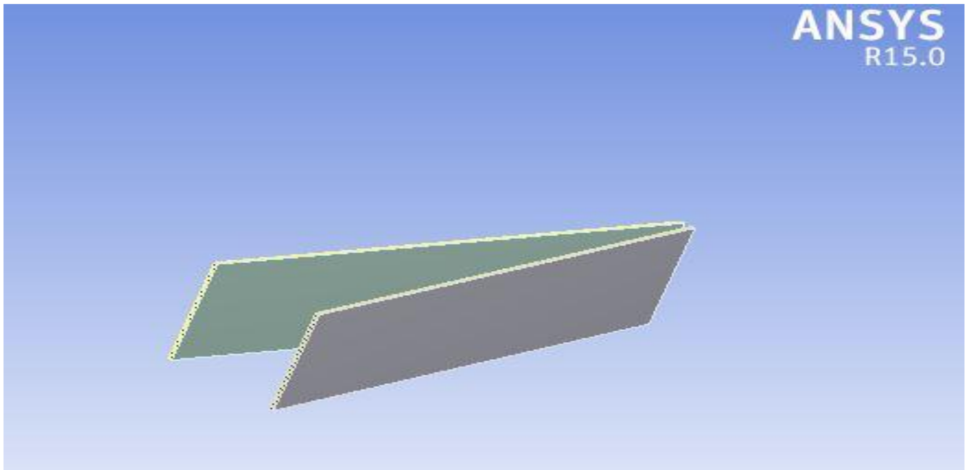


Figure 6: General geometry of bimetallic strip considered

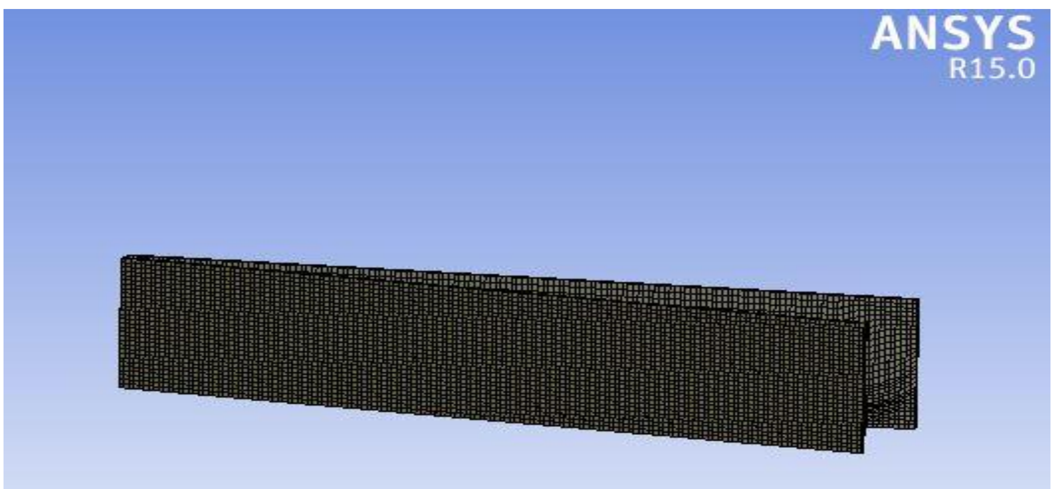


Figure 7: Meshed Bimetallic strip

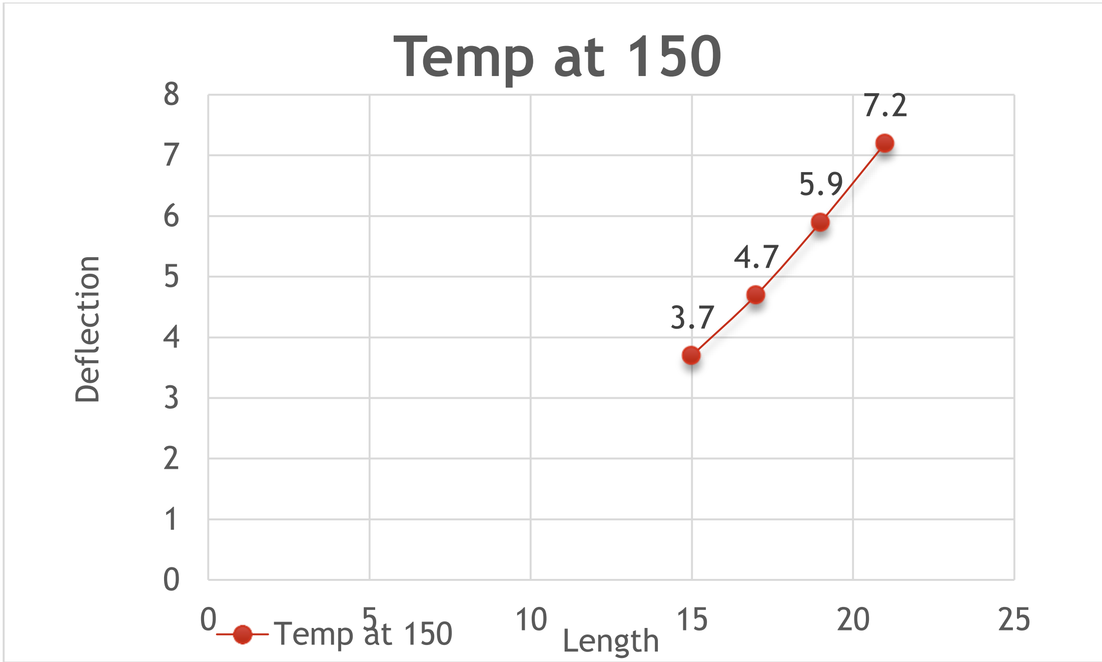


Figure 8: Length vs deflection

From the comparison we can watch that Deflection is specifically to corresponding to the square of the length. So little change in length may bring about huge variety in deflection. As indicated by our geometry we utilized aggregate of 2 bimetallic strips which are slanted towards each other and the slant point depends on the length, so we enhance the length and slant edge as indicated by our necessity to get great deflection with the goal that we can manage water out when the temperature increments. From the above diagram we can watch that at 150^{o} C for PEEK and Nitinol we can watch an deflection of 3.2mm with the length of 15mm and deflection increments to 7.2mm when the length increments to 21mm.

5.2 Deflection vs thickness

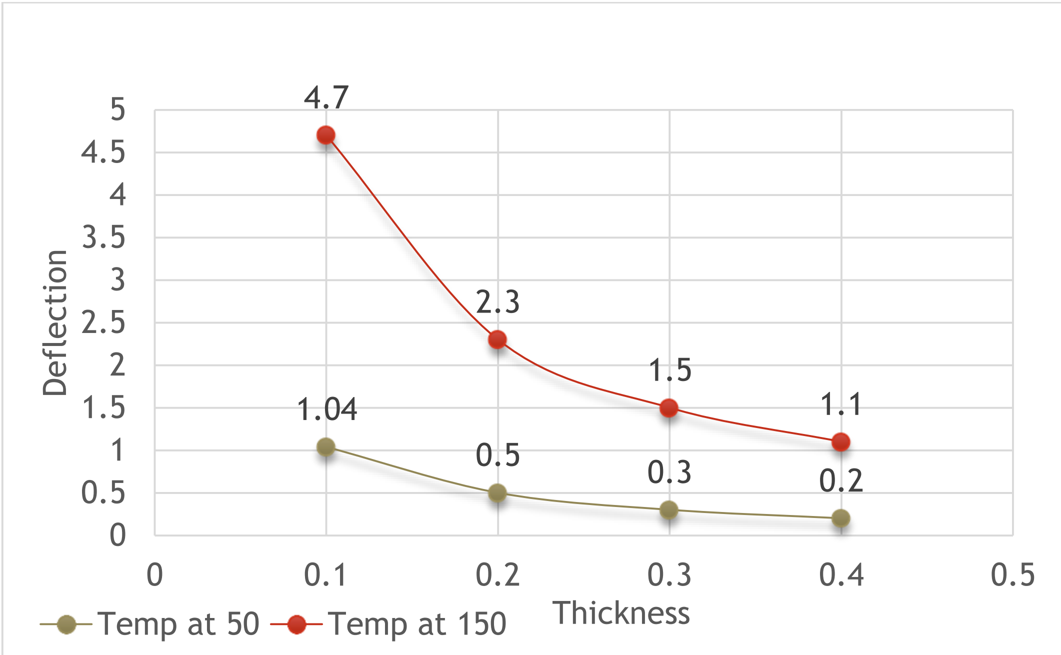


Figure 9: Thickness vs Deflection

In this graph we can observe that deflection decreases as thickness of the strip increase as deflection is inversely proportional to the thickness from the equation. We can observe that at 50^{o} C at 0.1mm thickness the deflection for PEEK and Nitinol is 1.04mm and it gradually decreases to 0.2mm when thickness went up to 0.4mm. Similarly at 150^{o} C at 0.1mm thickness the deflection is 4.7mm and it decreased to 1.1mm for the thickness of 0.4mm.

5.3 Deflection vs thermal expansion coefficient

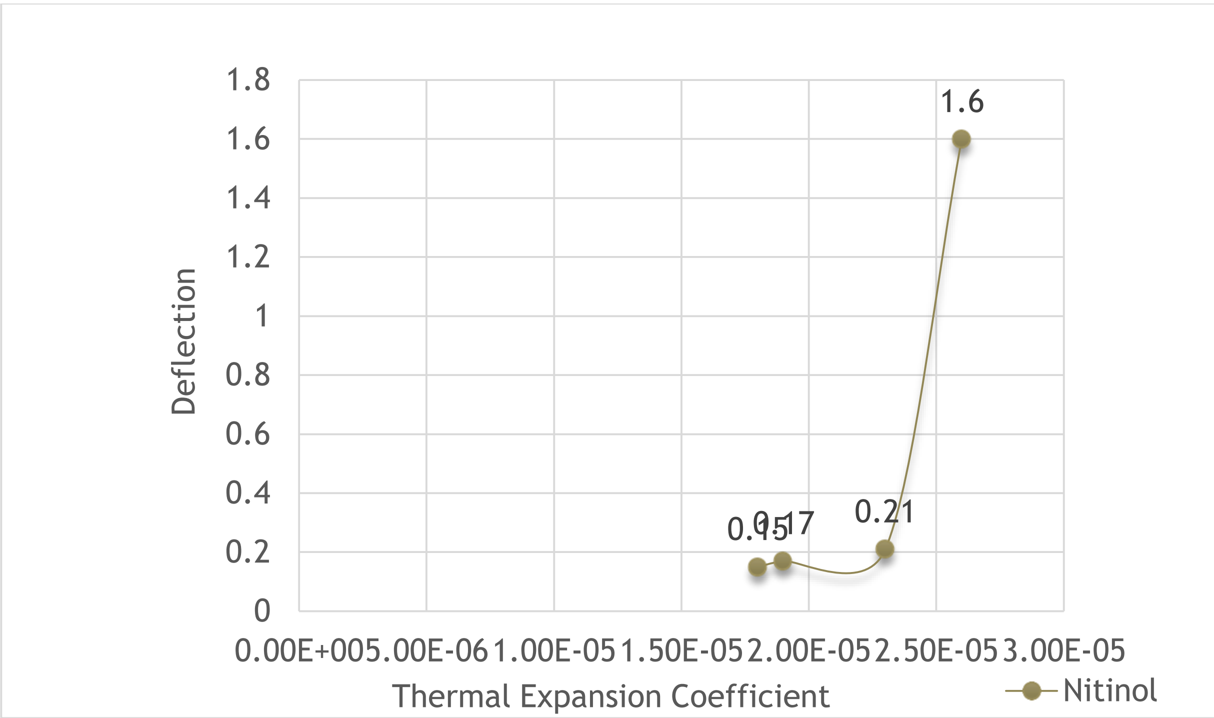
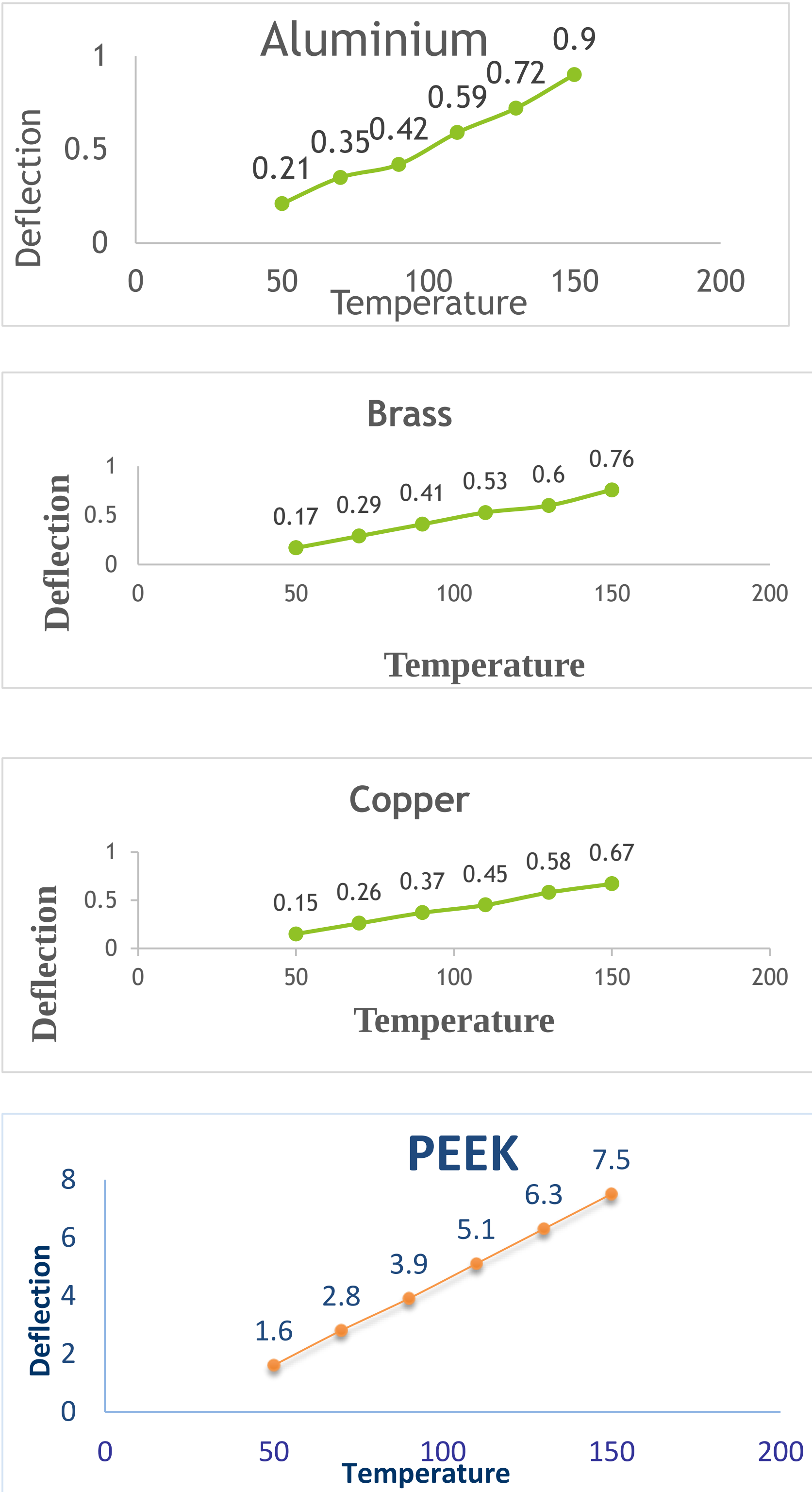


Figure 10: Thermal expansion coefficient vs Deflection

As thermal expansion coefficient of material increases the deflection also increases that trend is shown in the above mentioned graph. We can observe for PEEK as the thermal expansion coefficient is high we observed a deflection of 1.6mm at 50 ^{o} C and for Iron we observed a deflection of 0.15mm.

5.4 Deflection vs temperature



(a) (b) (c) (d)

Figure 11: Temperature vs Deflection (a) Aluminum (b) Brass (c) Copper (d) PEEK

CHAPTER 6

6.1 Deflections for different set of Parameters for PEEK and Nitinol

Table 4: Deflection for different parameters for PEEK and Nitinol

Inner side	Outer side	Length (mm)	Thickness(mm)	Inside temp(^{o}C)	Outside temp(^{o}C)	Deformation(mm)
PEEK	Nitinol	15	0.1	50	22	1.6
PEEK	Nitinol	15	0.1	110	22	5.1
PEEK	Nitinol	15	0.1	70	22	2.8
PEEK	Nitinol	15	0.1	90	22	3.9
PEEK	Nitinol	19	0.1	50	22	1.3
PEEK	Nitinol	21	0.1	50	22	1.5
PEEK	Nitinol	19	0.1	150	22	5.9
PEEK	Nitinol	21	0.1	150	22	7.2
PEEK	Nitinol	17	0.1	50	22	1.04
PEEK	Nitinol	17	0.1	150	22	4.7
PEEK	Nitinol	17	0.3	50	22	0.3
PEEK	Nitinol	17	0.2	50	22	0.5
PEEK	Nitinol	17	0.4	50	22	0.2
PEEK	Nitinol	17	0.3	150	22	1.5
PEEK	Nitinol	17	0.2	150	22	2.3
PEEK	Nitinol	17	0.4	150	22	1.1
PEEK	Nitinol	15	0.1	50	22	0.82
PEEK	Nitinol	15	0.1	150	22	3.7
PEEK	Nitinol	15	0.1	130	22	6.3
PEEK	Nitinol	15	0.1	150	22	7.5

6.2 Feasible dimensions and conditions for the bimetallic strip

Material **: -** PEEK and NITINOL

Dimensions **: -** 15*3*0.1 mm^3

Type of Analysis **: -** **S**tatic Structural

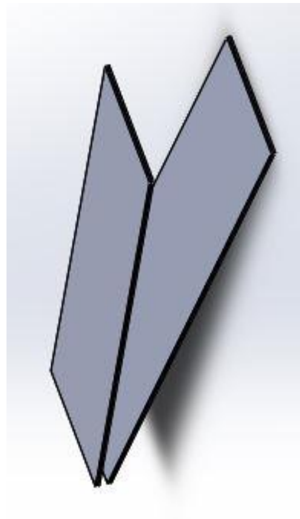
Meshing:-

1. Element size : 0.0001mm
2. Behavior : Hard
3. Type : Edge sizing
4. No of Edges : 40

Boundary conditions:-

1. Min Temperature Inner interface : 50^oC
2. Max Temperature Inner interface : 150^oC
3. Outer Surface Temperature : 22^o
4. Fixed Supports : 4 faces

1. L * S * B : 15 * 0.1 * 3 mm^3
2. Materials: Inner Interface - PEEK (Poly ether ether Ketone)
   Outer Side - Nitinol (Nickel and titanium alloy)



(a)

(b)

Figure 12: (a) 3D view of bimetallic strip (b) 2D view of bimetallic strip

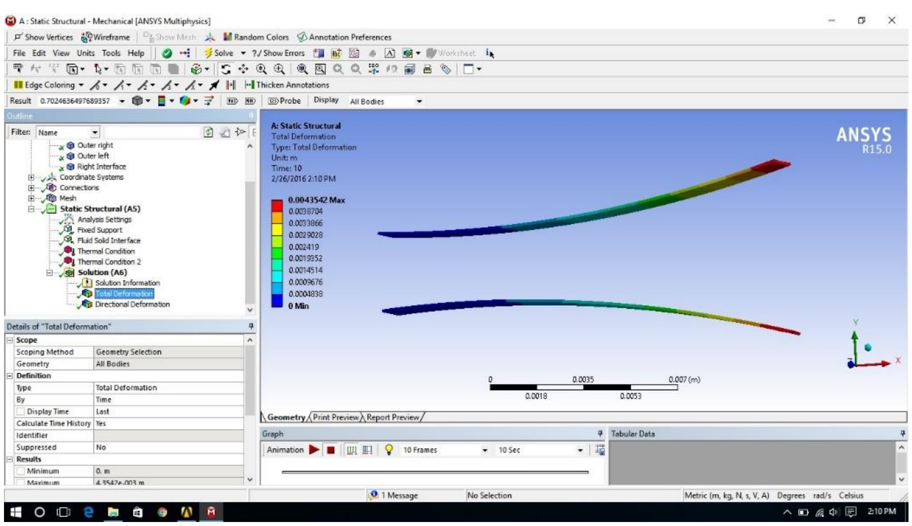


Figure 13: Deflection of PEEK and Nitinol

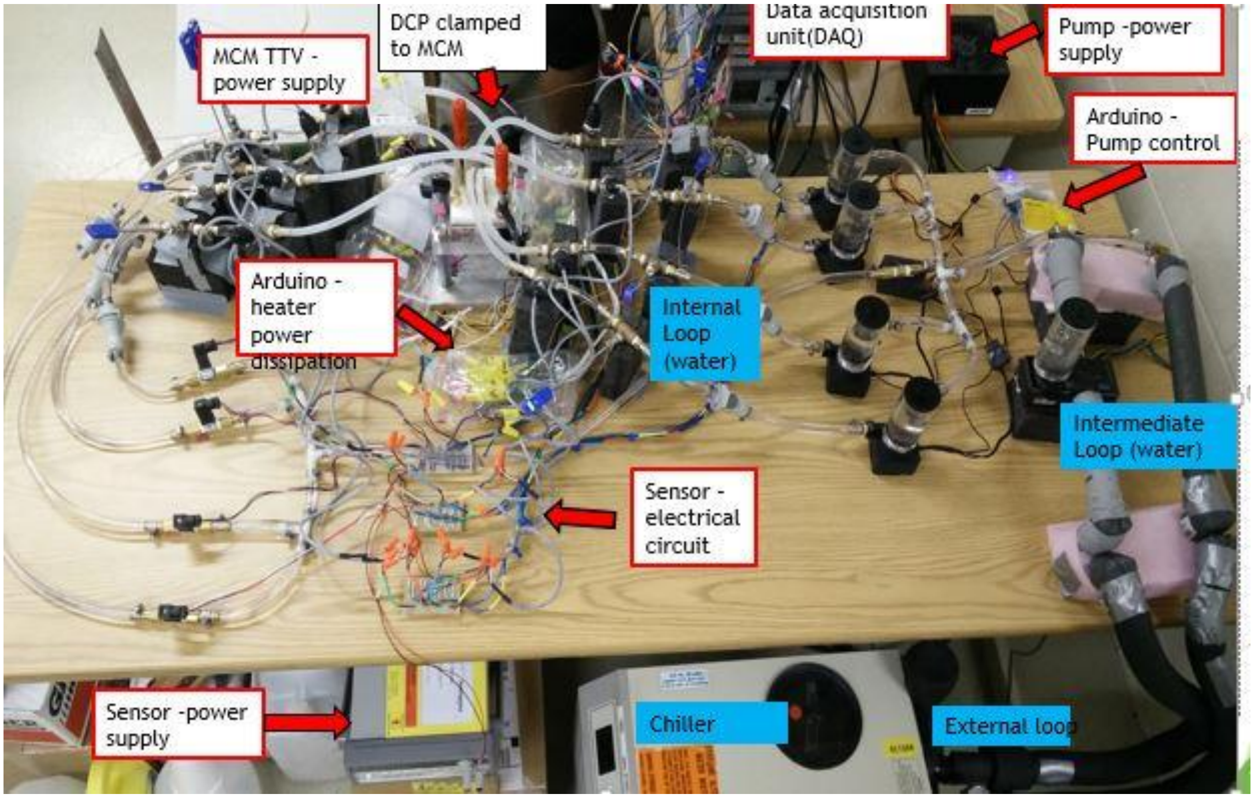


Figure 14: Experimental layout

CHAPTER 7

Conclusions

The concept for a dynamic cold plate which works on segregating flow control of cooling resources based on requirement for thermal management of high power devices was introduced. A multichip module (MCM) with 485Watt thermal design power was selected as the reference platform for designing such a solution. As we have drawbacks of hot spots and non-uniform temperature distribution, we came up with a flow control device outside the dynamic cold plate in order to reduce the heat losses and also increase the efficiency of the system. Bimetallic strip which is compact, reliable and less costly acts as temperature sensor and flow control device for the outflow of water, initially we considered bimetallic strip to be placed inside the water, due to corrosion effects and also heat transfer coefficient of water, we placed the flow control device outside water in order to reduce the heat losses and make the system more efficient. In this thesis we mainly concentrated on the parametric study of the bimetallic strip by considering different materials and changing the sizes and also the temperature in order to get good deflection so that we reduce the hot spots and maintain uniform distribution throughout the system.

CHAPTER 8

Future Scope

Increment in number of centers in processors a dynamic cold plate for such gadgets will serve as effective cooling arrangement. A study of accessible flow control valve should be possible to assistance to manufacture a dynamic cooling arrangement. Change in number of bimetallic strip and also the arrangement of bimetallic strip will help to get more deflection. Force and pressure calculations for flow control device can be done to get more efficient solution to reduce the hot spots and gain uniform temperature distribution. Some of the arrangements and their respective deflection trend are shown below.

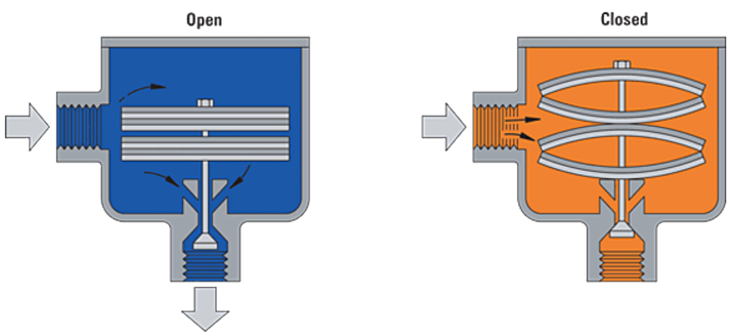
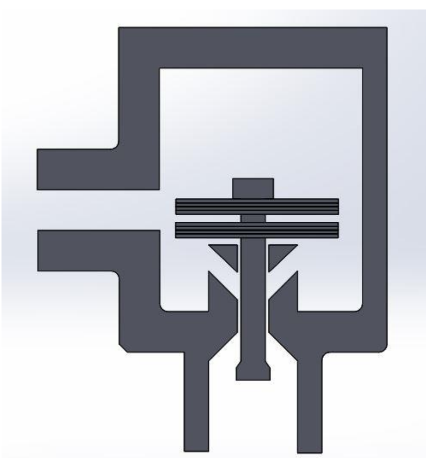
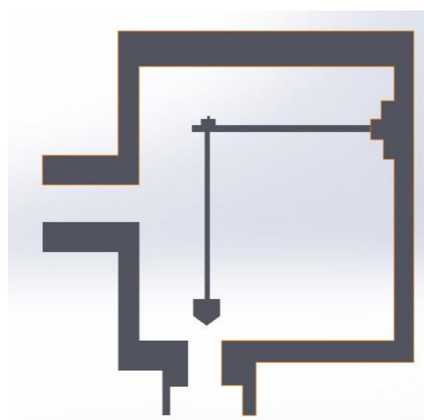


Figure 15: Basic idea of different arrangement of bimetallic strip



(a)



(b)

Figure 16: (a) CAD model of type 1 flow control device (b) CAD model of type 2 flow control device

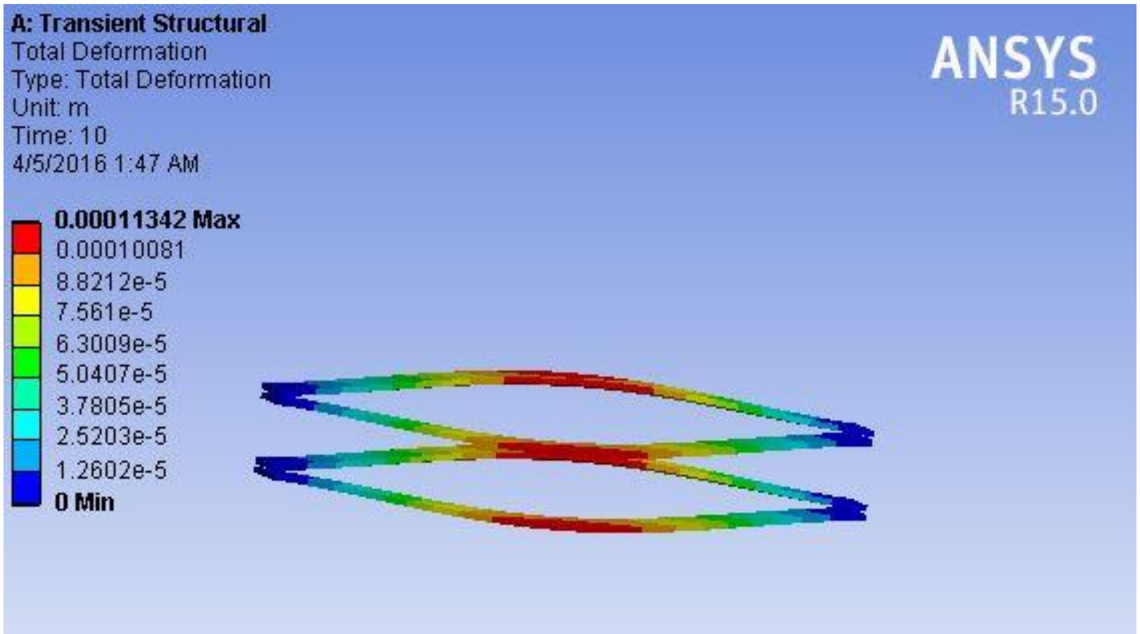


Figure 17: Deflection of bimetallic strips of type 1 flow control device

REFERENCES

1. U. Hwang and K. Moran, "Cold Plate for IBM Thermal Conduction Module Electronic Modules," Heat Transfer in Electronic and Microelectronic Equipment, vol. 29, pp. 495-508, 1990.
2. S. Kabbani, R. Beyerle and D. Bachelder, "Active thermal control system with miniature liquid-cooled temperature control device for electronic device testing". United States of America Patent US 7355428 B2, 8 April 2008.
3. M. K. Patterson, "The effect of data center temperature on energy efficiency," in Intersociety Conference on Thermal and Thermomechanical Phenomena in Electronic Systems (ITHERM), Orlando, FL, 2008.
4. R. Eiland, J. Fernandes, M. Vallejo, D. Agonafer and V. Mulay, "Flow rate and inlet temperature considerations for direct immersion of a single server in mineral oil," in IEEE Intersociety Conference on Thermal and Thermomechanical Phenomena in Electronic Systems, Orlando, FL, USA, 2014
5. M.-C. Lu, B.-C. Yang and C.-C. Wang, "Numerical study of flow mal-distribution on the flow and heat transfer for multi-channel cold-plates," in Semiconductor Thermal Measurement and Management Symposium (SEMI-THERM), San Jose, CA, 2004.
6. E. Frachtenberg, A. Heydari, L. Harry, A. Michael, J. Na, A. Nisbet and P. Sarti, "High-efficiency server design," in Proceedings of 2011 International Conference for High Performance Computing, Networking, Storage and Analysis, Seattle, WA, 2011.

7. http://www.syska.com/cms/docs/articles/KKhankari.ASHRAETransPaper._01.28.11.pdf
8. http://www.x8solutions.com/index.php?option=com_content&view=article&id=62&Itemid=583#vertical-cooling-technology
9. http://www.42u.com/rack-cooling.htm
10. http://www.42u.com/42u-rack-cooling.htm
11. http://www.electronics-cooling.com/2005/08/liquid-cooling-is-back/
12. https://buildings.lbl.gov/sites/all/files/direct_liquid_cooling.pdf
13. file:///C:/Users/Aravind/Desktop/avinash/5_916.pdf
14. Ruturaj and JE Fernandes thesis reports
15. http://www.kanthal.com/Global/Downloads/Materials%20in%20wire%20and%20strip%20form/Thermostatic%20bimetal/Bimetal%20handbook%20ENG.pdf