# THE DESIGN AND LINEARIZATION OF FLOW CONTROL DEVICE AND PRESSURE FORCES ON VALVE

by

PENCHALA SUMANTH REDDY CHALLA

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 2017

To my Mom for giving me this opportunity and believing in me.

Acknowledgements

First, I would like to thank my thesis advisor Dr. Dereje Aganofer for all his support though out my work and learning process. I also like to thank him for giving me this opportunity to gain knowledge academically and morally.

I would also heartily thank my thesis committee members Dr. Haji-Sheikh and Dr. Fahad Mirza for their presence and their valuable suggestions and comments to improve this report.

I would like to thank Rajesh Kasukurthy for guiding me throughout my work. I also like to thank my friends Kunal Shah, Rishi Ruben, Hemanth and Barath for easing the stress and making it fun during my work. I like to thank all EMNSPC member and my remaining family of friends for their support.

My special thanks to my Mother for giving this opportunity and believing in me and for all the sacrifices she made for my bright future. I thank my sister and brother-in-law for their love and support.

November 17, 2017

Abstract

DESIGN AND LINEARIZATION OF FLOW CONTROL DEVICE AND

PRESSURE FORCES ON VALVE

PENCHALA SUMANTH REDDY CHALLA, M.S.

The University of Texas at Arlington, 2017

Supervising Professor: Dereje Aganofer

Emerging technologies are pushing the limits by reducing the size of the nodes, raising the heat densities of packages thereby demanding better thermal management. The cooling power requirement increases drastically when air is used as the cooling medium in high power density servers as air has a low heat transfer coefficient. Very viable replacements for air as the cooling medium are water and oil. Oil is not as widely used as it has its own disadvantages when compared to water. Water has appreciably higher heat transfer coefficient, which helps it to remove heat from the server at a much faster rate when compared to air. Finally, the abundant availability of water makes it the perfect replacement for air in high power electronic systems. Another issue unique to multichip scale modules is the uneven heat generation by various packages of the module, usually creating localized high temperature regions called "hotspots". This issue can be addressed by using dynamic cold plates.

Dynamic cold plates are designed to have sections isolated from each other to cool multichip scale modules. In order to reduce pumping power for liquid cooling, dynamic cold plates can distribute flow between various sections within the cold plate based on cooling requirement in each section of the module. Each section of the cold plate has a dedicated flow control device, that can sense temperature and regulate flow rate accordingly.

This thesis presents the flow analysis of a self-regulating flow control device (FCD) designed for cooling a 160 W module. The flow control device controls flow by the use of an axially rotating butterfly valve mechanism. Linearization of the flow with respect to damper angle is studied by modifying the dimensional ratios of the rectangular cross section of the FCD. Pressure drop and flow rate characterization is done for the FCD. Effects of fluid flow on the structural integrity of the FCD as a whole is also studied.

Table of Contents

List of Illustrations

List of Tables

# Chapter 1
# INRODUCTION

Growth in all sectors has been increasing immensely over a decade. All sectors have been linked to one another. Every sector has enormous amount of data that needs to be stored and shared with another sector. Data storage and data sharing has become vital in the growth of all industries. Storage and sharing of data is no longer happening locally, now it is doing globally. Also, high computations started playing in all sectors. The users and industries has been increasing which resulted in increasing of data storage in Banking, Communication, cloud computing, logistics, artificial intelligence etc. in turn resulted in invention of Datacenters. In simple words, Data center is a large facility which stores and shares huge amount of data globally. Data centers has become an industry and there was a lot growth in it. It became very crucial to run the Data center very efficiently in optimal space and resources and in the same time cost effectively.

Figure 1.1 Inside view of Data Center
Source:http://www.datacenterknowledge.com/sites/datacenterknowledge.com

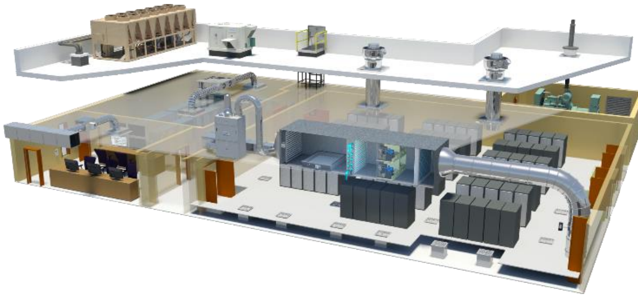


Figure 1.2 Schematic view of Data Center                Figure 1.3 Server

Source: http://www.johnsoncontrols.com/buildings, https://cdn.ttgtmedia.com/rms

With increases in usage of datacenters, the development in chip level also increased. This increased the load densities in a module. Increase in temperature across the module was observed due to the high load densities. This reduced the performance and reliability of the modules which became big problem to data centers. This made the need for better cooling techniques has led to invention of many cooling processes. Air was used as the cooling medium. But with the increase in the cooling requirements the need for better cooling medium was raised. Liquids became the viable replacement because of its variety of options and properties needed for cooling. The load densities caused heat densities called as Hot Spots across the modules giving rise to irregular temperature across the module. The conventional cooling techniques has no longer became efficient for this problem. The search for new dynamic techniques for cooling has begun.

## 1.1 Background and Motivation

Maintaining temperature uniformly among the electronic components has become high ranked problem. To maintain high life span of an electronic components especially electronic chips this needs to be achieved. Also, electronic chip manufacturing industry is following the Moore's law of exponential rise in transistors. Dr. Gordan Moore, cofounder of intel predicted this law and it states that the transistors per square inch will double for every eighteen to twenty-four months.


Figure 1.4 Moore's law Trend
Source: http://www.singularitysymposium.com/moores-law.html

Temperature caused by high heat generation is the main cause for the components failure. These failures are due to thermal de-bonding, burnouts, thermal fracture and mechanical stresses. So, maintaining the low uniform temperature across the module is very important for efficient of the device. To counter the non-uniform distribution of temperature and hot spots on the module, a dynamic cooling system is needed which cools the exact spot on the module when needed.

1.2 Loads on CPU

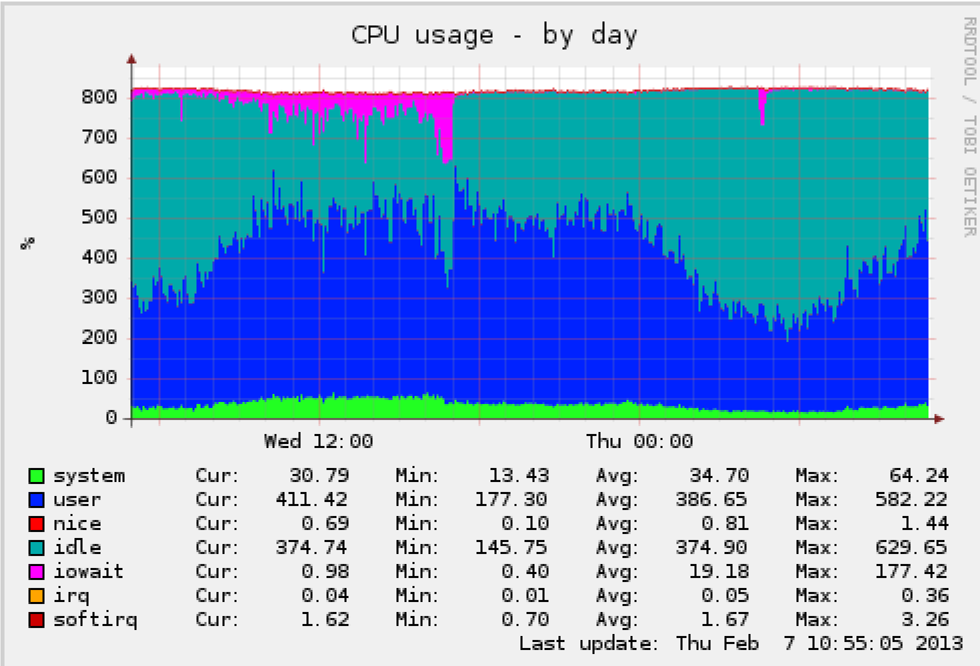



Figure 1.5 CPU Usage per Day

Source: https://2bits.com/sites2bits.com

It is evident that the usage of CPU is never the same or uniform. This say that the loads on the CPU is always inconsistent resulted in varying heat at different times. This fluctuating heat generation need the cooling which adjusts according to the heat. Also, usage of core is different at different loads and at different times. This gives rise to varying temperature across the module. This needs the cooling technique which is capable of cooling different cores in a module independently.

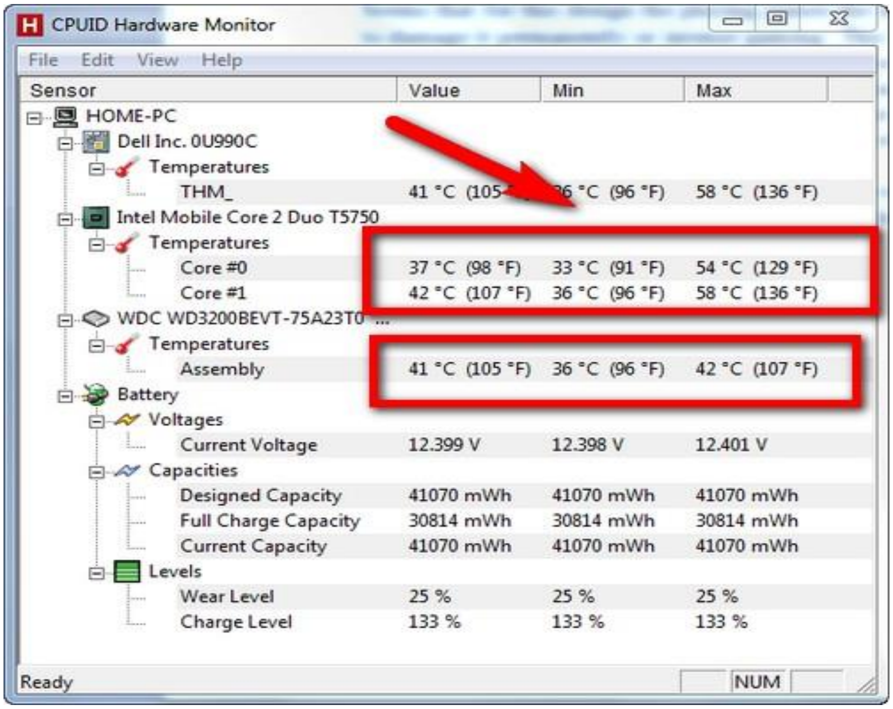



Figure 1.6 Hardware Monitor showing cores with corresponding temperatures
Source: http://www.the-computer-problems-guru.com/images

1.3 Problem Description

This thesis addresses proposing of a flow control device and its working. Also, the problem of linearizing the flow control device by talking different ratios of dimensions and by simulating them in ANSYS and finding the linearized model. This involves determining hydraulic diameter, pressure drop and max flow rate needed. Also looks into pressure forces on the valve to determine whether moment created by it and its effect on valve. An experimental setup for testing the flow control device is also proposed.

1.4 Thesis Outline

This thesis is organized as follows: In Chapter 2, literature review for the thesis is discussed. In Chapter 3, design and working of the model in consideration is discussed. Hydraulic Diameter, Mass Flow Rate and pressure drop calculations are discussed in chapter 4. Linearization of Flow Control Device simulations, its results and optimized design is discussed in chapter 5. Pressure forces on valve and force contours are discussed in chapter 6. Chapter 7 discusses the experimental setup that can be used to do experiments on any Flow Control Device. Chapter 8 Discusses Conclusion and Future work.

# Chapter 2 Literature Review

2.1 Liquid Cooling

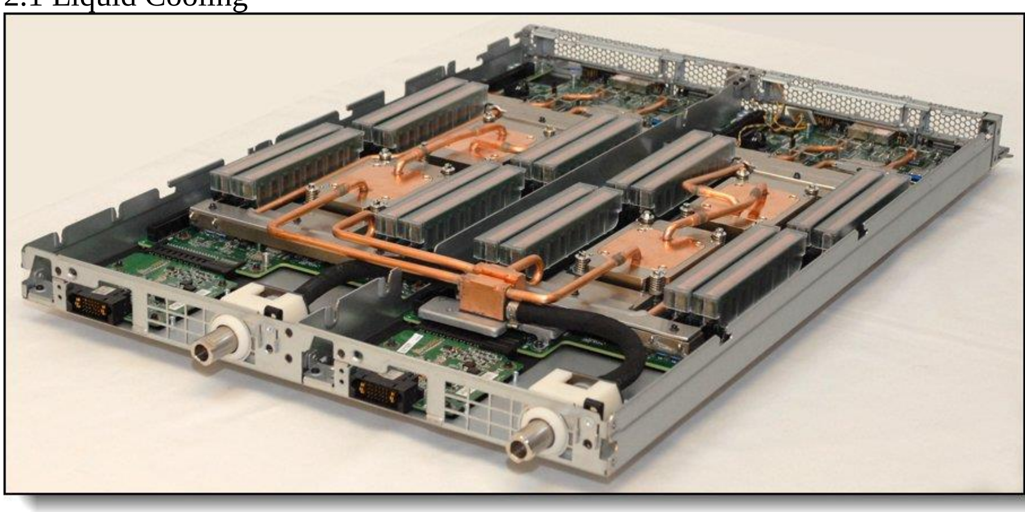


Figure 2.1 Server with Lquid Cooling
Source: https://lenovopress.com/assets

From cellphone to super computers every device works at its high potential and produces high heat. This heat has no use and it damages the device. So, cooling the device is necessary to work normally for a recommended period of time. The device temperature needs to be maintained at a limited temperature range. Normally fans, heat sinks etc. are used to cool the devices. Fans uses air as medium and heat sinks uses air or water as cooling medium. Air is commonly used as cooling medium for many devices. For devices with dynamic cooling air can't play an effective role. So, liquids became viable replacement with its high thermal properties. Liquid became very efficient for an optimized cooling. Among liquids water became most usable cooling medium because of its high thermal conductivity and abundant availability. So, water became successful cooling medium.

| Fluid Medium | Heat Capacity | Conductivity | Kinematic Viscosity |
|---|---|---|---|
| Air | 1.01 | 0.02 | 0.16 |
| Dielectric mineral oil | 1.67 | 0.13 | 16.02 |
| Water | 4.19 | 0.58 | 0.66 |

Table 2-1 : Comparison of different Cooling Medium

## 2.2 Cold Plate

Cold plate is a metal plate which has high thermal properties. Using liquid as the cooling medium, it is a most efficient cooling system than many other passive and active cooling solutions. Water can be used as the cooling medium because of its high thermal property and feasibility. In this, cold plate is placed on the hot surface and by letting water enters into it through an inlet, water flows through the channels inside the cold plate carrying heat along with it. This water can be cooled through a heat exchanger and can be recirculated into the system.

## 2.3 Original Cold Plate

Original cold plate is a copper body made by assembling multiple layer by brazing to avoid leakage and it is in assemblage with the MCM in service. It has one inlet and one outlet for the coolant to enter and leave the cold plate. Inside the cold plate, it is provided with channels for the flow of coolant. But the passage for the coolant might be serpentine or multi channeling or other based on the design required.

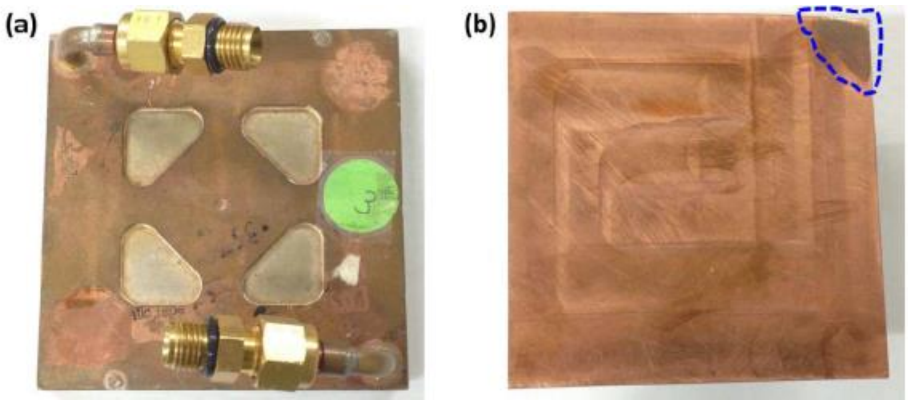
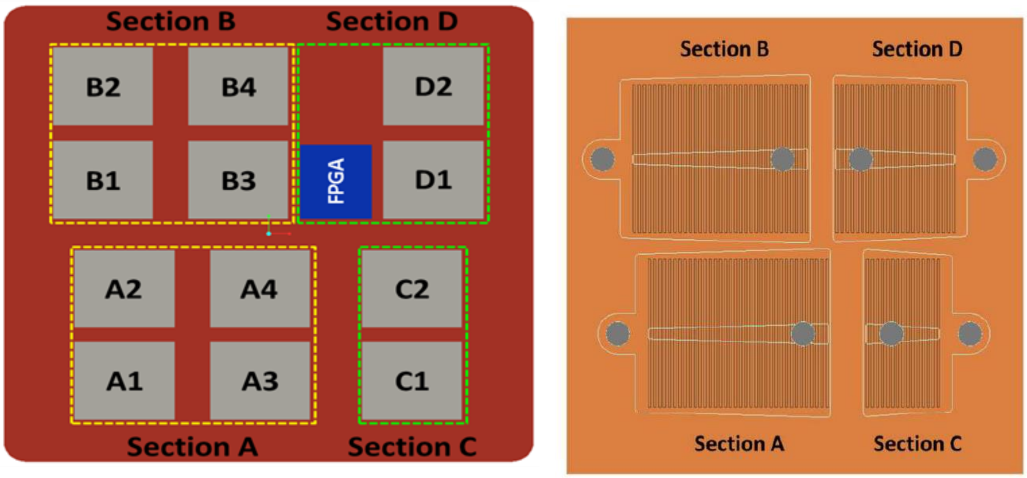



Figure 2.2a Front view 2.2b Back view of Original Cold Plate

2.4 Dynamic Cold Plate




2.3(a) 2.3(b)

Figure 2.3 (a) Dynamic Cold Plate showing sections and its components and

(b) Fins for each section

| Component | Quantity | Power (watts) |
|---|---|---|
| ASIC | 12 | 40 |
| FPGA | 1 | 5 |

Table 2-2 Components and its Power Input

Multi-chip modules are the modules with more than one chip and each chip generates heat independently. Imitating the MCM, A model was made with 4 parts in it and a total of 13 heat generating cores. As shown in figure 2.3a, two parts have 4 cores each, one part has 2 cores and one part has 3 cores. Out of these 13 cores 12 are ASIC with 40-watt power and one is FPGA with 5 watt power. The system is set in such a way to vary the heat generated by each part and this model was made to test the dynamic cold plate. The dynamic cold plate has 4 inlets and 4 outlets, like one inlet-outlet set for one part of MCM. Also, the passage for water flow inside the cold plate was also made to 4 chambers, like one for one part of MCM. The flow of coolant is controlled by flow control device. Since there are 4 chambers which has separate Inlet and outlet, this needs 4 flow control devices one for each chamber.

| | Original cold plate | Dynamic cold plate | Savings |
|---|---|---|---|
| $P_{pump}$ for 4lpm | 3.85 W | 2.76 W | 27.32% |
| Δ T | 12.87 | 6.13 | 52.36% |

Table 2-3 Savings by Dynamic Cold Plate

## 2.5 Flow Control Device

Flow or pressure of liquid is controlled by flow control liquid. A flow of fluid can be controlled by varying the pressure difference or by varying flow rate of fluid. An efficient flow control device is always useful for an efficient cooling system.

Signals or data generated by the sensors like flow meters, pressure sensors and temperature sensors are the cause for the response in flow control devices or valve systems. Usually flow control devices are controlled by the control system which uses the sensor data. The control system takes the input as sensor data and it goes through some computation which is unique to our usage. The output of the computation goes to the flow control device in the form of a signal. The fluid flow through the flow control device changes based on the signal generated by the control system. This a passive system. The flow control device with active system should need an actuator which control the flow fluid(water).

### 2.5.1 Positioning of Flow Control Device

As mentioned earlier, the cold plate has 4 parts and a flow control device for each. The figure 2.4 shows the placement of flow control device at the dynamic cold plate. Each flow control device is positioned at immediately at the outlet of each part of the multi-chip module.

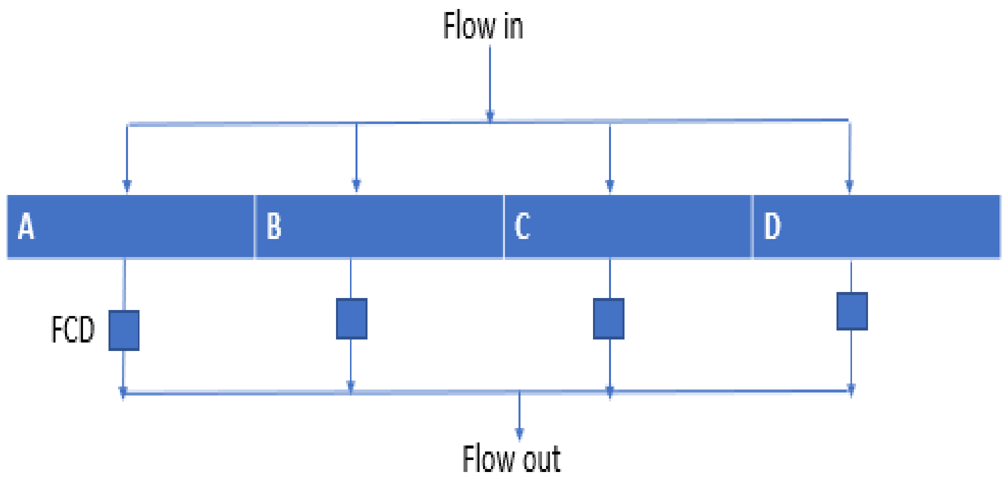



Figure 2.4 Positioning of Flow Control Device

2.5.2 Existing Flow Control devices:

Swiftech MCP50X pump is used to pump the fluid though the dynamic cold plate. It is powered with DC power supply. It's a centrifugal mechanized pump. It controls the fluid flow in the system with pulse with modulation. The pump acts as the flow control device, since it is the only flow controlling part. Pump speed is controlled by the Arduino. Arduino is used to vary pump blade speed using pulse with modulation. Arduino is an electronic device which has ports to which the pump is connected. The Arduino can be connected to the control system. The control system sends signal to the Arduino and it controls the pump accordingly.

Figure 2.5 Swiftech MCP50X pump
Source: http://www.swiftech.org/images

2.5.3 Necessity for other type of flow control device

- The present flow control device is costly and bigger is size.
- The cannot be placed immediate after the module.
- Since there are 4 of them, it occupies a lot space. Because one server has 4 modules making total of 16 flow control devices.
- The compact sized model of this becomes even more expensive and the design becomes very complex.
- Most of the available flow control devices are complex to assemble to the present system and they themselves consumes lot amount of power which is undesirable.

- A system with low cost, less complexity and less power consumption are needed for the present problem.

A new Flow control device is designed to overcome these problems and rest of the report discusses about it.

### 2.5.4 Flow Control Device Actuator

| Materials and Selection Criteria | TM2 | TM5 | NiTi and Fluro-Polymer Fused Plate | Nitinol @ 65 | Soft Polymer coating over deflecting material | NiTi @ standard and body temperature |
|---|---|---|---|---|---|---|
| Composition of the Material | 53% MnCuNi + 43% NiFe | 80% MnCuNi + 20% NiFe | NiTi + PEEK or NiTi + PES | NiTiCu | NiTi Coated with PES or PEEK | NiTi |
| Deflection | 1 | 1 | 3 | 4 | 4 | 4 |
| Cost | 5 | 5 | 4 | 4 | 2 | 4 |
| Corrosion | 2 | 3 | 3 | 3 | 5 | 4 |
| Energy consumed for deflection | 0 | 0 | 1 | 0 | 3 | 5 |
| The amount of energy that gets transferred to water | 2 | 2 | 3 | 2 | 5 | 5 |
| Relaxation time | 4 | 4 | 4 | 5 | 2 | 3 |
| Repeatability of N number of cycles | 4 | 4 | 3 | 5 | 2 | 5 |
| Ease of developing and availability in market | 5 | 5 | 3 | 4 | 3 | 4 |
| Flexibility in operation as per aging and changing need | 3 | 3 | 2 | 3 | 3 | 2 |
| Can thermal gradient within the pipe create issues | 5 | 5 | 3 | 5 | 5 | 3 |
| Effect of Cooling and Heating Hysterisis curve on performance | 3 | 3 | 3 | 3 | 3 | 2 |
| Total | 34 | 35 | 32 | 38 | 37 | 41 |
| Can it be used passively for given application | No | No | **Yes** | No | No | **Yes** |

| Fail Criteria | Worse | Bad | Good | Excellent |
|---|---|---|---|---|
| 0 | 1 | 2 | 4 | 5 |

Table 2-4 Materials comparison for Flow Control Device Actuator

So, Nitinol was chosen as the actuator material for the Flow control device that the rest of report discusses about.

2.5.5 Nitinol as Actuator

Figure 2.6 Nitinol in Wire form and Spring form
Sources: http://jmmedical.com/images/uploads

Nitinol is an alloy and a phase change material. It changes its phase from Martensite to the Austenite as the temperature increases. Nitinol shrinks when the temperature increases and expands when it’s cool down. There are two Nitinol and one-way Nitinol. Two-way Nitinol contracts and expands as temperature increases and decreases respectively. But, one-way Nitinol contracts as temperature increases but it needs extra force to expand when there is decrease in temperature. Nitinol can be manufactured for different actuating temperature ranges. So, we can use Nitinol for various temperature ranges according to the requirement.

Advantages:

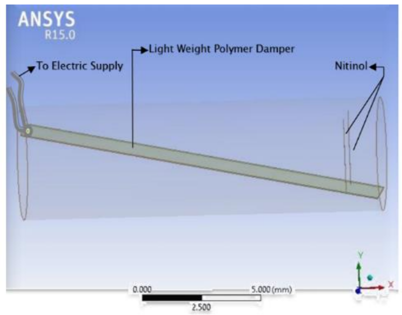
- Nitinol has more deflection with respect to other metals.
- Change in length per unit change in temperature is high than other metals.
- As it changes its phase from Martensite to Austenite, its stiffness also increases.
- Nitinol is available in rod, wire and spring forms. Custom designs can also be made.
- It occupies less space than other actuator materials.
- This can be cast into springs or wires or plate based on our need.
- It has high elastic limit.

Nitinol properties:

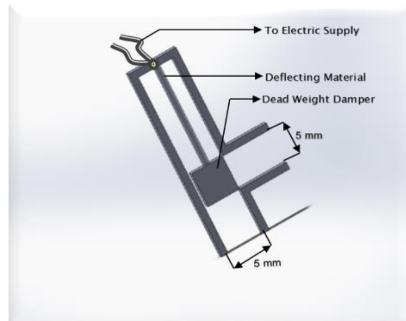
| | |
|---|---|
| Alloy Mixture | Ti, Ni, CU |
| Density(g/cc) | 6.5 g/cc |
| Specific Heat | 0.2 |
| Thermal expansion(/°C) | Martensite - 6.5<br>Austenite - 11 |
| Electrical resistivity(µΏ-Cm) | Martensite - 76<br>Austensite - 82 |
| Melting point(°C) | 1310 |
| Elastic Modulus(GPa) | Martensite – 40<br>Austenite - 11 |

Table 2-5 Nitinol Properties

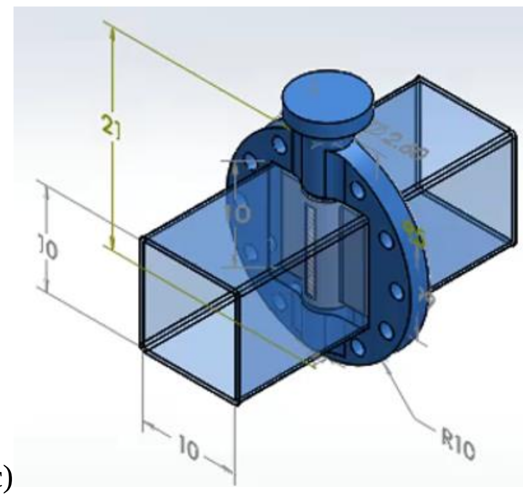
2.6 Initial designs




(a) With one damper (polymer) one and two springs/wires (nitinol)




(b) Design to keep actuator outside cold plate




(c)

Design with actuator inside

Figure 2.7 Initial designs or researched Flow control devices

In the design shown in figure 2.7a the actuator is actuated by electric supply which consumes significant amount of power. So, this design won't be of much use for this problem. The same disadvantage arises with the design shown in figure 2.7b. The design shown in figure 2.7c has actuator lies inside the pipe which means it goes in direct contact with the water which is coolant. So, here the actuator(Nitinol) actuates with the change in temperature of the water. This doesn’t need any external power source to trigger it. But this design uses two-way Nitinol as spring to rotate the valve. Since it is two-way Nitinol, it has hysteresis between cooling and heating. So, the design is at a disadvantage. This hysteresis is a serious problem in this problem because it makes an extra consumption of pump power which depends on the opening on valve which in turn depends on Nitinol or damage of module because of improper cooling.

# Chapter 3 Design in Consideration and Working

## 3.1 Design Iteration

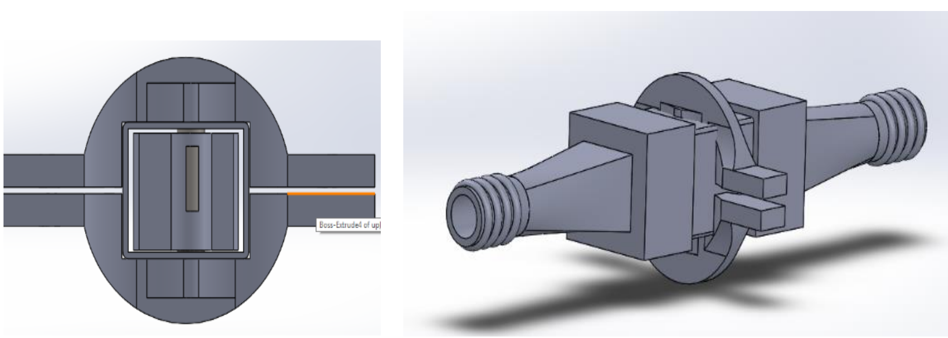


Figure 3.1 Flow Control Device Design Iteration

The figure 3.1 is the model with out pipe and isometric view of the design modified from the design showed in figure 2.7c which is explained in section 2.6. This design is made to simplify the assembly and manufacture of the parts. It has the same two-way nitinol which gets actuated by the water temperature and changes its shape or length which controls the movement of the valve. But it has the same disadvantage of Hysteresis as I explained in 2.5.5.

A new design was made to counter this problem of hysteresis with one-way Nitinol and two spring system.

## 3.2 Model in Consideration

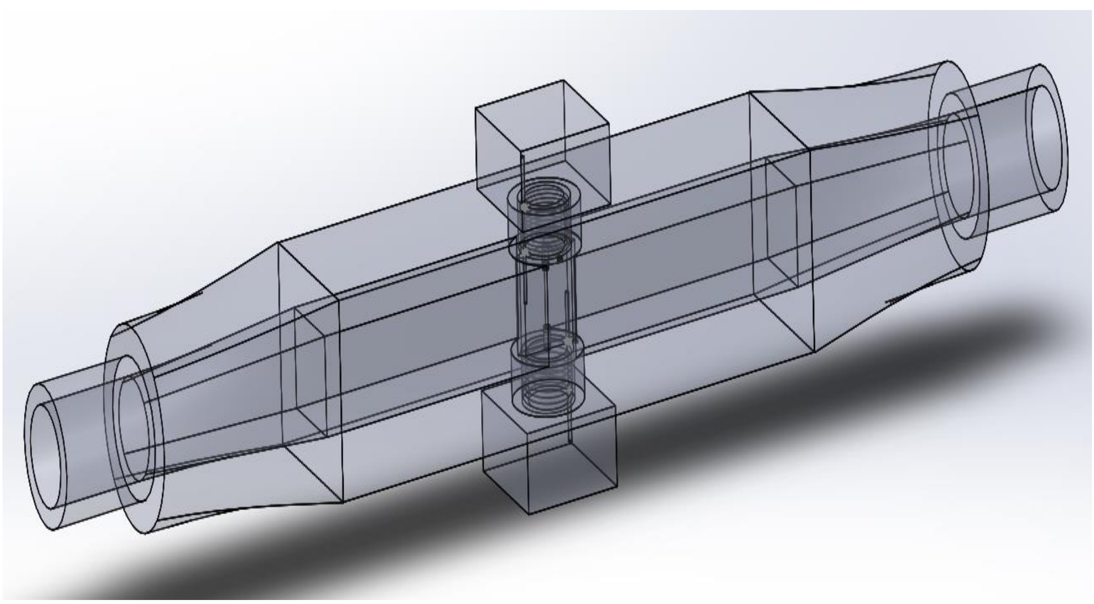


Figure 3.2 Flow Control Device Model in Consideration

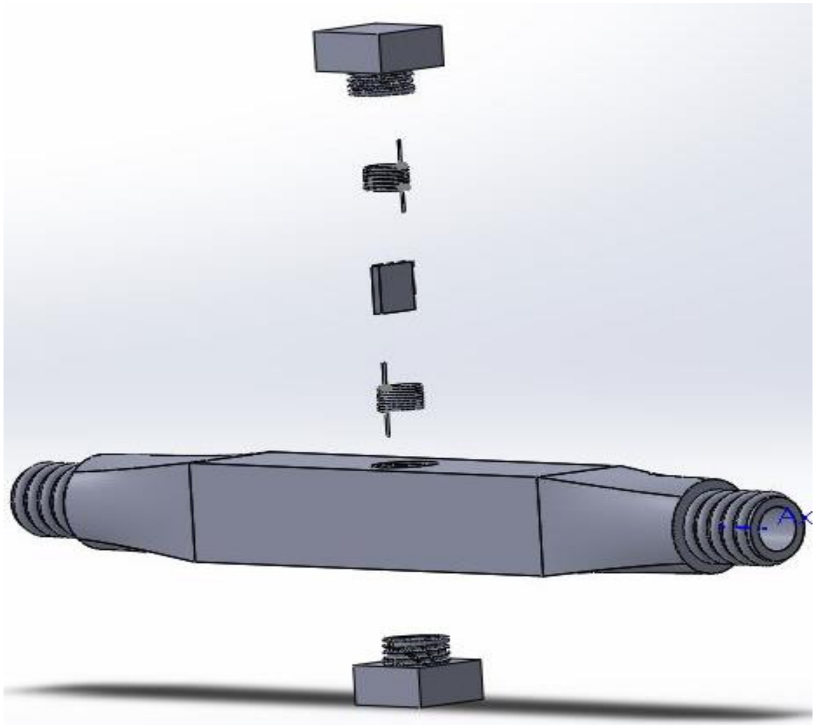


Figure 3.3 Exploded View of all Parts of Model in Consideration

3.2.1Parts:

- 2 Caps: These positioned at Top and Bottom of the pipe. Each has one hole to accommodate for the spring extrusion. Also, one cylindrical extrusion as a pivot for the valve to rotate.
- 1 Nitinol torsion Spring: It lies inside the bottom cap and connected with both bottom cap and Valve through cylindrical extrusions from it.
- 1 Steel torsion spring: It lies inside the top cap and connected to both top cap and Valve through cylindrical extrusions from it.

- The 2 springs are designed in such a way that the 2 springs moments oppose each other when they are assembled to form the flow control device.
- 1 Valve: The valve was designed in such a way to rotate by the moments created by the springs and it is stationed inside the pipe. It has holes on the top and bottom to fit the extrusions from the spring and to fit the extrusion from the caps which helps as pivot for the rotation.
- 1 Pipe: It is a square cross sectioned pipe like part with holes on top and bottom to fit the Caps. The ends of the pipe are made to circular cross-section for ease connectivity with other objects. Also ends of the pipe was made as rugged surface for the tight fit when connected to another pipe.

3.2.2 Assembly:

- Initially, insert nitinol spring into the bottom cap and steel spring into the top cap in such a way that the extrusions from the goes inside the holes made in caps.
- Now, insert valve into the pipe from the bottom or the upper hole.
- Now assemble the bottom cap and pipe in such a way that another spring extrusion from the Nitinol spring goes inside the hole in the valve.
- Similarly, assemble the top cap and pipe.

- In the end, connect the ends of the pipe part to other pipe for the flow circulation.

### 3.2.3 Spring Design and Torque Calculation

Figure 3.4 Spring Model

The figure 3.4 shows the model of torsion spring (Nitinol spring and steel spring). It has two extrusions on top and bottom as mentioned in previous section.

Nitinol torsion spring has 8 turns and steel torsion spring has 10 turns.

Diameter of the Nitinol spring coil is 0.5 mm.

The mean diameter of the Nitinol torsion spring is 7mm.

Torque developed by the torsion spring for a deflection of 90° angle can be calculated by

$$M = \frac{Ed^4T}{10.8\mathrm{Nt}D}$$

Where,

M = Torque developed

E = Modulus of elasticity

d = Diameter of coil

$N_t$ = Number of turns

D = Spring mean Diameter

T = Deflection, number of turns or revolutions of spring

Torque developed by Nitinol torsion spring in Martensite state for a deflection of 90° = $0.723*10^{-6}$ Nm.

Torque developed by the Nitinol torsion spring in Austenite state for a deflection of 90° angle = $2.114*10^{-6}$ Nm.

Steel spring is considered in such a way that its torque lies in between the Nitinol's Martensite state torque and Austenite State torque.

### 3.2.4 Equilibrium for Springs

An equilibrium state between the two springs in load when they are in the flow control device can be achieved. To achieve this equilibrium, the steel spring should produce a torque equal to the torque produced by the Nitinol spring in martensite state at 90° angle loaded position.

By equating torque equations of Nitinol spring at 90° loaded position and steel spring, the deflection needed for steel spring for equilibrium can be calculated and it is found to be 62.56° angle. Which means, by keeping Nitinol spring in martensite state at 90° angle loaded position and steel spring at 62.56° angle loaded position, both springs stays in equilibrium in completely closed position of valve. The figure 3.5 shows the assembly of springs with caps and valve in a sectioned view.

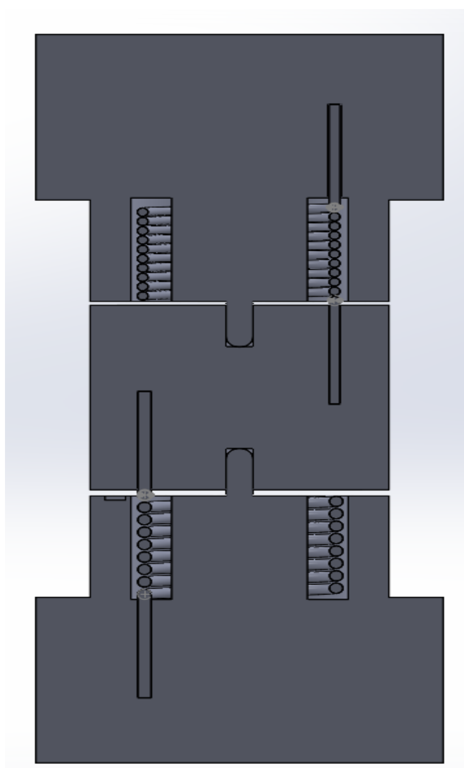


Figure 3.5 Springs Assembly

### 3.3 Working of Flow Control Device

All the parts and functioning of them was mentioned in section 3.2.1 and 3.2.2. water flows from one side(inlet) of pipe part and leaves it from the other side. The amount of flow depends upon the movement of valve which in turn depends on the spring setup.

Initially, the valve stays in completely closed position where both the Nitinol and Steel springs are in equilibrium by keeping them in 90 angle and 62.5 angle respectively. At this point, both the springs produces equal amount of torque.

The springs stays in contact with flowing water all the time. When the temperature of the flowing water increases, Nitinol temperature also increase and changes its state from Martensite to Austenite. At the same time while its phase change, the torque producing by the Nitinol also increases. Increase in Nitinol spring's torque becomes greater than the torque producing by Steel spring at that point resulted in pushing the steel spring. This causes the valve to open.

Once the temperature of the water decreases, the Nitinol spring goes back to its initial state of Martensite while reducing the torque producing by it. Now, Steel spring starts pushing the Nitinol spring resulted in closing the valve until torque producing by both the springs becomes equal which is completely closed position of valve. The processes repeat continuously depending only on the temperature of the water making it Active Flow Control Device.

# Chapter 4 Hydraulic Diameter and Mass flow rate calculations

## 4.1 Hydraulic Diameter ($D_H$)

Hydraulic diameter is a diameter of the circular cross-sectioned pipe which is completely filled with water without any air bubbles or vacuum. It used for pipes to determine the Reynolds number. So, it is very important in determining the flow properties. Hydraulic diameter of a square cross-sectioned pipe can be determined by using the formula

$$DH = 4 * \frac{Area}{Perimeter}$$

The Model in consideration for this thesis uses the square cross-sectioned pipe.

If X and Y are length and breadth of the square cross-section.

Then,

$$DH = \frac{2XY}{X + Y}$$

The graph shown in figure 4.1 is between hydraulic diameter and power input for a chip. From this graph we can determine hydraulic diameter needed for cooling chips with different power inputs. That graph was drawn by keeping velocity at 0.2 m/s fluid flow and a temperature difference of 12 °C as constant.

So, a hydraulic diameter of 10 mm was considered for the testing convenience to cool 160-watt power for 12 °C temperature difference. This reduces the velocity of flow to a value less than the velocity considered to draw the graph in figure 4.1. Because from the graph 160-watt power input need 4.5mm diameter producing 0.2 m/s velocity of fluid flow and by increasing the hydraulic diameter, velocity decreases.

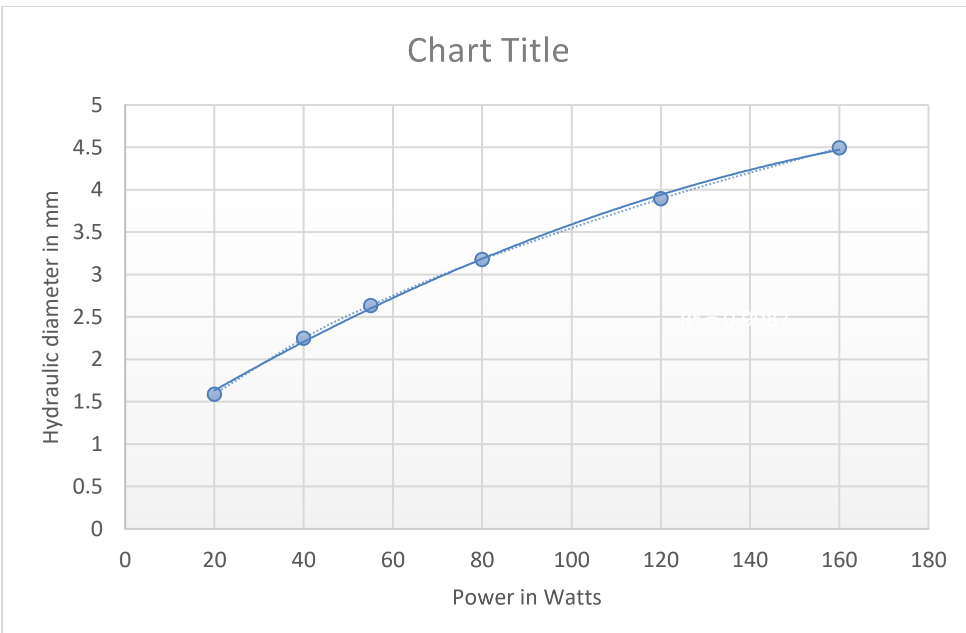



Figure 4.1 Graph between Hydraulic Diameter and Power for 0.2m/s velocity

## 4.2 Dimensionless Parameter (r)

A dimensionless parameter with length and breadth is considered to create a sole variable for further design variations.

$$r = \frac{x}{y}$$

Using this 'r' and by substituting it in $D_H$, we can get

$$X = DH\frac{r+1}{2}$$

By varying 'r' and by keeping $D_H$ constant, different models can be designed.

'r' becomes sole variable for the design.

## 4.3 Mass Flow Rate Calculation

The amount of fluid in mass flowing through the pipe per unit time is mass flow rate. The present flow control device was designed for 160-Watt module.

Design considerations:

- The present flow control device was designed for 160-watt module.
- Assuming 10°C temperature difference across module.

Using the equation between power and Mass flow rate required,

$$P = M * Cp\,\Delta T$$

Where,

P = power in watts.

$M_*$ = Mass flow rate of fluid.

$C_p$ = Specific heat of water = 4.19 kJ/Kg°C

$\Delta T$ = Temperature difference

Mass flow rate required for 10°C temperature difference across the 160-watt module was calculated. A 0.3 lpm of mass flow rate was chosen including factor of safety.

## 4.4 Pressure Drop across the Flow Control Device.

A mass flow rate of 0.3 lpm was chosen in last section. A pressure drop across the flow control device due to cross sectional change, bending losses and viscosity was determined using ANSYS FLUENT.

Simulation was done on the device by keeping the valve in completely open position and using the properties mentioned below.

Properties:

- Flow condition = Laminar
- Fluid = Water (liquid)
- Boundary conditions:
- Inlet condition : 0.3 lpm Mass flow rate
- Outlet condition : Pressure outlet

Finally, a 5.5 Pa pressure drop was chosen for further simulations by changing the angle of valve which will be explained in later sections.

4.5 Circular vs Rectangular Cross Section

Simulations were done between circular cross section model and rectangular cross section model to compare them to see which one is better in use. It can be observed from the graph shown in figure 4.2 that the pressure drop across the flow control device with rectangular cross section is less than the flow control device with circular cross section. This graph is based on the simulations done at a flow rate of 0.3 lpm.

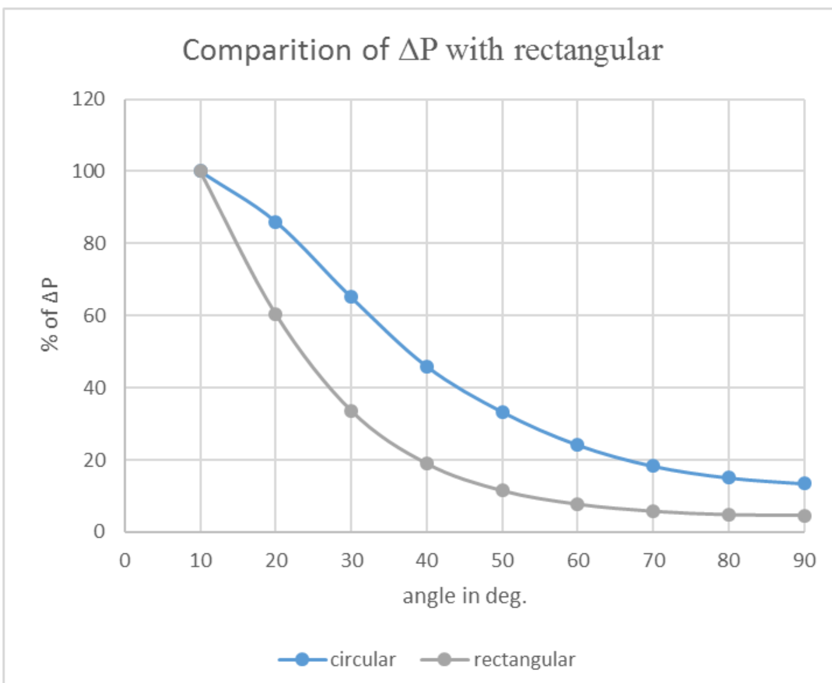



Figure 4.2 Graph between pressure drop and valve angle for rectangular and circular cross section models.

Also, another useful comparison to state that the rectangular cross section is advantageous is mass flow rate. Mass flow rate is compared for both the cross sections for various valve angles and the graph between mass flow rate and valve angle is shown in the figure 4.3. From the graph, it can be observed that a wider range of mass flow rates can be obtained with rectangular cross section than the circular cross section. Also, linear trend is much more consistent with the rectangular design especially in angles nearing closed position. This graph is based on the simulations done at a pressure of 5.5 Pa.

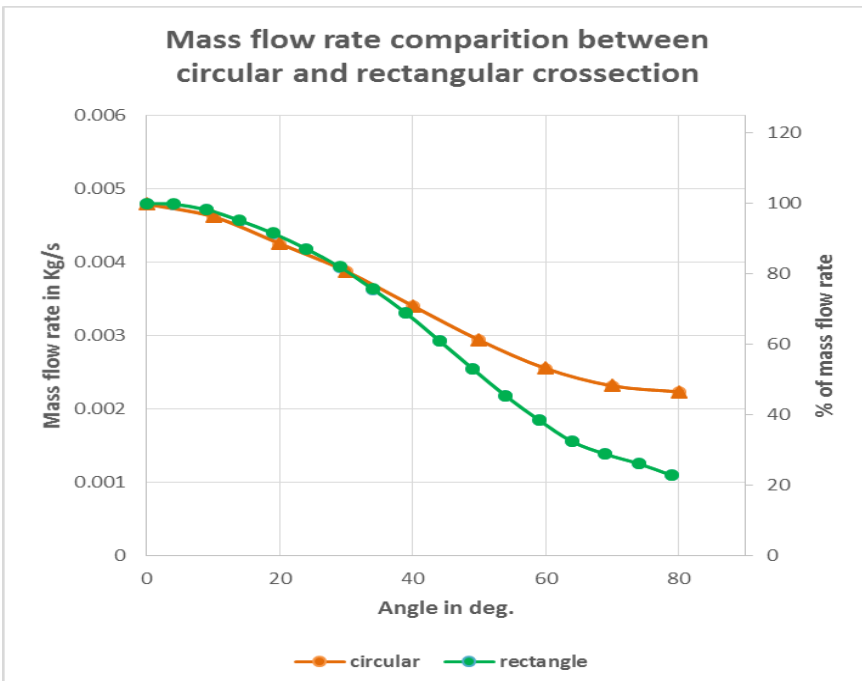



Figure 4.3 Graph between mass flow rate and valve angle for rectangular and circular cross section models

# Chapter 5 Linearization of Flow Control Device

By varying dimensionless parameter ‘r’ mentioned in section-4.2 from 0.8 to 1.5, different values of ‘X’ can be determined. By using ‘X’ values, corresponding ‘Y’ values can be calculated. Using these X and Y values as length and breadth of the pipe Cross-section, flow control devices with different dimensions were modelled. Valve dimensions also changed accordingly. So, a total of 8 flow control devices with different dimensions were modelled. ANSYS was used to do all the simulations to determine Mass Flow Rate.

## 5.1 Design Modeler

All these models were imported into the Ansys design modeler. Fluid was extracted into all the designs and all the unnecessary parts were suppressed. The figure 5.1 shows the model after extracting the fluid into it and suppressing all the parts except the fluid.

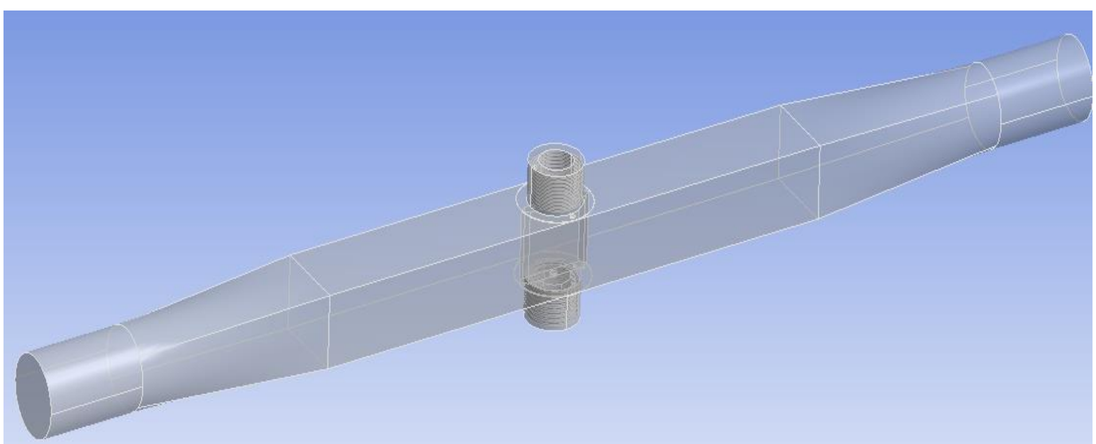


Figure 5.1 Fluid extract of Flow Control Device

## 5.2 Meshing:

To solve the Fluid model in CFD, the continuous fluid medium has to be partitioned into discrete volumetric cells vertices or nodes and elements. A node is a point in fluid space defined by position vector and all these nodes are connected to form elements. Connecting two nodes forms a line or line element which features a curve in 2-dimensional space. A surface which consists of many faces is featured by the face elements formed by connecting four nodes in 3-dimensional space. A volumetric cell is a 3-dimensional element formed with lines and faces. Meshing is the combination of all the volumetric cells. In a study using CFD solver, fluid properties like velocity, temperature, pressure etc. are calculated at every volumetric cell and are integrated and averaged to get a total value of all the properties for whole fluid. Increase in the number of volumetric cells results in more refined results which imitate real life experimental results.

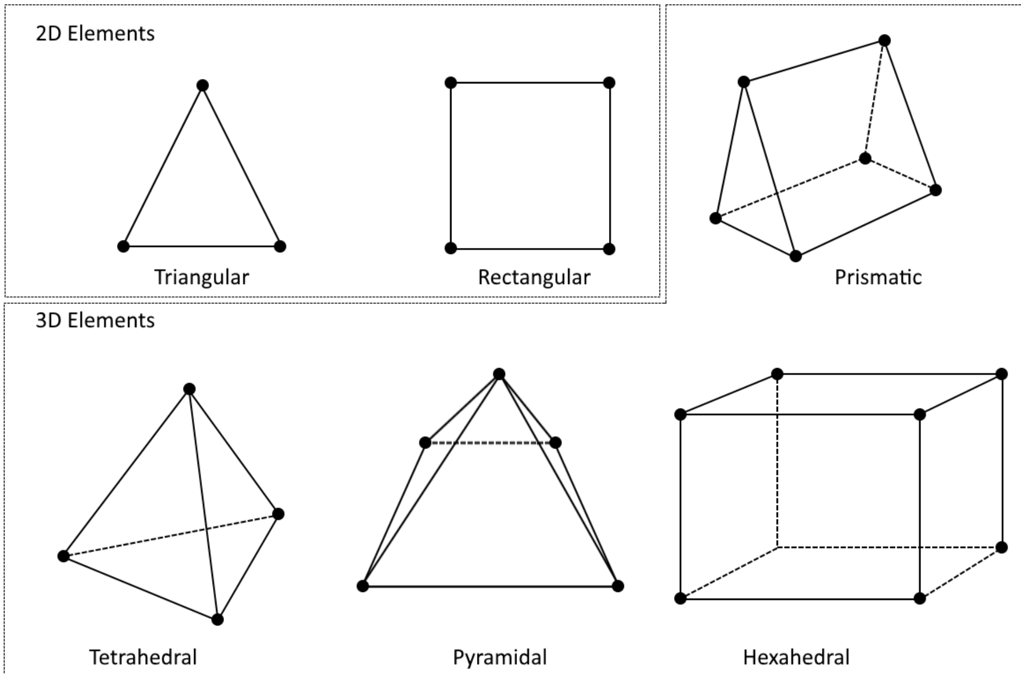



Figure 5.2 2-D and 3-D Mesh Elements
Source: http://scdn.com/sol.com/cyclopedia

In the present problem, CFX fine meshing is used with slow transition and fine span angle center. The cell geometry features min size as $2.5*10^{-2}$, Max face size and max Tet size as 5mm. Inflation is used for fluid around the valve to capture refine flow features around the valve. Inflation is a meshing property which creates a fine and slowly growing mesh at a surface to capture more accurate fluid properties around that surface. All the models extracted with fluid are imported into Meshing.

Meshing properties:

- Physics preference: CFD

- Solver Preference : CFX
- Min size : $2.5*e^{-2}$ mm
- Max face size : 5 mm
- Max Tet size : 5mm

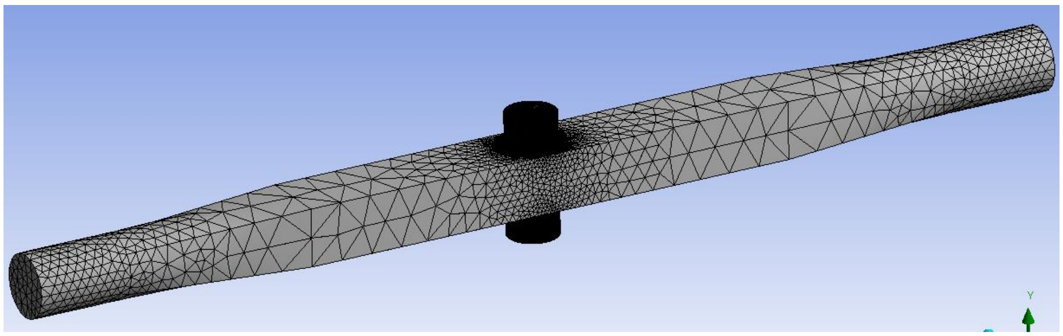


Figure 5.3 Fluid Extract after Meshing

Inflation was added to get précised flow output around the Valve.

Inflation properties:

- Boundary : Valve
- Inflation option: Smooth transition
- Number of layers: 5
- Transition ratio: 0.5
- Growth rate: 1.2
- Inflation algorithm: Pre

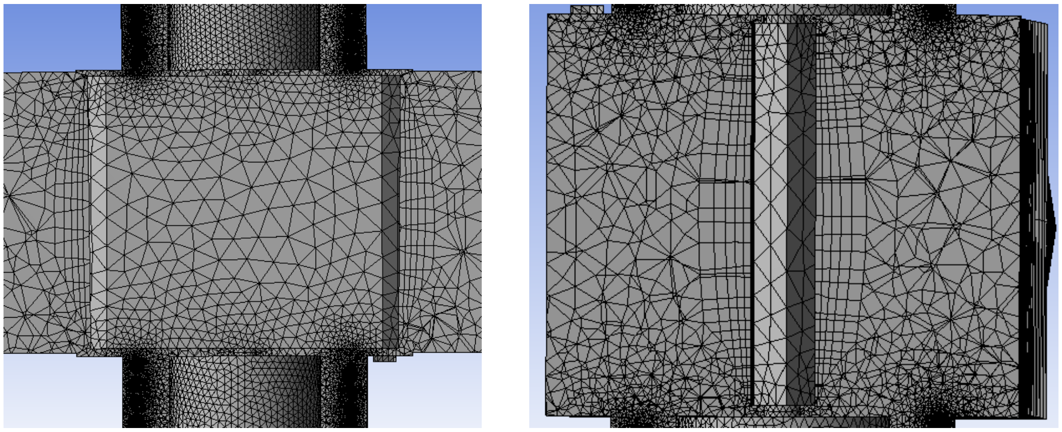


Figure 5.4 Sectioned View of Mesh around Valve showing inflation

It can be observed that the meshing has connectivity between all the nodes. So, it is conformal mesh. The mesh is filled to the maximum with Prism elements in the volume with Inflation and Tetrahedral elements in the remaining fluid Volume.

## 5.3 CFX Pre-conditions:

- Material: water
- Reference pressure: 1 atm
- Turbulence option: k-epsilon
- Wall function: scalable
- Inlet condition: Total pressure-5.5 Pa
- Outlet condition: Static pressure-0 Pa

Parametric Simulation:

- Input parameter - Valve angle from completely open position to closed position(0°-90°)
- Output parameter - Mass flow rate( kg/s)

5.4 Result:

After the parametric simulation, mass flow rate for all the designs for various valve angles was obtained. The graph in figure 5.5 shows the trend of mass flow rate variation for change in valve angle for all the 8 models. Valve angle is in X-axis and Mass flow rate is in Y-axis.

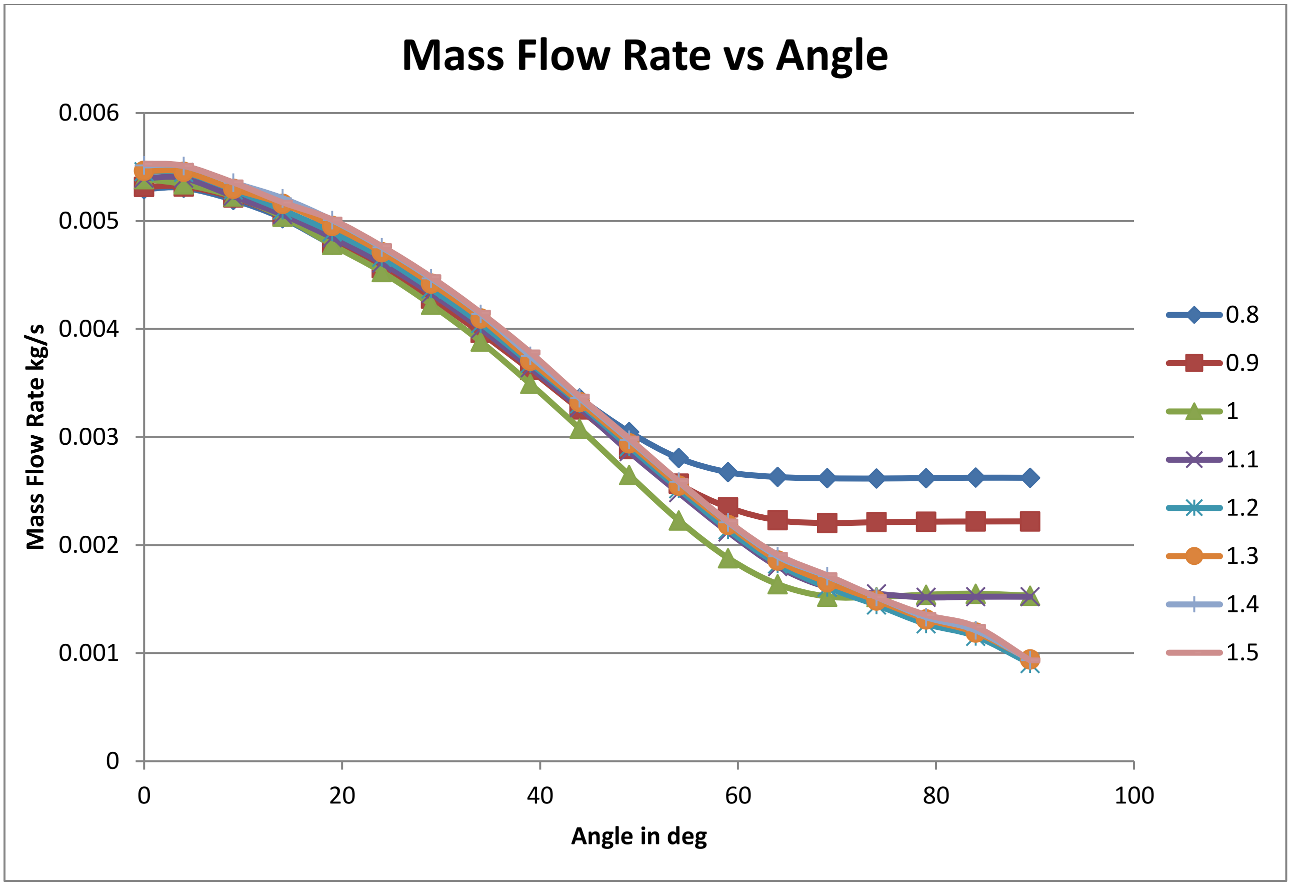



Figure 5.5 Graph between Mass flow Rate and Valve angle for All Models

5.5 Mesh Sensitivity Analysis:

Grid Independence for any simulation is very important. The result obtained should be independent of Grid size. Mesh sensitivity analysis was done comparing mass flow rate for different mesh sizes. Mesh size was varied by varying the size of the element in body sizing option in ANSYS Meshing. it can be observed from the graph shown in figure 5.6 that there is no significant change in the mass flow rate when mesh density goes above 50 elements per cubic millimeter. The chosen cell geometry has even more elements which results in much higher element density then the above mentioned highly accurate results.

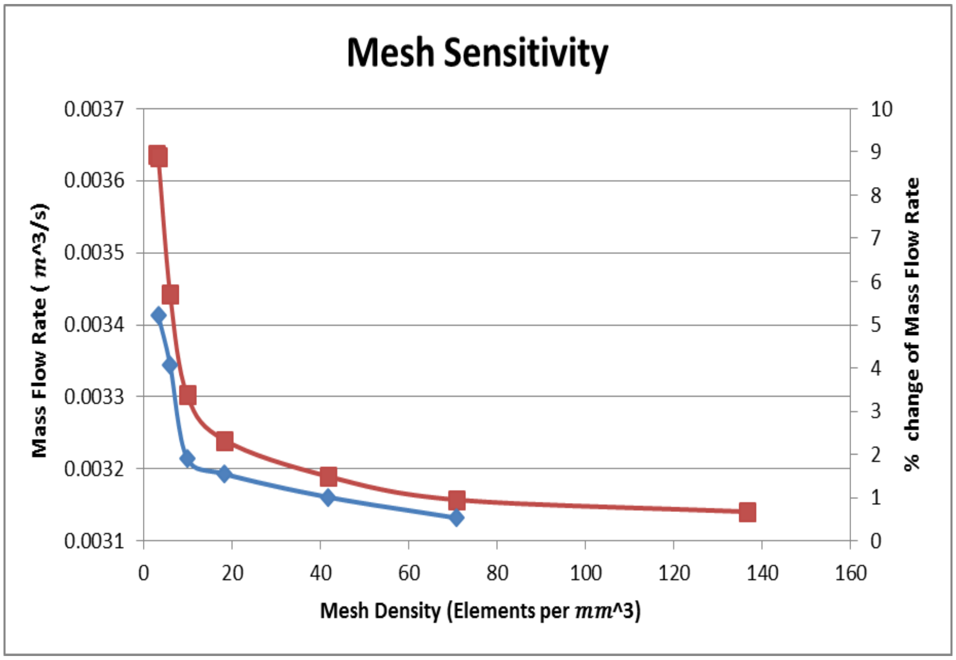



Figure 5.6 Mesh Sensitivity Analysis

5.6 Optimized Design:

From the graph shown in figure 5.6 in previous section, designs with dimensionless parameter 'r' valve 1.2 and more has better linearization of mass flow rate with angle. Means, the variation of mass flow rate with change in angle of valve is more linear in the designs with 'r' = 1.2, 1.3, 1.4 and 1.5.

Design with ‘r’ value 1.2 was chosen as the optimized design for ease manufacturing and usage than other designs because of its near length and breadth values.

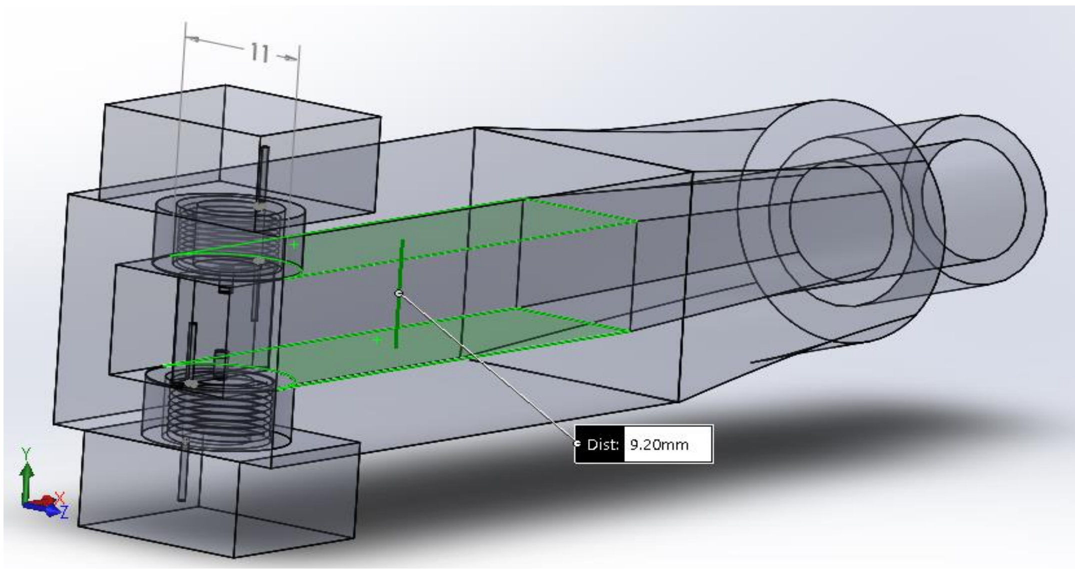



Figure 5.7 Sectioned View of Finalized Flow Control Device(r = 1.2)

The graph in figure 5.8 shows the valve angle vs mass flow rate trend for r =1.2 model with angle on X-axis and mass flow rate on Y-axis.

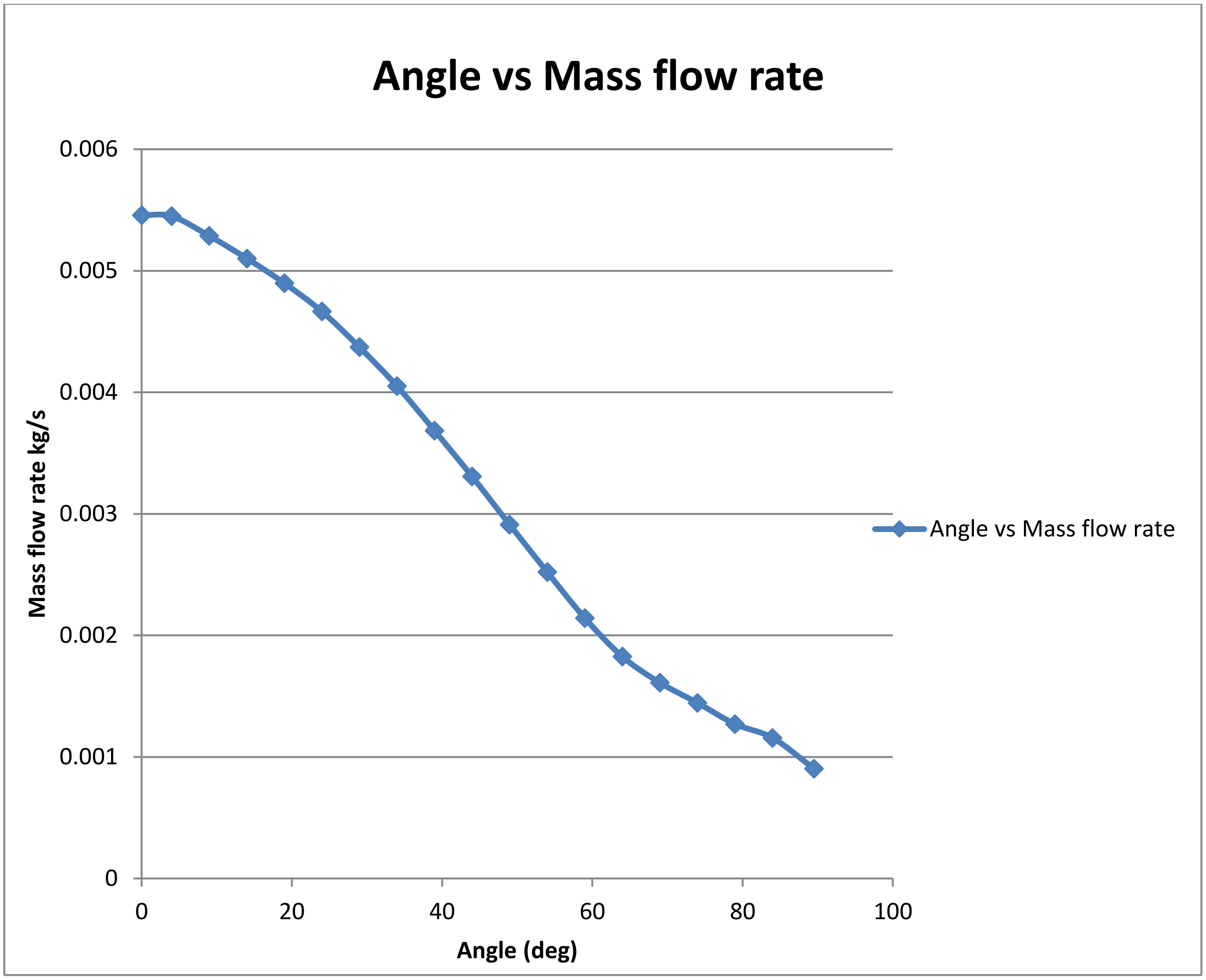



Figure 5.8 Graph between Mass Flow Rate and Valve angle for r = 1.2 Model

# Chapter 6 Pressure Forces on Valve

Model with r = 1.2 was chosen as optimized design in the previous section. Pressure forces on valve at angles varied from 0° to 90° was calculated using ANSYS CFX. Meshing and Inflation options are same as the options mentioned in Linearization section.

Parametric Simulation:

- Input parameter – Valve angle from completely open position to closed position (0°-90°).
- Output parameter - Force on the Valve.

6.1 Result:

The graph in figure 6.1 shows the trend of moment created by pressure or fluid forces on valve for the variation in valve angle from 0° to 90° for r = 1.2 model.

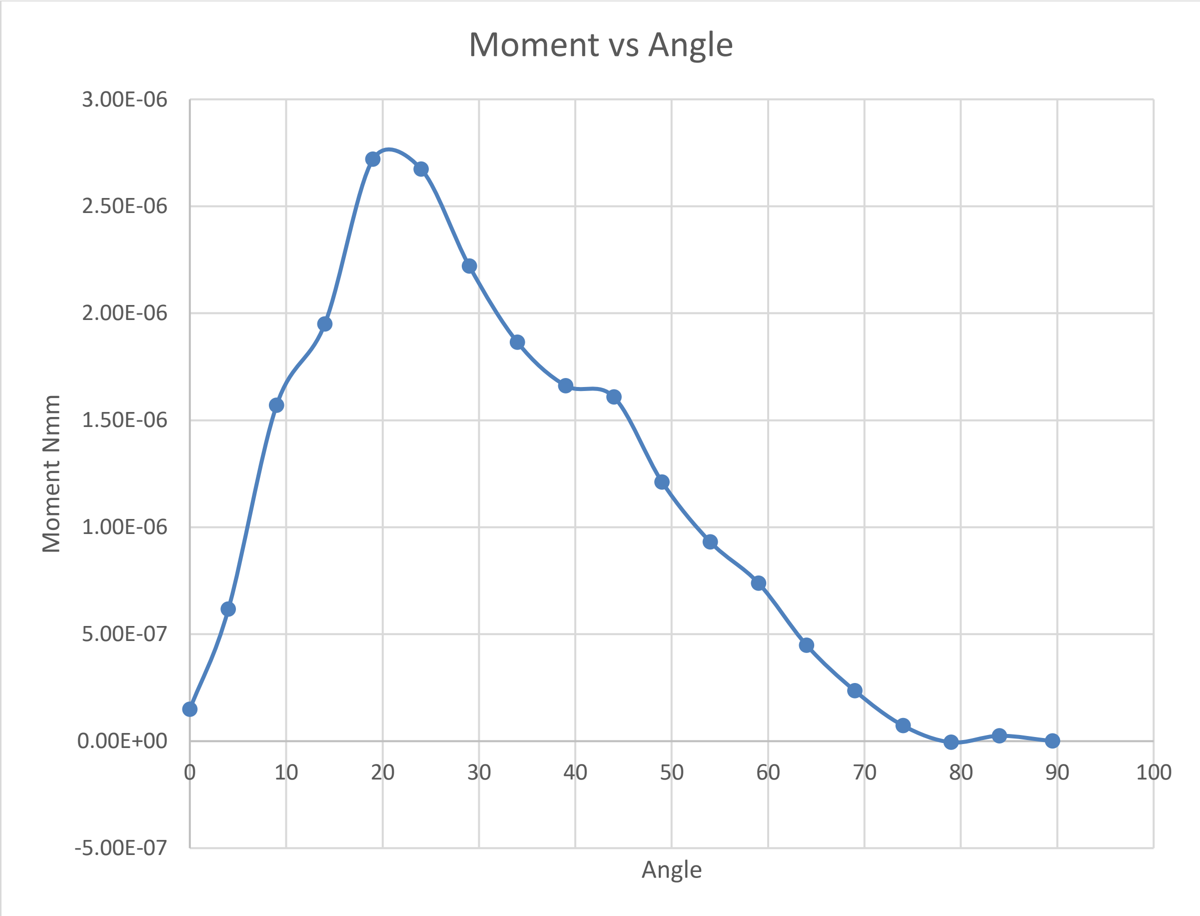



Figure 6.1 Graph between Moment by pressure forces and Valve angle

From the graph in figure 6.1, it is clearly observed that the moment created by pressure or fluid forces is maximum which is about 5E-06 N-mm around 20° valve angle from completely open position and has minimum moment at 80° to 90 valve angles. From the graph in figure 6.2 shown below trend of moment is similar for models with r = 1.2 and r = 1.5. Also, moment because of pressure forces generated by the r = 1.2 model is far less than moment generated by the r = 1.5 model. Model with lesser hydrodynamic moment or moment caused by pressure forces is more desirable because this moment is opposing moment for the moment generated by springs to rotate the valve. This strengthens the decision of choosing r = 1.2 model as optimized model.

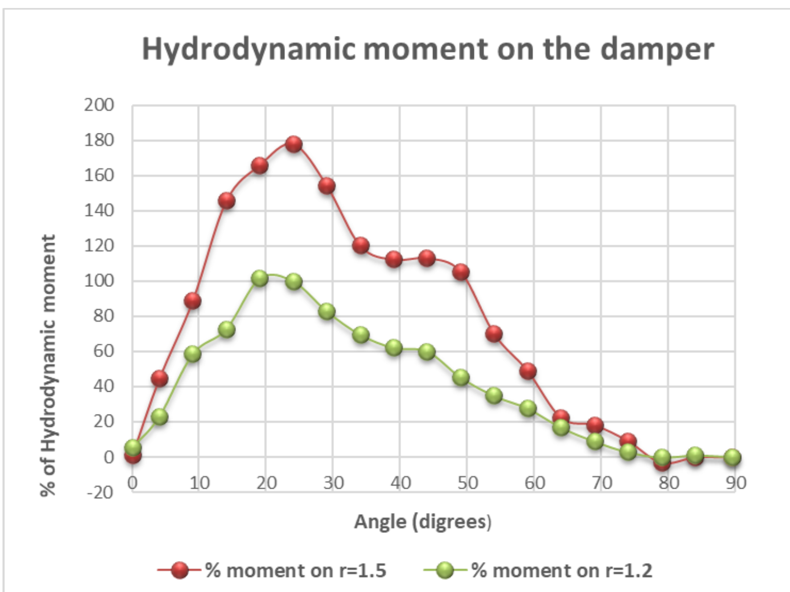
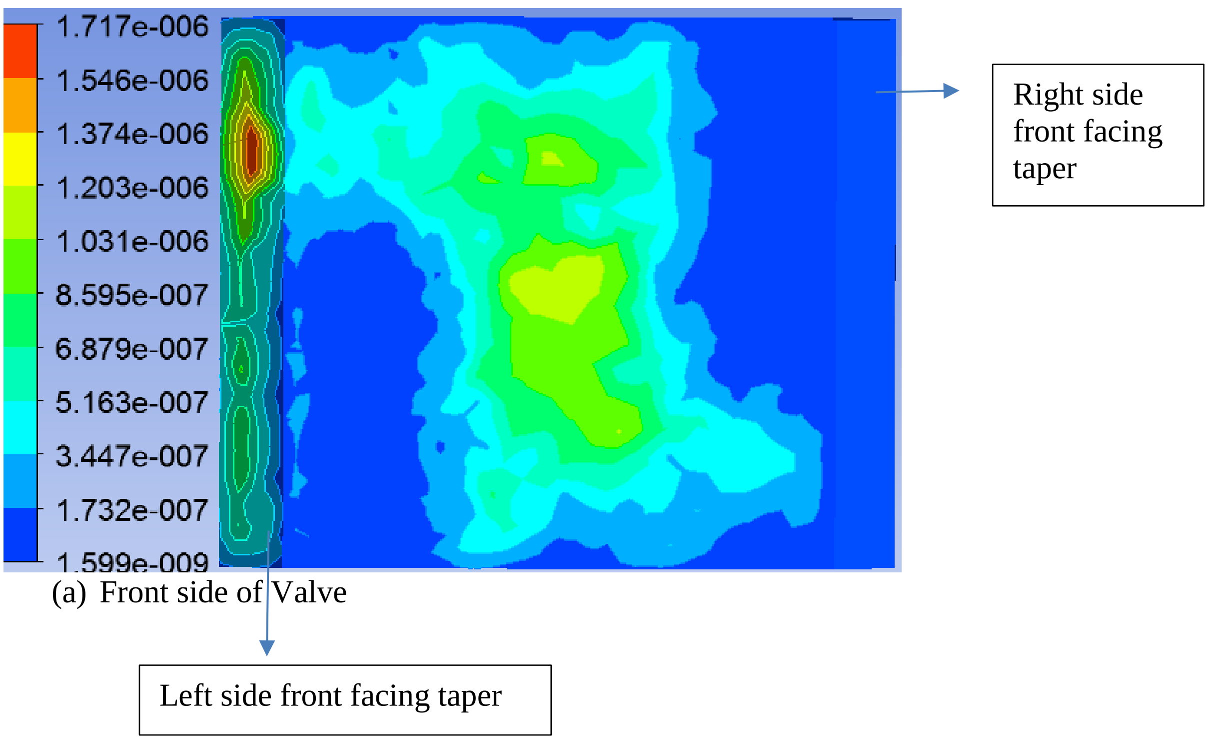



Figure 6.2 Moment Vs Valve angle for models r = 1.2 and 1.5

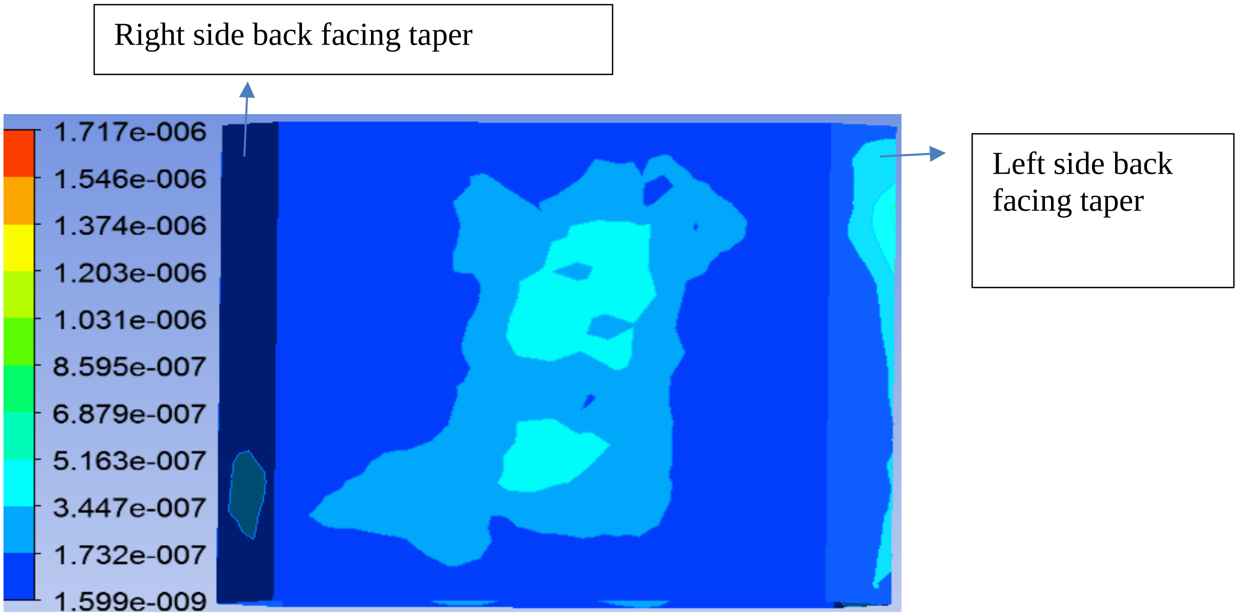
6.2 Force Contour:

At 20° angle:

It observed from the graph in figure 6.1 that the max moment generated by the pressure force is around 20° valve angle from the completely open position. At this position, water comes in direct contact with the left side front facing taper and losses its most of its contact with the left side back facing taper. Also, there is minimum direct contact of water with the right-side taper of the valve at this position. Because of this reduction in forces on left side back facing taper and right-side front facing taper, the pressure forces are maximum around 20°valve angle.




(a) Front side of Valve

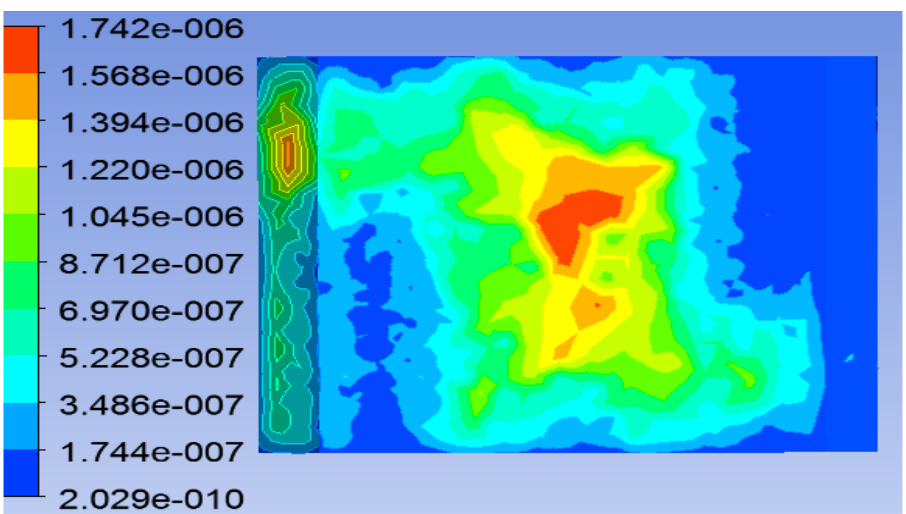



(b) Back side of Valve

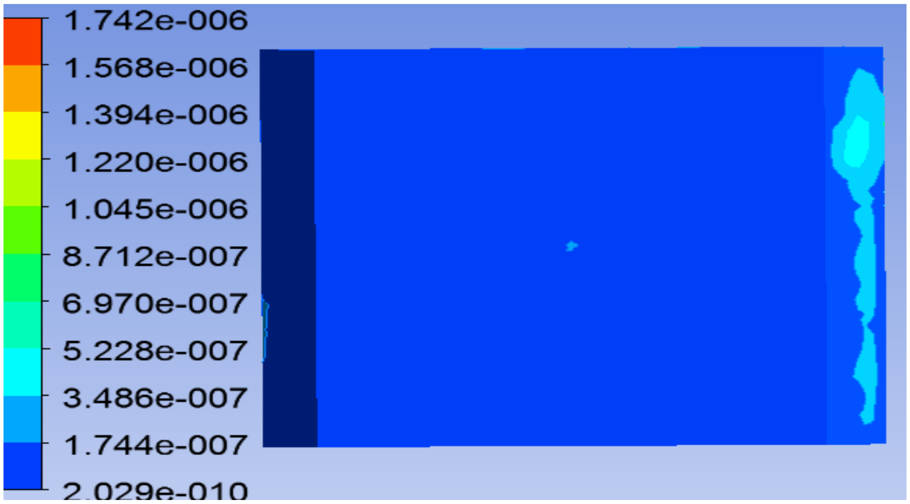
Figure 6.3 Force Contour on the valve at 19° angle

At 45° angle:

This is the angle at which the left side taper becomes completely perpendicular to flow of the water. So, from the graph in figure 6.1 in previous section, it is clearly observed that there is some abnormality around 45° valve angle.




(a) Front side of Valve

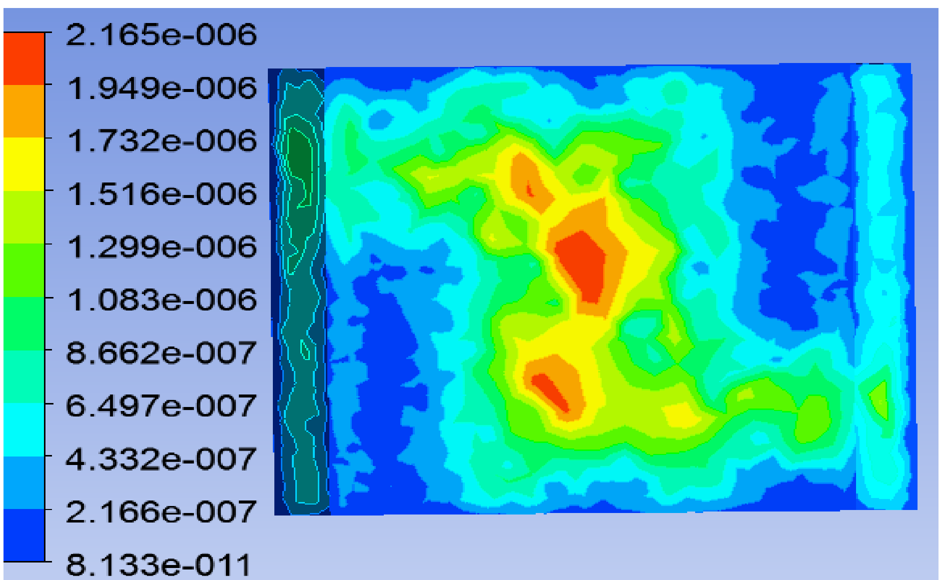



(b) Back side of Valve

Figure 6.4 Force contour on the Valve at 44° angle

At 90° angle:

From the graph in figure 6.1 is observed that the moment is minimum between 80° - 90° valve angle. The pressure forces are equally distributed on both left and right front facing tapers at this position.




(a) Front side of Valve

(b) Back side of Valve

Figure 6.5 Force Contour on the Valve at 89° angle

# Chapter 7 Experimental Setup Proposal

## 7.1 Schematic Diagram:

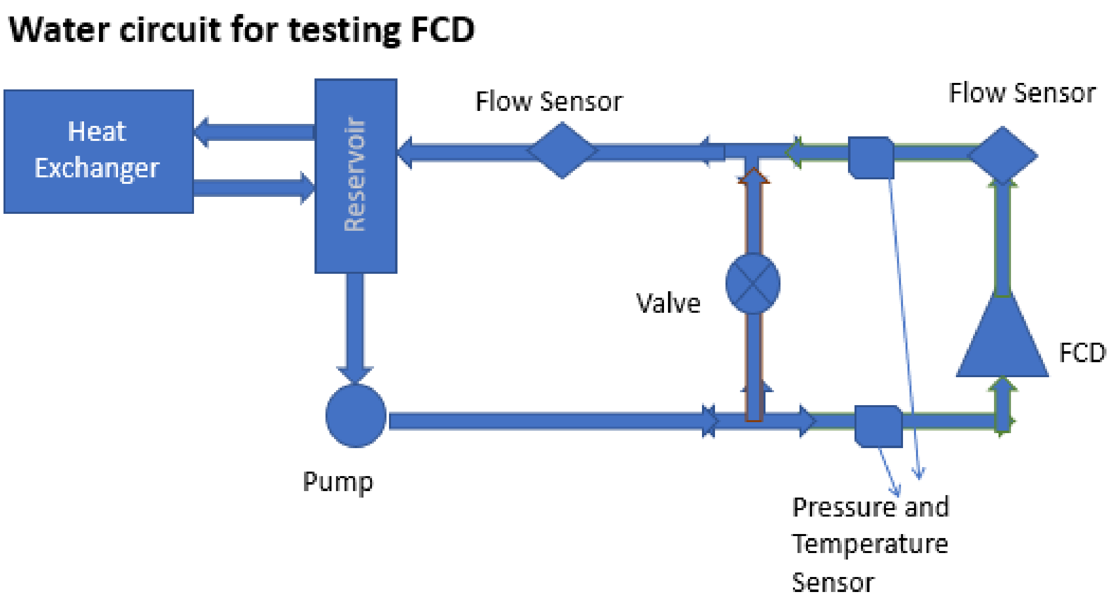



Figure 7.1 Schematic diagram of proposed Experimental setup

The figure 7.1 shows the schematic diagram of the experimental setup that is proposed to test the flow control device. It has heat exchanger, sensors, pump and flow control device.

- Pump: Constant pressure pump – It maintains constant pressure drop across the flow control device by varying mass flow rate with change in valve angle.
- Sensors: Temperature, Pressure and mass flow rate sensors are connected to the flow circuit before and after the flow control device to check the variations in flow properties.
- Heat exchanger: A heat exchanger is positioned between the water reservoir and flow control device outlet.
- Reservoir: It is the starting and ending point of water that is flowing through the circuit.

Working:

- Initially, when power supply is switched on, pump takes the water from the reservoir and starts pumping it to flow circuit based on the fixed pressure difference and opening of valve.
- Sensors that are positioned before the mass flow rate takes the pressure, temperature and mass flow rate values and sends them to data acquisition

unit(DAU). These properties can be viewed in the computer through specific platform specific to the DAU.

- Water enters the flow control device, valve rotates based on the temperature of water as explained in section 3.3.
- Based on the valve movement, the amount of water flows through the flow control device and flows through the remaining flow circuit containing another set of sensors.
- Now, water goes into the heat exchanger where it exchanges its heat with the coolant of the heat exchanger.
- Water after cooling in the heat exchanger, goes to the reservoir and the process continues.
- Here, the working of the flow control device can be checked for different temperatures by heating the water and at different pressure drops.

7.2 Power Supply and Control System:

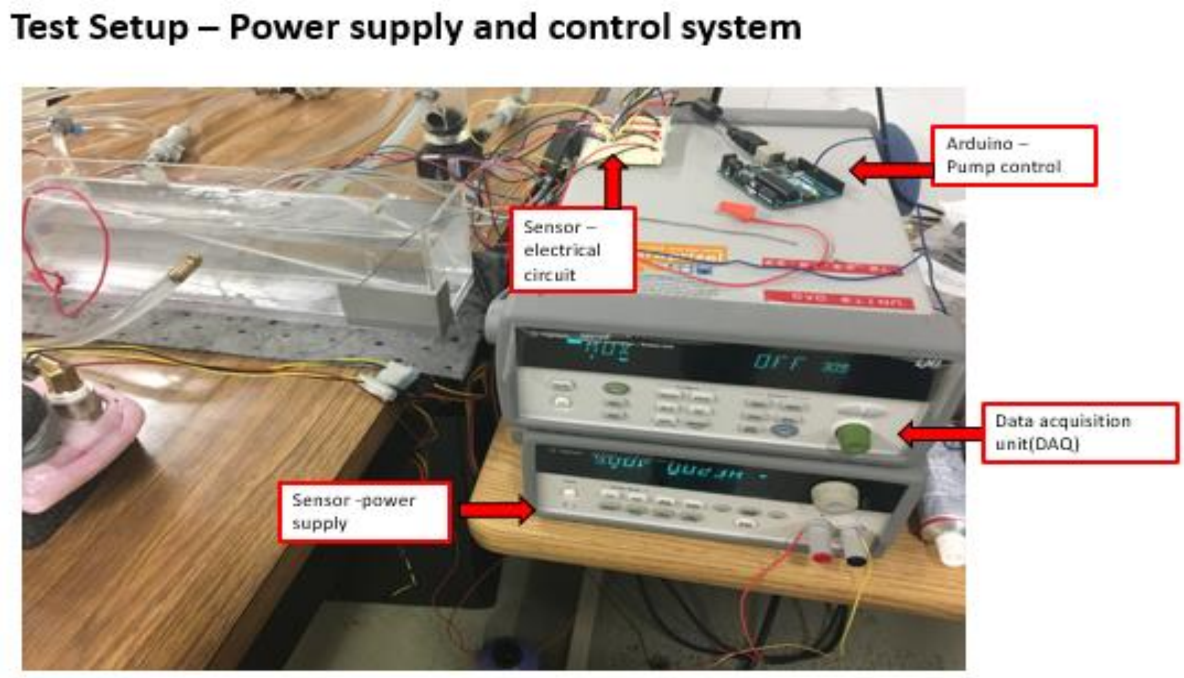



Figure 7.2 Power supply, Data acquisition unit and Electric Circuit

The figure 7.2 shows the Data Acquisition unit which collects the sensor data and power unit which supplies the power to the pump and sensors. Arduino is to control the pump at specific pressure difference across the flow control the device. Bread board connects the sensors to the data acquisition unit and power supply unit.

7.3 Flow Circuit:

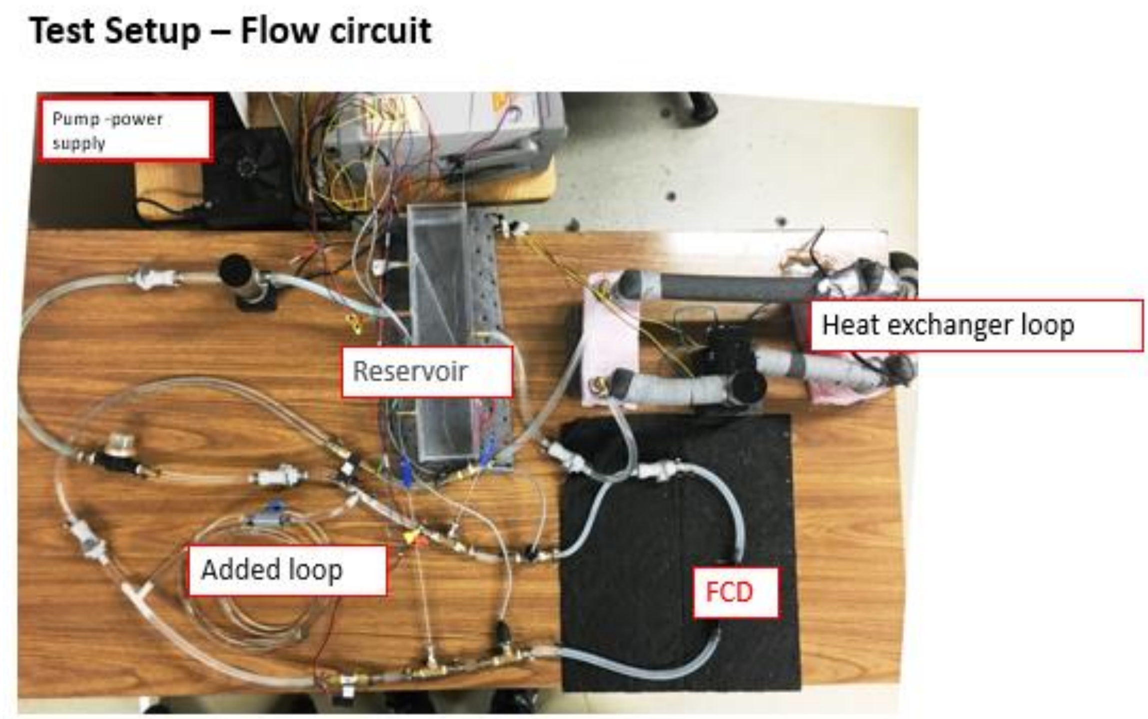



Figure 7.3 Flow Circuit with heat exchanger, reservoir, sensors and Flow Control Device.

The figure 7.3 shows the physically presented experimental setup and its parts. The added loop in the figure 7.3 is for emergency whenever there is pressure buildup in the flow control device or whenever there is sudden leaks in the device.

# Chapter 8 Conclusion and Future Work

## Conclusion:

The dynamic cooling can be achieved with a smart flow control device which effectively does the job of combination of temperature sensor, control system and an actuator. The present flow control device can accomplish all these jobs. An active material(Nitinol) is used in the present flow control device which is sensitive to temperature and which rotates the damper with respect to change in temperature. Rectangular butterfly valve was used to have better control over mass flow rate at different valve angles than traditional circular butterfly valve because variation in mass flow rate for change in valve angle is more linear in it and also it has lesser pressure drop across the flow control device than the circular valve. Through CFD analysis model with r = 1.2 was concluded as the optimized model because it is good in linearizing the flow while also keeping the moment by pressure forces minimal. The moment generated by pressure forces which is at the order of $10^{-9}$ N-m is very less when compared to the moment generated by the springs which is at the order of $10^{-6}$. So, the moment generated by the pressure forces can be neglected. The proposed experimental setup has all the features to test the flow control device. It can also be used to test various other similar type of flow control devices.

Future Work:

Testing of present flow control device to see the practical results and compare it with the results mentioned in this thesis report. The proposed experimental setup can be used to test this flow control device. Testing this flow control device in rack level by using one flow control device for one server or one for one rack. Similar research can be done using tension Nitinol spring and appropriate flow control device design.

# Appendices

## Appendix A

## Computational Fluid Dynamics

The equations that govern the motion of a Newtonian fluid are the continuity equation, the Navier-Stokes equations, the momentum equation and the energy equation. The set of equations listed below represents seven equations that are to be satisfied by seven unknowns [3]. Each of the continuity, energy, and momentum equations supplies one scalar equation, while the Navier-Stokes equations supply three scalar equations. The seven unknowns are the pressure, density, internal energy, temperature, and velocity components. The scope of our analysis predominantly lies in the laminar region of flow owing to low flow velocities and relatively simple geometries. The only instance where a k-Epsilon turbulence model is used is in the region between when the damper is completely closed and when it is open by an angle of 10 degrees. The equations used for solving in the laminar as well as turbulent regions are listed below.

$$\text{Continuity}: \quad \frac{\partial \rho}{\partial t} + \vec{\nabla} \cdot (\rho \vec{u}) = 0$$

$$\text{Momentum}: \quad \rho \frac{D\vec{u}}{Dt} = -\vec{\nabla} p + \nabla(\mu \nabla \vec{u}) + \vec{f}_b$$

$$\text{Energy}: \quad \rho \frac{DE}{Dt} = -\vec{\nabla} \cdot (p\vec{u}) + \vec{\nabla} \cdot \left(k_t \cdot \vec{\nabla}(T)\right) + \Phi + S_E$$

Turbulent kinetic energy : $\frac{\partial(\rho k)}{\partial t} + \vec{\nabla} \cdot (\rho k \vec{u})$
$= \vec{\nabla} \cdot \left[\alpha_k(\mu + \mu_t) \cdot \vec{\nabla}(k)\right] + 2\mu_t E_{ij}$
$\cdot E_{ij} - \rho\varepsilon$

Turbulent dissipation : $\frac{\partial(\rho\varepsilon)}{\partial t} + \vec{\nabla} \cdot (\rho\varepsilon\vec{u})$
$= \vec{\nabla}\left[\alpha_\varepsilon(\mu + \mu_t) \cdot \vec{\nabla}(\varepsilon)\right] + C^*_{1\varepsilon}\frac{\varepsilon}{k}2\mu_t E_{ij}$
$\cdot E_{1j} - C_{2\varepsilon}\rho\frac{\varepsilon^2}{k}$

where

$$\mu_t = \rho C_\mu \frac{k^2}{\varepsilon}, \quad C_\mu = 0.0845, \quad \alpha_k = \alpha_\varepsilon = 1.39,$$
$$C_{1\varepsilon} = 1.42, \quad C_{2\varepsilon} = 1.68$$

and

$$C^*_{1\varepsilon} = C_{1\varepsilon} - \frac{\eta\left(1 - \frac{\eta}{\eta_0}\right)}{1 + \beta\eta^3}, \quad \eta = \left(2E_{ij} \cdot E_{ij}\right)^{1/2}\frac{k}{\varepsilon},$$
$$\eta_0 = 4.377, \quad \beta = 0.012$$

REFERENCES

[1] Fernandes, J. E. (2015). Minimizing Power Consumption at Module, Server And Rack-Levels Within A Data Center Through Design And Energy-Efficient Operation Of Dynamic Cooling Solutions.

[2] Del Toro, A. (2013). Computational fluid dynamics analysis of butterfly valve performance factors. Utah State University.

[3] Currie, I. G. (2012). Fundamental mechanics of fluids. CRC Press.

[4] Manual, F. L. U. E. N. T. (2017). ANSYS/FLUENT Release Version 18 Ansys Inc.

[5] Errukula, S. (2016). COMPUTATIONAL DESIGN AND FLOW ANALYSIS OF SMART FLOW CONTROL DEVICE FOR DYNAMIC COLD PLATE USED IN COMPUTER SERVER COOLING (Doctoral dissertation).

[6] Kokate, R. K. (2015). EXPERIMENTAL ANALYSIS VALIDATING A CONTROL SCHEME TO DEVELOP A DYNAMIC COOLING SOLUTION FOR NON-UNIFORM HIGH POWERED ELECTRONIC DEVICES IN DATA CENTER(Doctoral dissertation).

[7] Shah, K. A. (2016). Design of an Improved Flow Control Device for Dynamic Cold Plate And Optimization of Servers to Decrease Junction Temperature Of Heat Sinks. (Submitted)

## Biographical Information

Penchala Sumanth Reddy Challa received his bachelor's degree in Mechanical Engineering from Sri Venkateswara University College of Engineering, Tirupati, India in 2015. He began his Master's degree in University of Texas at Arlington, after completing a 3 month course in ANSYS in Techzilon Training solutions, bangalore, India. He joined in in EMNSPC team for research and for his Thesis work. His area of interest includes Design and Thermal Engineering especially by using Modeling and Computational software. He worked as Teaching Assistant for CATIA, a modeling software. He has good Modelling software skills like SolidWorks, CATIA and good computational software skills like ANSYS CFX, FLUENT, ICEPAK. He Completed his Master of science Degree in Mechanical Engineering from University of Texas at Arlington in December 2017.