IMPROVING AIR COOLING EFFICIENCY OF 2OU HIGH-END WEB SERVER BY USING BIGGER RACK LEVEL FANS AND CONTROLLING FLOW USING BIMETALLIC STRIPS

by

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To my parents for their motivation and suppport.

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ABSTRACT

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Due to the doubling of processing power ever so often, designing an efficient thermal management system for database centers is becoming more and more difficult. Two studies have been done, one on air cooling using bigger rack level fans and another in liquid cooling minimizing the size of flow control devices.

Fans are one of the most inefficient and power hungry devices used in an air cooled database center. Study has been done to improve the air cooling efficiency using larger rack level fans on 2OU open compute server. Simulations have been done using commercial computational fluid dynamic (CFD) software and power consumption of this rack level fan configuration has been compared with the baseline server level fans. Fan failure scenario is also studied by failing one fans and observing the flow through the servers using CFD.

An innovative concept of liquid flow controlling device is introduced for liquid cooling applications. These mini flow control devices (MFCD) use thermostatic bimetallic effect. This mode of flow control is cost effective, scalable, and easy to

control by passing current directly through the strip. The advantages and applications of this flow control devices are great. This flow control device is designed and analyzed using theoretical formulas for passive flow control in Dynamic liquid cooling plate. Structural and flow interaction is also simulated by using computational flow dynamics.

Six 120mm Rack level fans are advisable for this open compute rack configuration, only if the servers are performing less than 70% of utilization above which we steadily loses the increased in efficiency. Initial cost of 6 fans costs approximately less than half of 30 server level fans. Designed MFCDS can be successfully used in efficient cooling of multi core processors.

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CHAPTER 1

INTRODUCTION

1.1 Data center: An overview on cooling

Database centers are information processing and data storage facilities. These are used in solving complex problems from traffic congestions to sending simple electronic mail to the intended person half way across globe. These datacenters not only have data storage and processing systems, but also have secondary thermal management systems like power supply and other communication hardware.

Cisco predicts global IP traffic would increase by 2.8 times in next 5 years [1]. Database centers have power densities of 10 to 100 times of that of typical office building, of which 50% of this energy in typical air-cooled data base centers is not used for processing data [2]. Database centers in general has become power hungry and inefficient than before as the density of transistors is doubling approximately every two years according to Moores law [3]. As the power of these devices is rising very rapidly, efficient thermal management in database center has become difficult. New ways to cool these devices is being studied by using phase change materials, immersing servers in oil tanks. These innovative cooling methods have their own set of problems to be solved before they can replace present liquid and air cooled thermal management systems.

Redundancy to a database center is a mission critical objective, as in many cases this data is too valuable to lose. Database centers also need to occupy smaller footprint as cooling larger areas is a waste of resources. While making any design modification to thermal systems aforementioned conditions should be taken into consideration.

There are three main methods to cool the semiconductor chips air cooling, liquid cooling and phase change technologies. Each cooling method has their own advantages and disadvantages. Of these cooling technologies, the most widely used cooling technique is by air cooling. Due to its abundant availability, ability to easily move air around and time tested technology. Whereas liquid cooling needs advanced technology due to the formation of corrosion, harmful bacteria and sedimentation in pipes in long runs. Water leakages are also a prime concern for liquid cooled computing devices as these chips are costly reliability and data is priceless in few applications. Similarly phase change cooling also have many problems like sedimentation, fluid leakage due to use of high pressurized fluids, constantly varying pressures causing wear out in piston rings and motors.

The main aim of this thesis is to increase efficiency of air cooled and liquid cooled database centers. Fans are one of the inefficient devices used in air cooling by using bigger rack level fans which are much more efficient than smaller server level fans would improve air cooling. This concept is applied for 2U Open compute rack.

To improve liquid cooling efficiency a study has been done on mini flow control devices, by using these flow control devices we can divide the single cold plate into many smaller islands and cool these islands individually. Presently the entire cold plate is being uniformly cooled for maximum die temperature using more power. We can also replace pumps at server levels with flow control devices and use a single constant pressure source. Thus mini FCDs improve both efficiency and reduce the capital cost of the liquid cooling devices. To explain further presently we are using small pump at every tap in a building instead of using a single constant pressure over head tank and multiple flow control devices at each faucet.

1.2 Air cooling

Air cooling can be done in many ways, some of the important methods are by using CRACS, direct fresh air cooling and indirect air cooling system etc., of all these systems plenum raised air cooling with CRACs is the most commonly used methods of air cooling. Figure 1.1 [4] shows the most commonly used plenum raised floor tile cooling system.

Raised floor provides cool air to the server racks from CRAC units, using the under floor ducts takes advantage of cool air coming from bottom and hot air rising above. This decreases the energy needed by the HAVAC systems and fans to move the air up to 10% [4]. This also provides consistent cooling, humidification, exhaust and good quality of air throughout the facility.

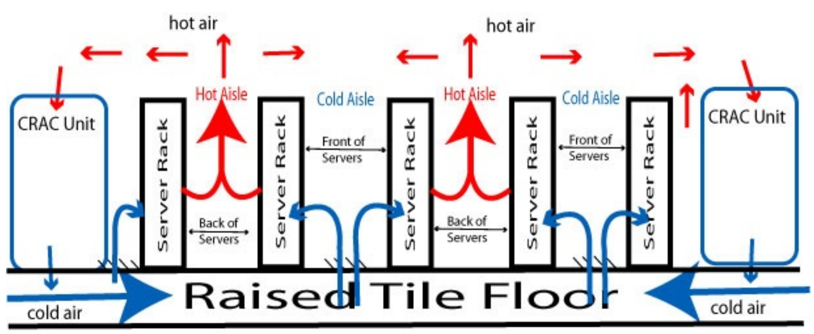


Figure 1.1. Typical thermal layout of a data center.

As shown in fig 1.1[4] cool air from CRACs enter the servers through the ventilation shafts under the floor. The fans at the server level pump air from the cold aisle through the server to hot aisle. As the air goes through the server it cools the electronics inside the servers and gets heated. This hot air is ventilated out of the servers by using exhaust fans. The hot air entering into the CRAC unit is cooled by using heat exchangers. Cooled air is again pump into the raised floor vents.

In general CRACs uses chilled water to cool the hot air. There are other methods where hot air is mixed with cold outside air when the outside environment matches the need of the database center known as direct air cooling. Optimizing air temperature and CRAC inlet water temperature would improve the air cooling efficiency significantly and use of outside air is also being used by many database centers for increase in cooling efficiencies significantly.

Fans are one of the most inefficient systems in this cooling technique use of bigger rack level fans or use of improves the air cooling efficiency. Previous studies on using rack level fans replaced 60mm fans with 80mm for first generation open compute server. It has shown a significant increase in efficiencies up to 50% decrease in fan power [5]. Similar study is need for new generation 2 OU open compute servers.

1.3 Liquid cooling

Many of the thermal management problems in high end servers, like high heat generation and cooling power consumption can be solved by using liquid cooling. Traditional air cooling wastes lot of energy in cooling these servers, using liquid cooling will improve power consumption and decrease the footprint by 40-60% [6].

Fig 1.2 [7] shows typical liquid cooling system in a data base center. In general cold water cools high power devices like CPU and GPU, whereas cool air from CRAC units cools the memory and other low powered devices. The hot water exited from cold plates is cooled by outside radiator or chillers.

The main disadvantage of using liquid cooling is, any possible leakages may destroy the equipment. The cost to setup and maintain the cooling system is high as the pumps at server level costs more. Use of a single pump for entire rack would significantly decreases the cost of the entire cooling system.

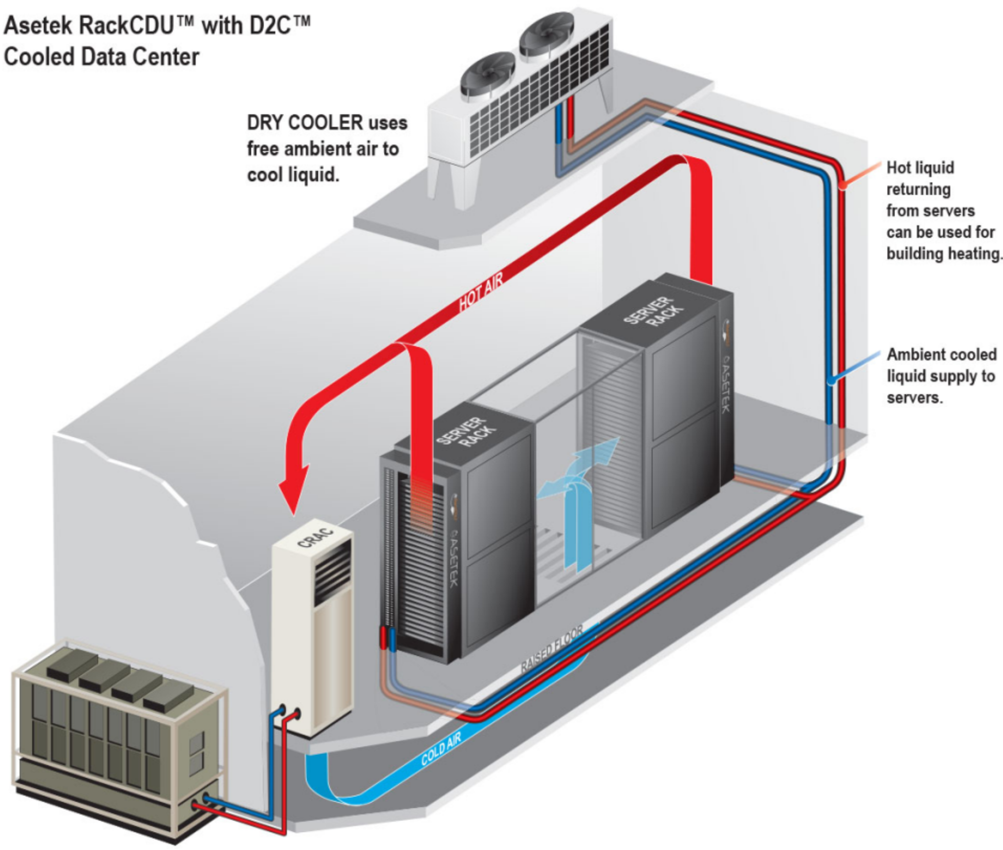


Figure 1.2. Typical thermal layout of liquid cooled data center .

Dividing each cold plate on CPU into multiple islands will decrease the total pumping needs by eliminating hot spots. This decreases the need for cooling the entire cold plate as in present direct cooled systems. As we are cooling the high temperatures areas the pressure drop of the cold plate is comparatively low thus we can use high flow rates and use warm water cooling instead of chilled water.

Use of single pump instead of several small server pumps would significantly decrease the total cost of the equipment. It also decreases the total pumping energy as bigger pumps are more efficient in general. The introduced flow control device in this thesis is reliable and sits in existing channels directly without any modification.

Other main advantage of using a single pump for the entire rack is eliminating leakage inside the server. As there is no pump to replace or repair and FCDs using bimetallic strips does not have moving parts. Cold plate and pipes can be completely sealed, thus eliminating the leakages inside server. This proposed idea has can eliminate possible leakage, improve cooling efficiency and at the same time decrease the total cost of the system.

CHAPTER 2

RACK LEVEL FANS

2.1 Introduction to Fan's

A fan is a machine that is used to move fluid, typically air from one place to another and it has rotating blades which propels air by creating a pressure difference between inlet and outlet. There are two types of fans axial fans and centrifugal fans. Axial fans create high flow and low static pressures, whereas centrifugal fans create high pressure difference at lower flow rates. In general, servers use axial exhaust fans to move air through the server. Whereas laptops use centrifugal fans or blowers, as laptops are compact and have high pressure drops.

2.2 Flow characteristics of a fan and server

Fan flow characteristics are specified by two characteristics mainly maximum flow rate at free flow and maximum static pressure at no flow condition. These two values are specified by every manufacturer along with the fan curve. A fan curve is a plot between static pressure and air flow rate at a rated rpm as shown in fig 2.1 [8].

Fan laws are basic laws specifying varying flow rates with varying diameters and changing diameters. By using these fan laws we can predict modified fan curves for different rotational speeds of fans very accurately as shown in fig 2.2. As derived in compressibility and fan curves by Jorgenson and Bohanons [9] the fan laws are as follows:

$q1/q2 = (n1/n2)(d1/d2)^3$

$dp1/dp2 = (n1/n2)^2(d1/d2)^2$

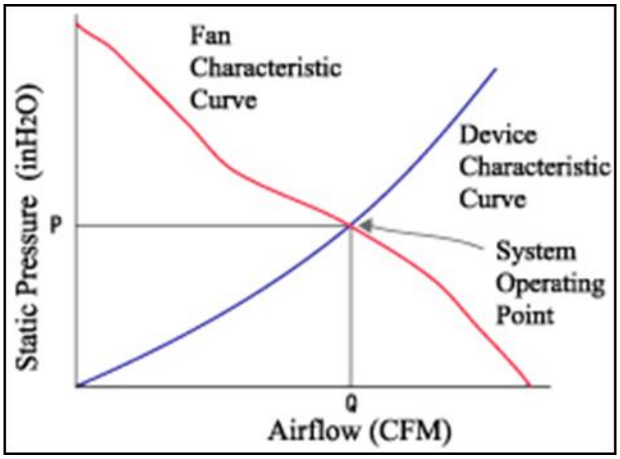


Figure 2.1. Fan characteristics.

$dp1/dp2 = (n1/n2)^3(d1/d2)^5$

q = volume flow capacity

n = wheel velocity in revolution per minute

d = wheel diameter

dp = pressure drop

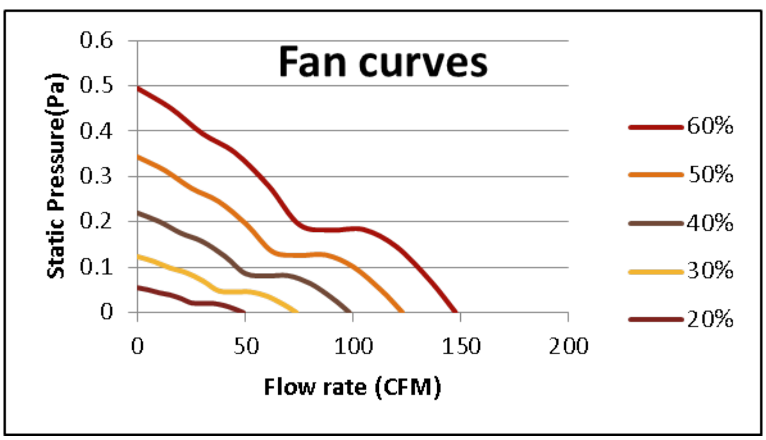


Figure 2.2. Fan curves for varying rpms.

Resistance curve is a curve, plotting pressure drop of a system for varying flow rates through the system. Resistance curve of a server is found experimentally using air bench by varying the flow rates through the server. Either pull or push configuration can be used in air bench for finding the system resistance curve accurately. While measuring the resistance curve in air bench we start with maximum flow rate required for cooling the system and slowly close the door decreasing the flow rate of the system.

Operating point is a point where the system resistance curve intersects with the fan curve. Operating points can be predicted using two methods through CFD or by directly plotting fan laws and resistance curves and finding intersecting points. Given system model and rated fan curve commercial CFD software can directly predict fan curves and corresponding fan curves. Experimental operating points can be found out simply by attaching the fan to system and measuring flow rates and pressure drops across the server using air bench.

2.3 Bigger rack level fans

Bigger fans are more efficient than smaller fans. The Air Movement and Control Association International (AMCA) specify airflow (CFM) as a function of fan diameter and thrust [10]. According to this formula increasing diameter or thrust increases flow rate, but increasing thrust requires more input power, while increasing diameter does not [10].

As shown in fig 2.3 increasing diameters increases efficiency up to a threshold limit after which efficiency varies slowly. Previous studies on increased diameter of rack level fans on 1.75U Open compute server have decreased fan power by 40-50% [5]. Rack level fans uses comparatively less number of fans and works comparatively at lower rpms. Thus decreasing bearing losses and the capital cost of the total fans.

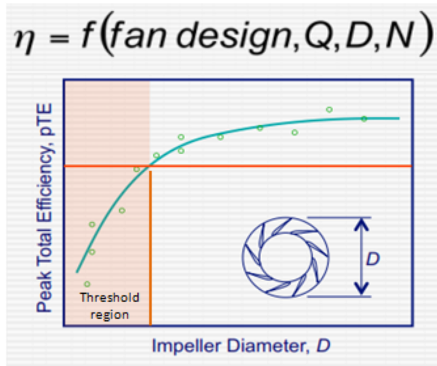


Figure 2.3. Plot between efficiency and diameter.

2.4 Server and fan in consideration

A 2U Open compute Winter-fell server is being considered for this rack level server analysis. This server is long and have approximately 1/3 width of a regular 1U server as shown in fig 2.4. These servers are provided with 2U width, where U is a server measurement unit rough equals to 1.75 inches. Due to increased height and use of bigger 80mm fans, these servers are very energy efficient in terms of air cooling efficiency compared to 1U servers. These servers have 2 bigger 80mm fans which are very efficient and operate at very low powers compared to typical 1U servers. The problem with this type of long broad and 2U design is severe thermal shadowing of CPUs and decrease in floor space. Also these servers are typically designed for efficiency and memory intensive applications. Due to increased height this server resistance is very low compared to 1U servers. Server resistance curve is found out in air bench by varying flow rates through the server and measuring pressure drop across the server. Power is calculated for varying flow rates across the server for different CPU utilizations.

A 120 mm fan is selected based on the lowest CFM to Power ratio from the available fans. Delta fan PFC1212DE is considered due to high energy efficiency and

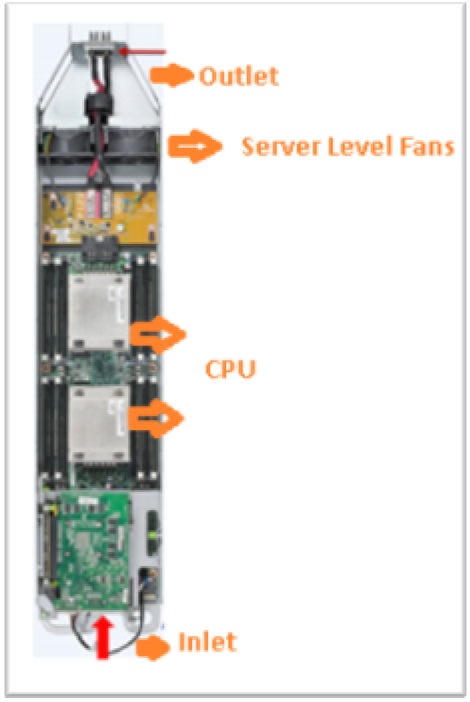


Figure 2.4. 2U Open compute winterfell server.

flow rates. Fan curve from manufacturer is compared with the experimental data as shown in the fig 2.5 and the experimental data is tabulated in table 2.1.

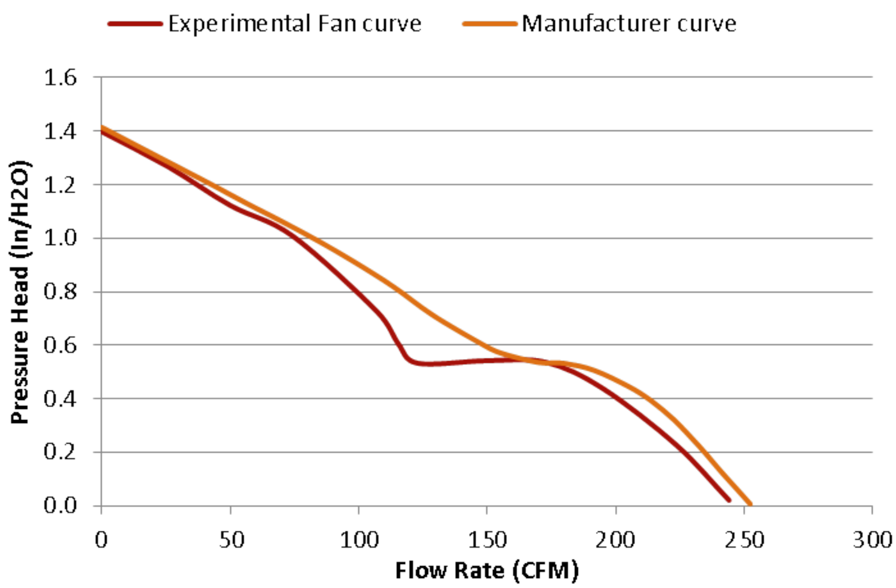


Figure 2.5. Experimental and manufacturers fan curve.

Table 2.1. Experimental Fan curve

Flow rate(CFM)	Pressure Head (In/H2O)
0	1.399
25.73	1.268
49.99	1.123
74.33	1.008
107.21	0.724
115.28	0.607
122.88	0.532
149.63	0.542
172.74	0.537
194.97	0.438
223.45	0.227
244.03	0.02

2.5 Rack in consideration

A 15 server rack is considered for this analysis and a picture of the rack is as shown in fig 2.6. Each server in this rack is modeled as a simple porous obstruction model as shown in fig 2.7. Using a porous obstruction model is a simple way to represent the resistance of the system, without the detailed model of the server internal components. Though a detailed model is not used, the model is accurate and solution is computed very quickly.

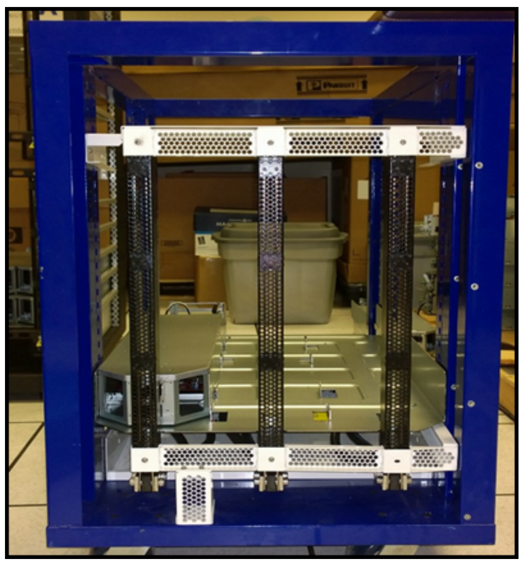


Figure 2.6. 15 Server rack in consideration.

The resistance curve given to the porous region is slightly modified to give us an accurate model. As the walls of the duct and outlet of server also gives an additional resistance to the model. Thus, resistance due to walls and vents is subtracted from the experimental resistance curve to get the porous obstruction model. Following table 2.2 shows the decreased pressure drop values.

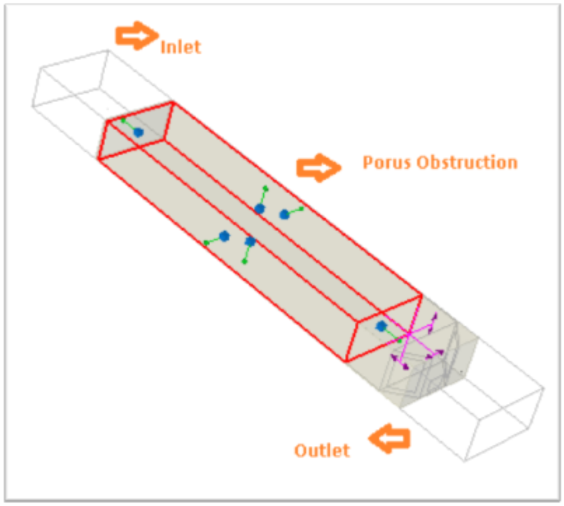


Figure 2.7. Server model with Porous obstruction.

Table 2.2. Resistance Curve

Flow rate(CFM)	Pressure Drop(In/H2O)	
	Server	Porus obstruction
0	0	0
25	0.033	0.03
50	0.105	0.096
75	0.214	0.194
93.75	0.322	0.292
100	0.363	0.329
125	0.549	0.499
150	0.774	0.706
175	1.037	0.951
187.5	1.183	1.087

2.6 CFD model

Two configurations of RLF are considered for the given rack, one with 12 fans as shown in fig 2.8 and 6 fans as shown in fig 2.9. First model with 12 fans offers more resistance, as few fans are placed straight in front of bus bars, whereas in 6 fan model, the fans are facing exactly before the exhaust vents of the server as shown in below figure.

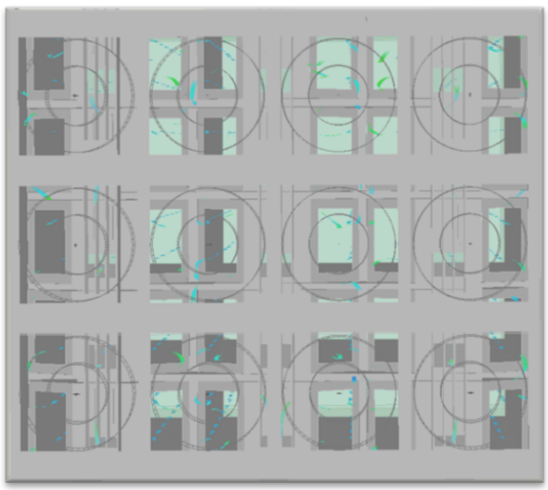


Figure 2.8. 12 Fan model.

In both models, the servers in rack are assumed to have uniform CPU utilization. It is also assumed that there are no leakages due to gaps between these two servers or between a server and rack frame.

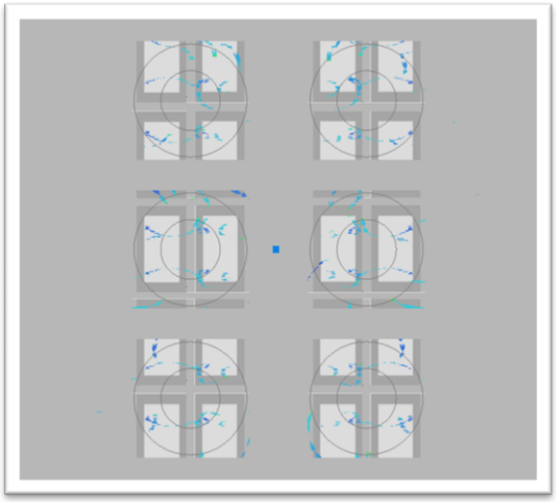


Figure 2.9. 6 Fan model.

2.7 CFD analysis

Different CFD analysis is performed on the model for finding the least no. of elements required for an accurate model. Analysis is done to find smallest distance between server and fans for an equal flow distribution among the servers. Finally analysis is done in finding fan operating points at different fan power. Grid independence test is performed in CFD by increasing total no of elements and seeing how the total CFM through the system varies. After 6 million no of elements, the model is grid independent as shown in fig 2.10.

Flow distribution test is performed for finding the relation between increase in distance between server and RLF to flow distribution between servers. As shown in fig 2.11 after 20mm distance there is very less change in flow distribution between servers, so 20mm is selected as the ideal distance between server and RLF inlet.

Operating points can be found out by varying the RPM of the fan in CFD. But the fans RPM is being varied in the same PWM and due to non-availability of air bench equipment all the fan curves from 60% PWM to Idle condition for the given fan

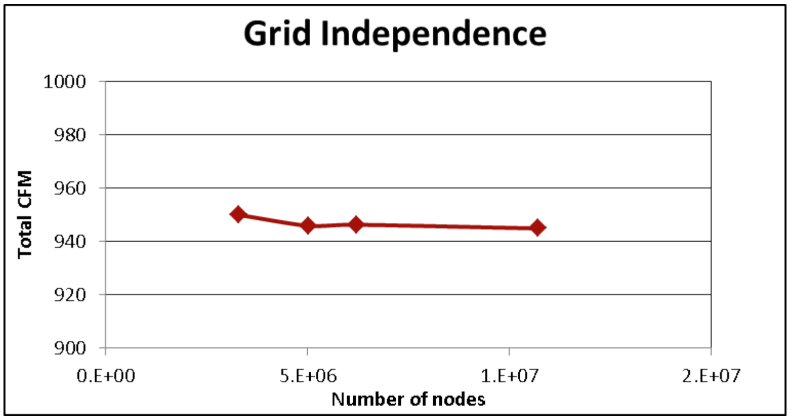


Figure 2.10. Grid independence graph.

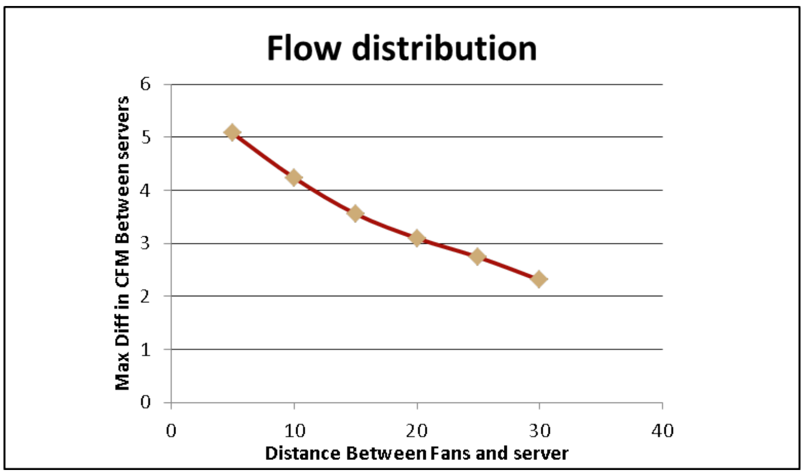


Figure 2.11. Varying flow distribution with increasing distance.

is experimentally found out. This fan curve is inputted into the CFD for calculating the operating point.

This method would be more accurate and simple compared to the traditional method. Power is also measured at all the give points in the fan curve, thus we can plot power curve and estimate the approximate fan power from those values. Fan curve and Power Curve for change in rpm is plotted in below figure.

2.8 Operating points from experimental fan curves

Fan curves for 60%, 50%, 40%, 30%, Idle have been measured for ten points on each curve. The fig 2.12 shows the fan curves from 60% to Idle along with the operating points from CFD. Power is also measured and respective power curves i.e., flow rate versus current is also plotted as shown in fig 2.13.

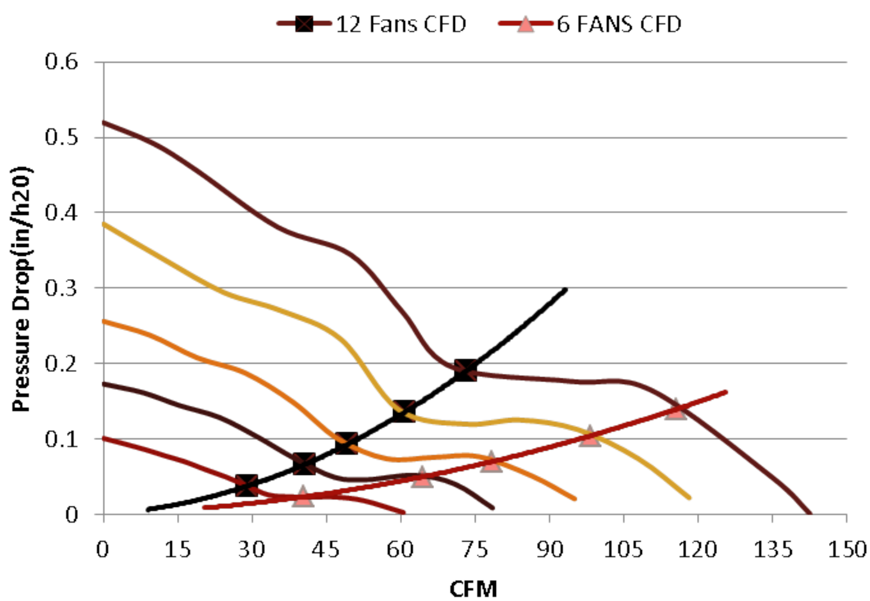


Figure 2.12. Fan curves and operating points from experiments.

As shown in fig 2.12 resistance offered by 12 RLF is high compared to the 6 fan case. Fig 2.13 also shows the same relation in efficiency, power consumed by 12 fans is higher compared to 6 fans. 12 fan case consumes almost same power as the present baseline server fans. Thus only 6 fans model is selected for further testing. To validate the values obtained from the graphs, operating points and power at these points is found out experimentally for 6 fans.

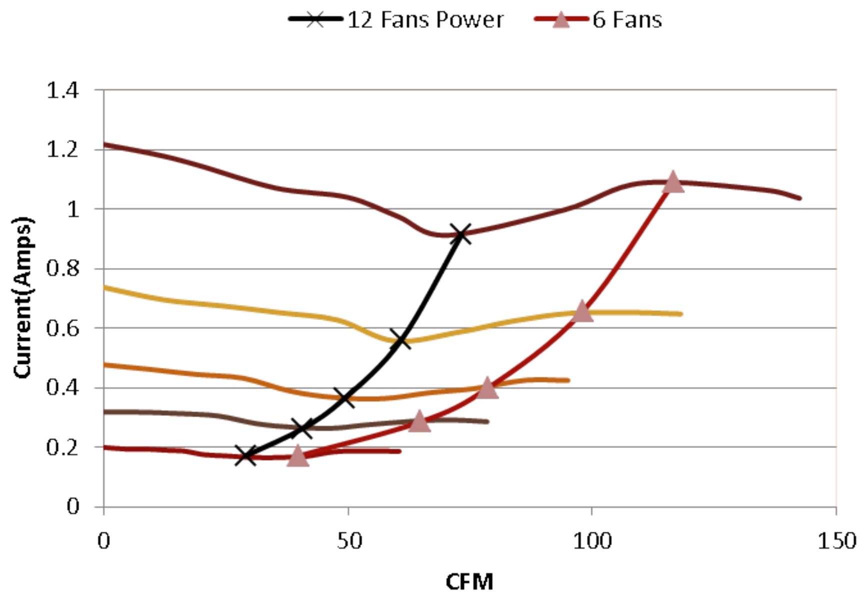


Figure 2.13. Power points from fan curves.

2.9 Measuring power at the operating points

For the given operating points from CFD, the power consumed by the fan at these operating points is measured experimentally. The experimental setup is as shown in fig 2.14.

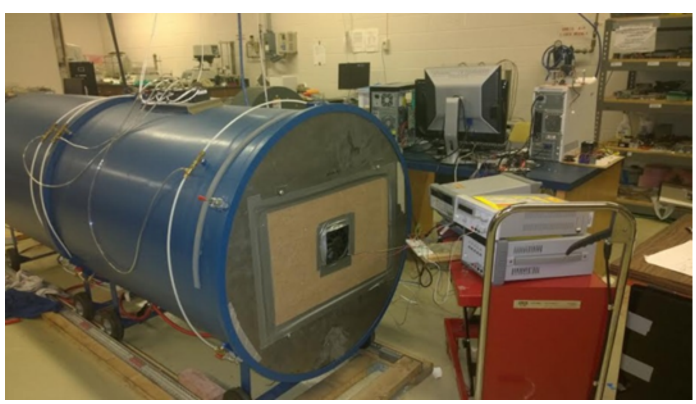


Figure 2.14. Experimental Setup.

All the Six individual fan's operating points from the model are taken and averaged. These operating points are replicated on an airflow bench and corresponding power values of fan is noted. A comparison of CFD and experimental values are shown in table 2.3. Corresponding fan power values at these operating points is tabulated in table 2.4.

Table 2.3. Comparision of experimental operating points (OP) with CFD

Speed		Flow Rate (CFM)			STP (In/H2O)		
PWM	RPM	CFD	EXP	Diff	CFD	EXP	Diff
60%	3300	115.57	114.98	0.58	0.14	0.17	0.03
50%	2900	98.35	98.3	0.05	0.1	0.11	0.01
40%	2400	78.33	77.83	0.5	0.07	0.07	0
30%	2000	64.4	64.55	-0.15	0.05	0.05	0
20%	1500	40.3	39.97	0.33	0.02	0.03	0.01

Table 2.4. Fan power at operating points from experiment

Speed		Flow rate	Power
PWM	RPM	CFM	(Watts)
60%	3300	114.98	5.4
50%	2900	98.3	3.504
40%	2400	77.83	2.04
30%	2000	64.55	1.4184
20%	1500	39.97	0.864

2.10 Comparison of fan power

Power per unit server is calculated for rack level 6 fans and these readings are compared with the base line 80mm fan configuration. The following table 2.6 and fig 2.15 compare fan power between baseline two 80mm server fans to rack level fans. The table 2.7 gives a comparison with respective to CPU utilization. For Idle case the efficiency is very low as the rack level fan's as shown in fig 2.15 reaches idle at 16 CFM where 80mm fans reaches at 11 CFM approximately. At 16 CFM, RLF is 22.7% more efficient than 80mm fans. This efficiency decreases at 60% CPU utilization to 15% and shows no change in efficiency at 80% CPU utilization. At 100% CPU load the RLF is 21% less efficient than baseline server fans.

Table 2.5. Fan power per server for baseline server fans

Flow Rate (CFM)	Power (Watts)
11.04	0.94
24.32	1.738494
30.12	2.213402
35.17	2.793736
43.37	3.874976

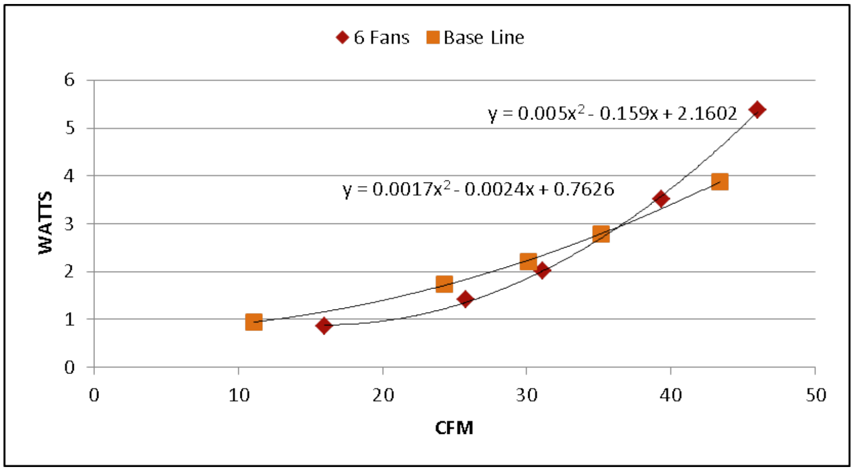


Figure 2.15. Power comparision between baseline and RLF.

Table 2.6. Fan power comparision

Flow Rate (CFM)	Power Baseline (Watts)	Power 120mm (Watts)	Efficiency
16	1.16	0.89	22.7%
20	1.39	0.98	29.7%
25	1.76	1.31	25.77%
30	2.22	1.89	14.88%
35	2.76	2.72	1.48 %
40	3.39	3.8	-12.21%
45	4.09	5.13	-25.21%

Table 2.7. Fan power comparision with varying CPU loads

		Fan power per server(Watts)		
CPU utilization	Flow (CFM)	Baseline	RLF 6 fans	Efficiency (%)
Idle	11.04	0.94	0.89	5.32
40	24.32	1.74	1.25	28.08
60	30.12	2.21	1.91	13.83
80	35.17	2.79	2.75	1.44
100	43.37	3.87	4.67	-20.50

2.11 Fan Failure

Fan failure scenarios are simulated for larger fans using CFD. Only single fan failure of top left as shown in fig 2.16 and middle left as shown in fig 2.17 are considered as remaining cases are identical to these two cases. Flow rate through the surrounding servers to the fans are noted. For worst case scenario i.e., for 100% CPU utilization each server needs 43.5 CFM.

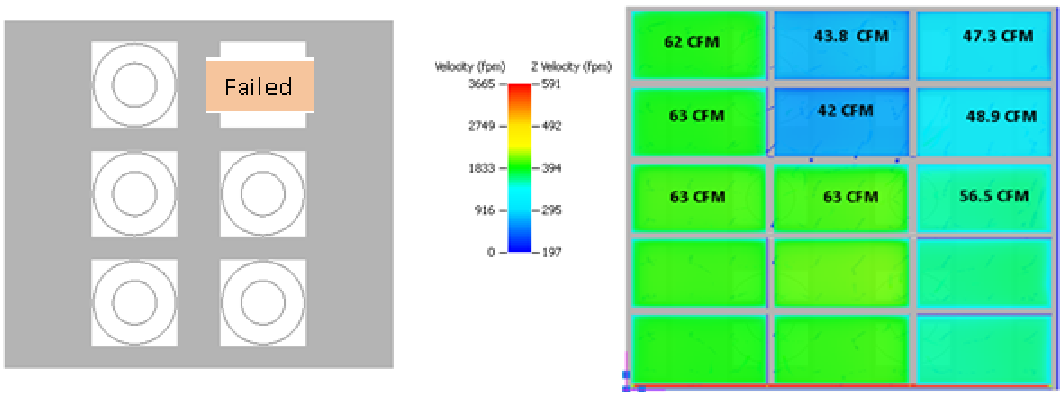


Figure 2.16. Flow distribution for fan failure scenario 1.

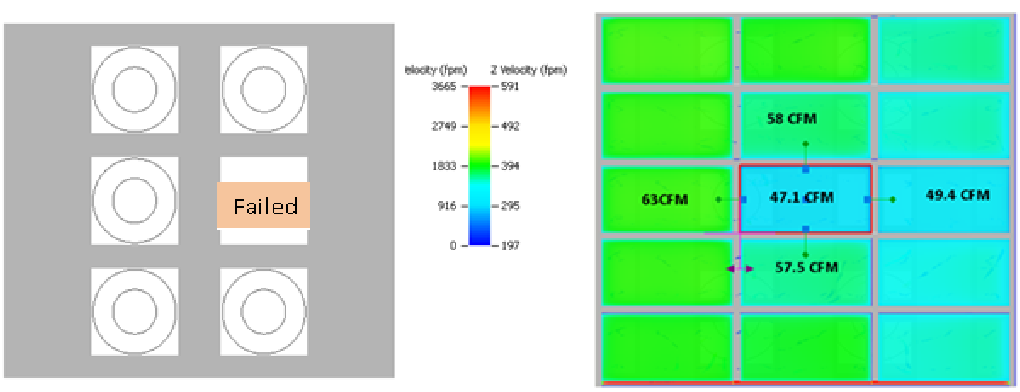


Figure 2.17. Flow distribution for fan failure scenario 2.

In first scenario i.e., failure of top left a least flow rate of 42CFM is observed only at one server as shown in fig 2.16. In second scenario as shown in fig 2.17 the flow distribution is very good. Modifying the bus bar to porous on the lateral sides may increase the flow rate in scenario 1.

CHAPTER 3

FLOW CONTROL DEVICES USING BIMETALLIC STRIPS

3.1 Introduction to flow control devices

Existing flow control device (FCD) needs a reliable actuator, a control system and a sensor to measure temperature and flow. All these parts should work precisely and reliably for long durations. These devices also take longer time to setup and repair in case of failures. The cost to setup and maintain these control systems in the long run is high. Thus we need a compact, reliable and cheap flow control device in liquid cooling for thermal managment in server. A present flow control devices is as shown in fig 3.1 [11]. These devices are of dimension 100mm*100mm for a 3 mm inlet pipe. These FCDS also needs a sensor and PWM control system. These devices cost as much as of a pump so in general we use pumps to regulate flow. Thus we need a small, reliable and active flow control device to regulate flow in these small channels.

Figure 3.1. Actuated flow control device.

Direct liquid cooling is more energy efficient for cooling current generation, high end multi-chip processors and super computers. This is also being used for cooling servers, due to their high efficiencies, reduced noise pollution and improved datacenter footprint. Though liquid cooling offers many advantages, it is costly to setup and maintain these servers. Thus we need a mini flow control devices for regulating flow to the required hot regions and replacing pumps. Mini FCD's using piezoelectric, electro mechanical, bimetallic technologies are searched for this liquid cooling application. Using bimetallic strips to regulate flow is considered for this study due to its active behavior to temperature.

3.2 Bimetallic strips

Bimetallic strips are thermostatic devices which bends on heating. These strips consist of two metals, one with very low thermal expansion on one side and higher expansion coefficient on the other. Both of these two metals are fused together showing a larger displacement than heating individual strips. Fig3.2 [12] compares the bending of the individual and bimetallic strips.

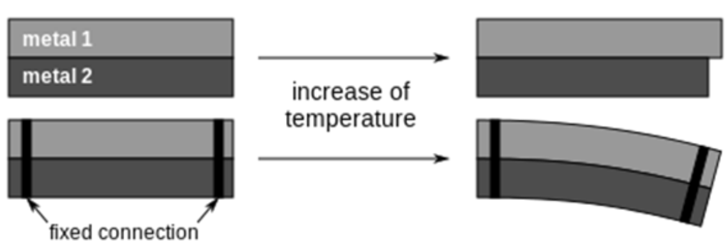


Figure 3.2. Bending of bimetallic strips on heating.

3.3 Concept

Four or more bimetallic strips can be fixed at the ends to form a closed loop as shown in below fig 3.3. As the temperature of these strips changes this device will open, thus increasing flow through the pipe. This entire device can be assembled in existing square channels with no modifications to the channels. We can also increase surface temperatures of these bimetallic strips by using surface heaters or directly passing current through these strips.

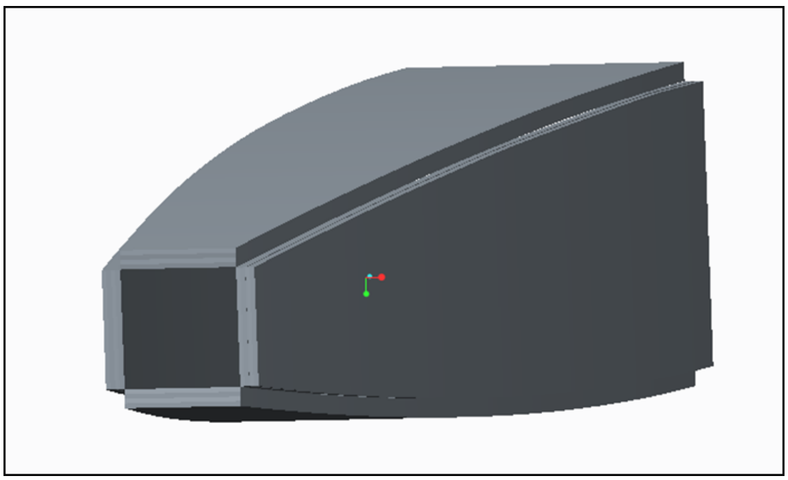


Figure 3.3. CAD Model of flow control device.

3.4 Design

Multiple preliminary designs are made out of which some of them are shown below in fig 3.4 and fig 3.5. This devices are designed in such a way that all strips are enclosed together to form a closed shape, such that this close shape sits in a channel or pipe without assembly thus reducing cost for manufacturing. As these devices are not bonded to any structure, failure of these devices is very rare, and caused only due to the failure of the bond between two layers or due to corrosion. Thus we have a high reliability, if the strips are designed properly within the total thermal and structural bending stresses not exceeding the strips bending stress.

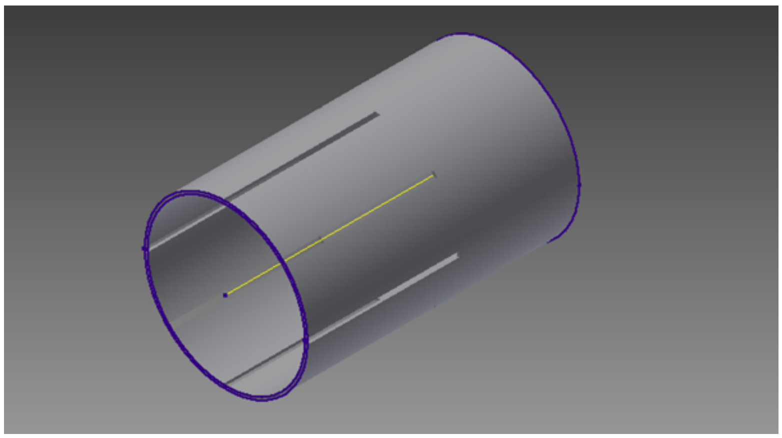


Figure 3.4. Preliminary Design 1.

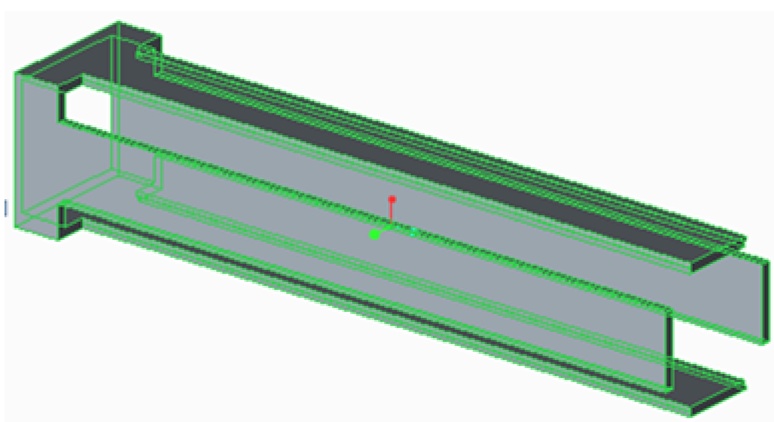


Figure 3.5. Preliminary Design 2.

The advantage of using more than one single strip is to provide more resistance to flow for a small change in temperature. Using 4 or more strips would increase the resistance of the flow control device than using two or three strips. The more resistance of the flow control device, more sensitive it is to the varying thermal loads. Thus we can actively control the strip with the varying temperatures of the device.

3.5 Deflection of bimetallic strip with change in temperature

For lengths more than 10 times of the strip width the temperature difference between reference temperature of the strip and present strip temperature is directly proportional to deflection. The analytical shown below and CFD model correlated exactly and it is as shown in fig 3.6 and fig 3.7. A Poisson ration of 0 is assumed for accurate prediction of deflection with varying temperature. Deflection is found out with varying temperatures using following two equations [13].

$$a = [A.s]/(T - T^{\circ})(L^2 + A^2)$$

$$a = 3/4(\alpha 2 - \alpha 1)$$

a = specific deflection

L =Length of the strip

s =thickness of the strip

T°= Reference Temperature

$\alpha 1$ = lower expansion coefficient of metal

$\alpha 2$ =higher expansion coefficient of metal

Specific deflection of Kanthal 230 (a) =		22.7e-6 K^-1	
Invar (α1)	1.50E-06	°C^-1	
Alloy 230 (α2)	1.78E-05	°F^-1	
Length (L)	14	mm	
Thickness (s)	0.2	mm	
Reference temp (T°)	22 °C		
Temperature Vs Deflection (A)			
Temp Difference (°C)	Analytical (mm)	Experimental (mm)	Error %
0.00E+00	0.00E+00	0.00E+00	0.00E+00
3.00E+01	1.78E-01	1.80E-01	1.33E+00
4.00E+01	4.01E-01	4.06E-01	1.32E+00
5.00E+01	6.24E-01	6.30E-01	1.02E+00
6.00E+01	8.48E-01	8.54E-01	7.49E-01

Figure 3.6. Comparison of experimental Vs analytical data.

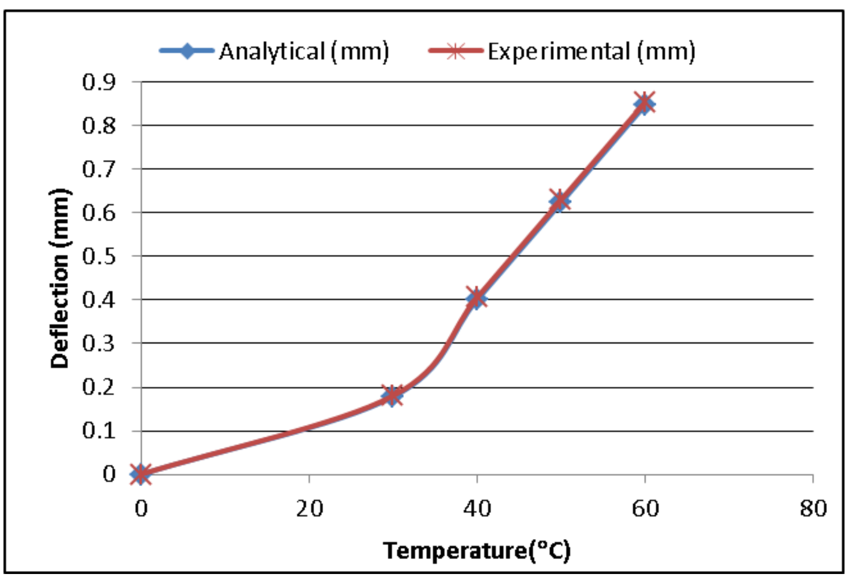


Figure 3.7. Correlation of experimental Vs analytical data.

3.6 FCD design for Dynamic cold plate

The design as shown in fig 3.8 is the final design made for 3mm channel for a dynamic cold plate. As the temperature of the chip increases, the temperature of bimetallic strips is raised by 30 Degrees to completely open the valve. This opening leads to more and more coolant out of the FCD. This saves in pumping power and cooling power of the overall data center by cooling Tj max region instead of cooling all the cold plate as currently being done. This design is verified for stresses due to fluid pressure and resistance offered by the FCD with currently available material data from the bimetallic strip manufacturer.

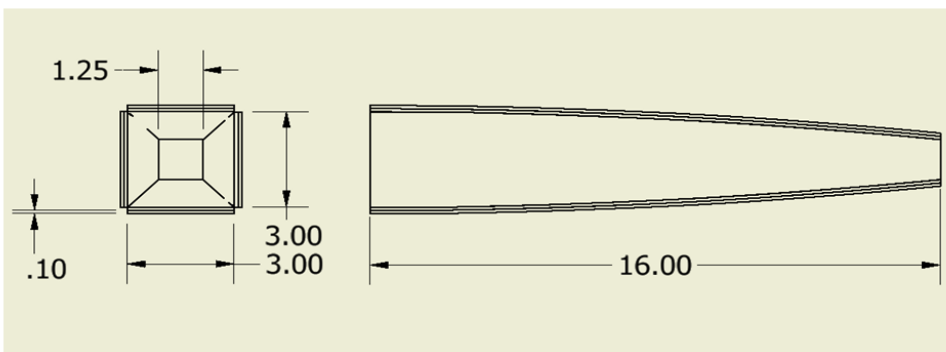


Figure 3.8. Design with Dimensions (All units are in mm).

3.7 Flow characteristics of FCD

A 3D fluid model of completely closed FCD is studied. This model is assumed to be completely closed without any leakages between the strips. And it also assumed all the wall are static. Hyper mesh is used for perfectly capturing the curve and a tetrahedron mesh elements are used. Using this model the change in resistance curve with change in opening and length can be easily studied by morphing tool in Hyper-mesh. But the motion of the strips due to fluid pressure cannot be studied.

In model fig 3.9 inlet velocity, outlet pressure and no slip boundary conditions are

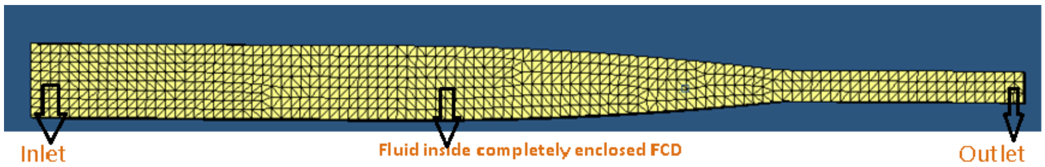


Figure 3.9. Mesh model with inlet and outlet.

used. As shown in fig 3.10 the velocities are parameterized thus giving us the resistance curve as shown in fig 3.11 automatically.

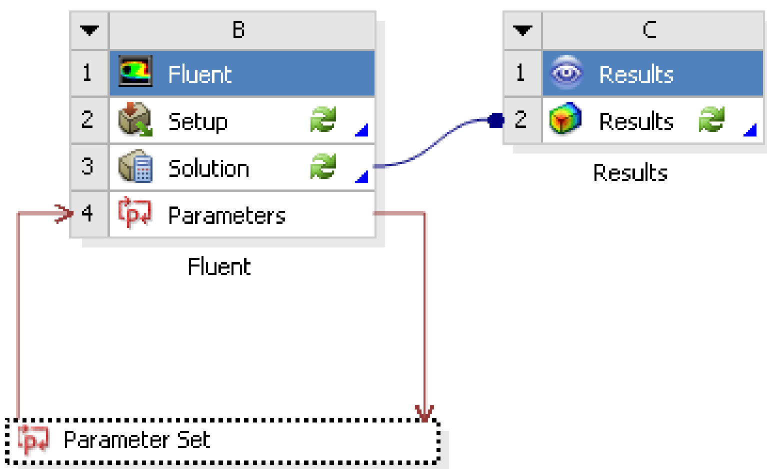


Figure 3.10. Ansys fluent with inlet velocity parameterized.

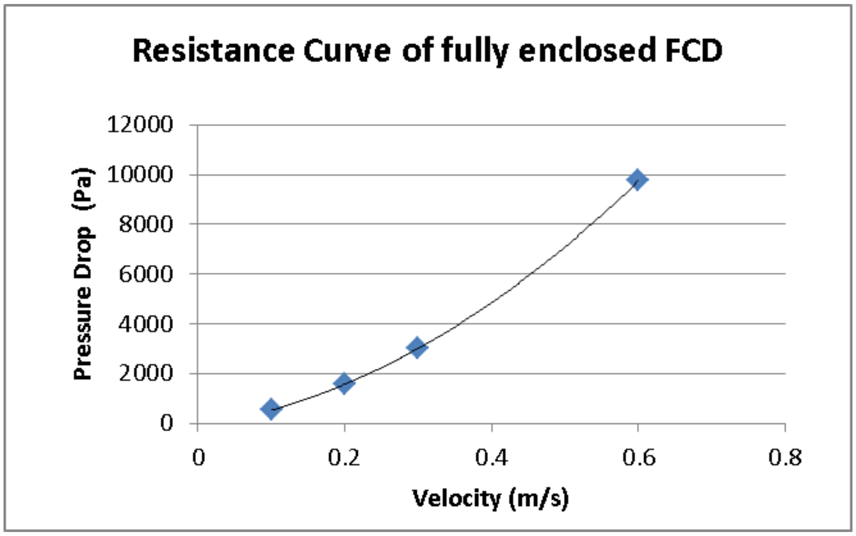


Figure 3.11. Flow characteristics of FCD.

3.8 Fluid structural interaction

The fluid structural interaction (FSI) of flow control device is studied by using Static Structural (SS) and CFX in Ansys workbench. A quarter symmetric model is considered as the model is symmetric in two axis. This model is as shown in below fig 3.12. FSI of this device is important as the deflection changes the flow through the system and vice versa. Thus CFX and SS have multiple iterations between them and gives us a steady state. A small gap is given between the two strips in this model. This is to decrease the negative volume of elements and improving the model stability.

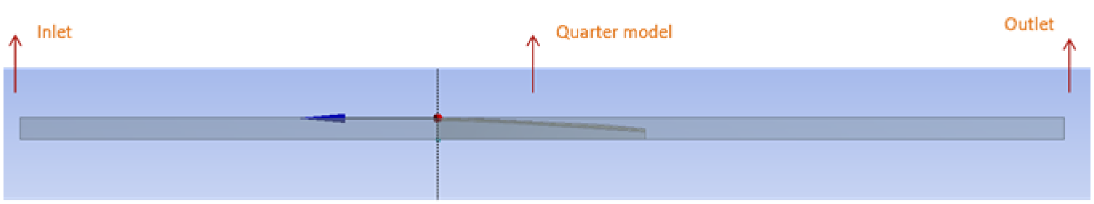


Figure 3.12. Fluid structural interaction model.

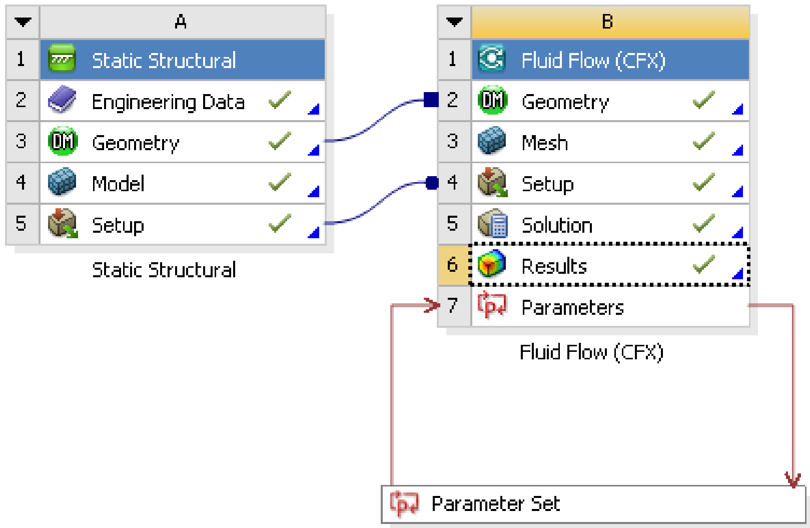


Figure 3.13. Fluid structural interaction using CFX.

As shown in table 3.1 the deflection for fluid flow rate is very low. The bending stresses on the cantilever strips is also well within the limits of 200 MPA. As there is no thermal load in this closed shape, thermal loads are not considered. The inlet velocity is parameterized as shown in fig 3.13 and similarly CAD model can also be parameterized for varying lengths and thickness of the strip.

Table 3.1. CFD and structural analysis

Flow (Liter/sec)	Flow (Kg/sec)	Disp (m)	Max stresses (pa)	Pressure drop (Pa)	Max Pressure on walls (Pa)
1.58E-03	3.95E-04	1.27E-08	2.61E+04	4.95E+01	6.22E+01
1.40E-03	3.50E-04	1.44E-08	2.28E+04	4.10E+01	5.12E+01
1.23E-03	3.08E-04	1.32E-08	1.90E+04	3.37E+01	4.33E+01
1.05E-03	2.63E-04	1.15E-08	1.51E+04	2.66E+01	3.67E+01
5.00E-04	1.25E-04	2.29E-09	4.32E+03	9.13E+00	5.78E+01
2.50E-04	6.25E-05	8.48E-10	1.02E+03	3.58E+00	7.13E+01
1.00E-04	2.50E-05	1.56E-09	2.68E+02	1.14E+00	8.01E+01

3.9 Comparison of resistance of FCD to Dynamic cold plate

Resistance by the closed FCD should be larger than the resistance of the cold plate being considered. Resistance of a dynamic cold plate is taken for an existing design. A dynamic cold plate (DCP) has 2 or more islands which are being cooled separately using pumps or FCD's. This increases the cooling efficiency of the system. The DCP considered is divided into 4 equal islands with 4 FCD's at each outlet. The flow rates are considered for cooling a 150 Watt CPU.

In the below table 3.2 and fig 3.14, pressure drop from FSI model is compared to the pressure drop offered by the 1/4 DCP for different flow rates. The resistance offered by the completely closed model in the fig 3.11 is significantly higher than partially opened FSI case in the table 3.2. Thus decreasing the gap between the two strips is causing a significant loss in pressure drop and should be decreased.

Table 3.2. Comparison of resistance curve of FCD and Cold plate

Liter/min	Flow (m/s)	Coldplate STP (Pa)	Pressure Drop of FCD (Pa)
9.48E-02	5.21E-01	6.40E+01	4.95E+01
8.40E-02	4.62E-01	5.35E+01	4.10E+01
7.38E-02	4.06E-01	4.43E+01	3.37E+01
6.30E-02	3.47E-01	3.55E+01	2.66E+01
3.00E-02	1.65E-01	1.34E+01	9.13E+00
1.50E-02	8.25E-02	5.91E+00	3.58E+00
6.00E-03	3.30E-02	2.17E+00	1.14E+00

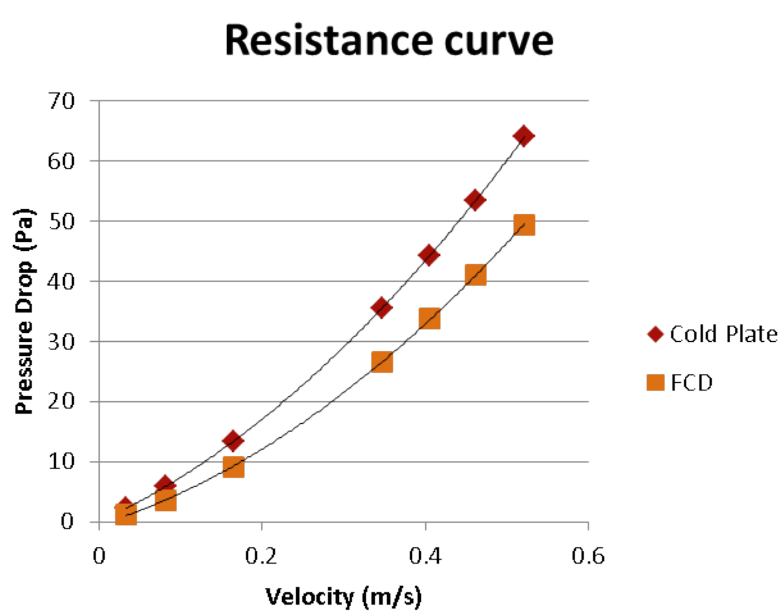


Figure 3.14. Comparision of resistance curves.

3.10 Advantages and savings

This device can save cooling energy by eliminating hotspots, thus improving the cooling efficiency. This device is more reliable compared to FCD and pumps as it has no moving parts. For an active FCD design each strip itself acts as an all in one sensor, actuator and valve. It also acts as an active controller effectively decreasing the capital costs.

For a passive FCD, flow rate can controlled by using surface heaters or by passing current through the strips also called as resistive heating. It is Easy to control this device by using a simple variable resistor than a servo system used in baseline FCD's. Comparatively these devices are cheap, easy to manufacture and assemble.

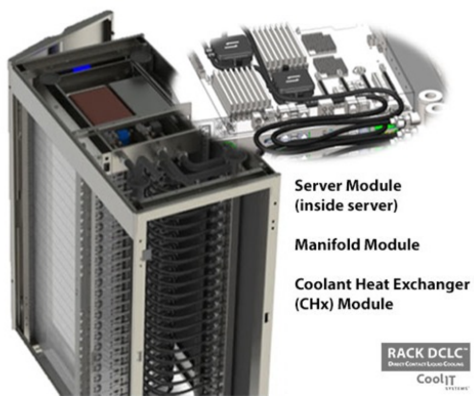


Figure 3.15. Pumps at server level.

Pumps at server level as shown in fig 3.15 [14] can be replaced with a one large rack level pump and a pressurized tank for supplying constant pressure coolant. This reduces the cost of the equipment significantly as each pumps cost $40-80, whereas these MFCD's costs $2-5 thus significantly reducing the cost of the liquid cooling system in database centers.

CHAPTER 4

CONCLUSIONS AND FUTURE WORK

4.1 Conclusion and Discussion

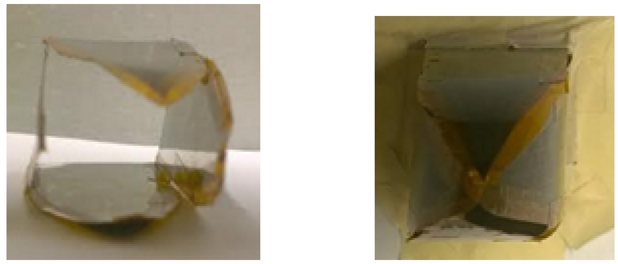
For CPU utilizations less than 60% six rack level fans are more efficient than baseline 30*80mm fans. 6*120mm fans costs less than half of 30*80mm fans.

Flow control device (FCD) is a possible solution for cooling dynamic cold plate devices. For given flow rates a very small deflection and stresses are observed in fluid structural simulation FSI simulation. Using these devices would significantly increase cooling efficiency and decrease the capital costs. Increase in length, decrease in the gap between adjacent strips, and decreasing thickness of the strip significantly affects the sensitivity of the FCD with temperature. Further optimizing the shape would give us active control.

4.2 Future Work

Experimental testing of 6 fans model can be built and the predictions can be validated. Further, single High volume low speed fans can be studied for the use at cabinet level. Individual flow through server can controlled by using FCDs for air cooling as shown in fig 4.1. These are tested on air bench and showed a very high resistance compared to the resistance of the server. This method would significantly decrease the overall cooling costs and capital cost of a database center.

Experimental validation of the model should be done. Optimization of FCDs can be studied by increasing length, decreasing thickness, and decreasing gap between adjacent strips.



Open at 20C   Closed at 24.5C

Figure 4.1. Air FCD prototype.

Other application for FCD's on fuel cells, lab on chips can be studied. Similar to liquid cooling we can use air flow control by using these bimetallic strips. A prototype is made as shown in fig 4.1 by using existing materials. It is aprroximately designed to close at room temperature i.e., 24.5 $°C$ and open at reference temperature $20°C$. These devices can be used in controlling HAVAC systems in large buildings or in database centers.

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BIOGRAPHICAL STATEMENT

Ravi Teja Mutyala was born in A.P, India in 1989. He recieved his B.E Degree in Mechanical Engineering (Mechatronics Engineering) from Mahatma Gandhi Institute of Technology, Hyderabad, India in May 2010. He qualified his Master of Science Degree In Mechanical Engineering at the University of Texas At Arlington in December 2014.

He worked as a Computer Aided Design Engineer from 2010-12. He has worked in structural analysis of home appliances and hydroelectric projects. While doing his masters he has worked in thermal management of database centers. He has also worked on various projects and came up with innovative concepts in evaporative cooling, aircooling, and liquid cooling. He worked extensively on flow control devices for liquid cooling and havac applications. He also worked on rim driven fans which are more efficient and silent and rotating cold plates for evoparative cooling. He gained lot of experience and knowledge in CFD analysis both in static and FSI models. He also gained knowledge in effcient cooling techniques of data base centers and current problems associated with them.