Development and Testing of a Control Strategy for Dynamic Cooling at Rack level in Data centers

By

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ABSTRACT

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Cooling is a critical part of data center's infrastructure, and with ongoing demands in data processing and storage, thermal management issues are of great concern. Some imperative methods of removing heat are either using air or liquid (preferably water or refrigerant). When high power density modules are involved, liquid cooling addresses some of the problems faced by air cooling as liquid coolants have higher thermal capacitance. Also, in the case of multi-chip modules, a non-uniform heating due to multicore generates hotspots and increases temperature gradients across the module. A dynamic cold plate along with a self-regulated flow control device was developed to address these issues. A temperature sensing self-regulated flow control device (FCD) is placed at the exit of each section to regulate the required flow. But to implement this at rack level, a good control strategy is required.

This study presents a CFD analysis of such control strategy to save Pumping power on a direct liquid cooled rack using a concept of dynamic cooling along with a self-regulated flow control device. It's important to save pumping power as it is one of the most energy consumed areas in the data center. The main objective of this study is to assess the flow rate and pressure distribution on the rack in order to control excessive pumping power usage and enhance cooling system efficiency.

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NOMENCLATURE

ρ Density (kg/m3)

k Thermal Conductivity (W/m-K)

v· Velocity (m/s)

μ Viscosity (N/m2S)

ε Kinematic Rate of Dissipation (m2/s3)

ṁ Mass Flow Rate (kg/sec)

Q Heat Load (KW)

P Power (W)

ϑ Volumetric Flow Rate (cfm)

p Pressure (Pa)

T Temperature (K)

Cp Specific Heat Capacity (J/kg-k)

Re Reynolds Number

l Characteristic Length (m)

FCD – Flow control device

DLC – Direct liquid cooling

MCM- multi chip module

LPM- liters per minute

DCP- Dynamic Cold plate

VFD- Variable frequency drive

TCM-Thermal conduction module

TDP-Thermal design power

CFD- Computational fluid dynamics

FDM-Finite difference method

FVM-Finite volume method

FEM-Finite element method

PUE-Power usage effectiveness

Keywords: Direct liquid cooling, Dynamic Cold plates, Flow control device, Energy efficiency, Control strategy, Pumping power savings.

CHAPTER 1

INTRODUCTION

1.1 Internet of things

There was a time when our information requirements were simpler. We had television for news, used paper for information transfer and backup, used wired phones and cell phones only for making calls. But with the emergence of the internet, high-bandwidth broadband, smartphones and all the new technologies, demand of more data on our computers, gaming systems, TVs and smartphones increased significantly. Everything got digitized. With this necessity of fast data delivery came the need for computer and networking equipment. Thus, the modern Data centers were born. [1-5]

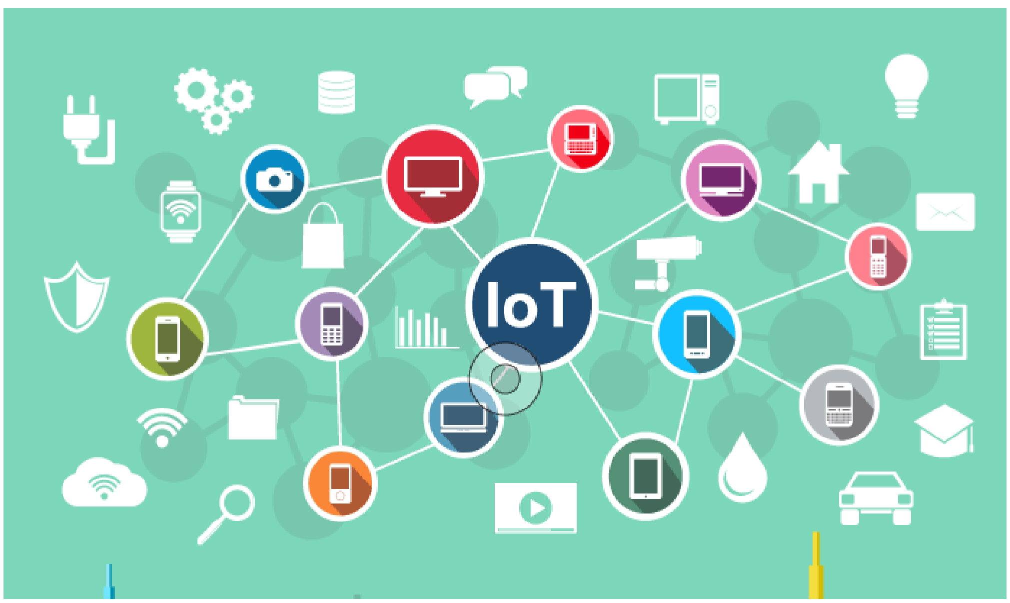


Figure 1 Internet of things

1.2 Data center

A data center is a facility composed of networked computers and storage that organizations use to organize, process, store and disseminate large amounts of data. Any company typically relies upon the applications, services, and data contained within a data center making it a crucial point and key asset for day to day operations. Due to the rapid surge in the corporate world, there is an increase in demands of processing and storage of data and with these increasing demands a corresponding increase in power density of servers is observed. Thus, because of this ever-increasing demand, data center cooling costs are constantly on the rise as they need huge amounts of energy for cooling purposes. Due to this vast energy consumption by data center facilities, operators have placed a significant emphasis on the energy efficiency of the building's overall operation. [1-5,9]

Figure 2 Facebook Data center [4]

1.3 Data center energy consumption

There has been a tremendous focus on Data center energy efficiency after about a decade of the "Report to congress on server and Data center energy efficiency" prepared by the United states Environment protection agency (EPA) in 2007.The focus resulted in stabilizing power consumption in data centers despite continuous growth in data center industry. A recent survey showed that data center electricity use in 2014 is only 4% more than that in 2010 and stayed at 1.8% of total electricity usage. [6,29-32]

According to recent statistics, data center consumed an estimated 416 terawatts of power or roughly 3 percent of all electricity generated on the planet in which Cooling itself is reported to consume 30-40% of total energy used. Despite the optimistic results for the current trends the average power usage effectiveness PUE is reported to be 1.8 a decade ago mostly due to inefficiencies in the cooling system. Several thermal management technologies are used in data centers cooling to address inefficiency challenge. [23-27]

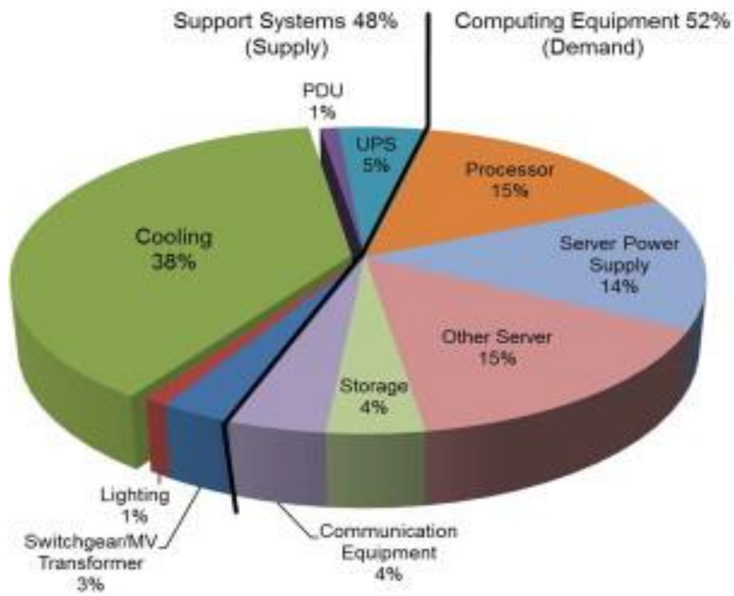


Figure 3 Power consumption in Data centers

1.4 Thermal management of data centers

Over conventional air cooling, both direct and indirect forms of liquid cooling offer numerous advantages such as higher heat capacities and lower transport energy requirements. The indirect methods of using water as a cooling medium through cold plates or rear door heat exchangers is a good example of the demonstration of the benefits of a liquid cooling strategy. Using water cooling, efficiency can be increased through the use of higher temperature fluids and possible use of waste heat for other applications. Cold plates have been a long-standing method of bringing water cooling to high powered devices as with the Thermal Conduction Module (TCM) of the late

1970s. The sources such as ASHRAE, TC(9.9) provided ample data and guidelines for implementing water-cooled data center environments. Direct liquid cooling not only increases the efficiency but also reliability of the system. Multi-chip modules that house several functional units on the same die can create hotspots due to non-uniform power distribution on the module. The large temperature gradients created across the module can negatively affect the performance and reliability of the module. Using conventional cold plates often results in over-usage of resources as the cost for cooling is directly proportional to the maximum junction temperature observed at any point across the entire module. [13,17-20]

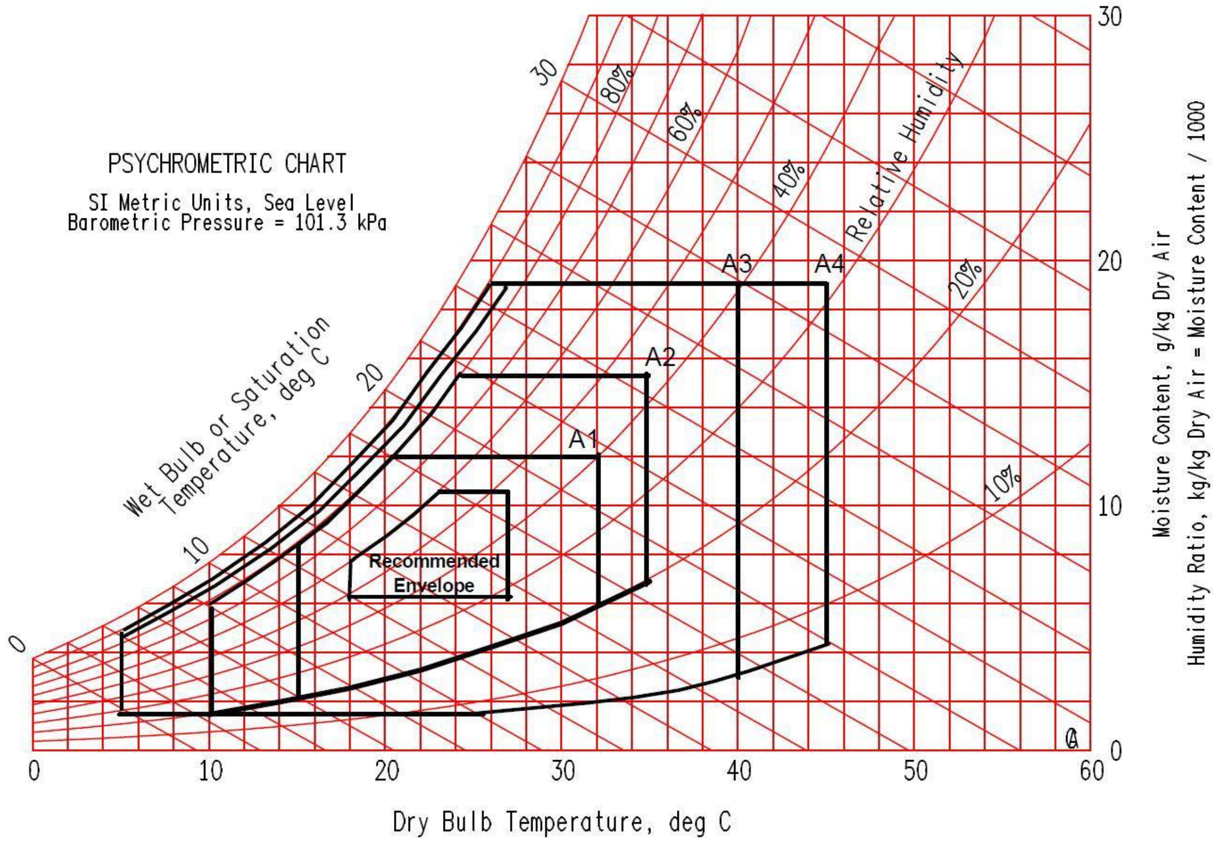


Figure 4 ASHRAE environmental classes for Data centers

1.5 Direct liquid Cooling

The notion of cooling electronic systems using liquids is not novel, however potential leaks and the capital cost have greatly restricted its application in real data centers. In direct liquid cooling technology, a liquid cooled cold plate is placed on top of a chip which reduces thermal resistance between chip junction and the cooling source providing opportunity to enhance thermal efficiency of the cooling system. The low thermal resistance path encouraged designs operate at higher cooling temperatures known as warm water cooling. Also, potential huge energy savings attracted industry develop commercial liquid cooled Data centers. [1-4,22-26]

One of the key areas in which electronic cooling research has been focusing on, is addressing the issue of non-uniform power distribution in the rack, server and even at package levels. Uneven heating at the chip level creates hotspots and temperature gradients across the module. This challenge has incited the use of numerous temperature sensing mechanisms for dynamic cooling of electronic components. A very effective way to conserve pumping power and address hotspots on the module is by target delivery of liquid coolant. One way to enable such targeted delivery of coolant is by using dynamic cold plates (DCP) coupled with temperature sensing flow control device based on temperature. [3,4]

1.6 Dynamic Cooling

What dynamic cooling effectively does is use feedback from sensors as inputs for the pumps, supplying more amounts of fluid to parts of the electronics that is warmer while supplying minimal fluid to the parts of the electronics that are relatively cooler. The necessity of numerous temperature and pressure sensors, a suitable control system and the maintenance and reliability issues that they present, can be significantly minimized with the use of a self-sensing and regulated flow control device.[1]

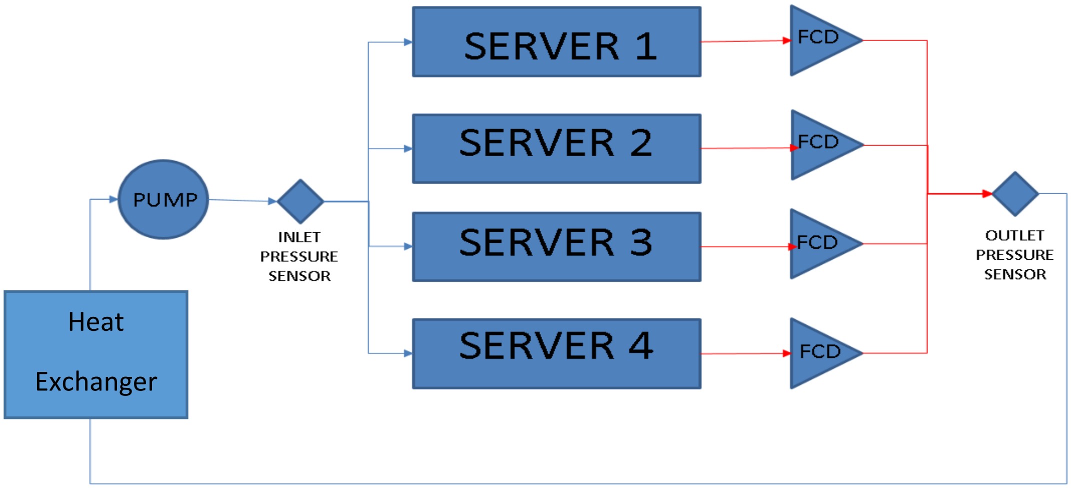


Figure 5 Schematic Representation of Dynamic cooling [1-4]

1.7 Flow Control Device (FCD)

FCD is driven by smart material Nitinol, a nickel Titanium alloy making it a passive control device and thus negating the need to be controlled externally by any power supply. Nitinol springs are characterized for a better understanding of the Nitinol behavior to achieve passive control and for minimal hysteresis. Hence found Nitinol material in the spring form is a good fit for the self-regulating flow control device minimizing the heat flux and providing efficient pumping power. The use of a heat sensitive flow control device negates the need of individual pumps thereby increasing operational reliability. [1-4]

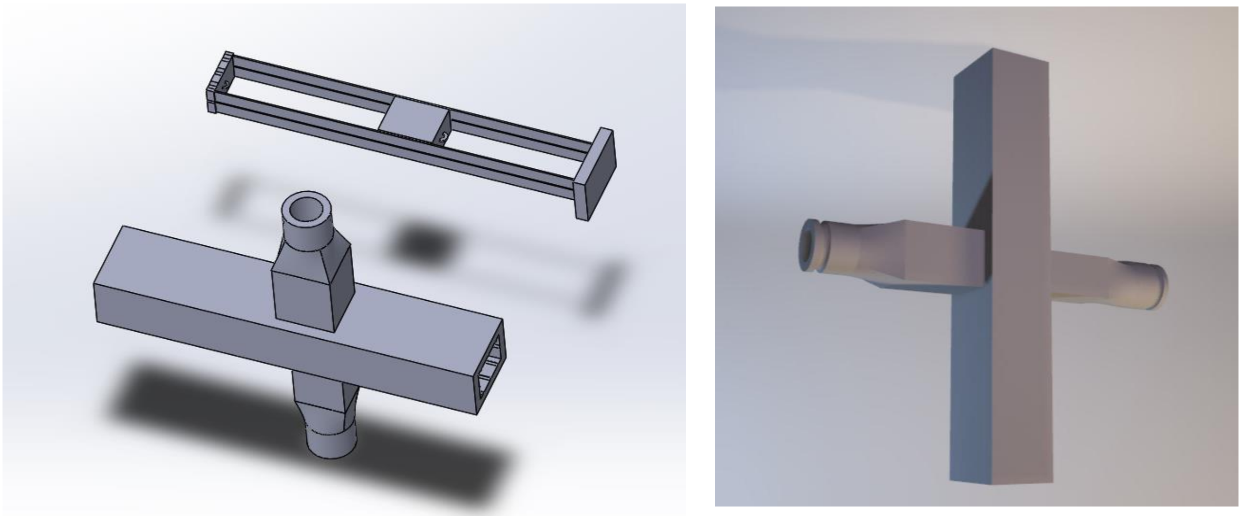


Figure 6 Flow control device [1-4]

1.8 Motivation

In a convectional data center not all the servers are utilized with same power at any given point of time. Considering the user role of a single server which is never continuous and based on the loads given to servers, an estimation can be made where 25% of the rack servers are idling and few others are running partially. We see most of the servers are not being utilized to 100 percent but lack a strategy to control the flow rate depending upon their power consumption, and hence ending up providing coolant at same flow rate even for those redundant servers. This is a scenario where energy is being wasted and can be retained.

Previous work on DCP and FCD done by Bharath and Rishi Ruben gave promising results where significant amount of pumping power saving was observed when the concept of Dynamic cooling along with Flow control Device is tested on a single server. Thus, giving an assurance control strategy plays an important role besides cold plates and FCD's. This study deals with the Computational analysis on development and testing of a control strategy implementing the above mentioned at rack level and optimization of the same to examine if dynamic cooling can obtain pumping power savings.

This chapter discussed about the basic introductory concepts of Internet of things, Data centers, direct liquid cooling, Liquid cooling over air cooling, and why is it preferred. Next chapter will talk over the basic Computational Fluid Dynamics (CFD).

CHAPTER 2.

COMPUTATIONAL FLUID DYNAMICS (CFD)

2.1 Introduction

Computational fluid dynamics (CFD) is the numerical simulation of fluid flow. Fluid flow can be wind, air pollution or contaminants, heating, ventilation and air conditioning, complex flow in furnaces, heat exchangers, blood flow and breathing of human body so on and so forth. Computational fluid dynamics provides qualitative and quantitative prediction of fluid flow by means of mathematical modeling (partial differential equations), numerical methods (discretization and solution techniques), and software tools (solvers, pre- and post-processing utilities). CFD enables engineers to perform numerical experiments (i.e. Computer simulations) in a virtual flow laboratory. The out coming of the CFD simulations can be used to analyze and optimize the design process and products. Computer processors are used for performing required calculations to simulate the fluid interactions with surfaces based on the boundary conditions. These days, data centers also use CFD to simulate air and liquid flow, temperature, pressure and other variables throughout the calculation domain. [1-5,21-23]

CFD gives an insight into highly detailed flow patterns that are difficult, expensive or not possible to study using experimental techniques. It is a link between pure theory and pure experiment. CFD works by discretizing forms of partial differential equations (PDEs) for fluid flow and heat transfer and gives approximate solutions of the governing equations at predetermined number of points that are specified by a grid of elements (Mesh) formed within a geometric boundary. Compared to conducting experiment, CFD provides faster results and does parallel simulations to solve different problem scenario. Thus, it is very less expensive for every change made to optimize the design.

CFD tools offers various features like designing, mesh generating, fluid flow animations, pre-installed libraries of material data with all the properties and several others. [1-5,21-23]

2.2 Governing Equations

The equations that govern the motion of a Newtonian fluid is the continuity equation The Navier-stokes equations are the base of computational fluid dynamics codes. The numerical solutions of fluid dynamics problems are obtained by solving series of three differential equations, the mass equation, the momentum equation and the energy equation. The set of equations listed below represents seven equations that are to be satisfied by seven unknowns. 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. The generalized form of these equations is given by [23-25]

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

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

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

2.3 Global Computational Domain

In general flow field, when considering a closed volume inside a finite region of flow defined as control volume solves the governing equations for mass momentum and energy. The control volume may be fixed or moving along with the fluid in space. For most computational problems the external ambient temperature, velocity, pressure, mass flow at inlet and outlet, fluid viscosity, thermal conductivity, specific heat and other environmental conditions are included in boundary conditions. Boundary conditions depends on the type of heat transfer such as conduction or convection and any radiation factors those make an impact on the model. By fixing the boundary conditions the solution of those governing equations are obtained and in addition the computational domain wall needs to be specified if they are open, closed (adiabatic) or symmetrical in nature.

CFD analysis process includes steps such as Problem statement, mathematical model, mesh generations, space discretization, time discretization, iterative solver, CFD software, simulations run, post processing and verification. Discretization in CFD process is important as it converts differential equations into algebraic equations. Depending on the discretization method, the governing equations as expressed in integral or differential form. The three main methods of discretization are finite difference method (FDM), the finite volume method (FVM) and finite element method (FEM). The FVM and FEM are integral schemes, while FDM is differential scheme and is based on Taylor series expansion. The FVM solves a problem by dividing it into small volume and integrate around the mesh elements. In the FDM method the differential terms are discretized into series of small grid points. [30-32]

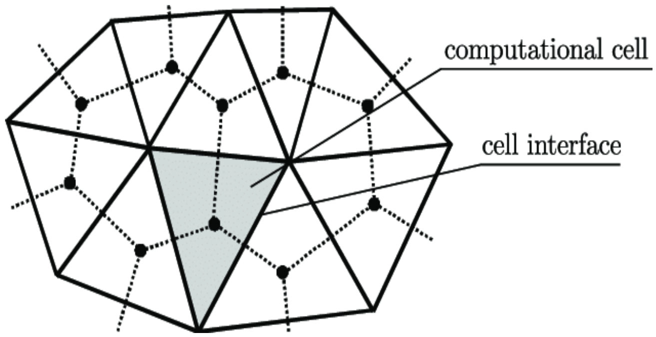


Figure 7 FVM Discretization

The present problem is solved by using CFD model based on finite volume method, using the future facility's 6sigmaET software. Thus the governing equations are solved by integrating over control volume and applying divergence theorem. The variable to be calculated are located at the centroid of the finite volume. FVM is locally conservative as it is based on balance approach.

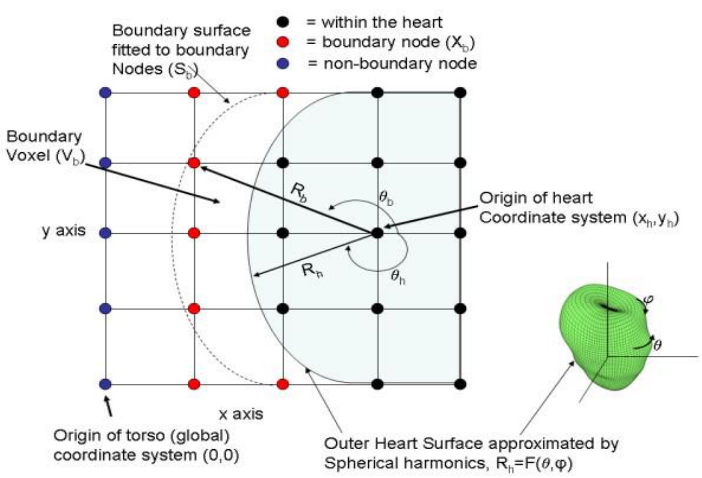


Figure 7 Graphical representation of 2D grid

2.4 Turbulence Modeling

All flow become unstable and random in every direction above certain Reynolds number. The velocity and all other properties of flow vary in a random and chaotic way,This regime is called turbulent flow. When the Reynolds number of a fluid flow gets above critical Reynolds number

Re_{crit}, the flow becomes turbulent and the fluid flow of a Reynolds number below Re_{crit} is considered to be laminar flow.[27,28]

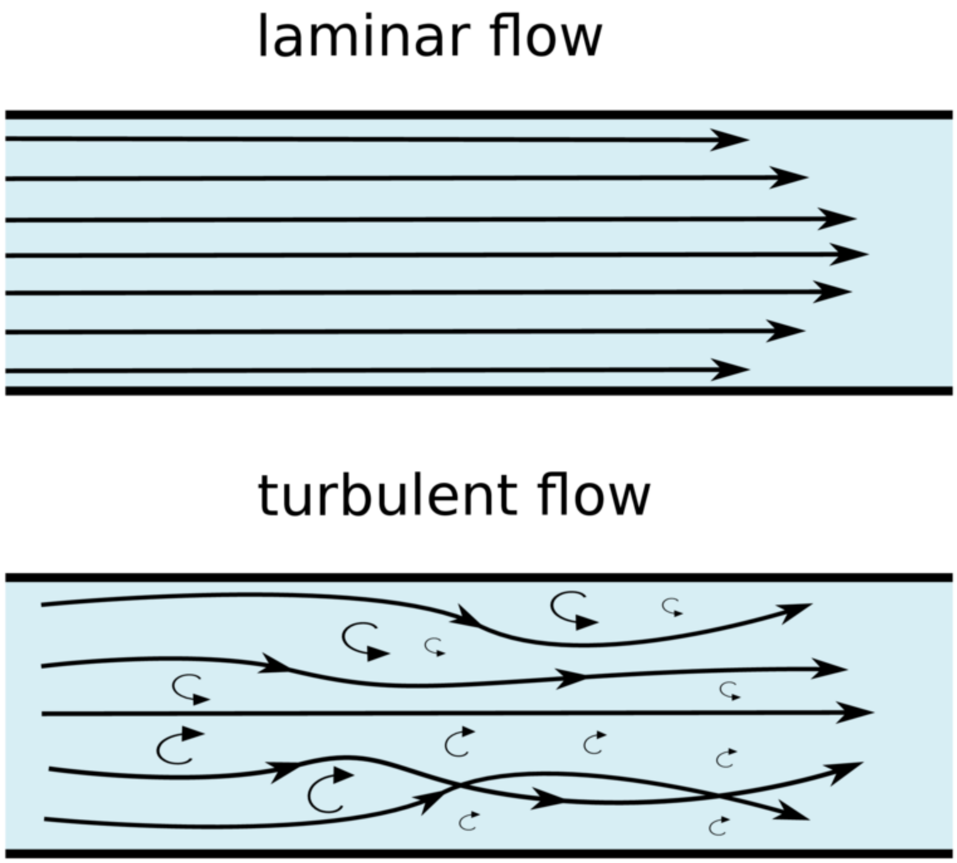


Figure 8 Laminar and Turbulent Flows [5]

2.5 K-Epsilon Turbulence Model

K-epsilon model is a two-equation and the most common model used in CFD to simulate characteristics of turbulent flow as it represents the turbulent properties of the flow. The first transport variable is turbulent kinetic energy and other one is turbulent dissipation. The variable of turbulent dissipation determines the scale of the turbulence whereas the variable of turbulent kinetic energy determines the energy. The following are the transport equation of K-Epsilon model. [5]

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

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

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

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

2.6 Grid constraints and Meshing

In 6sigmaET grid constraints are used for specifying limits of maximum number of cells across the geometry. It uses Cartesian grid and object-based gridding, which means it has predefined grid control settings for specific objects such as PCB, chassis, heatsinks, cold plates, chip socket, capacitors, power supply unit, vents, fans, hard drives etc. [5,7]

2.7 Objects in 6sigmaET

As mentioned above 6sigma has pre-defined objects used in electronics industry. The entities are parametrically defined with their characteristics and function. This feature of 6sigmaET helps building and analyzing the model with ease. Although it includes aforementioned objects instead of solid blocks for representing, can be modified based on our requirements.

2.7.1 Test chamber

A test chamber is a virtual wind tunnel where you can set up your model and apply fluid flow within it in several ways. It works as an environment in 6sigmaET. The walls of the test chamber can be defined as open or any specific environment like constant fluid flow. It can also be disabled or uninstalled if not required.

2.7.2 Chassis

A chassis is the default solution domain in 6sigmaET. All objects get placed inside a chassis unless a test chamber is used. If the physical structure of the chassis is not required, the sides can be uninstalled. Modification can be done with the parameters of the chassis such as material, thickness, dimensions etc. The Objects directly attached to chassis are organized under chassis node.

2.7.3 Chassis objects

• Cooling - Fans, blowers and heatsinks

• Electronics - All hard disk drives and bays, PCBs and the components mounted on them (including all their associated hardware)

•Fluid Cooling - Includes internal ducting for fluid cooling system and pumps

• Obstructions - Used for modeling non heat producing items such as internal ironmongery, DIP switches and any heat creating items such as transformers and large inductors

• Power – includes simple power supplies and their attached fans

• Sensors – Consists of only the sensors that are attached to chassis. Sensors can be attached anywhere inside the test chamber and chassis for pressure, temperature, velocity, density etc.

2.7.4 PCB

Printed circuit board (PCB) is combinations of layers of copper and non-conductive materials. It consists of several conductive paths to transfer data leaving other area non-conductive. The components are mounted on PCB and are connected through copper paths.

2.7.5 Cooling Duct

Ducts are used for cooling the electronics equipment by providing fluid flow throughout them.

2.7.6 Heatsink

Heatsinks are passive heat exchangers that are used to transfer heat away from the electronic component into fluid medium (air or liquid). They are mounted onto the heat generative components such as CPU and GPU.

2.7.7 PAC

In 6sigmaET PAC stands for Parameterize, Analyze, and Compare. PAC is used for performing parametric analysis for alternative cases. It practically allows us to change the variables for different cases and can solve multiple cases parallelly. It reduces the time to compare the different cases by giving results in a tabulated format. In this study PAC is used to obtain mesh sensitivity analysis, optimization of cold plate, system resistance and thermal resistance of the system.[10-13,15]

CHAPTER-3

CFD Setup & Procedures

3.1 Detailed test setup

To test the developed control strategy a rack was replicated in 6sigmaET. The pipe network is build using an inbuilt duct feature. Cold plate is made with the help of heat sink and ducts, dampers are added at the exit of every server along with a temperature sensor to recreate FCD functionality and the exact experimental data is given as input through MATLAB integrating it with 6sigma.

Temperature, pressure and flow sensors are incorporated for every segment in the model to monitor flow at required points of interest. An inlet manifold is made with constant pressure boundary condition. All the cold plates are connected to the inlet manifold to which a flow rate sensor is installed to find the inlet flow rate of the water. Two pressure sensors are installed to study pressure difference across every cold plate. The raise in outlet temperature of the fluid decides the % of FCD opening accordingly. Here, temperature sensor is installed at the damper and connected to it using inbuilt direct controls in ET. This sensor and damper combination represent the functionality of the self-regulating FCD. Power at the module will be varied to look at the control system functionality. Along with this pressure boundary condition is also changed. [15,16]

A rack level system with direct liquid cooling (DLC) uses water to carry the heat away from the cold plates. A properly designed cold plate thus not only have high heat transfer performance but also minimal pressure drops across itself, as higher pressure drops results in a penalty to the pumping power.

3.2 6SigmaET

A model with 4 servers is developed to replicate rack of a Data center. A pump for which PWM is changed to save pumping power based on the pressure drop of the system is attached from the Multi-fluid feature of the software. Various cooling ducts are developed to drive the flow, where these ducts act as pipes that carries coolant to cold plates. To mimic a Server, a component is created which is provided with the power and Cold plate is developed using Heatsink feature. The green board is a Printed circuit board (PCB) object in ET. [14,27]

Dampers are placed at the exit of every server which resist the fluid path acting as FCD allowing the minimal amount of fluid to flow through it. Since the dampers which are acting as FCD's are self-regulating and temperature driven temperature sensors are placed at exit of every server along with them. Pressure sensors are placed at main inlet and outlet to determine the whole system pressure and also a bypass loop is created to maintain the system at any pressure loss conditions.[28]

3.3 Integration of MATLAB with 6SigmaET

MATLAB is integrated with 6SigmaET to customize the controls of the damper according to the FCD functionality. A code is developed using experimental data of FCD and is incorporated to dampers as input through controllers thus rendering the damper to perform as an FCD

The controller will change the opening area of the damper based on the values given by MATLAB to regulate the flow rate. Dead band width is set as 0.1 to have high accuracy. Every iteration will report the temperature values to MATLAB and the output from the code is used by the solver as new inputs. These inputs will let the dampers in the model know what exact % of opening with which FCD reacts at that point w.r.t the temperature of exit fluids of the server. All the MATLAB integrations are taken from 6Sigma user manual.[14]

The figure shows the model in 6SigmaET. The blue tubes are duct objects. A pump is attached at the inlet to supply the required flow rate.

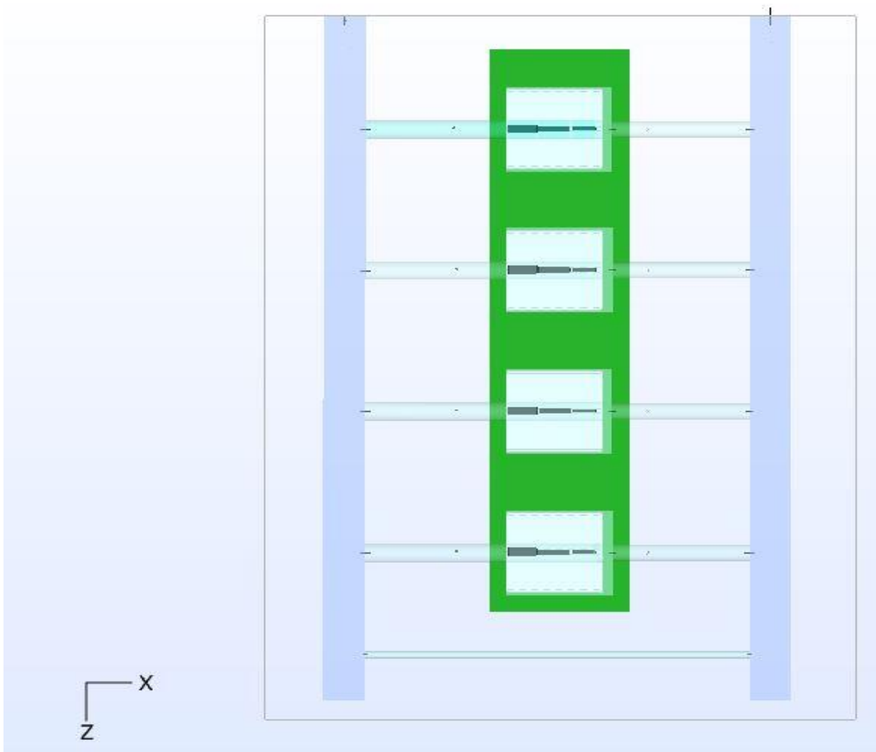


Figure 9 6 Sigma Model

3.4 Cold plate

Cold plates are heat transfer devices that uses liquid flow to cool microprocessor chips. In this case it's used to cool 4 Components. Although all three types, the serpentine channel, the parallel channel and the impingement channeled cold plates were considered for this study, overall efficiency was higher for Impingement type which impinge cooling fluid into the fins in the form of small jets. Water was selected as coolant and thus it passes through the fins of the cold plate and carry out heat from the components. Graphical design and characterization is shown in the following figure.[8-10]

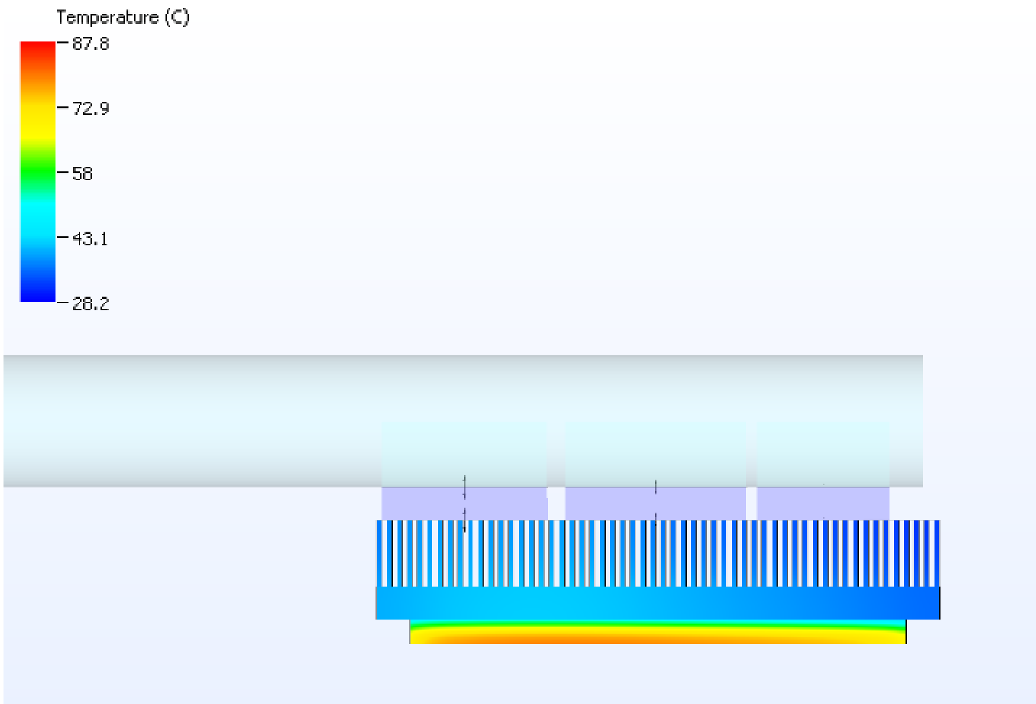


Figure 10 Impingement channeled cold plate (Front view)

3.5 Modeling and characterization of cold plate

This study uses liquid cold plate to cool the components. Cold plates are heat transfer devices that uses liquid flow to cool the microprocessors chips. In this case 4 cold plates were used to cool 4 servers connected parallelly .The cold plate used for the server is jet flow impingement type, which impinge the cooling fluid into the fins, where small jets of high velocity fluid is made to strike a target surface. Water was selected as cooling fluid. The cooling fluid then passes through the fins of the cold plate and carry the heat out of the component. The graphical design and characterization of cold plate is shown below. [2,5]

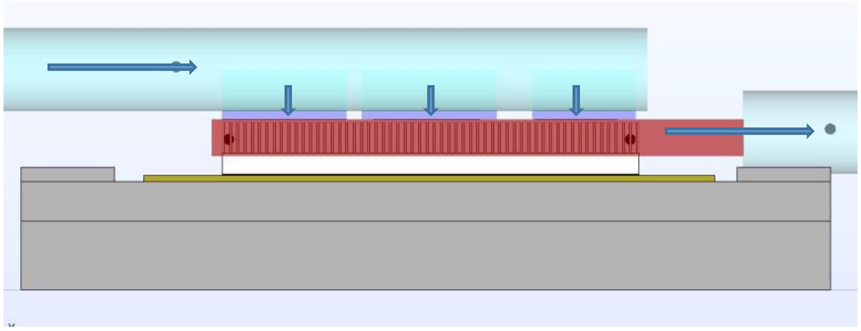


Figure 11 Cold plate indicating direction of flow [5]

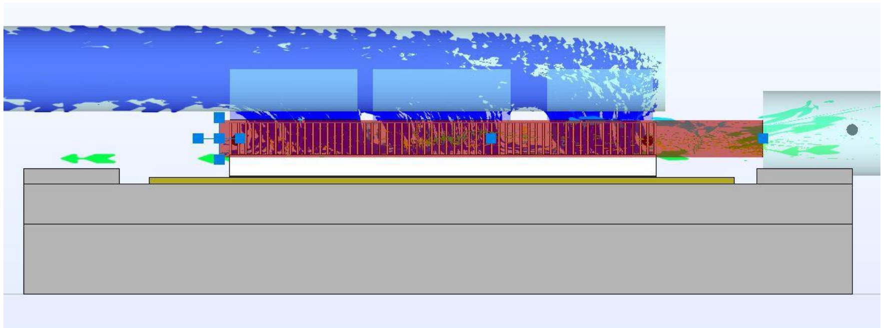


Figure 12 Cold Plate side view [5]

3.6 Cold Plate Characterization

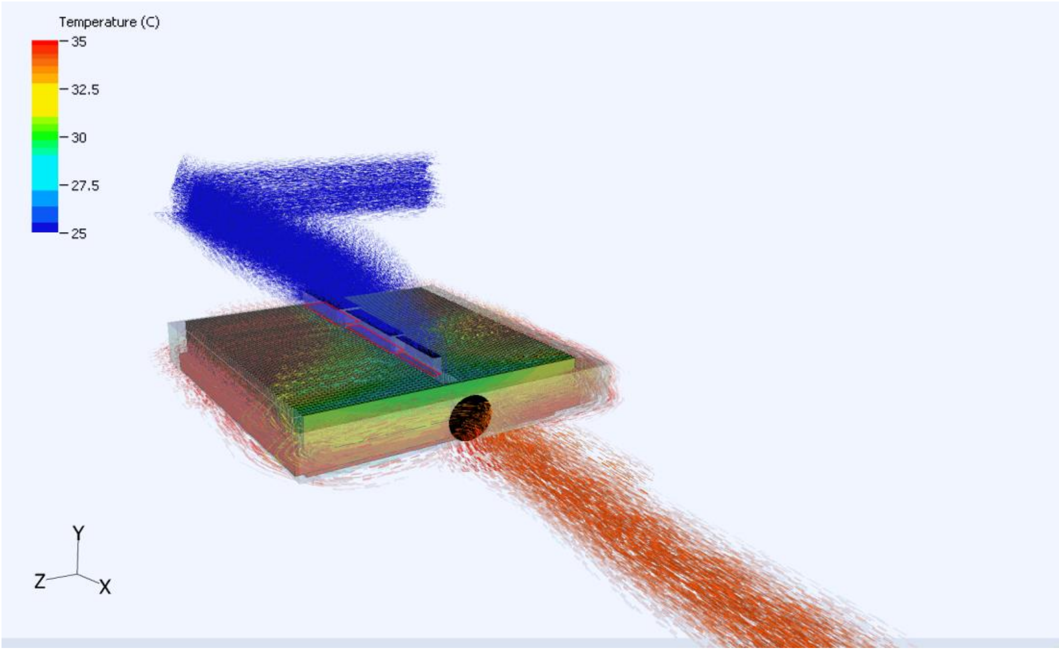


Figure 13 Impingement channeled cold plate (Isometric View)

The fig shows side/isometric view of the cold plate. Coolant is at room temperature i.e., at 25°C coming from the pump supply passes through 3 ducts through which it is being impinged on to the cold plate. These 3 ducts are maintained in such a way that the pressure and liquid distribution of fluid remain almost equivalent throughout the cold plate. The cold plates are given with paths perpendicular to the fins which carry the fluid to outlet to return pipe. This particular cold plate is designed for cooling high power chip with TDP up to 500 watts. [5,17-21]

Power W	**Fin thickness mm**	**Number of fins**	**Fin separation mm**	**Flow rate L/min**	**Supply temperature °C**	**Component temp °C**	**Pressure Difference pa**	**Temp difference °C**
500	0.1	101	0.3004	1	15	52.81	1035.9	7.92
500	0.1	51	0.7008	1	15	58.95	919.81	7.32
500	0.1	37	1.0122	1	15	64.22	1114.8	7.45
500	0.3	67	0.3036	1	15	52.32	997.18	7.26
500	0.3	40	0.7215	1	15	61.14	945.4	7.29
500	0.3	31	1.028	1	15	62.8	1059.4	7.3
500	0.5	50	0.309	1	15	53.32	1057.51	7.26
500	0.5	34	0.7012	1	15	62.33	933.2	7.29

Table 1 Characterization by fin separation and fin thickness [5]

The characterization by fin thickness and fin separation is shown in table. Fin thickness is chosen as 0.1, 0.3 and 0.5 mm and separation of fins chosen are 0.3, 0.7 and 1 mm the flow rate of fluid is 1 L/min, height of the fins, for this stage was 3 mm default. The supply temperature of the water was 15℃. The TDP of the chip was 500Watts. As we can see from the results that two cases of fin geometry are highlighted. These two cases have relatively low component (chip) temperature. Pressure difference shown is between inlet and outlet of the cold plate which contributes in pumping power. The temperature difference between inlet to outlet remained similar for almost all the cases. Temperature difference of 7.92℃ means that there is an increase of 7.92℃ in the fluid temperature compared to inlet temperature.

Now case of fin thickness 0.1 and fin thickness 0.3 with component temperature 52.81℃ and 52.32℃ are to be characterized further by using different fin height.

Fin height mm	**Fin thickness mm**	**Number of fins**	**Component temperature ℃**	**Pressure Difference Pa**	**Temperature difference ℃**	**Return temperature ℃**
3	0.1	101	52.81	919.81	7.26	22.26
4	0.1	101	52.3	964	7.3	22.3
5	0.1	101	58.8	816.4	7.3	22.3
3	0.3	67	52.32	997.18	7.92	22.92
4	0.3	67	51.4	914.5	7.3	22.3
5	0.3	67	54.3	788.4	7.4	22.4

Table 2 Characterization by fin separation [5]

As it can be seen from the obtained results from table that when the fin height is 4 mm, fin thickness is 0.3 mm and number of fins is 67 mm we get the best possible temperature for the GPU (component). Which is 51.4℃. The cold plate with this geometry is used for simulations.

Cold plates are characterized for its fin height, thickness and separation and designs for their optimum values. These optimized cold plates are now placed on the components of the control model to carry out further study. [4,20,33]

3.7 Six sigma simulation

6sigmaEt allows single phase liquid cooling. It has features to provide fluid control system through user interface.

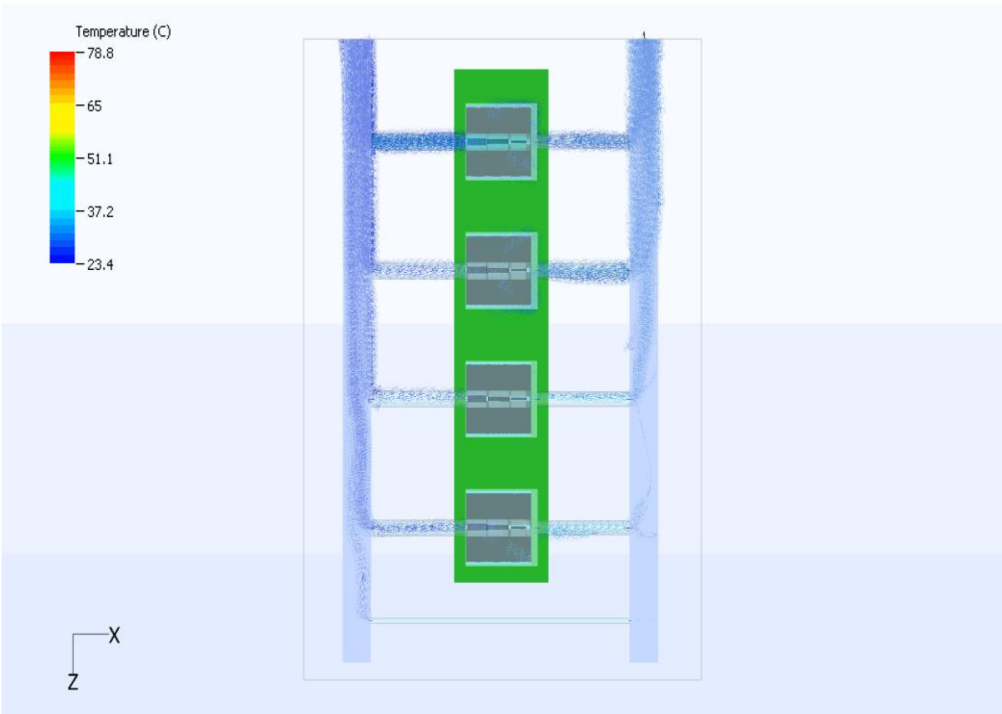


Figure 14 Six sigma Simulation

This is how a typical running simulation in 6 sigma looks like. In further chapters let's go through the control strategy adapted and how is it implemented to carry out our study

CHAPTER 4

CONTROL STRATEGY & MATLAB Integration

4.1 System Description

A control strategy is developed to test the concept of dynamic cooling at rack level in a data center. Temperature, pressure and flow sensors are incorporated for every segment in the model to monitor flow at required points of interest. The pipe network is build using duct feature in 6SigmaET. An inlet manifold is made with constant pressure boundary condition. All the cold plates are connected to the inlet manifold to which a flow rate sensor is installed to find the inlet flow rate of the water. Two pressure sensors are installed to study pressure difference across the cold plate. The raise in outlet temperature of the fluid decides the % of FCD opening accordingly. Here, temperature sensor is installed along with the damper and connected to it using inbuilt direct controls in ET. This sensor and damper combination represent the functionality of the self-regulating FCD. Power at the module will be varied to look at the control system functionality. Along with this pressure boundary condition is also changed.

Control strategy tested is a constant pressure with variable frequency drive pump. This type of pumps will save energy by reducing the electricity consumption. The pressure difference across the system will be taken into MATLAB and processed based on the set value. The set value is dependent on the system

4.2 Control Strategy

Control strategy was developed in 6sigmaEt using the ducting feature. It is very difficult to mimic the model with the actual components in CFD and hence 6 sigma tools were used to replicate the model. In this model several major flow restricting and heat generating components are chosen.

Components considered for modeling are a pump, 4 processors and 4 Dampers which replicate the actual working of an FCD, 4 heat sinks replicated to act as cold plates as this control strategy was developed for liquid cooling purposes.

For this to be executed further, a control strategy is required. To have a good energy saving model control strategy plays important role besides DCP's and FCD's.

Hence the urge of developing a control strategy lead to a prominent path where pumping power savings using FCD and a DCP is attained.

- Pressure based control
- Temperature and pressure-based control

4.2.1. Pressure based control

In this control pressure across the system is monitored. Inlet supply temperatures are maintained constant varying loads on the servers due to which there will be pressure difference created in the whole system. But since the pressure difference across the system is urged to be maintained constant, the system tries to attain the constant pressure input varying the flow rate. The flow distribution between the cold plates will be taken care by self-regulating FCD's.

Pressure sensors will be used to monitor the overall pressure drop of the system and will be controlling the pump based on the utilization of the rack. The heat exchanger can or cannot be included in the system

We are monitoring pressure with the help of pressure sensors placed at inlet and outlet which are used to control the pump reducing its pumping power and helps in reducing maximum junction temperature clearing out hotspots.

4.2.2. Temperature monitored flow

In this type of system, a constant heat extraction heat exchanger is used, such as liquid to liquid heat exchanger. Here, both pressure drop across the system and outlet temperature are monitored giving the system enough flow rate at respective temperatures. Weights will be given to Temperature and pressure drop as the heat exchanger is also in the system loop.

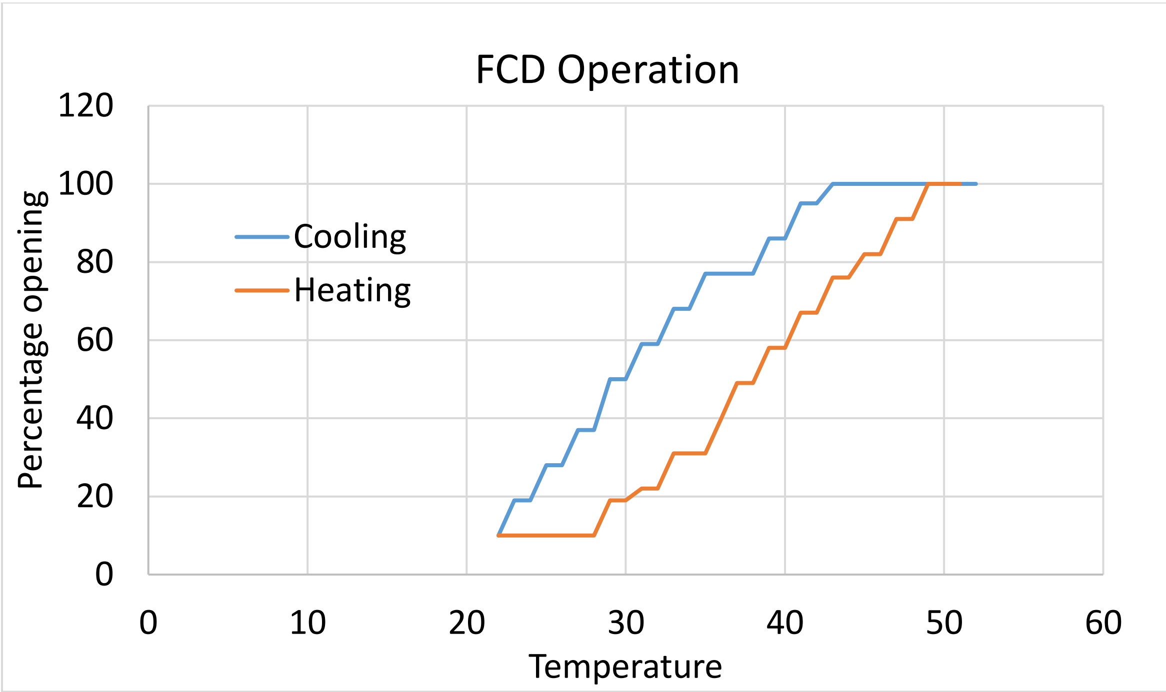
The same principle can be applied at the cold plate level in which we have a multi-chip scale module where the cold plate can be divided into sections based on the design and requirement and this section can be attached with miniaturized FCD which acts in similar manner.

With this concept we can prioritize higher utilized servers which in return reduce pumping power and increase chiller efficiency.

4.3 MATLAB Integration

MATLAB is integrated with 6SigmaET to customize the two control strategies through which system is being controlled. For the Pressure Based Control, depending upon the pressure difference created in the system based on different loads, controller varies the PWM of the pump to attain the constant pressure input given to it. Dead Band width is set as 10 to have high accuracy.

For the Pressure and Temperature based control, the controller will change the opening area of the damper to regulate the flow rate. These Damper openings follow a hysteresis curve drawn from the experimental results of the FCD. Dead Band width is set as 0.1 to have high accuracy.



Graph 1 FCD Hysteresis curve via MATLAB

Every iteration will report the temperature values to MATLAB and the output from the code is used by the solver as new inputs. All the MATLAB integrations are taken from 6Sigma user manual.

Cold plates are used to cool various temperatures with 1insq. area. This component will be maintained at designed range of temperatures. Component temperature is not reported as it is proportional to the flow rate and temperature rise of the coolant.

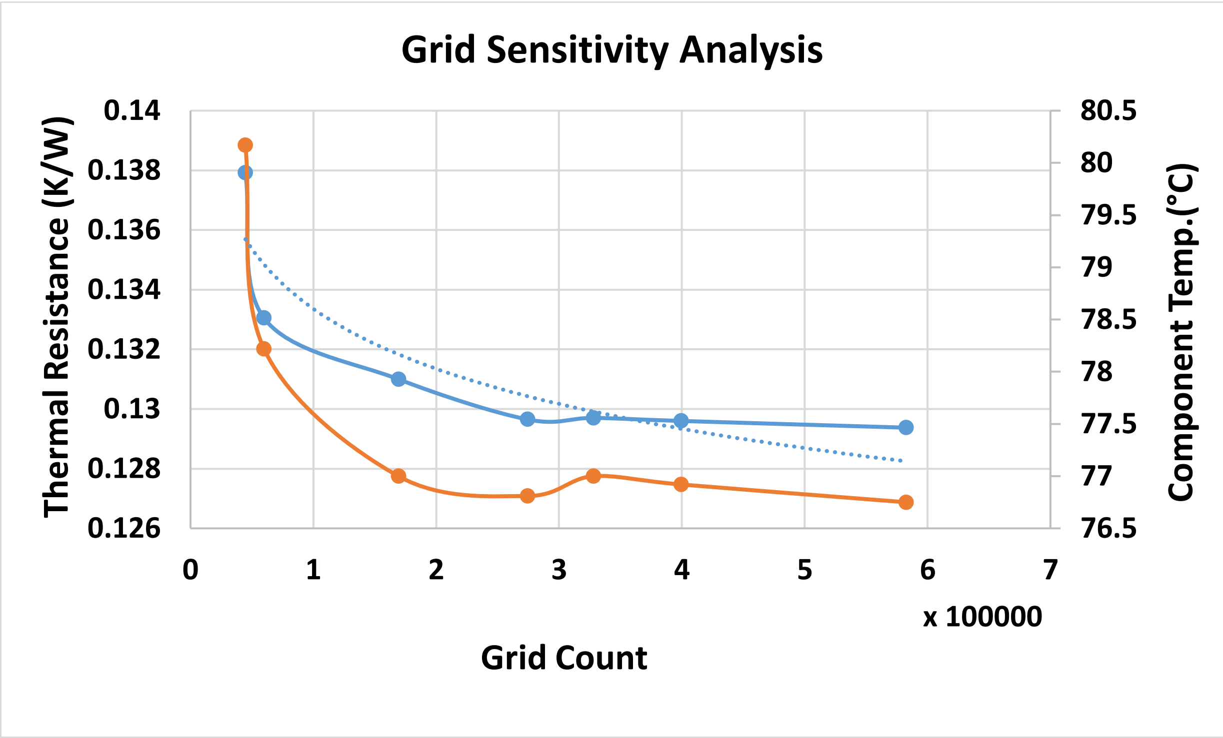
The coolant considered in the study is water. Initial flow rate of water is set based on the initial power given per each component.

Control strategy tested is a constant pressure with variable frequency drive pump. This type of pumps will save energy by reducing the electricity consumption. The set value is dependent on the system and varies from system to system.

4.4 Mesh Sensitivity Analysis

To make a heatsink 6sigmaET requires thermal resistance curve data which is thermal resistance obtained vs flow rate of the coolant. And thermal resistance is a ratio of temperature difference between inlet and outlet of chamber vs total power supplied which is 400 watts.

A grid analysis is carried out at different level to look at the grid sensitivity. 6SigmaET has the capability of adopting the grid based on the model. A local gridding feature in the software is used to create enough grid to capture the heat transport. This model uses around 2 million grid for all the simulations.



Graph 2 Grid sensitivity analysis

4.5 Model for testing controls

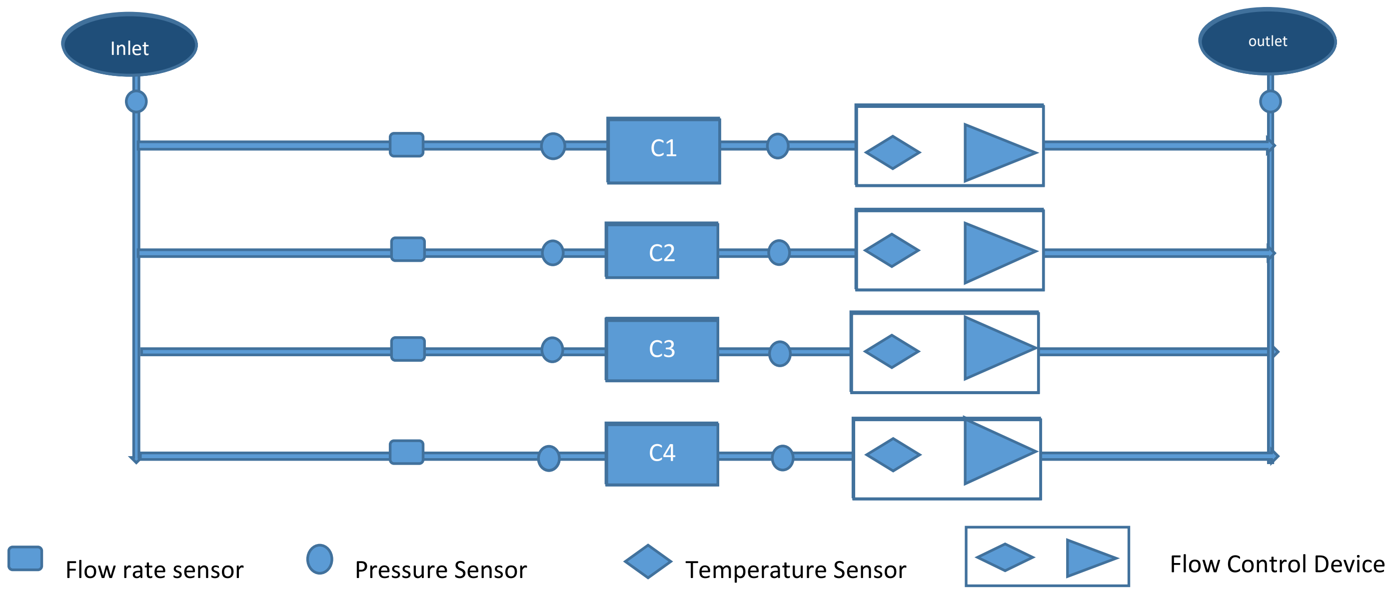


Figure 4-1 schematic representing controls

The schematics shows 4 cold plates connected in parallel representing the cold plate sections. Damper is attached at the outlet of the cold plate which will regulate the flow rate based on the temperature. The pressure sensors at each are just to monitor the pressure drop across the cold plate. There are pressure sensors at the inlet and outlet to look at the overall pressure drop across the system. The flow rate sensors will help in monitoring the flow for each cold plate. Inlet temperature of the coolant is kept constant.

Cold plates are used to cool 400W component with 1insq area. This component will be maintained at designed range of temperatures. We will not be reporting the component temperature as it is proportional to the flow rate and temperature rise of the coolant.

The coolant considered in the study is water. Initial flow rate of water is set based on the 400Watts power per each component.

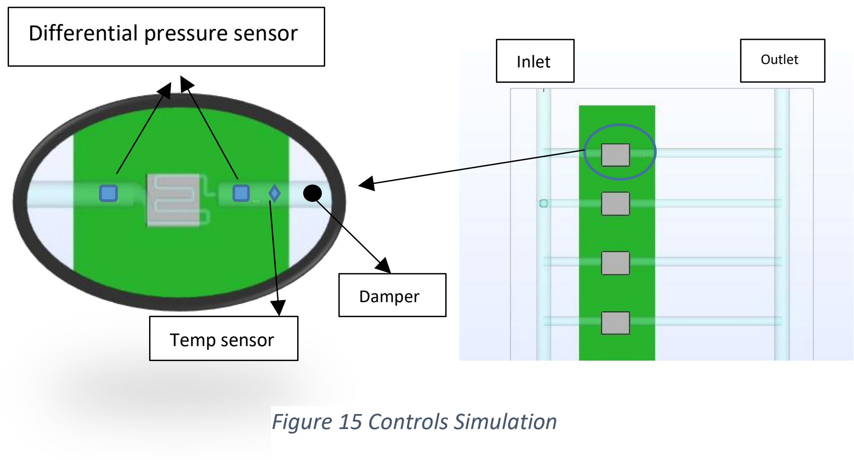


Figure 15 Controls Simulation

4.6 MATLAB controls

Control strategy tested is a constant pressure with variable frequency drive pump. This type of pumps will save energy by reducing the electricity consumption. The flow chart shown in figure 3 shows that the pressure difference across the system will be taken into MATLAB and processed as shown based on the set value. The set value is dependent on the system and varies from system to system.

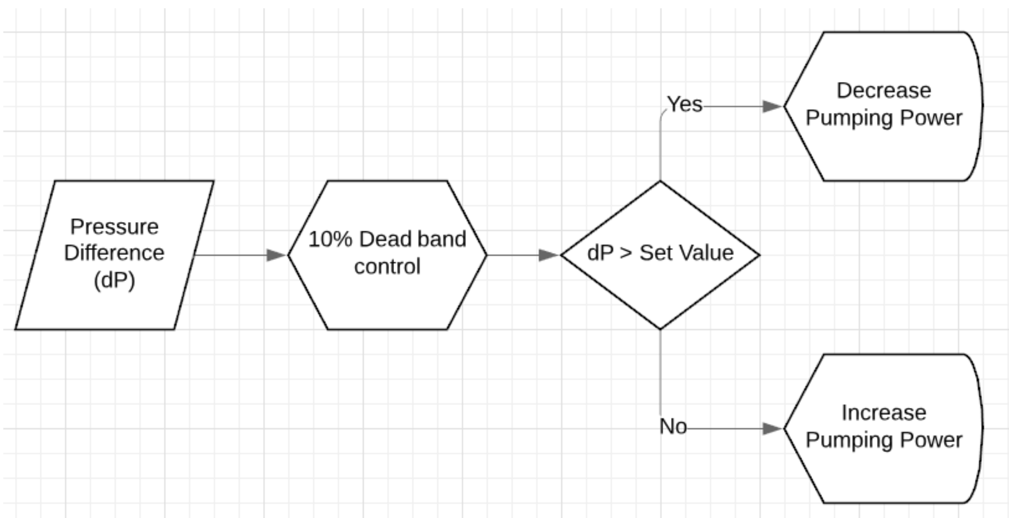


Figure 16 Control system Flow chart

CHAPTER 5

RESULTS

5.1 Simulation

Considering the model developed to be a rack with 4 water cooled servers.

Iteration	U1	U2	U3	U4	Total Power
1	100	100	100	100	400
2	100	100	100	200	500
3	100	100	100	300	600
4	100	100	100	400	700
5	100	100	300	300	800
6	100	100	300	400	900
7	100	200	300	400	1000
8	200	200	300	400	1100
9	200	300	300	400	1200
10	200	300	400	400	1300
11	200	400	400	400	1400
12	300	400	400	400	1500
13	400	400	400	400	1600

Table 3 Parametric simulation

ASHRAE water standard envelope W2 is considered and used for the study. Inlet temperature of the water is constantly maintained at 25℃ and all the possible power combinations as shown in the table above to test the control strategy

5.2 System pressure drop analysis

System pressure drop is calculated to provide the set point values for the control strategy. The table below shows the results for various pressure drops across the system and the damper response with the fixed flow rate and having the FCD maintaining the outlet temperatures at 37˚C.

Pressure (Pa)	D1	D2	D3	D4
300	**28.31**	**40.12**	**69.98**	**64.86**
400	**18.02**	**20.25**	**24.3**	**24.08**
500	**13.42**	**14.64**	**17.69**	**17.63**
600	**10.84**	**11.33**	**13.96**	**13.97**

Pressure (Pa)	T1	T2	T3	T4
300	**37.11**	**37.12**	**37.38**	**37.28**
400	**36.92**	**37.02**	**37.11**	**37.12**
500	**36.99**	**36.93**	**36.94**	**36.95**
600	**36.95**	**36.97**	**37**	**37.01**

Table 4 damper opening & Outlet Temperature with constant pressure input

Red color indicates that box with high damper opening value with same power, whereas green indicates the least value. Four different of pressure are tested to find out the best pressure. The values D1, D2, D3, D4 indicate respective dampers at the cold plates 1, 2, 3, 4.

The values T1, T2, T3, T4 indicate the outlet temperatures of coolant at the respective cold plate1, 2, 3, 4. Table shows that at 300 Pa dampers open at different percentages. Once the pressure is more than 400Pa the damper openings are relatively close to each other with a maximum difference of 6% which is good to able to consider 400Pa as the set value for the pressure difference. The temperature values also agree with the damper openings. Only 300Pa pressure drop has elevated outlet temperatures more than 37˚C.

5.3 Controls testing

The set value is used in the controls and is tested for different powers. The table 5 below shows the iterations with different sets of power. U1, U2, U3 and U4 represent the power of the component with respective to the cold plate 1, 2, 3, 4. The power is varied from 250W to 500W and the control strategy was applied to look at the damper opening and temperature outlet.

		Component Power (W)					Outlet Temperature(°C)					Damper % open area			
		U1	U2	U3	U4		T1	T2	T3	T4		D1	D2	D3	D4
Case	1	400	400	400	400		34.12	35.1	35.34	34.56		35.2	35.2	35.2	35.2
	2	300	400	400	400		34.11	34.24	34.29	34.69		35.2	43.3	43.3	43.3
	3	200	300	400	400		31.06	32.58	35.41	34.72		27.1	35.2	35.2	35.2
	4	100	200	300	400		28.25	30.93	32.79	34.77		19	27.1	35.2	35.2
	5	100	100	300	300		28.9	28.8	32.67	32.93		19	19	35.2	35.2

Table 5 Component power vs outlet temp vs Damper open area %

Table shows the damper openings with respect to the power at the component. Green color represents the low value and red color represent the highest value. The color pattern is same in both power and damper opening, which mean that the damper openings are in alignment with the required flow rate.

Temperature at the outlet is also equivalent to 37˚C for all the iterations for all cold plates. This temperature at the inlet is taken as 25˚C and the outlet temperature is set to have 37˚C. These values are taken just to test the control strategy.

5.4 Pumping power

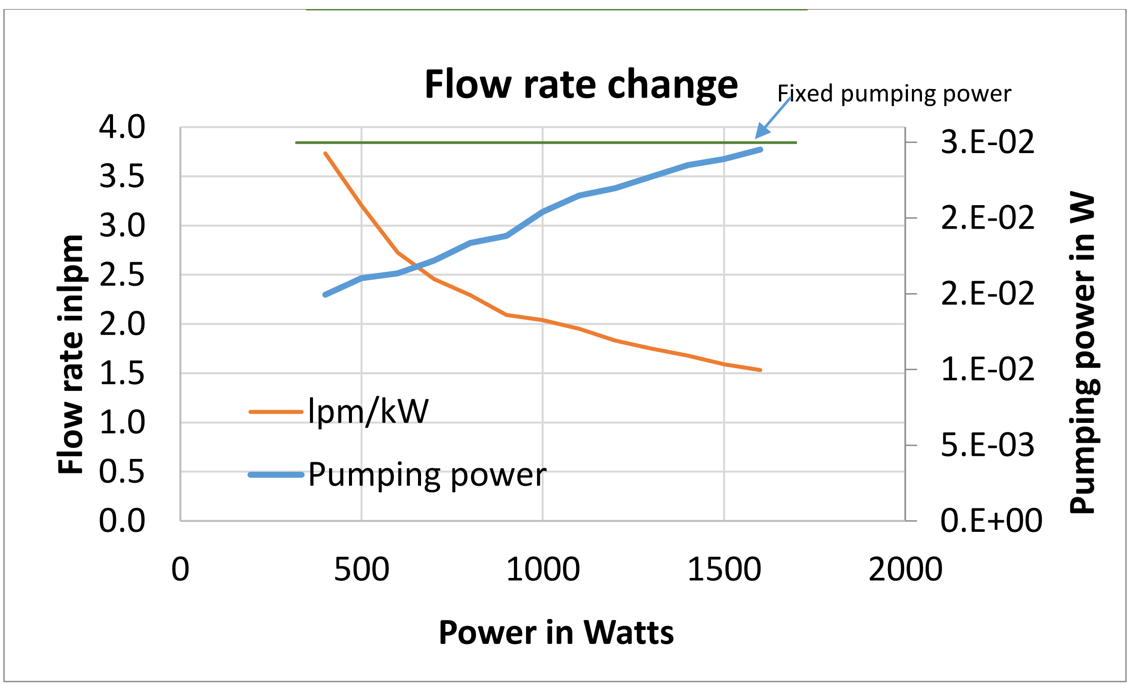
Flow rate change in the overall system due to the control strategy applied the pumping power is saved. Using theoretical calculations from the simulation results 64% pumping power reduction is possible. This is just by using an FCD that can change the hydraulic diameter by 30%.

5.5 Partial PUE

Power Usage Effectiveness (PUE) has been widely adopted and used throughout as the standard efficiency metric for data centers. PUE determined as the total power consumed by the data center divided by the power consumed by the IT load (useful work of the data center). Partial PUE (P_{PUE}) metrics can be developed to understand the efficiency of specific subsystems and subsets of the data center. P_{PUE} of cooling systems can be expressed as follows:

$$P_{PUE}cooling' = Cooling\ Power + Server\ Load\ (Server\ Power)$$

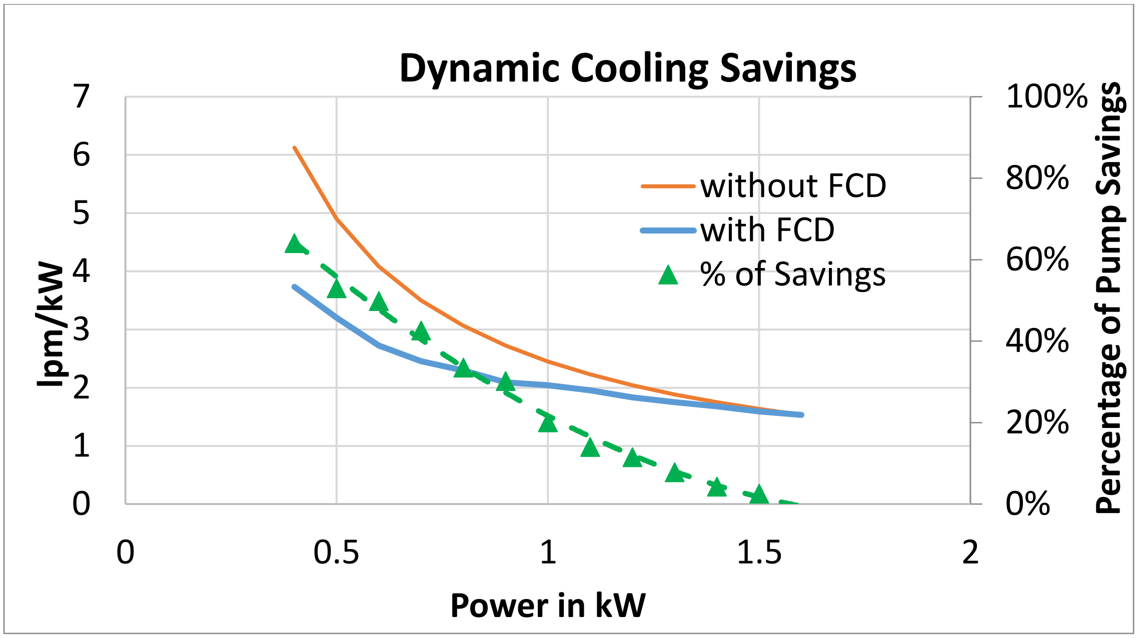
Based on the power consumption of the pump the PUE will be varying. With the test scenarios shown in the results we are able to observe the PUE varying between 1.007-1.01. This is only due to pumping power change.



Graph 3 Pumping power vs Flow rate

Pumping power is proportional to junction temperature, so with the gradual increase in Junction temperature (T_{jmax}) pumping power increases with requirement

Whereas in a fixed pumping power, irrespective of junction temp pumping power is constant



Graph 4 Pumping power vs savings

Pumping power changes as the utilization power increases. Using FCD and dynamic cooling, up-to **64%** of pumping power can be saved.[1]

CHAPTER 6

CONCLUSION

In this study, two different control strategies were developed and tested to save overall pumping power at a rack level in a data center. Implementation of dynamic cooling along with Flow control device is effective with a good control strategy.

To prove that a control strategy with two control methodologies were developed. The control strategy developed is tested using simulations in 6sigmaET. Pressures are calculated for individual components at 100% possible flow rate, and then cumulative pressure is given as a pressure boundary condition to the system for the first methodology adopted whereas maximum temperature that a cold plate can bare for a given area is an addition to the former in the second methodology. The controls are optimized to have only single sensor input to control the VFD pump.

Various possible powers are varied and tested to show how Dynamic cooling and FCD help saving pumping power. It is proven that the control strategy is fully functional with the test setup developed in 6SigmaET. A 64% variation of pumping power is observed in the iterations performed.

6.1. Acknowledgement

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BIBLOGRAPHICAL INFORMATION

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During her master's Amrutha worked on several projects under Dr.Dereje Agonafer at The University of Texas, Arlington. She associated herself with significant industry collaborated research projects and studied areas of air cooling, liquid cooling, reliability etc. She has gained fundamental knowledge of CFD and worked on data center specific codes like 6sigmaET,6sigma room, Ansys Icepak and Flotherm.she has worked developing and testing various experimental setups. Amrutha was a member of about four NSF and IUCRS funded projects collaborated with university and some of the industry peers and gained publications from IMECE, IMAPS, and INTERPAK conferences