COMPUTATIONAL DESIGN AND FLOW ANALYSIS OF SMART FLOW CONTROL DEVICE FOR DYNAMIC COLD PLATE USED IN COMPUTER SERVER COOLING

by

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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

December 2016

Acknowledgements

I am grateful to Dr. Dereje Agonafer for not only being my thesis supervisor but also for his wisdom he never kept away from me. I would also like to thank him for his encouragement throughout my journey at UTA both academically and morally. I greatly appreciate the thesis committee members Dr. Haji sheikh and Dr. Ratan Kumar for their presence and valuable suggestions to improve this manuscript.

I am very much obliged to Ms. Sally Thompson and Ms. Debi Barton for helping me with the administrative and other academic related work. They have been extremely kind and supportive whenever I needed their assistance.

I also wish to convey my gratitude to all members of EMNSPC team especially, Ruturaj and Mullai. The help and support from the group members at various phases of my thesis project have been of great importance.

I would like to thank my father Mr. Srinivas and my mother Mrs. Manjula and my sister Miss. Keerthi thousands of times for everything. I hope I deserve to claim their name. I would like to thank one last person Krish, for always being my side and motivating me at every stage of my life.

November 21, 2016

Abstract

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One of the areas which Electronics cooling research is focusing on is high heat fluxes and non-uniform power distribution. Cooling is always required for maximum junction temperature and as such it is important to mitigate hot spots. These hot spots result in large temperature differences across the surface of high-end devices such as multi-core chip scale packages. One possible solution for non-uniform power distribution across the chip can be use of dynamic cold plate cooling along with smart flow control device and thus this project aims at developing and testing of dynamic cold plate integrated with use of smart flow control devices.

Bimetallic strip which shows good mechanical displacement on application of heat and is also cost effective will be the best choice for flow control device to regulate flow of liquid to the cold plate. Parameters like thermal performance and compatibility with water are considered for selection of materials for bimetallic strips. A careful analysis is made in choosing the material for bimetallic strips. Bimetallic strips are used along the path of the flow to regulate the flow of liquid through the device. Bimetallic strips get activated automatically based on the temperature of the liquid flowing through it and thus, no additional power is required. A design is made based upon the cold plate and device dimensions. Transient structural analysis is made by applying thermal boundary conditions to test for temperatures up to 100degree centigrade. Conjugate heat analysis is made to study the behavior of the bimetallic strips under thermal loads in interface with fluid flow and conclusions are derived based on the results.

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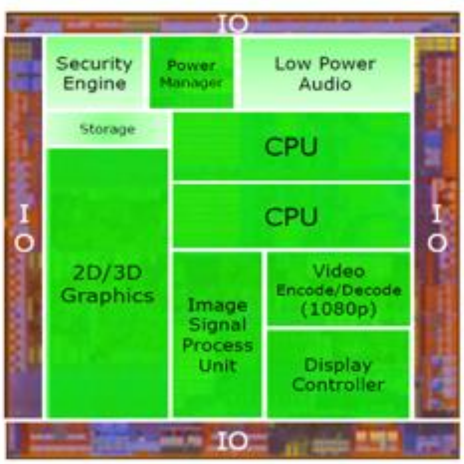
Chapter 1 Introduction

Demand for high computation and more data storage has led to the growth of large data centers. A Data center is basically repository of networked computer servers typically used for remote storage, management, processing and distribution of huge amount of data. Now-a-days there are more Users, more workloads and a more amount of data transaction across the current cloud and data center platforms. Trends show that this growth will continue to increase. The value around data and information has become very crucial than ever before. This indicate that content delivery, User Optimization and data quantification play vital role in current industry. It is always important to optimize and run data centers as efficiently as possible along with cost efficiency.

Because of increasing heat load densities in data centers, it requires more and more sophisticated methods for cooling. One of such approach for effective cooling is liquid cooling. (1)



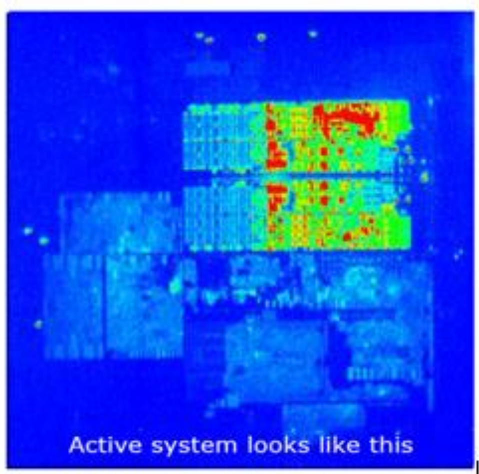


Figure 1-1 Active CPU processing and corresponding heat generation in the system (2)

This thesis will focus on implementing a cost-effective way of direct liquid cooling of a server which is used in data centers mainly concentrating on design of new flow control device that regulates the flow through cold plate used in Liquid cooling process.

1.1 Background and Motivation

Thermal Management of Electronic components rank among the important technical problems that need to be solved to achieve high power density and longevity of the electronic components. One of the important electronic components that require cooling are electronic chip. Chip Scale industry is currently trying to maintain the pace of Moore's prediction. (3)

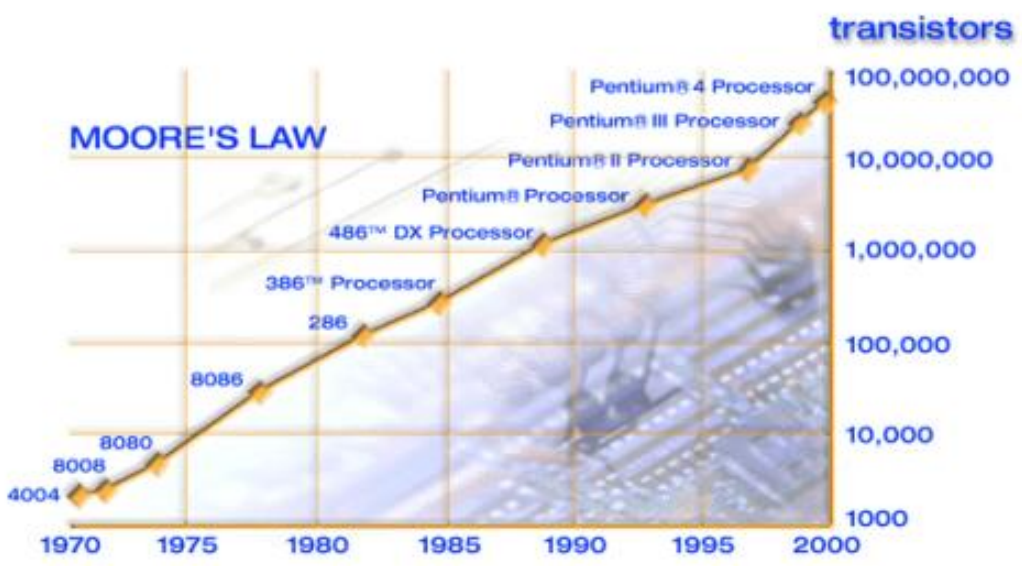


Figure 1-2 Timeline Plot of Transistor counts on Intel Processor Based on Moore's Prediction (3)

Moore's law is basically a prediction or an observation made by Dr. Gordon Moore, co-founder of Intel and is illustrated in figure 2. He noticed that the number of transistors per square inch on integrated circuits had doubled every eighteen months or so. Heat issue becomes a major threat to the continual achievement of Moore's prediction.

Another major effort being carried out over years to reduce the size of the devices alone with minimization of the cost incurred for designing the device. With the increase in power dissipation and reduction in the size, the growth in power density defines the limits of performance, functionality and reliability of electronics system.

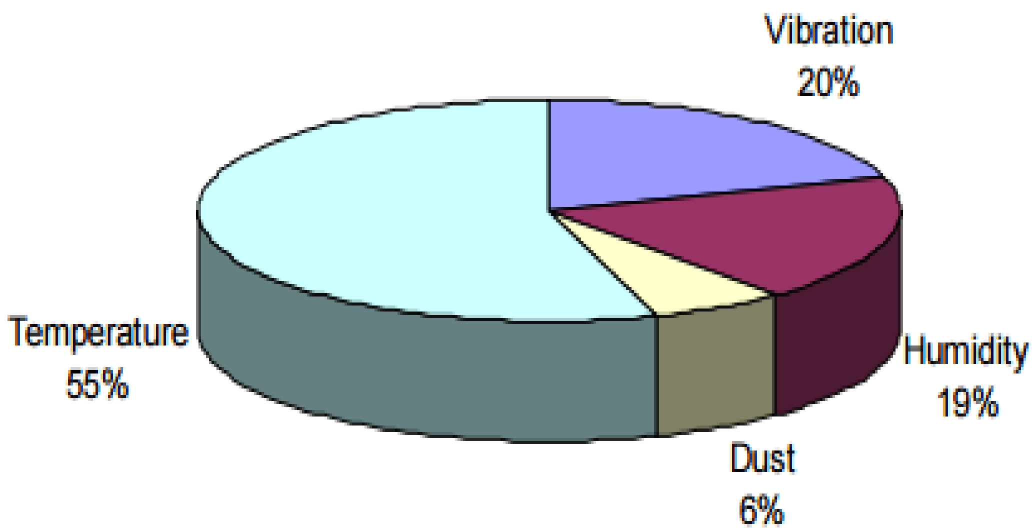


Figure 1-3 Reasons for failure in Electronic Components (4)

High heat generated in the chip causes thermal failures such as mechanical stress, thermal de-bonding and thermal fracture. And the main reason for failure of any electronics is due to temperatures. Figure 3 shows that failure in electronics during operation due to temperature is as high as 55% and highest among all the reasons that causes failure. So, it is very important to remove heat generated. There are many cooling techniques that are present in the market current. One of the most efficient way is Liquid cooling using cold plates So, we came up with a new design of cold plate for high performance namely, Dynamic Cold Plate. Dynamic cold plate has 4 inlets and 4 outlets for which we end up using 4 flow control devices to control flow through each inlet which adds up to total cost of the device along with increasing the size of the total device. So, building an inexpensive flow control device reduces the size as well as reduces heavier cost involved in former device. (4)

1.2 CPU Usage and Load analysis statistics

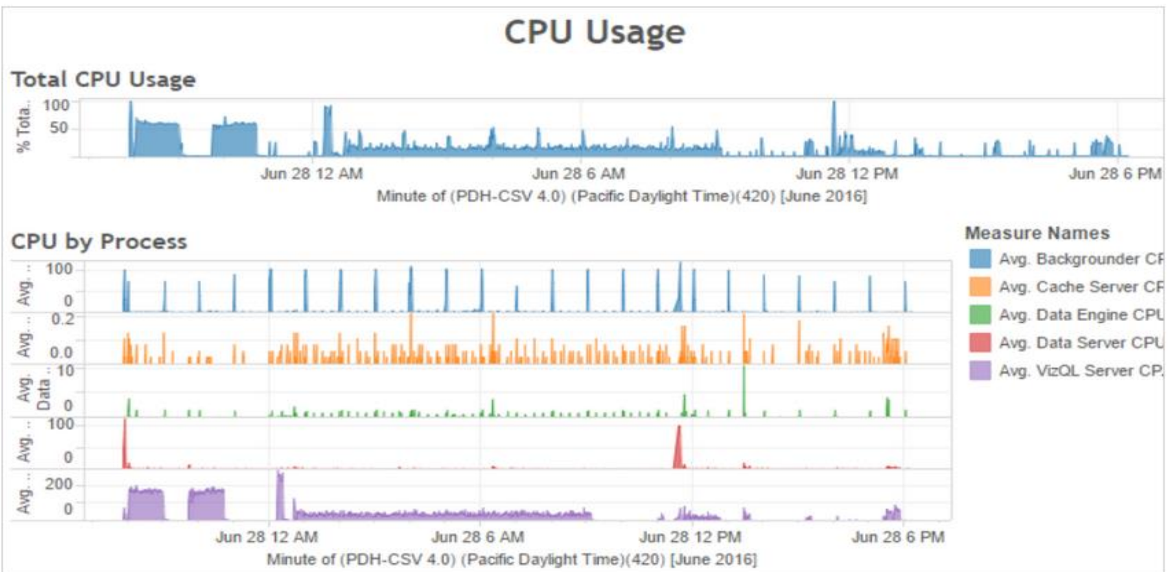


Figure 1-4 CPU Usage during a day (5)

CPU usage is not consistent over a time – hour or day. Due to this inconsistent usage, there will be inconsistent load applied on CPU which results in inconsistent heat generation. When heat generated is different, cooling requirements will also differ. Cooling required for high load condition will be high whereas during low load condition, cooling required will be less (5).

1.2.1 CPU Utilization & Core temperatures

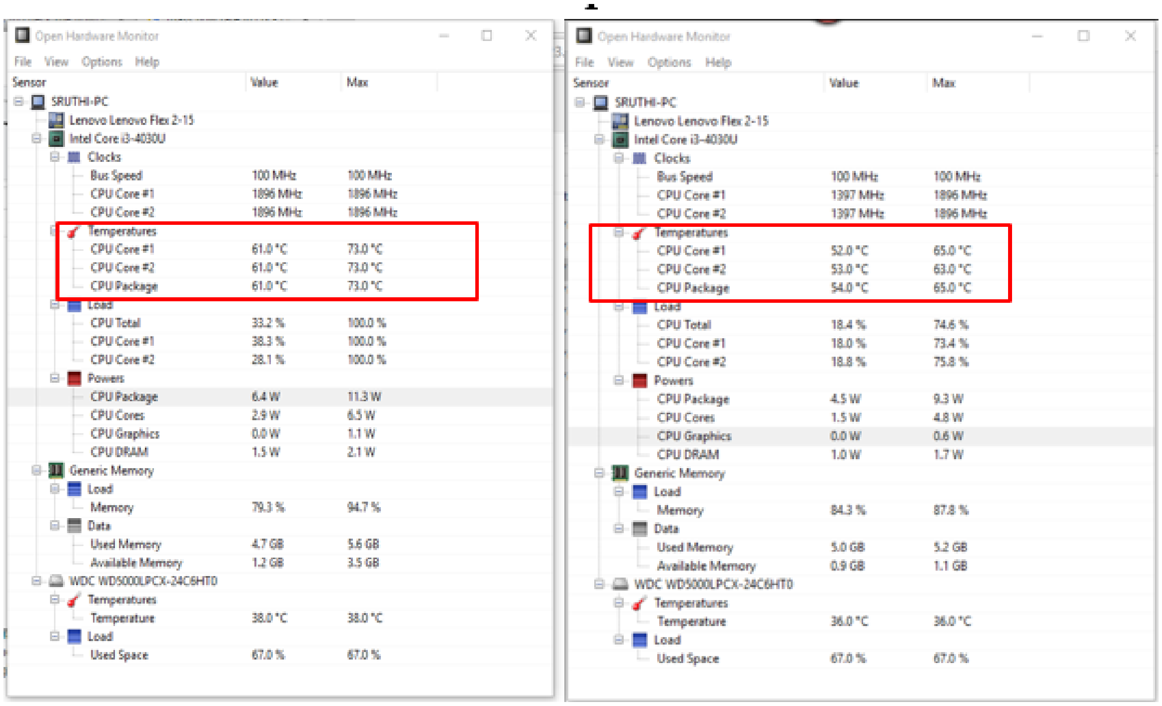


Figure 1-5 CPU Utilization and corresponding heat generation in CPU

Software Used: Open Hardware Monitor (6)

Hardware Monitoring Application

From Figure 5 it can be noticed that CPU temperature is not same during all the time of the day and so is the microprocessor chip temperature which varies regularly based on the load upon the system. And same cooling at different loads is not advisable. Less cooling during high loads results in less removal of heat from the chip generating heat and more cooling during low load condition results in more utilization of power. So, it is important to regulate the coolant supply to the chip generating heat based on the load condition in turn based on the temperature generated in the chip during operation.

1.3 Scope of the Work

1.3.1 Objectives

The objectives of this thesis are as follows:

- Importance of Dynamic cold plate
- Purpose of Flow control device in Dynamic liquid cooling
- Propose for Smart flow control device
- Material Selection for the new smart device
- Design Proposals for Dynamic Smart flow control valve
- Computational Structural Analysis of the designed model using Designer tool
- Designer tool selection for the structural analysis
- Computational Fluid Dynamic Analysis for water flowing through the Smart valve designed.
- Design compatibility results.

2.1 Liquid Cooling

Every computer from small personal computer to bigger gaming gadgets, supercomputers produce heat during their processing. The heat which is generate is waste and has no use for the system. If cooling of that system is not done, heat will kill the internal parts of the computer and system stops working. So, cooling is mandatory. It is important to keep components within permissible operating temperature limits. The most common way to cool these hot components is by using cooling fans and heat sinks. Basically, this type of components use air as the coolant. Broadly, classified as air cooling process. Fans run at a greater RPM (Revolutions per minute) and are quite loud. By installing liquid cooling we can get rid of noisy fans and water has good thermal conductivity property so it is better at transferring heat from the hot components compared to air. (7)

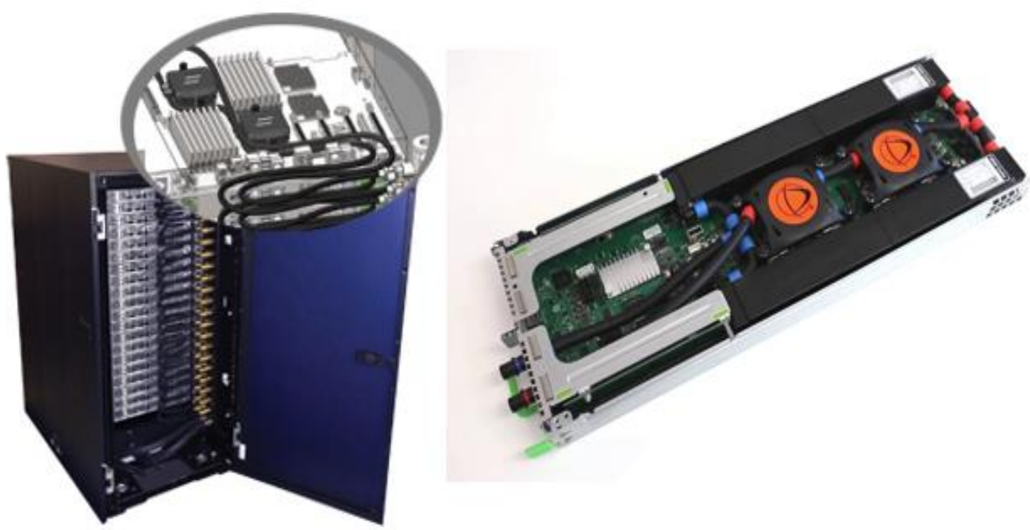


Figure 2-1 Liquid Cooling Examples (8)

Most of the Liquid cooling processes use water as coolant, so it can also be called as water cooling. Because of excellent thermal performance, liquid cooling is listed as one of the best solution for heat removal. It is the ONLY solution that allows successful heat removal from critical hot spots in the modern-day computer with absolutely zero noise pollution. (8)

2.2 Cold Plate

Use of Liquid Cold Plates for cooling process is the most efficient way to optimize liquid contact with hot surfaces and has the highest rate of heat transfer. Liquid cold plate cooling process can dissipate more heat than other active or passive cooling methods. Liquid cooling is a process where coolant gets circulated through a cold plate that collects heat from components that produce heat and then heat is dissipated through a liquid-to-air heat exchanger or liquid-to-liquid heat exchanger. (9)

2.2.1 Original cold plate

Basic Cold plate consists of a copper heat spreader, one inlet and one outlet.

Figure 2-2 Ordinary Cold Plate (9)

Copper Heat spreader designed to account for dissipation of heat in component heights and spreading of heat that is generated in the chip or in a multi-chip scale package. Inlet is used for the flow of water into the cold plate which is used as the coolant for the removal of the heat that is spreading over the copper plate (9)

2.2.2 Dynamic cold plate (DCP)

Multi chip model is basically a model that consists of multiple chips and chips are the components for heat generation. Model that we have used has 13 chips, these 13 chips are grouped into 4 sections namely A, B, C and D. Each section is provided 4 Inlets and 4 outlets. Flow of coolant through each section is independent of another and each section has isolated set of fins and same is shown in figure 6. Flow of the coolant is regulated by flow control device. As it involves 4 flow control loops, we need to use 4 flow control devices.

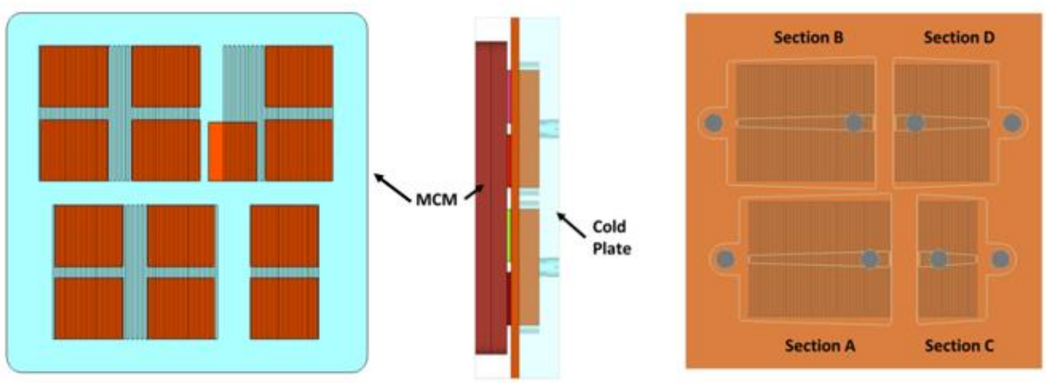


Figure 2-3 Multi-chip module and Dynamic cold plate (9)

2.3 Flow Control devices

Flow Control device or valve is used to regulate the flow or pressure of a fluid (Water in this case). In short, it controls the flow rate of the fluid that is flowing through it. Flow control allows to improve cooling efficiency by channeling the flow to hot spots.

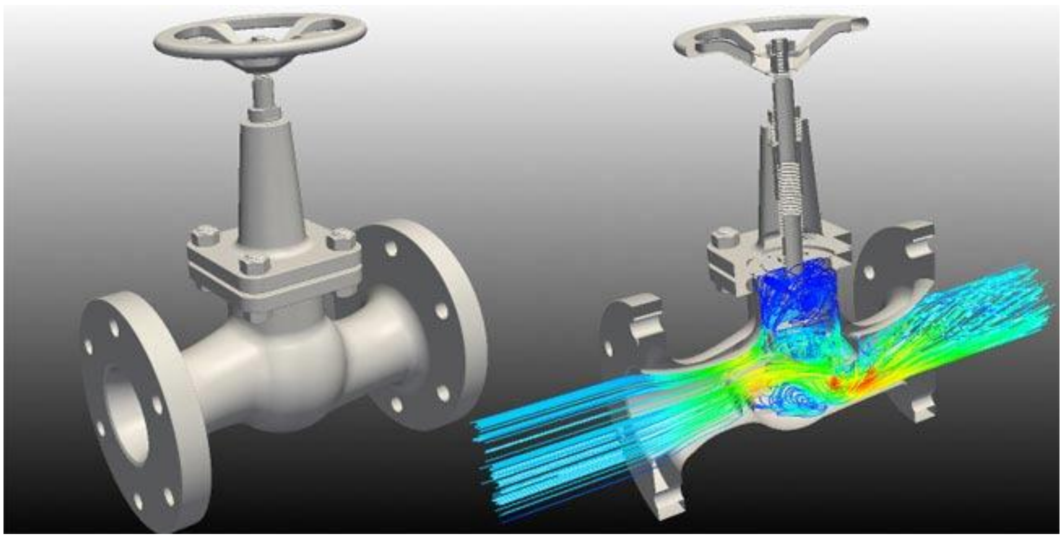


Figure 2-4 Flow Control Device example

These types of valves normally respond to the signals which are generated by other connected devices such as flow meters or other independent regulating meters. Automatic flow controller is a series of functions to control the Automatic water flow circuit in a water or hydraulic system. Automatic Flow control device consists of a Sensor, Actuator and a valve that regulates based on the actuator and sensor. Due to activation of the valve, controlling of the flow of the water takes place. (10)

2.3.1 Positioning of Flow Control devices in Dynamic Cold Plate setup

Figure 7 illustrates the cold plate sectioning and flow control devices attached to it. S1, S2, S3, S4 are four sections of Dynamic cold plate. Each section has one inlet and one outlet. All the four inlets have one flow control device attached to it. Hence, we need four flow control devices for the operation of the Dynamic cold plate which increasing total cost of the device as well as operation along with increase in overall size of the device which is not favorable for operation. (9)

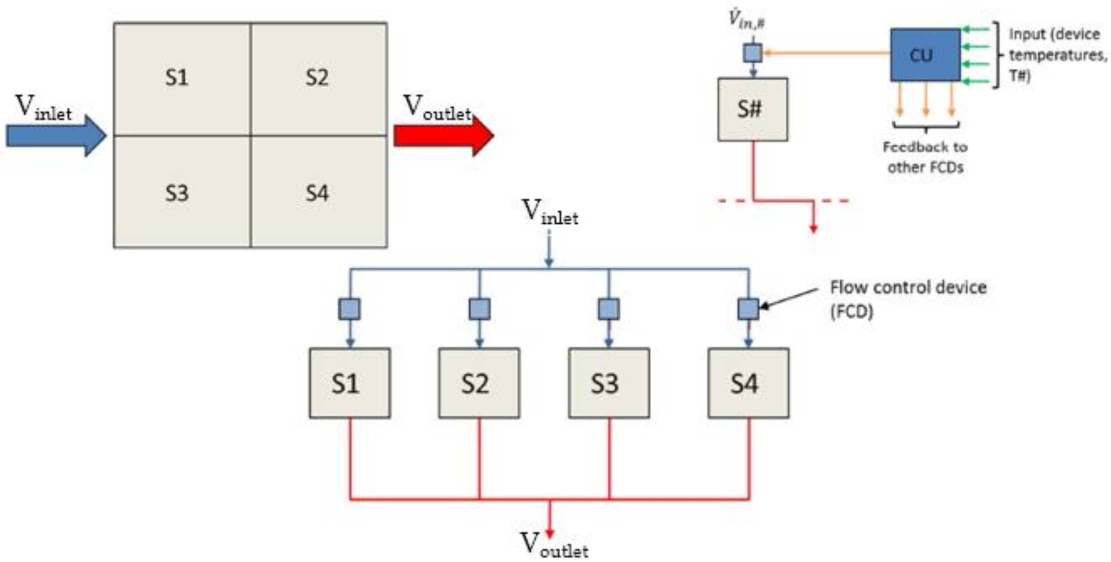


Figure 2-5 Looping and positioning of flow control device (9)

2.3.2 Present Flow Control device

- Swiftech MCP50X pump

Swiftech MCP50X pump is used to control the flowrate of the water coolant with pulse width modulated (PWM) control. Because of this pulse width modulation, there no need of any other component for the flow control, pump itself acts as flow control device. It works on centrifugal pumping mechanism. (11)

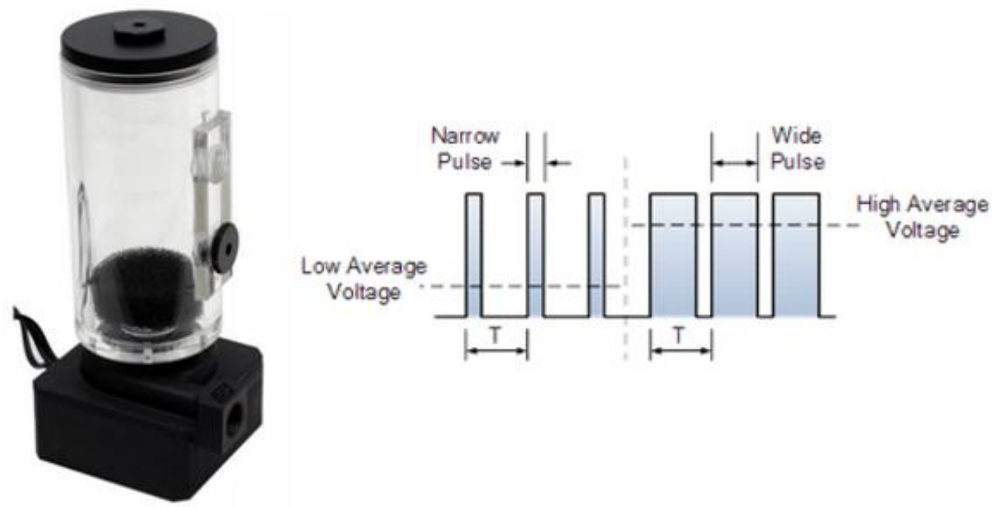


Figure 2-6 Present Flow Control device (Pump) (11) and Pulse width modulation (12)

For pulse width modulation control, it has 4-wired connector and SATA cable is used for DC Power supply. Arduino is used for controlling pump speed or for varying pump speeds through Pulse width modulation mechanism.

Arduino is an open-source platform. It has electronics platform based on easy-to-use hardware and software. Arduino senses the signals by receiving inputs from sensors, and change the surrounding environment as per the requirements and this is done by controlling actuators. (12)

2.3.3 Need for other type of Flow Control device

- Present Flow Control Devices present in the market are robust and costly. Swiftech MCP50X Pump flow control device is one among them
- It should include a reliable valve, actuator, control system and a sensor, which increases the complexity of the device.
- Cost for designing and manufacturing such devices are high.
- Cost to assemble and maintain them is high Using four such costly devices increases overall cost of device by four times.

- These devices have longer assembly time
- In case of a failure, the equipment downtime for such devices is more.

So, to overcome these problems we came up with a new flow control devices which will be induced within the pipe flow avoiding additional robust flow control devices like pumps with Arduino controls.

2.3.4 FCD Actuators

Following table lists some of the flow control device actuators available and that can be used for controlling of the flow:

Actuators	Pressure	Stroke (displacement)	Response Time	Reliability
External				
Solenoid plunger	Small	Large	medium	Good
Disk type piezoelectric	Small	very small	fast	Good
Stack type piezoelectric	very large	very small	fast	good
Pneumatic	Large	large	slow	good
Shape Memory Alloy	Large	large	slow	Not enough
Micro machinable				
Electrostatic	Small	Very small	Very fast	Very good
Thermopneumatic	Large	medium	medium	good
Electromagnetic	Small	Large	fast	good
Bimetallic	Large	Small	medium	enough

Table 1 FCD Actuators (13)

Pressure:
very large - 100 $kgf/cm^2 < p$
large - 1 $kgf/cm^2 < p < 100$ kgf/cm^2
medium - 0.5 $kgf/cm^2 < p < 1$ kgf/cm^2
small - $p < 0.5$ kgf/cm^2

Stroke:
large - 100 $\mu m < d$

medium - 30 µm < d <100 µm
small - 10 µm < d < 30 µm
Very small- d < 10 µm

Response time:

Very fast - t < 0.1 msec
fast - 0.1 msec < t < 1 msec
medium - 1 msec < t < 1sec
slow - 1sec < t

2.3.5 Bimetallic Strips as FCD actuator

Following are the reasons for selecting Bimetallic strips as flow control device for dynamic cold plate setup cooling:

- Using bimetallic strips, we can control flow in mini 3mm channels like pipes without any additional attachments to the strips for actuation.
- Bimetallic FCD's can be actively controlled for dynamic cold plate application to efficiently cool the hot spots
- Bimetallic Strips itself acts as an **all in one** sensor, actuator, valve. So, there is no need any other additional actuators or sensors.
- It has a simple and compact design so it is easy to manufacture
- It can be easily assembled into the existing pipes without much modifications
- It is very reliable and cost effective
- Displacement of strips due to fluid pressure is less.
- Since stresses are very low, we can increase the length further and decrease the thickness. Making the device more sensitive to the change in temperature.

Chapter 3 Bimetallic Strips

3.1 Working Principle

A bimetallic strip consists of two metals amongst which one is of higher thermal expansion and other is of lower thermal expansion and both are bonded together This difference in thermal expansion in the two metals leads to a much larger sideways displacement of the strip.

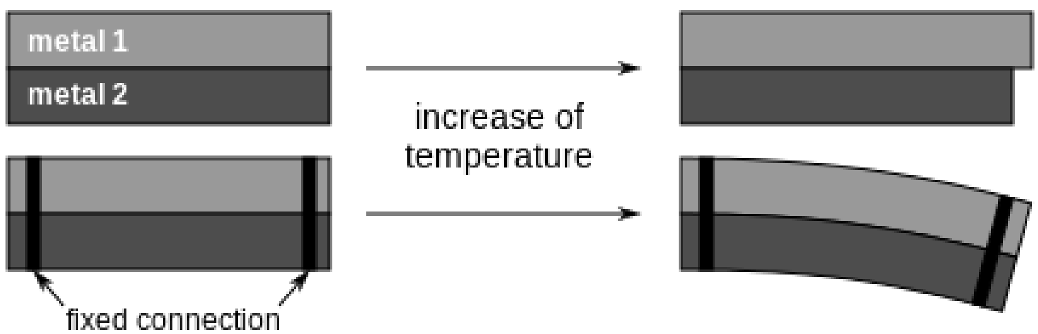


Figure 3-1 Working Principle (14)

3.2 Material Selection for Bimetallic strip FCD

ASME defines a type of composite material known as Thermostat Metal which are usually in the form of sheet or strip consisting of two materials. These materials can either be materials of comparative nature or materials of different Thermal Expansion coefficients. When metals of different Coefficient of thermal expansion are soldered together then the component tends to alter its curvature when temperature induced to it is changed. Though a thermostat metal is usually made of two metals, it can also contain third component or even more. This scenario will generally arise when electrical restivity of the metal is critical to its application. The difference in expansions of these two metals generate stresses upon change in temperature, these stresses are the reason for deflection and/or force induced in the strips. (15)

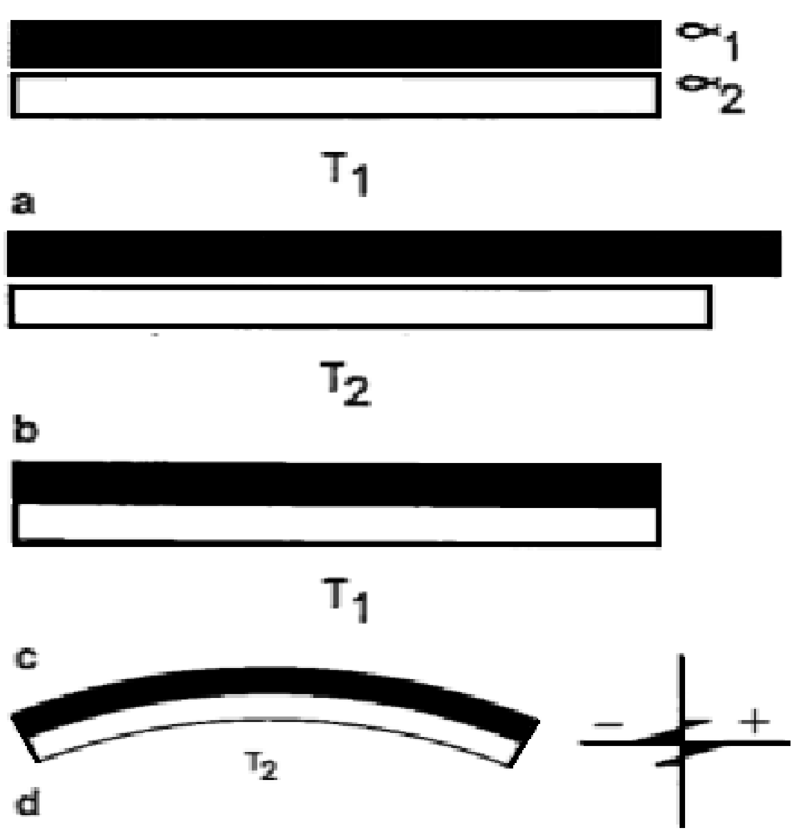


Figure 3-2 Principle operation of thermostat metal (15)

α_1 and α_2 are the coefficient of thermal expansions of two metals, one with higher CTE and other with lower CTE compared to former metal. Here, α_1 is greater than α_2. In the figure 9a, two strips of metal with different CTEs at a temperature of T_1 is shown. Figure 9b shows relative change in lengths of these two metals at two temperatures T_1 and T_2 where T_2 is greater than T_1. Figure 9c shows that strips that are present in 9a are rigidly bonded together at T_1. In Figure 9d, it shows the behavior of bonded strips upon application of heat of T_2 temperature.

Tensile (+) and compressive (-) stresses generated at the bond between two metals as shown in the figure and is given by following formula:

$$\sigma = \frac{E}{2}(\alpha_1 - \alpha_2)(T_2 - T_1)$$

Here, E is elastic modulus of two metals (assuming it to be same) and thickness of both the plate is same

3.2.1 Flexivity (F)

The Unique term known as flexivity is defined specially for thermostat metals and defined by ASTM. ASTM states flexivity as the change in curvature of the longitudinal centerline of the specimen per unit temperature change for unit thickness and is calculated by using following formula:

$$F = \frac{\left(\frac{1}{R_2} - \frac{1}{R_1}\right) t}{T_2 - T_1}$$

Where t is total thickness of the thermostat metal beam, if we assume that both the metals have same thickness then thickness of each strip is assumed to be t/2. And T_2 and T_1 are final and initial temperatures respectively.

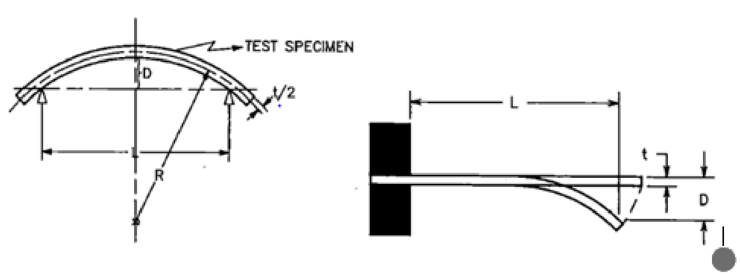


Figure 3-3 Test Specimen Analysis

Radius can be calculated from the geometry and is calculated by following formula for rectangular geometry strips:

$$\frac{1}{R} = \frac{8D}{L^2 + 4Dt + 4D^2}$$

Where D (value of deflection at the centerline) and L are defined as shown in Figure 10. The values of $1/R_1$ is calculated at temperature T_1 and similarly $1/R_2$ is calculated at temperature T_2. Flexivity of thermostat metal is specified over range of temperatures and it has an instantaneous and unique value at given temperature.

General range of flexivity of the thermostat materials that are available commercially range from 10×10^{-6} to $38 \times 10^{-6}\ {}^{o}C^{-1}$. Flexivity lets us calculate the expected deflection of any thermostat materials for change in temperature. Flexivity of thermostat metal is proportional to force or stress generated by a bimetallic element when part or all its deflection is suppressed. CTE is a function of temperature and flexivity is proportional to CTE so in term flexivity is a function of temperature.

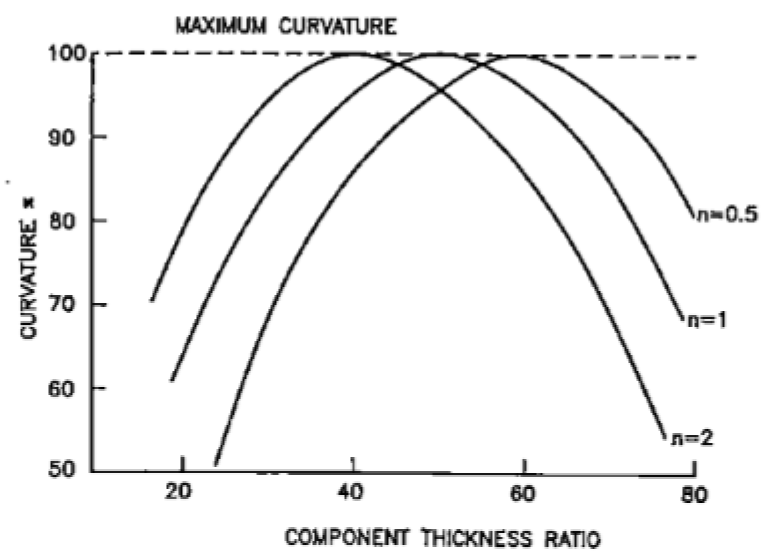


Figure 3-4 Component Thickness Ratio Vs Curvature % (15)

Composition	TM1	TM2	TM3	TM4	TM5	TM6	TM8	TM9	TM10
High Expansion (wt. %)									
Nickel	22	10	25	25	25	22	10	22	22
Chromium	3	-	8.5	8.5	8.5	3	-	3	3
Manganese	-	72	-	-	-	-	72	-	-
Copper	-	18	-	-	-	-	18	-	-
Iron	75	-	66.5	66.5	66.5	75	-	75	75
Intermediate (wt.%)									
Nickel	-	-	-	-	-	-	-	100	100
Manganese	-	-	-	-	-	-	-	-	-
Low Expansive (wt. %)									
Nickel	36	36	42	45	50	40	36	36	36
Iron	64	64	58	55	50	60	64	64	64
Cobalt	-	-	-	-	-	-	-	-	-
Component Thickness Ratio (%)									
High Expansive	50	53	50	50	50	50	80	27	34
Intermediate	-	-	-	-	-	-	-	46	32
Low Expansive	50	47	50	50	50	50	20	27	34

Table 2 ASME TM materials composition (15)

Properties	TM1	TM2	TM3	TM4	TM5	TM6	TM8	TM9	TM10
Max. Sensitive Temperature Range(^{o}C)	-18-149	-18-204	93-316	121-371	149-454	38-288	-18-204	-18-149	-18-149
Max. Recommended Temperature (^{o}C)	538	260	538	538	538	538	260	482	482
Flexivity (X 10^{-6})									
10-93 ^{o}C	27.0	38.7	18.7	15.1	11.3	23.2	28.6	20.2	22.3
38-149 ^{o}C	26.3	38.0	19.1	15.5	11.5	23.2	28.6	20.2	22.3
Heat Treatment (^{o}C)	371	260	371	371	371	371	260	371	371
Electrical Restivity (μΩm)	0.790	1.12	0.732	0.665	0.582	0.732	1.41	0.166	0.208
Modulus of Elasticity(GPa)	182	138	172	172	176	172	134	179	179
Specific Heat (J/kgK)	500	500	500	500	500	500	500	500	500
Density (g/cm^3)	8.03	7.75	8.03	8.03	8.03	8.03	7.47	8.58	8.3

Table 3 ASME TM materials composition (15)

From the above tables, we can see the properties of list of few thermostat materials that are commercially available in market. We can choose deflection of thermostat material based on the application requirement. As deflection is based on thermal expansion coefficients of both the metals forming the bimetallic strips, flexivity is one such property that is defined by using thermal expansion coefficients of both the metals hence calculating the deflection i.e., Deflection is directly proportional to flexivity of the thermostat material.

Thermostat materials are used in various shapes and forms. Thermostat materials can be used as temperature sensors as they can sense the temperature and deflect based on the temperature input. They are also used as temperature controllers. Major criteria in designing such elements is amount of deflection and force required to do work. Deflection due to temperature change depends on flexivity of thermostat materials and geometry of the element.

$$B = \frac{K_1 \mathrm{F} \Delta \mathrm{T} L^2}{t}$$

Force generated in the element is basically thermal force and is dependent on elastic modulus of the thermostat metals. It also depends on flexivity and geometry of the element.

$$P = \frac{K_2 F E \Delta T w t^2}{L}$$

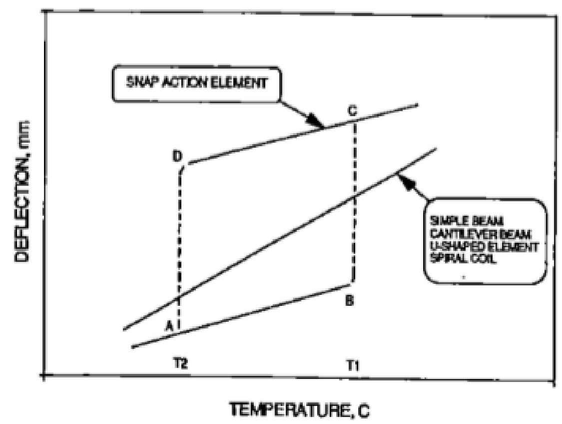


Figure 3-5 deflection vs temperature curves for typical thermostat metal element (15)

From the table, we can notice that flexivity for TM5 is least which is 11.3 X 10-6 oC and TM2 is maximum whose flexivity is 38.7 X 10-6 oC. But TM2 corrodes faster with water so It will be bad choice when system deals with water. Then we go for next choice for maximum flexivity material which is TM8 whose flexivity value is 28.6 X 10-6 oC and TM8 is friendly with water. Hence TM8 will be best choice for higher expansion material and TM5 for low expansion material. (15)

Chapter 4 Case Study

4.1 Design Proposals

A method for controlling of velocity of water that is flowing through the pipe, can include a temperature-sensitive bimetallic valve comprising a bimetallic strip, a blocking device and a flow control structure. When hot water flows through the pipe that has bimetallic strip value, transfers heat from the hot water to the bimetallic strip. This results in change of temperature of bimetallic strip from a normal temperature to the temperature of hot water. This changes the position of the bimetallic strip and allowing the space for delivering water based on temperature from the temperature-sensitive bimetallic valve at a secondary velocity and latter velocity of the water changes based on the position of the bimetallic strip. Two types of value designs are proposed based on positioning of the bimetallic strips over or inside the Pipe. (16)

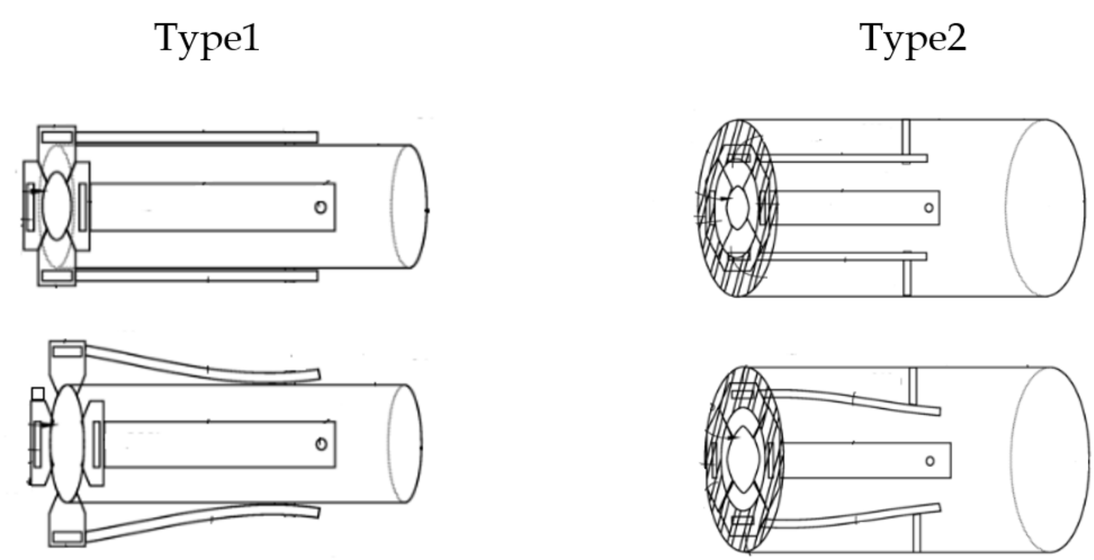


Figure 4-1 Design Proposals- Type 1 and Type 2 (16)

4.2 Flow Setup

4.2.1 Previous Flow Control Device (Pump) operation in Dynamic cold plate setup

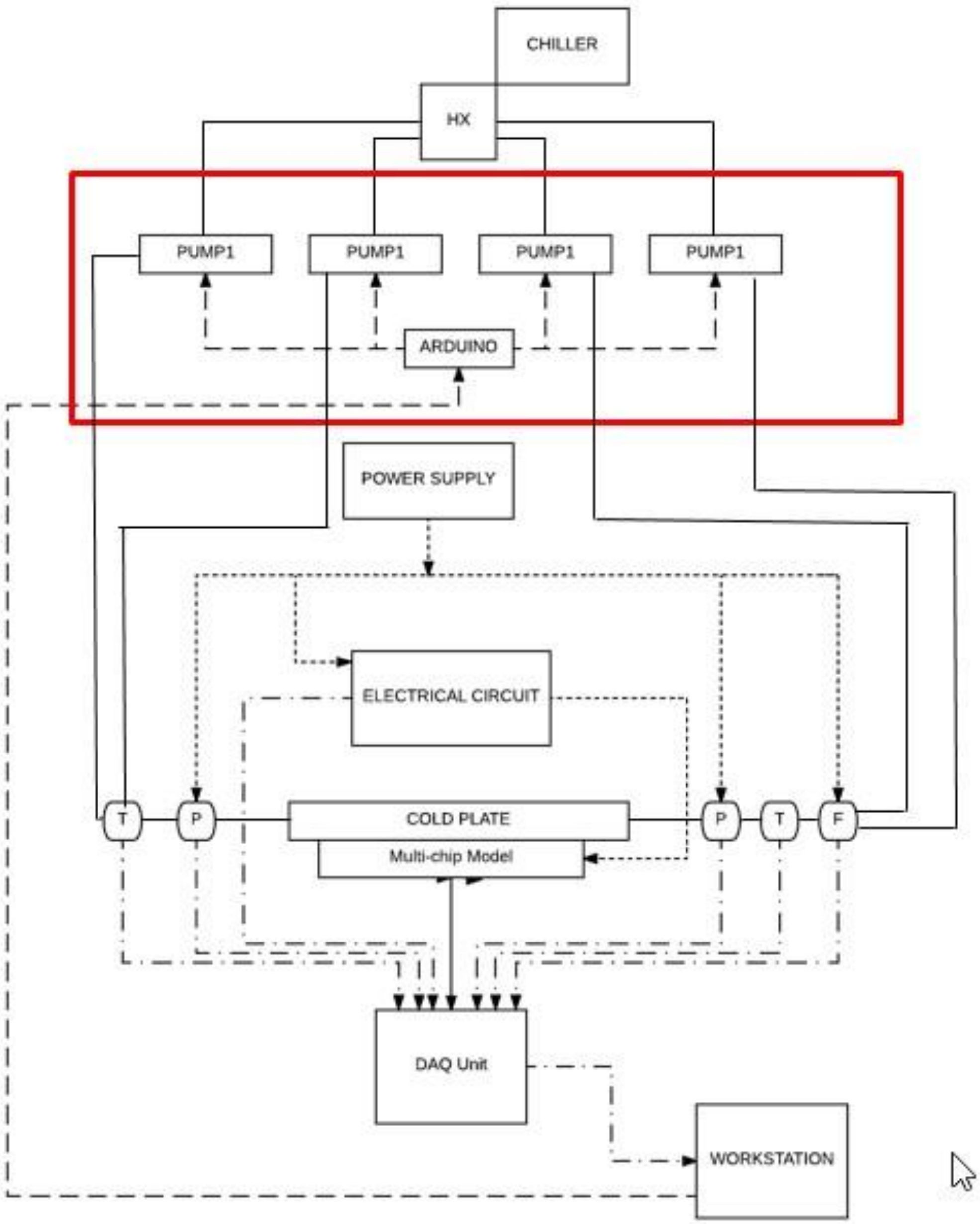


Figure 4-2 Present Dynamic cold plate Flow Control setup

4.2.2 Newly Designed Flow Control Device Operation in Dynamic cold plate setup

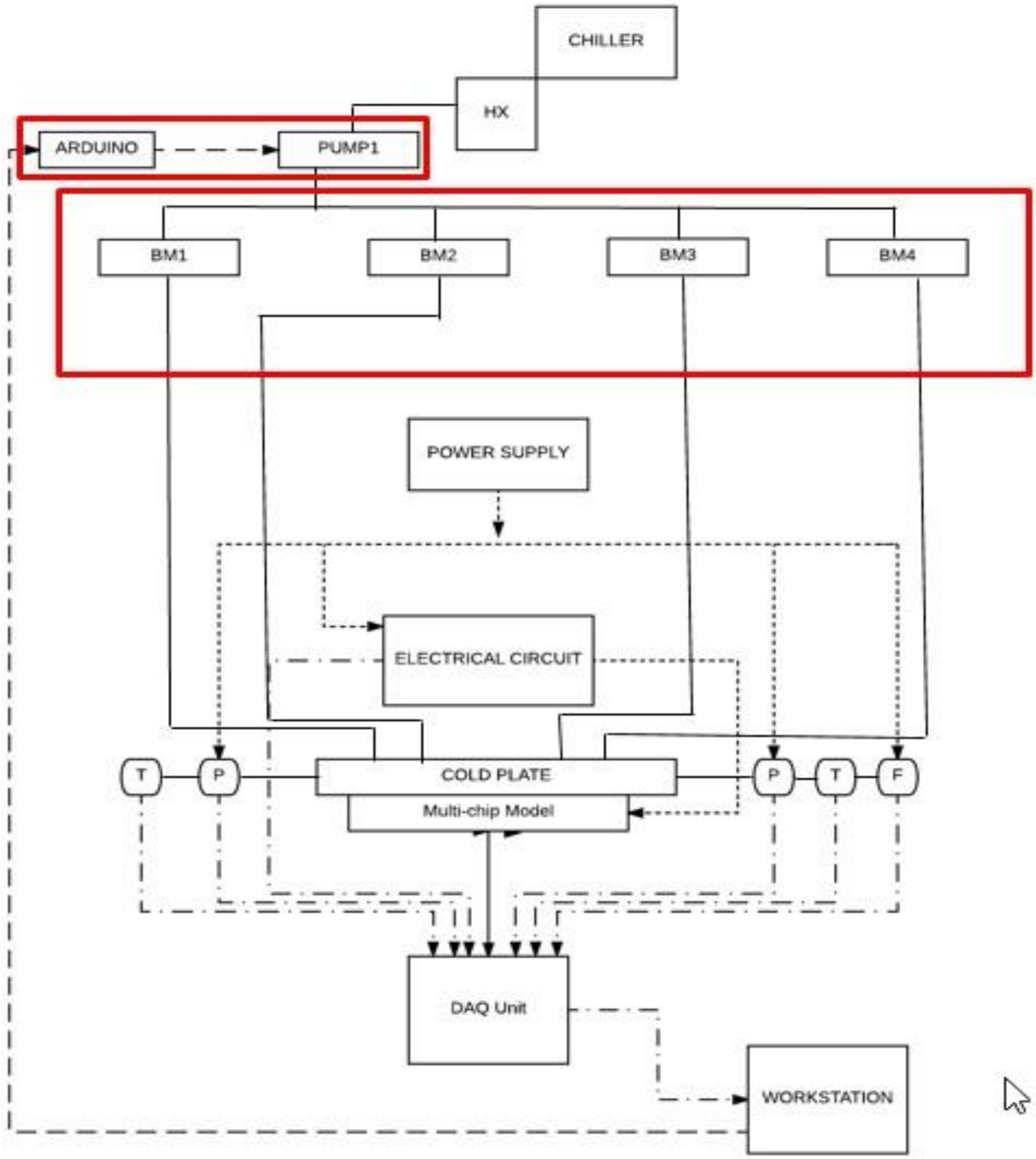


Figure 4-3 Modified Dynamic cold plate Flow Control setup

4.3 Arduino Programming

Sample Code: We use Java Programming Language for programming Arduino board.

Following is a sample code for controlling pump revolutions that is present in Setup.

```
byte half_revolutions;
 int rpm;
 long time;
 void setup()
 {  Serial.begin(9600);
   attachInterrupt(0,
rpm_fun, RISING);
   half_revolutions = 0;
   rpm = 0;
   time = 0;
 }
 void loop()
```

Figure 4-4: RPM over time (17)

```
{  if (half_revolutions >=20)
{     rpm = 30*1000/(millis() - time)*half_revolutions;
     time = millis();
     half_revolutions = 0;
     Serial.println(rpm,DEC);
   } }
 void rpm_fun()
 {   half_revolutions++;
} (17)
```

4.4 Computational Analysis

4.4.1 Pipe Properties

Following are the dimensions and requirements of a pipe in which bimetallic strip flow control Device is attached:

- Pipe Cross-Section: Circular
- Pipe Material: PVC (Poly Vinyl Chloride) pipe
- Diameter: 12mm
- Length: 100mm (varies)
- Liquid flowing through pipe: Water
- Four Bimetallic strips are inserted in the middle of the flow with some attachments and supporting structures

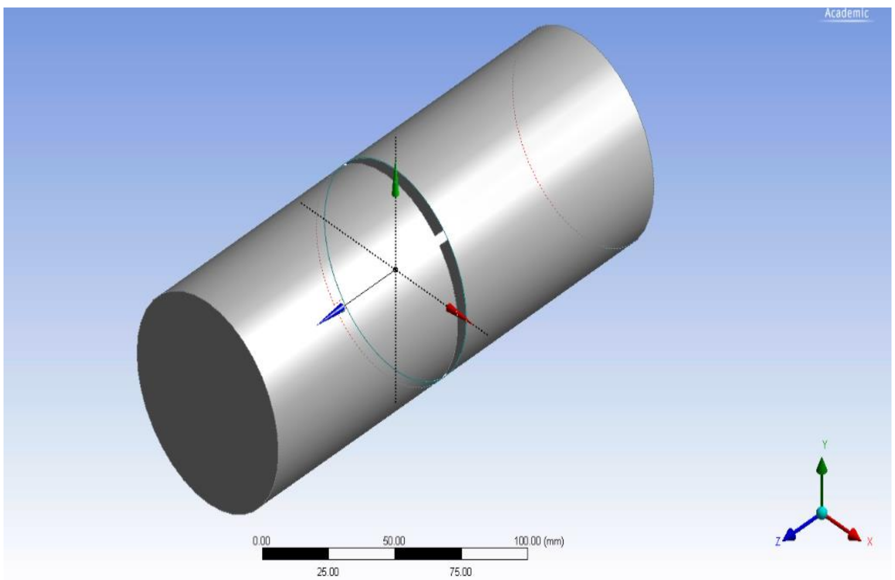


Figure 4-5 Pipe Design

4.4.2 Type 1 Flow Control device placement in a pipe

i) In case of Type1 design of bimetallic valve, four slots are made over the pipe to insert four bimetallic strips and an enclosure will be placed over the bimetallic strips valve

ii) In case of Type 2 design of bimetallic valve, no such slots are needed and it can be used without any enclosure as the valve is present inside the pipe itself.

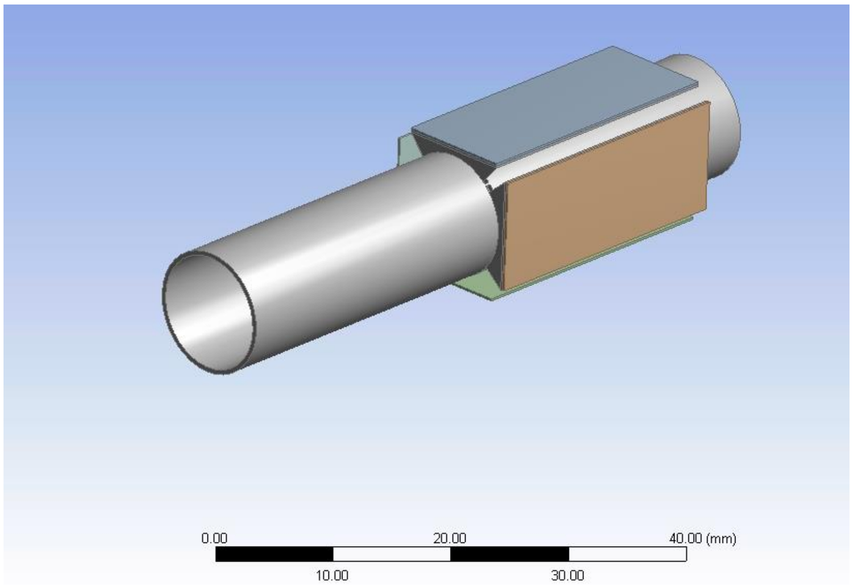


Figure 4-6 Pipe with Bimetallic Flow Control Valve attached

4.4.3 Enclosure Design

- Enclosure for a Bimetallic strip flow control valve is mandatory in case of Type 1 type of design because of following reasons:
    - (a) To avoid leakage of water that is flowing through the bimetallic strip valve and pipe system.
    - (b) To protect the bimetallic strips from corrosion or dust deposition due to atmospheric conditions.
    - (c) To avoid contamination of distilled water that is flowing through the pipe system.

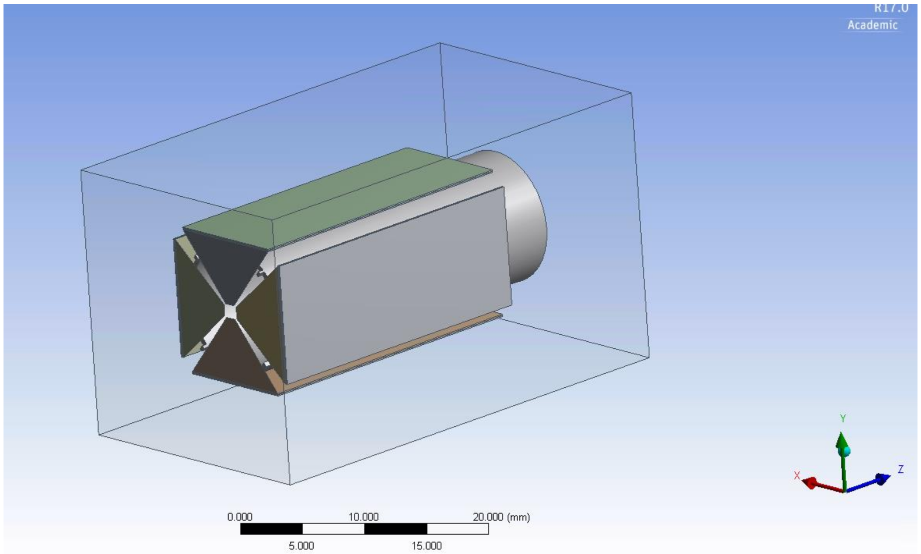


Figure 4-7 Enclosure Design

4.5 Software Used

- Work Station: Ansys Workbench 17.0

1) Structural Analysis: Design Modeler / Space Claim

Figure 4-8 Transient structural Analysis Menu Box

2) Fluid flow Analysis: CFX

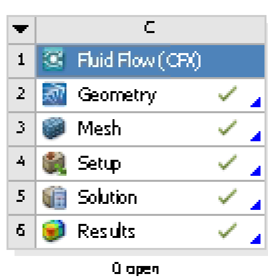


Figure 4-9 Fluid Flow Analysis Menu Box

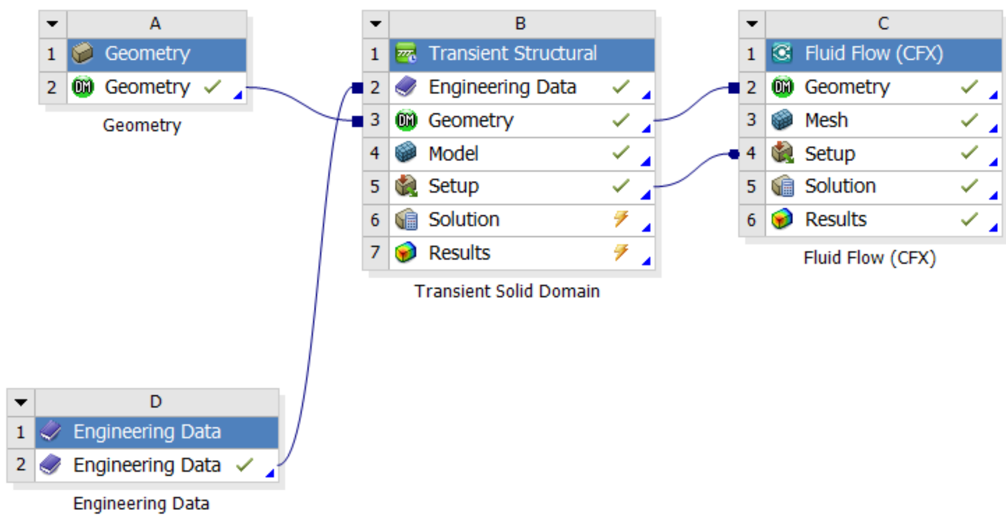


Figure 4-10 Flow Diagram of Computational Analysis

4.6 Engineering Data

Thermostat materials are not present in the Engineering source data which are inbuilt present in Engineering data of Ansys workbench 17.0. So, we need to add the required TM materials to the Engineering Data. This is done by Engineering Data Manager which is one of the main features of Ansys 17.0.

Engineering Data Manager is used mainly for

I. Defining
II. Organizing
III. Storing material properties.

A list of material properties is available in the Toolbox menu for defining the material properties of new material that need to be added to the project. These newly created Material data can be stored in Material data library which will be used for future accessing in related project.

Thermostat Material TM5 Properties:

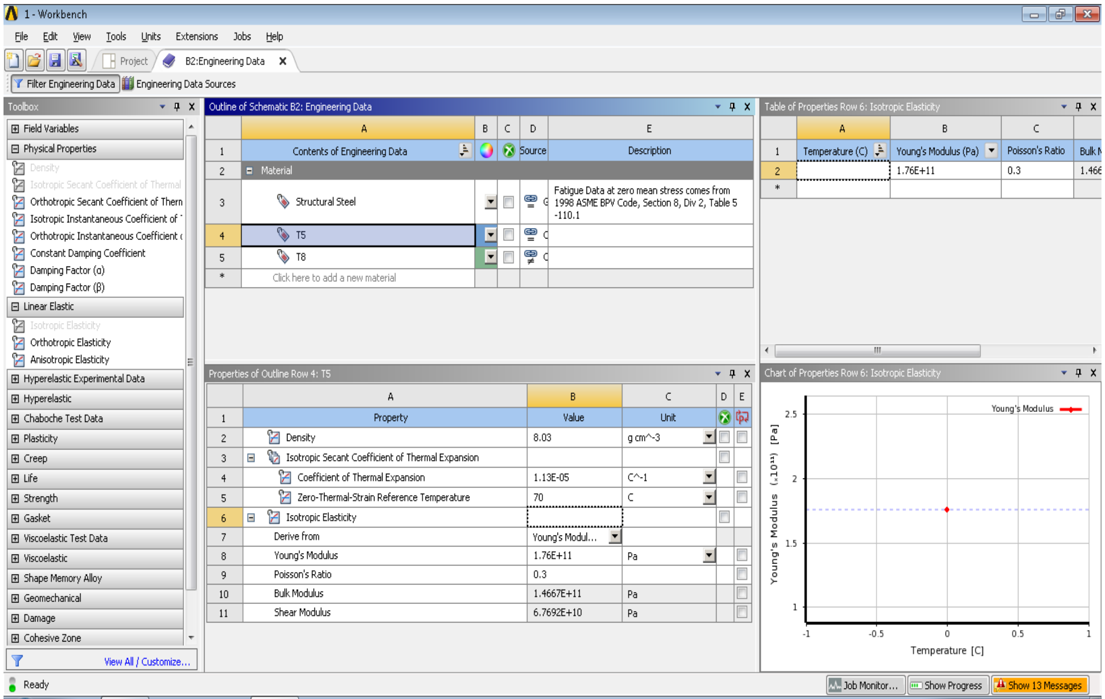


Figure 4-11 TM5 Propertied

Thermostat Material TM8 Properties:

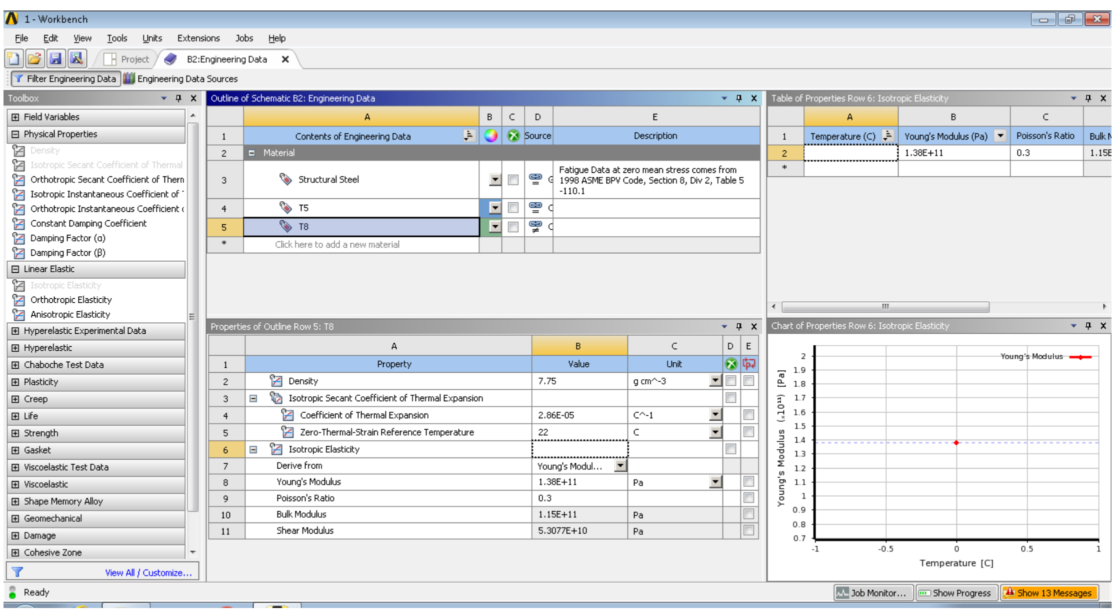


Figure 4-12 TM8 Properties

4.7 Structural Analysis

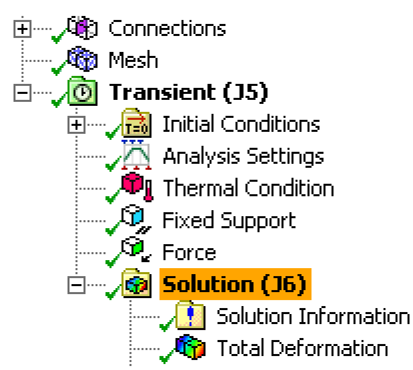
Parameters Used:

Properties/Materials	ASMT TM5	ASMT TM8
Max. Sensitivity temperature range	149-454	-18-204
Flexivity (*10^6)		
10-93^0C	11.3	28.6
39-149^0C	11.5	28.6
Heat treatment(^{0}C)	371	260
Electrical Resistivity at 25^0C (μΩm)	0.582	1.41
Modulus of Elasticity(GPa)	176	34
Specific Heat(J/Kg.K)	500	500
Density (g/cm^3)	8.03	7.47
Thermal coefficient of expansion (*10^5 C^{-1})	1.26	1.82

Table 4 Parameters used in Structural Analysis

Transient Analysis is performed for structural analysis of Bimetallic strip valve. In this case, Thermal Condition are applied in time steps

	Steps	Time [s]	Temperature [°C]
1	1	0.	35.
2	1	0.5	40.
3	1	1.	45.
4	1	1.5	50.
5	1	2.	55.
6	1	2.5	60.
7	1	3.	65.
8	1	3.5	70.
9	1	4.	75.
10	1	4.5	80.
11	1	5.	90.
12	1	5.5	100.
13	1	10.	= 100.



4.8 Type1 Results

(1) Total Deformation

Total Deformation is defined as square root of sum of squared stretching deformation and shearing deformation. Here, deflection is caused due to transient thermal load condition applied.

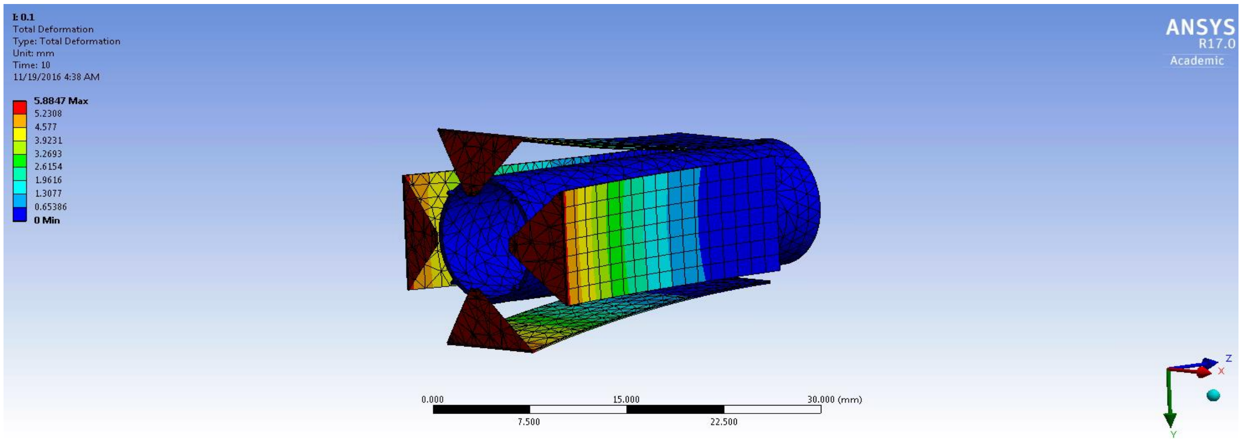


Figure 4-13 Total Deformation Results

(2) Directional Deformation

Directional Deformation is defined as displacement caused to a system in a particular axis or direction (pre-defined or user-defined)

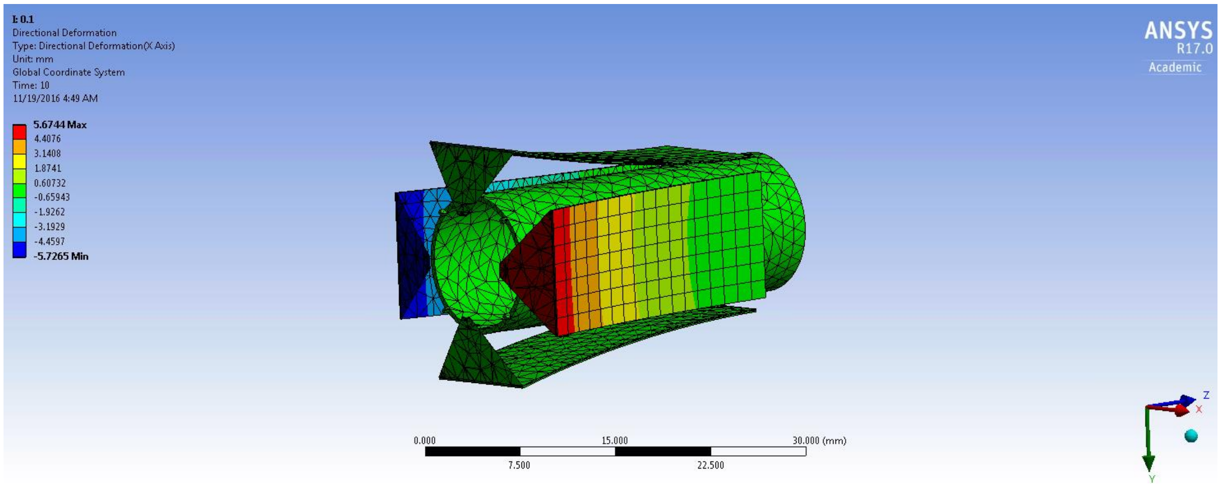


Figure 4-14 Directional Deformation Results

(3) Normal Stress

When a member is loaded by any axial force i.e., when a member is put to tension or compression, normal stress will occurred. Normal stress analysis is important for any design.

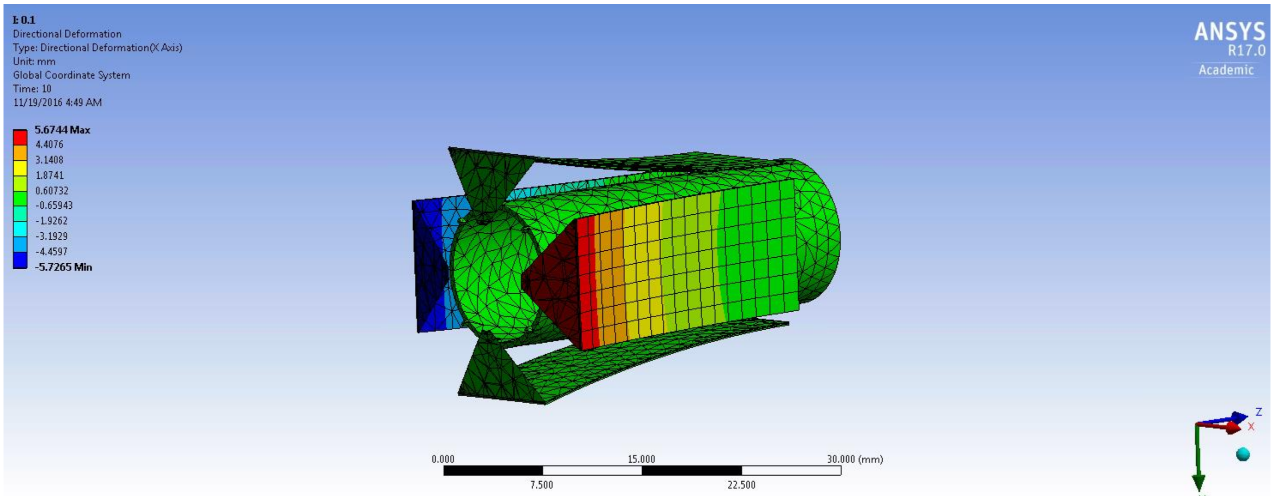


Figure 4-15 Normal Stress Results

(4) Equivalent Stress

This is generally used to test whether the design will withstand a given load or not. In this scenario, as the equivalent stresses are either Zero or very less we can say that this design is good for manufacturing purpose.

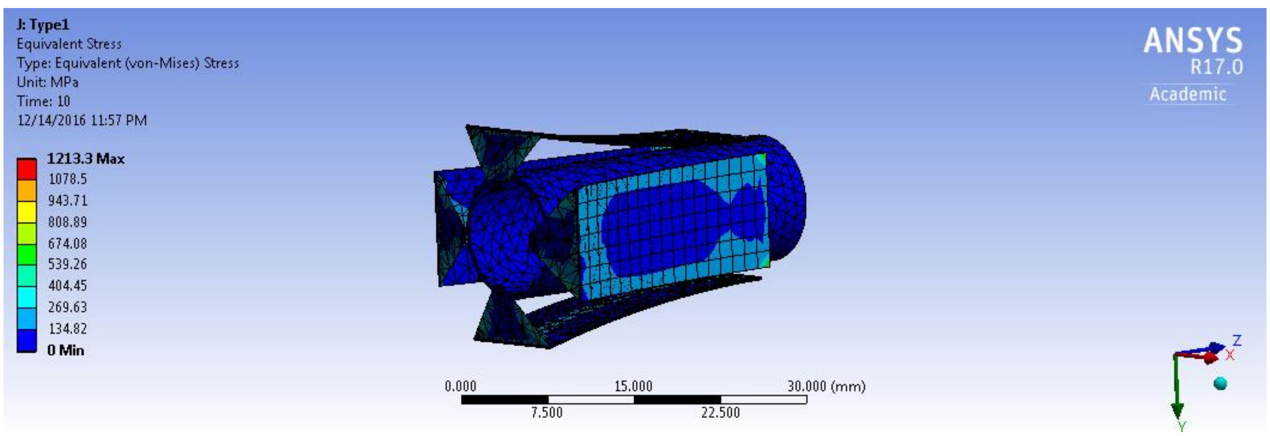


Figure 4-16 Equivalent Stress Results

(5) Maximum Shear Elastic Strain

Shear strain is result of shear stress. Any force applied to elastic member results in deformation. Stress and strain will be result of such deformation and shear strain is defined as change in deformation divided by original deformation and is dimensionless.

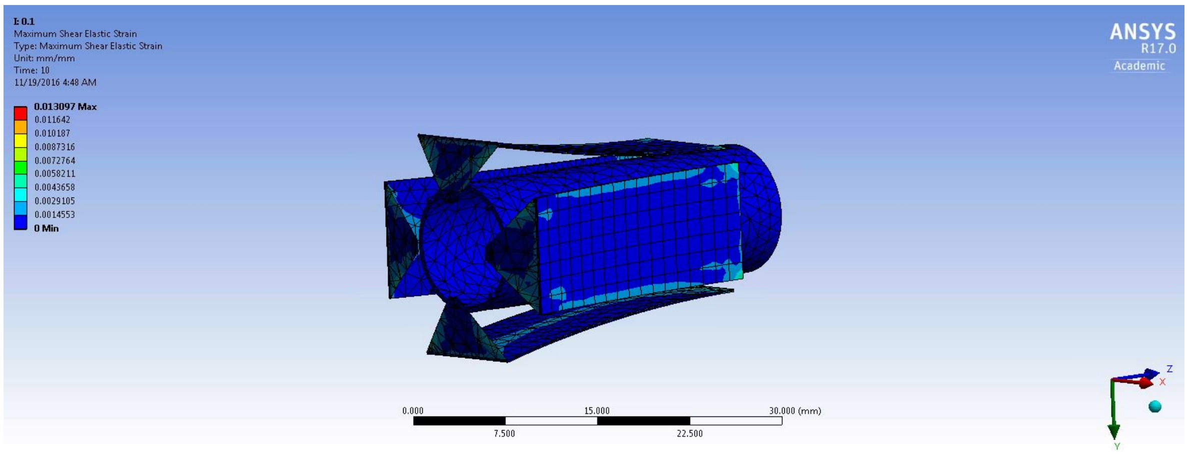


Figure 4-17 Maximum Shear Elastic Strain Results

(6) Strain Energy

Energy stored in an elastic body which is subjected to loading. Here, load that is subjected to the member is thermal load. Following analysis shows how strain energy is stored at different sections of the member.

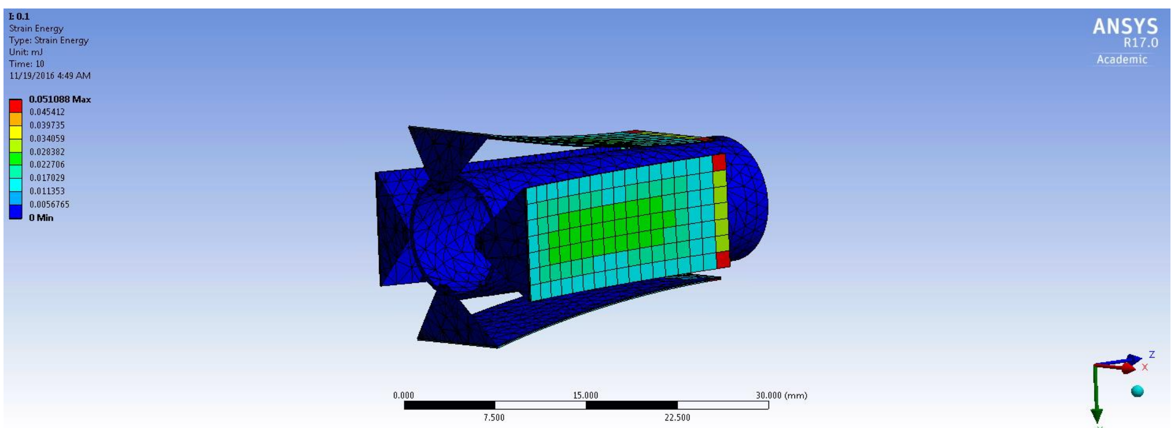


Figure 4-18 Strain Energy Results

4.8.1 Plate thickness Vs Total Deformation

Plate Thickness (mm)	Total Deformation (mm)
0.1	5.8847
0.15	3.8536
0.2	2.9198
0.25	2.3557
0.3	1.9689
0.35	1.6758

Table 5 Plate thickness Vs Total Deformation

Figure 4-19 Plots for Plate Thickness Vs Deformation

4.8.2 Temperature Vs Deformation

Temperature (C)	Deformation (mm)
30	1.7852
40	2.5382
50	3.279
60	4.0156
70	5.139
80	5.9123
90	5.9141
100	5.9147

Table 6 Temperature Vs Deformation

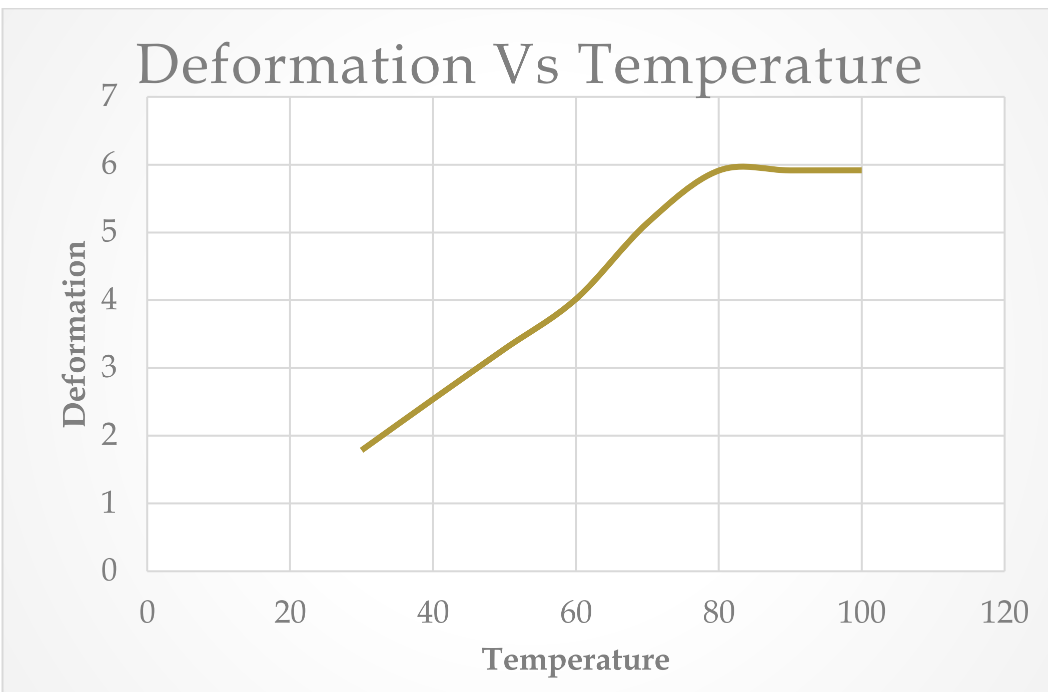


Figure 4-20 Plot for Temperature Vs Deformation

4.9 Type 2 Results

(1) Total Deformation

Total deformational is vector sum of all directional deformations and physically indicates the total displacement of the component caused due to application of a load condition like force load or temperature load.

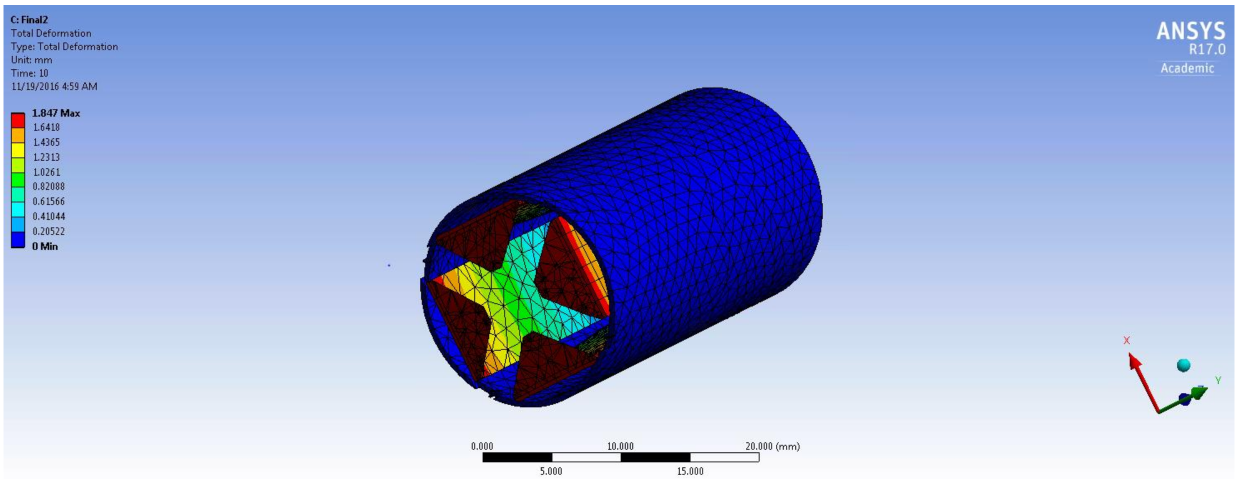


Figure 4-21 Total Deformation Results

(2) Directional Deformation

Directional Deformation is defined as displacement caused to a system in a particular axis or direction (User-defined). Type 2 model has less directional and total deformation compare to Type1 model.

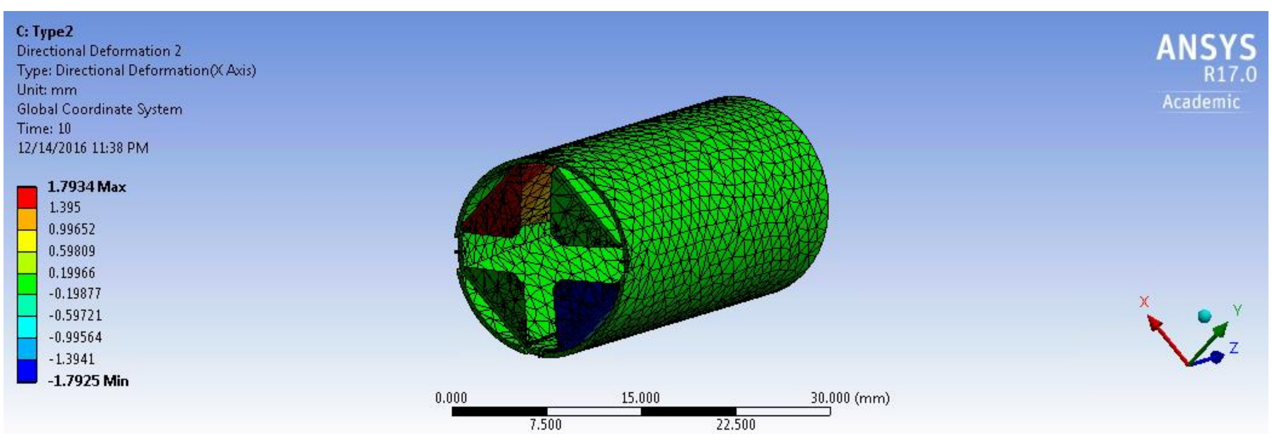


Figure 4-22 Directional Deformation Results

(3) Normal Stress

When a member is loaded by any axial force i.e., when it is put to tension or compression, normal stress will occurred. Normal stress analysis is important for any design.

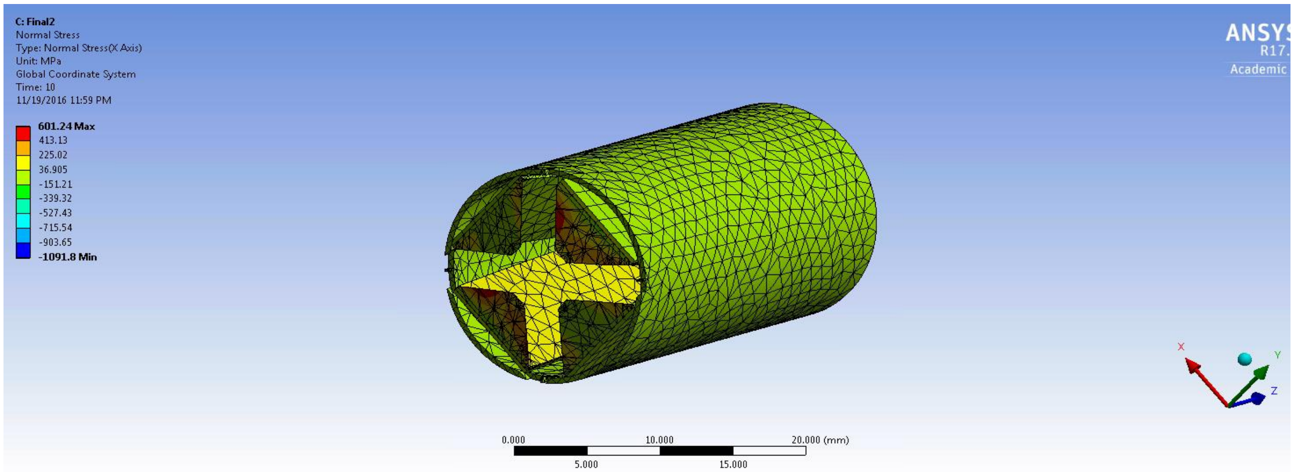


Figure 4-23 Normal stress Results

(4) Equivalent Stress

This is generally used to test whether the design will withstand a given load or not. In this scenario, as the equivalent stresses are either Zero or very less we can say that this design is good for manufacturing purpose.

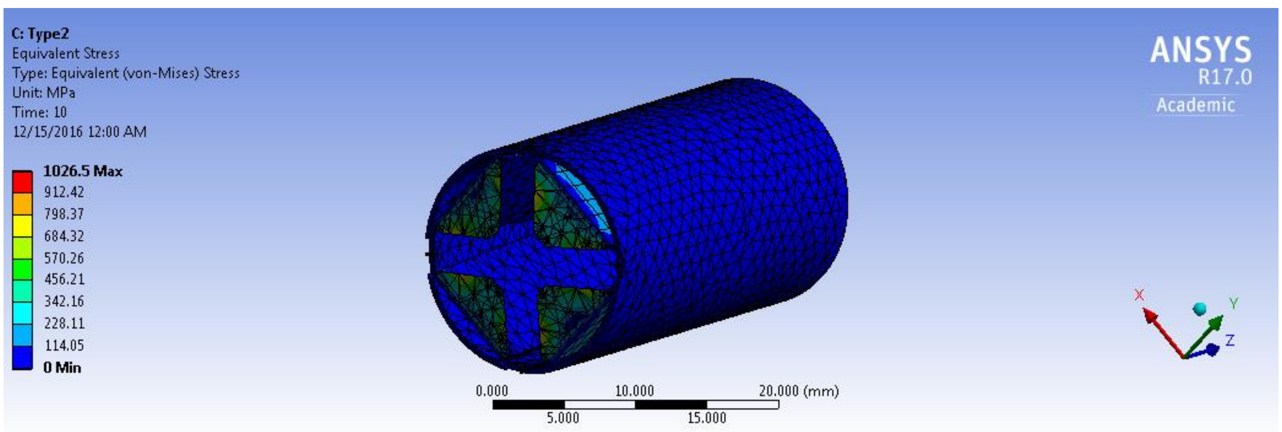


Figure 4-24 Equivalent Stress Results

(5) Maximum Shear Elastic Strain

Shear strain is result of shear stress. Any force applied to elastic member results in deformation. Stress and strain will be result of such deformation and shear strain is defined as change in deformation divided by original deformation and is dimensionless.

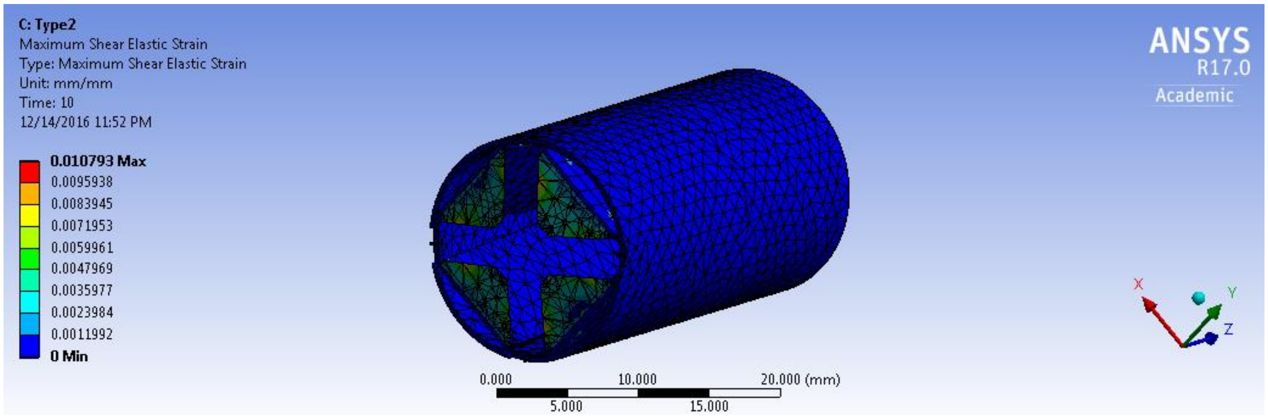


Figure 4-25 Maximum Shear Elastic Strain Results

(6) Strain Energy

Energy stored in an elastic body which is subjected to loading. Here, load that is subjected to the member is thermal load. Following analysis shows how strain energy is stored at different sections of the member

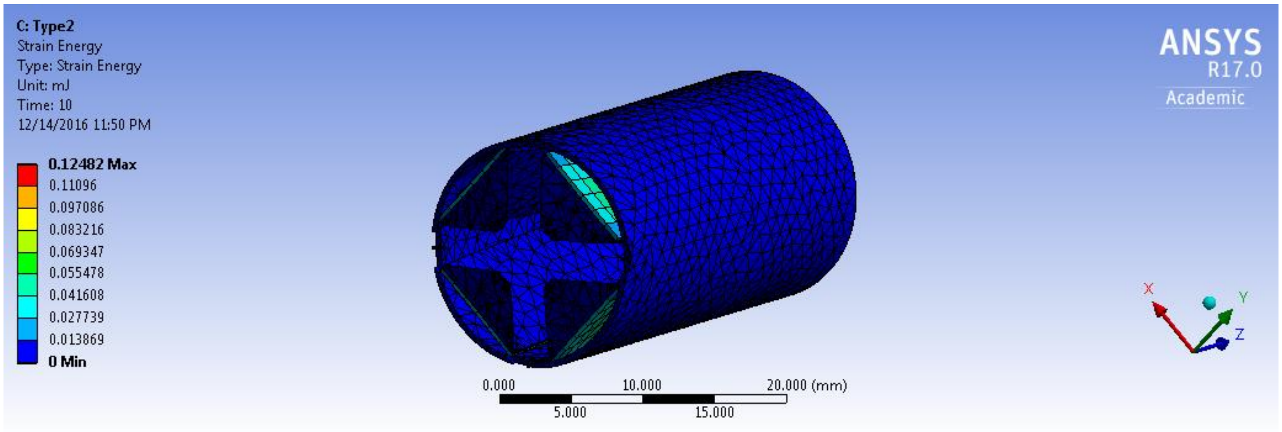


Figure 4-26 Strain Energy Results

4.9.3 Disadvantages of Type 2 model

As Bimetallic strips are present in the flow path,

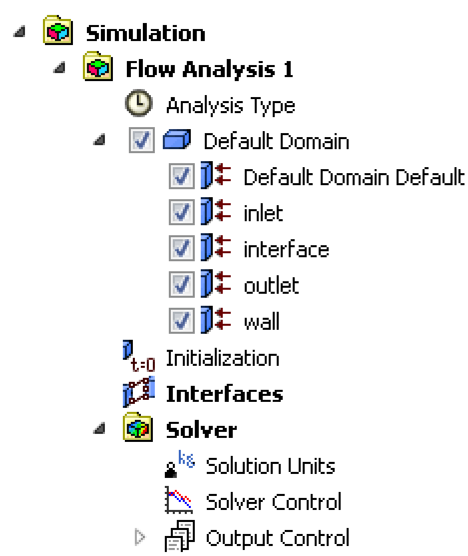
1. they obstruct the flow
2. creates negative or very low pressure right in front of the outlet opening
3. More critical during ideal or less load condition
4. More Stresses are observed compared to Type1 and less deflection.

4.10 Parameters used for Ansys CFX Analysis

Property of water at 35^0C	Value
Density(kg/m^3)	993.59
Specific Heat(J/kgK)	4068.5
Conductivity (W/mK)	0.62614
Dynamic Viscosity(kg/m.s)	7005.7

Table 7 Properties of Water

- Mass flow rate – 0.145, 0, 1, 1.5, 2litres/min
- Inlet Boundary condition: Velocity of water
- Volumetric flow rate = Area * Velocity
- Mass flow rate = density*Area*Velocity



Following Figure shows Inlet, wall and outlet domains in 20% open area scenario of bimetallic strip valve opening:

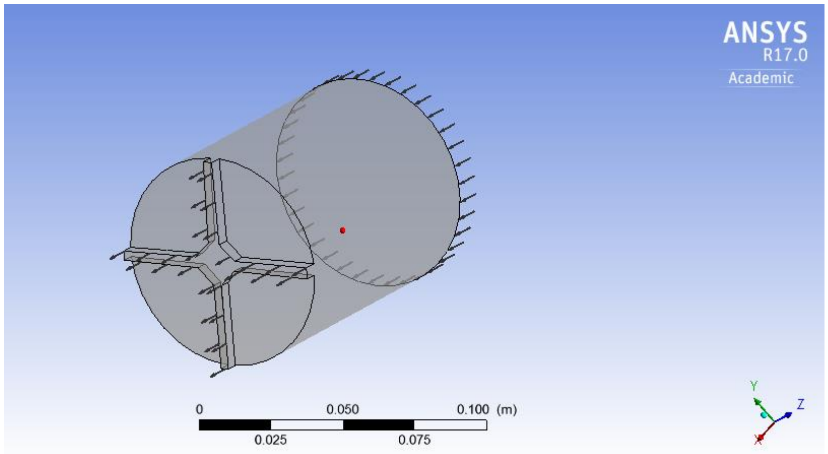


Figure 4-27 CFX Model of flow through Bimetallic valve

4.10.1 CFX Results

Following are Velocity Analysis plots of water flowing through the bimetallic strip valve with different open areas:

1) 20% Open area

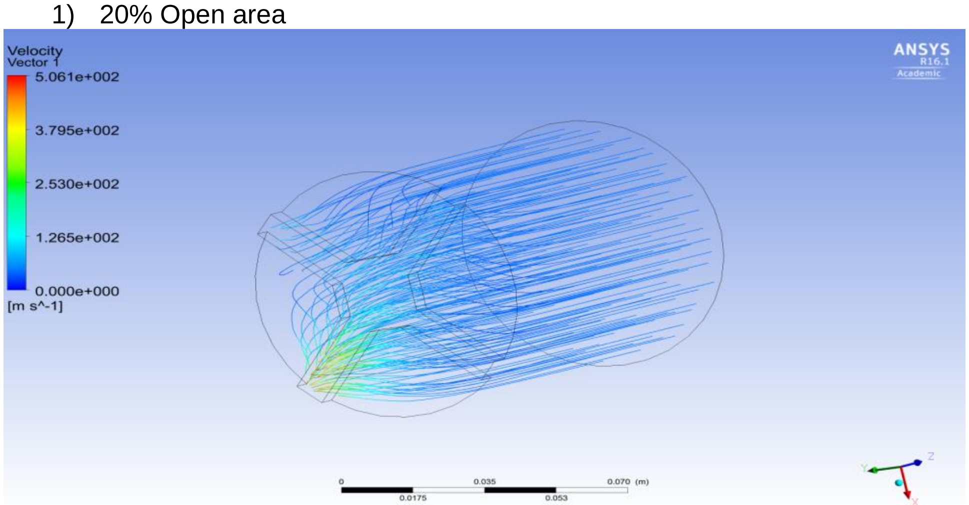


Figure 4-28 20% Open area flow results

2) 40% Open Area

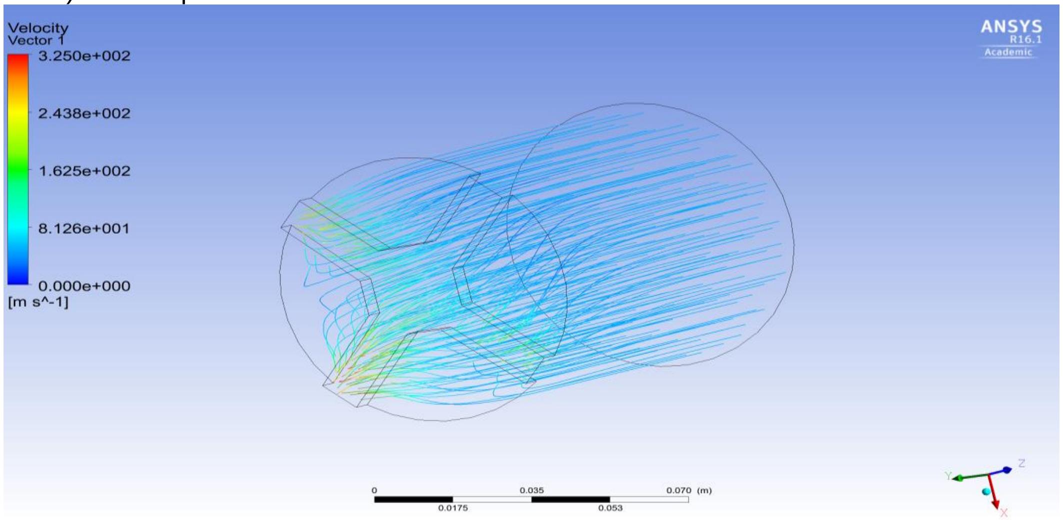


Figure 4-29 40% Open area flow results

3) 50% Open Area

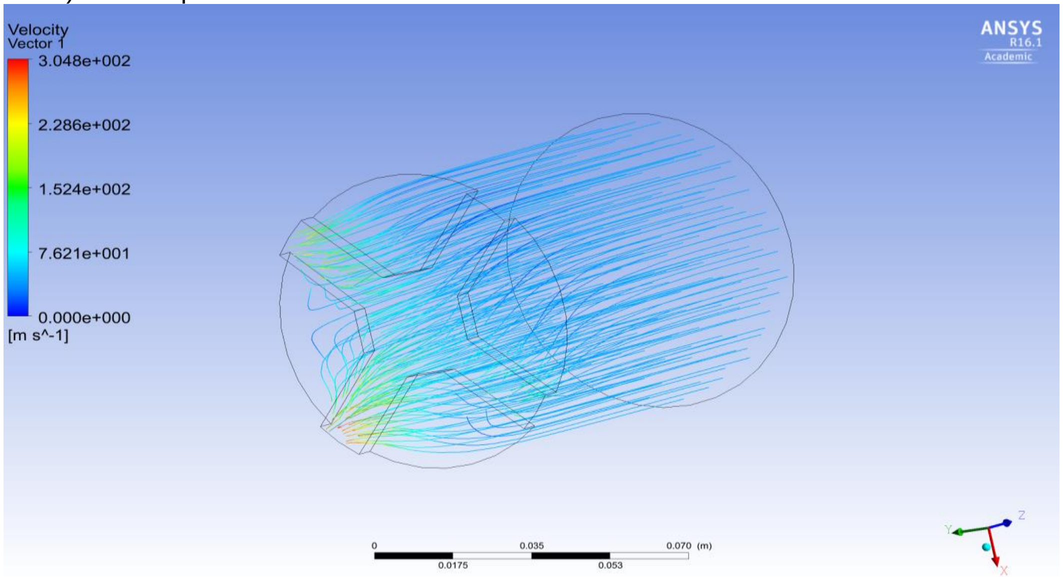


Figure 4-30 50% Open area flow results

4) 80% Open Area

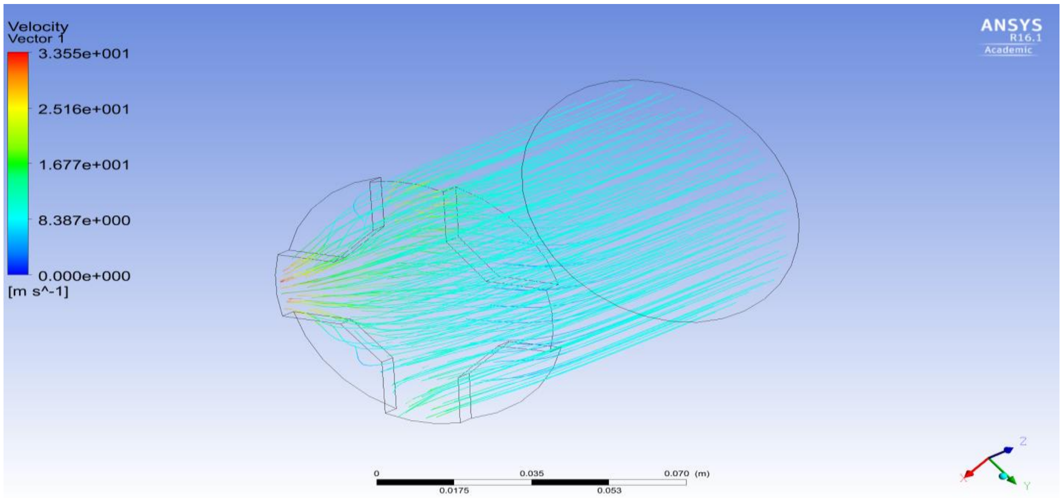


Figure 4-31 80% Open area flow results

4.10.2 Flow Rate Vs Open Area

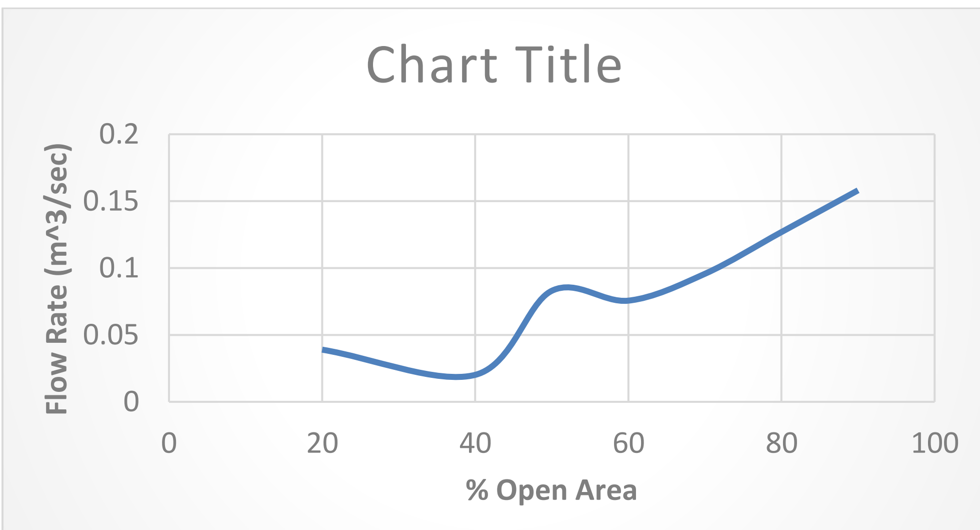


Figure 4-32 Flow rate Vs % Open Area plot

4.11 Corrosion Effects

4.11.1 Need for Corrosion Analysis

Corrosion is caused when metal (mostly copper) dissolves into water potentially causing failure and damage of the metal component system in which water is stagnated or flowing.

As we are leading with water and copper components, corrosion effects will be observed. We observe local thinning of the metal. This results in scratches, gullies and undulations. Temperature at which system is operating can also effect corrosion rate of the material. Heavy corrosion causes system damage which results in plant shutdowns, wastage of valuable resources, contamination of products, loss of products, great reduction in efficiency, malfunctioning of equipment, increase in maintenance cost, expensive over design etc. It also causes damage to the safety of employee and reduces technical progress (18)

Important Parts that are effected by corrosion

1. Cold plate body – Copper
2. Bimetallic strip

4.11.2 Types of Corrosion

(1) Below image shows Uniform corrosion product film on inside surface of horizontal hot water tube approximately 18 inches downstream from fitting

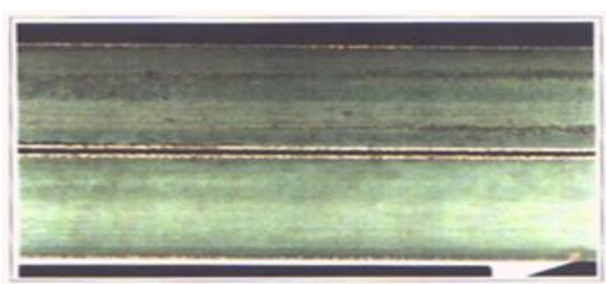


Figure 4-33 Film Corrosion

(2) Below image shows corrosion nodules primarily on lower half (at top) of horizontal tube approximately 48 inches downstream from fitting.

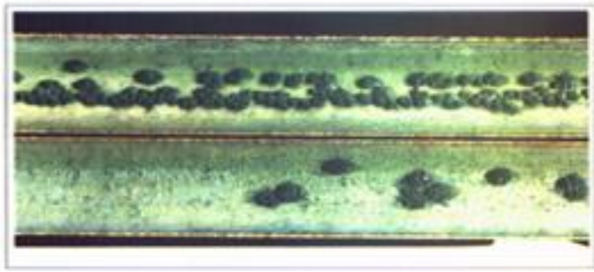


Figure 4-34 Nodular type of Corrosion

(3) Following picture shows Flux deposits on inside of ¾ inch copper Type M cold water tube at soldered elbow, lower half at top

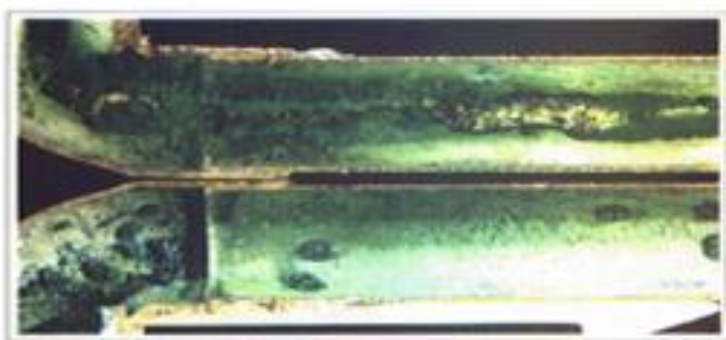


Figure 4-35 Flux type of Corrosion

(4) Below picture shows that an example of flux induced pitting corrosion on ¾ inch cold water: flux and corrosion product on upper half, cleaned to

Figure 4-36 Pitting corrosion

(5) Following image shows inside surface of ¾ inch copper Type M hot water tube at soldered tee, lower half at bottom

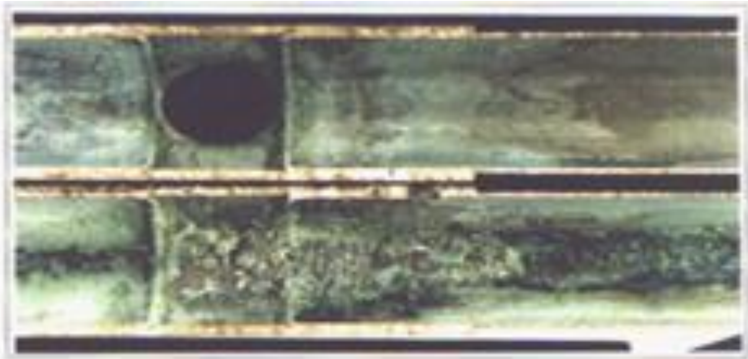


Figure 4-37 Hot water corrosion (18)

4.11.3 Methods to minimize Corrosion

1. Using filtered and distilled water
2. By forming vapor cavities in flowing liquid (Cavitation)
3. Copper should be free of pores/discontinuity coz creates small anode-large cathode leading to rapid attack at the damaged areas
4. Minimize or eliminate fluid turbulence and impingement effects

Chapter 5 Conclusion

5.1 Advantages

- This device itself acts as an all in one sensor, actuator, valve.
- More reliable as it has no moving parts
- No noise generated
- Capital Cost and maintenance cost is very low.
- Reliable, compact, easy to manufacture and assemble into the existing pipes without modifications
- Passive control of the device is also easy (by passing current through the metals).

5.2 Cost Savings

- Pumps at server level can be replaced with a one large rack level pump and a pressurized tank for constant pressure, reducing the cost of the equipment significantly.
- Each pumps cost 40-80$, our devices costs 2-3$, optional heaters cost extra.
- Design is easy and cost very less.

5.3 Conclusion

The following conclusion can be made from the analysis:

- Bending stresses are very low.
- Displace1ment of strips due to temperature is significantly high so that more water is delivered during high load condition and vice versa.
- Displacement of strips due to fluid pressure is less
- Since stresses are very low, we can increase the length further and decrease the thickness. Making the device more sensitive to the change in temperature.

Hence, Bimetallic strips FCD designed can be actively used to automatically control the dynamic cold plate cooling.

5.4 Future Work

As a part of future work,

- Fluid Structural Interaction with detailed analysis of water pressure upon Bimetallic strips
- Test the designed Flow control value experimentally, by placing it into the Dynamic cold plate setup present in our lab
- Test can be performed in analyzing corrosion effects on cold plate setup and implement ways to reduce them.

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Biographical Information

Sruthi Errukula is a Mechanical engineer graduate student at University of Texas at Arlington completed her Master's degree in fall, 2016. She had a great opportunity to work for a IUCRC Project and her area of interest has always been design and thermal engineering and the thesis work speaks about her interest. She has good computational software skills like Ansys workbench 17.0. She worked as Teaching Assistant for CATIA Software. She has good skills in Java Programming language – J2SE and J2EE. Sruthi graduated from Osmania University, India as an undergraduate in ME in 2013 during which she did an internship with Nuclear Fuel Complex India Ltd., a Central Government based company which mainly deals with Power generation during Nuclear Energy. Sruthi Errukula lives in Arlington, Texas, USA. In future, Sruthi would like to work for a company where she gets an opportunity to improve her knowledge along with good industrial exposure.