EXPERIMENTAL ANALYSIS VALIDATING A CONTROL SCHEME TO DEVELOP A DYNAMIC COOLING SOLUTION FOR NON-UNIFORM HIGH POWERED ELECTRONIC DEVICES IN DATA CENTER

by

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Abstract

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The trend towards higher heat fluxes and non-uniform power distribution continues as we follow Moore’s law with technology nodes now approaching 10nm. Cooling is always designed for maximum junction temperature and as such it is important to mitigate hot spots. All cold plates have a static design by nature and do not possess the capability to respond to non-uniform heat dissipation. The unique “dynamic cold plate” concept aims to improving on conventional static designs through implementation of sensing and control, by redistributing the liquid across its body to counter varying power dissipation across the device being cooled.

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CHAPTER 1

Introduction

The data center industry has experienced significant growth over the past decade with the introduction and explosion of on-line banking, cloud computing, internet entertainment and social networking services. Such are the implications that, it has been reported, the national energy usage by data centers more than doubled between 2000 and 2005 and it was projected that consumption would continue to rise over the course of the following five years [1]. It was reported that by 2010 data centers accounted for around 2% (between 1.7% and 2.2%) of the total national electricity consumption [2]. With a sizeable portion of power consumption attributed to cooling and power distribution, which are categorized as parasitic loads, it has become imperative that energy savings and efficiencies be pursued in the aforementioned components at various levels within the data center facility. This thesis work will focus on cooling requirements at the device and server levels through the application of module-level, water-cooled cold plates.

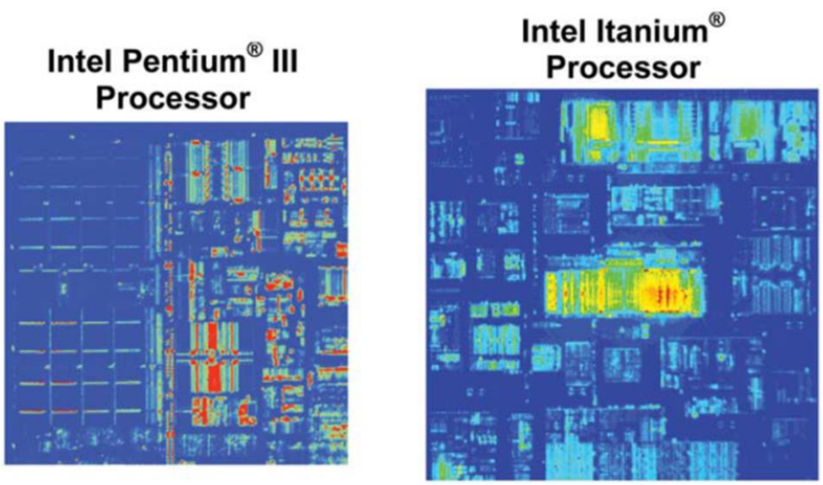

Figure 1 Hot spots on die [3]

The need for energy-efficiency has coincided with continuing trends of increasing microprocessor power densities and non-uniform temperature distributions which pose a significant challenge to the cooling requirements of high power devices. Post-Pentium 3 era of microprocessors introduced non-uniform power distribution at the die with varying power densities assigned to different functional units. This gave rise to localized regions of high temperature known as 'hot spots', as seen in figure 1 [3]. Thus, a substantially large temperature difference can be observed across the surface of the device which is detrimental to its performance and reliability. As a result, conventional static cooling solutions have to be designed to cool these high temperature regions which increase the thermal budget and in-turn the cost of cooling these devices. It has also been predicted that, with further advancement in microprocessor technology, the temperature difference across the chip will soon outweigh all other thermal factors and cooling solutions will need to be designed to counter this issue. In addition, data center servers are the most energy efficient when they operate close to maximum utilization [4]. Therefore, the primary requirements of next-generation solutions are high power cooling and selective distribution of resources for promotion of uniform die temperatures. This requires a detailed understanding and integration of microprocessor architecture, electronic packaging, and control systems to produce a robust solution. The objective of this work is to develop an experimental models to design dynamic, energy efficient and practical water-cooled cold plates for very high power devices in data center and telecommunication facilities.

As previously mentioned, reducing the maximum device temperature while promoting a uniform surface temperature are the primary objectives of the dynamic cold plate. These requirements give rise to benefits that further promote the need for such a solution. This involves setting an aggressive target for the maximum junction temperature by running the device as close to ambient conditions as possible. By reducing the operating temperature, the effect of static power consumption due to leakage can be minimized. As shown in figure 2, the cooling solution should be setup to effectively minimize system power consumption (Psystem = Pdynamic + Pleakage + Pcooling) by establishing a sweet spot between leakage and cooling [5]. Microelectronic device speeds (clock frequency) and reliability are also known to increase with reduction in operating temperature. Failure rates of microprocessors are known to double with every 10°C increase in operating temperature [6]. The objective of this project is to design the dynamic cold plate solution to realize these improvements in device performance and reliability, and minimization of system power consumption.

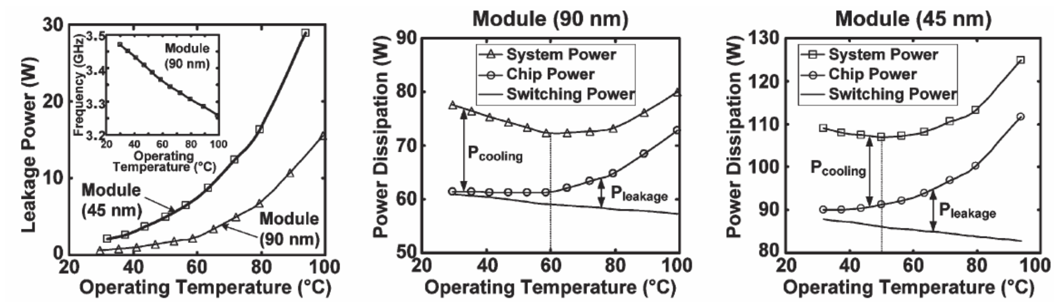

Figure 2 Effect of operating temperature on leakage power [5]

1.1 Scope of the Work

The proposed effort is divided into four sub-tasks. In the first sub-task, we will investigate different types of flow control devices that will serve to provide targeted delivery of cooling resources to different parts of the cold plate based on the amount of heat being dissipated in adjoining active regions. Careful consideration is paid to dimensional and power consumption constraints involved in employment of these devices in the solution. Generating the cooling circuit and selection of heat transfer surfaces within the body of the solution are also required exercises. The cold plate is then designed for a reference multi-chip module (MCM) platform, as shown in figure 3, while taking into consideration the aforementioned requirements. The second sub-task involves studying the steady state performance of the solution to determine its range and sensitivity. It is imperative that the steady state performance of the design be superior to conventional single-phase, water-cooled solutions currently employed in industry. Based on the results from these sub-tasks, the third sub-task comprises building a working prototype of the dynamic cold plate and experimental validation with a MCM test vehicle. It is importance to study and improve response and performance range and sensitivity of the flow control devices to ensure energy-efficient operation of the MCM. The final task shifts the focus from the module level to the server and rack levels with testing the final design in a data center environment. Investigation of control systems at the server and rack levels is required for seamless deployment of the dynamic solution in a working facility. This work will lead to the establishment of detailed guidelines for the design, testing and validation of dynamic cold plates for a given high-power platform.

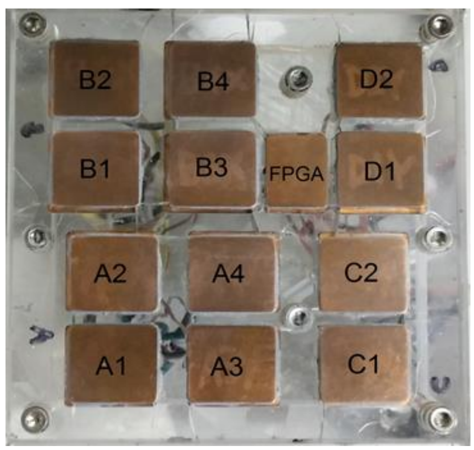

Figure 3 MCM platform serving as the basis for the cold plate design

CHAPTER 2

Literature Review

Liquid cooling is growing in concurrence with cooling novel, high-powered microelectronic devices [7]. Cold plates with working fluid as water are one of the many prominent liquid cooling solutions available. IBM 3081 mainframe computer incorporated water-cooled thermal conduction modules (TCMs) which were the earliest direct to chip liquid cooling incorporated in1982 [8, 9]. The cold plate assist to remove the heat dissipated by a total module power of up to 2KW within the body of the TCM [10, 11]. The departure from bipolar devices and the introduction of CMOS technology in the early 1990's increased the air cooling for a more cost-effective method due to the significant reduction in heat dissipation. Regardless of the change in technology the module powers began to increase and around a decade later it reached the levels of its bipolar counterpart and liquid cooling was once again being considered for thermal management of microelectronic devices [12].

Water cooling has various advantages like greater heat carrying capacity, targeted delivery and lower transport power over air cooling. Also, the servers are more energy-efficient when operating at higher utilization [13] making liquids more appropriate for heat transfer while maintaining desired operating temperatures. There is a comprehensive review of cold plates employed for thermal management of high density servers in [14]. Application of CFD analysis to target improvements in existing cold plate designs is not uncommon. A methodology for multi-design variable optimization of a water-cooled cold plate is mentioned by Fernandes et al. [15] which employed user defined functions to fix the pumping power. A multi variable design optimization to minimize the thermal resistance was evaluated by varying width and height of the serpentine channels in an IBM ES/9000 cold plate. The numerical model was validated by comparison with published experimental data [16] and the predicted thermal resistance (baseline design) was found to be in excellent agreement. Fernandes et al. [17] previewed novel designs to extend performance of static cold plates. Remsburg [18] reported a solution that utilized impingement heat transfer along with non-linear fin patterns for thermal management of a 1080W IGBT/diode assembly. When compared to conventional designs formed tube designs to machined pin fins the proposed solution reported visibly lower maximum temperatures for a series of fixed flow rates. This was attributed to a combination of improved heat transfer due to impingement and reduced pressure drop through optimized fin design.

In all the aforementioned publications, all cold plates have a static design by nature and do not possess the capability to respond to non-uniform heat dissipation by modulating the cooling resource accordingly. In this report, the proposed unique “dynamic cold plate” concept aims to improve on conventional static designs through implementation of sensing and control, by redistributing the liquid across its body to counter varying power dissipation across the device being cooled.

CHAPTER 3

Dynamic Cold Plate For A High Powered Electronic Package

The footprint of the cold plate is divided into individual channel sections depending on the complexity of the device and its power map as shown in figure 4. Each section has a different inlet conduit that is fed by the main point of ingress to the cold plate, making each independent from the others. In order to counter different power dissipations beneath the active region of each section, the introduction of sensing and control is necessary. By utilizing readings from temperature diodes integrated into the dies, or embedded thermocouples within the cold plate body, an indication of power dissipation variation may be established between different sections. These representative readings are then fed into a control unit wherein a preset algorithm determines the magnitude/proportion of flow that needs to be distributed to each section based on cooling requirement. This signal is then given into a FCD that regulates flow as per requirement. Thus flow to each section is controlled in real-time depending on representative temperature readings to promote lower temperature differences between individual sections. It is imperative that the proposed design be scalable to ensure application for high power devices with different footprints.

The layout and operation of the dynamic cold plate can be easily visualized as seen in figure 4.

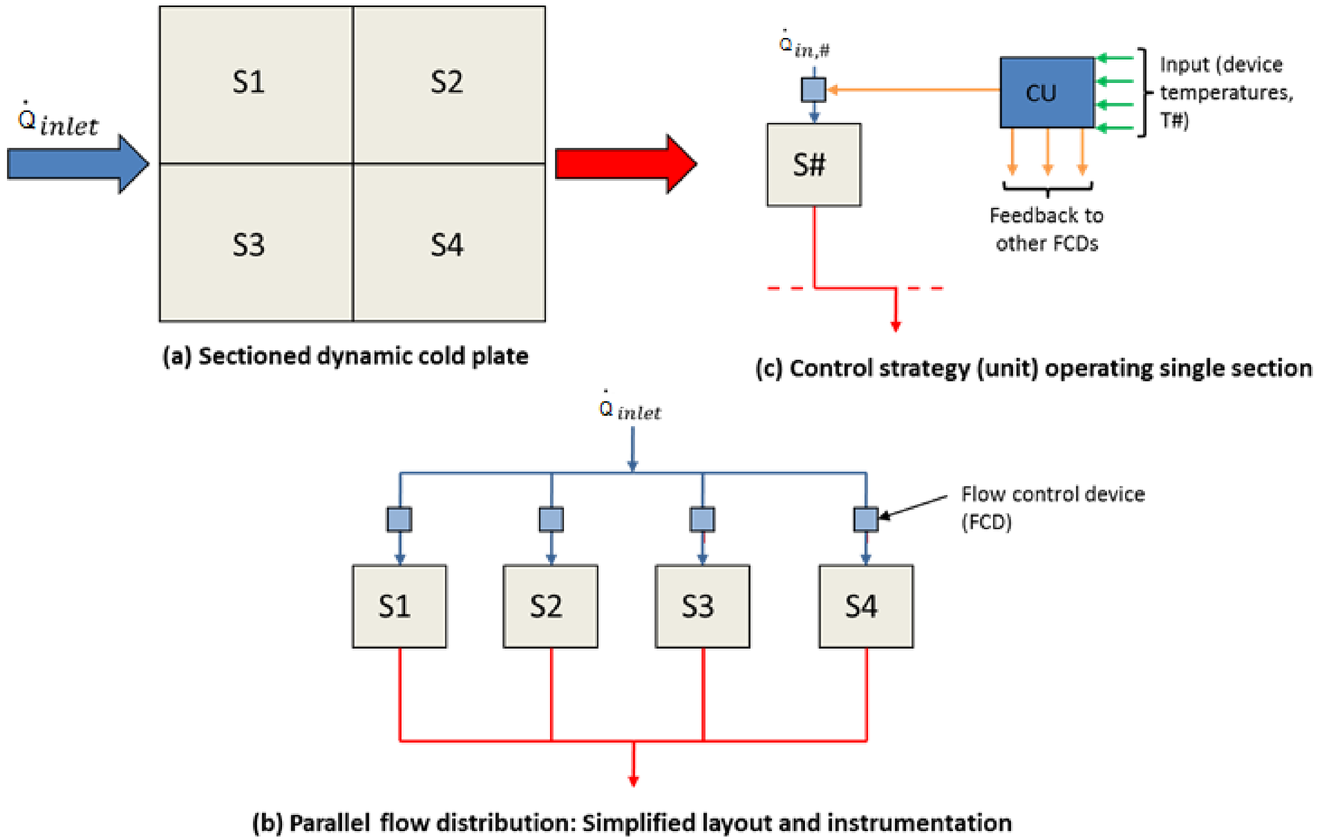

Figure 4 Conceptual layout for a cold plate with segregated flow control

3.1 Reference MCM Platform

In order to apply the preceding concept, a reference platform is required for design of such a dynamic solution. Figure 3 shows a high-power mutli-chip module (MCM), provided by Endicott Interconnect Technologies Inc. (now i3 Electronics, Inc.), that serves this purpose. The module is populated with an array of surface mounted components (ASICs, LICAs and a FPGA) and setup to have a maximum power dissipation of 485 watts over a 78mm by 78mm footprint.

Table 1 Details of MCM components

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

A list of component power specifications can be found in table 3-1. It is apparent that the only heat generating components of interest are the ASICs (application-specific integrated circuit) and FPGA (field-programmable gate array). The former is 14.71mm x 13.31mm x 0.8mm in size and the latter is 10.50mm x 12.70mm x 0.8mm in dimension. The LICAs, while much greater in number, do not dissipate (significant) heat and are therefore disregarded for the purpose of this study. A copper heat spreader, designed to account for disparity in component heights and spreading of heat, is not considered in this study to take advantage of multiple spatially-separated heat sources on the module.

3.2 Original cold plate (OCP)

The MCM, being a product in service, was assembled with and thermally managed by a static cold plate. Top views of this solution are shown in figure 5. The cold plate has a copper body measuring 92mm x 92mm x 12mm (excluding ports) with multiple layers assembled by brazing to prevent leaks. Single points of ingress and egress of coolant are setup in this design, similar to the proposed concept. NPT fittings at the inlet and outlet facilitate connection at the system-level (see figure 5).

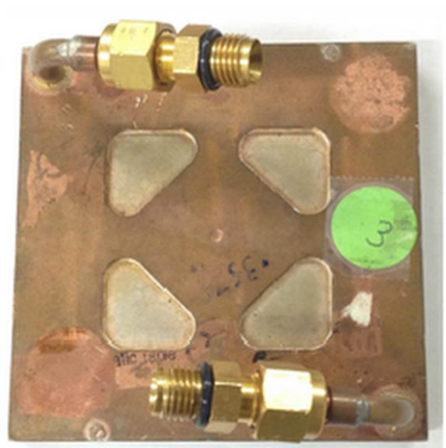

Figure 5 Top view of original cold plate

Internal circuiting of coolant within the body of the cold plate is unknown. Experimental testing should provide insight whether the design is based on serpentine channeling, parallel networks or otherwise.

3.3 Dynamic Cold Plate (DCP)

Heat generating components of the MCM (13 in total) were grouped into four distinct regions based on proximity as seen in figure 6. These clusters, henceforth referred to as sections, were named A to D and individual components were numbered starting from the bottom left corner and moving in an „N" pattern. Sections A and B have a similar footprint and account for maximum power dissipation of 160W. Section D is dissimilar to C as it accommodates the FPGA. Flow of coolant to each section must be independent and have an isolated islands of fins. This is shown in figure 6 (a). To improve cost effectiveness of manufacturing the base plate, fins were fabricated from a leading edge before a fly cutting operation created the aforementioned islands. As a result, in some sections, fins extended beyond the span of components. In section D, FPGA area was partially accounted for. This was to provide space for walls to isolate flow from section A. In addition, this component dissipates a relatively lower power of 5W. The envisioned cold plate design has a footprint of 90mm x 90mm.

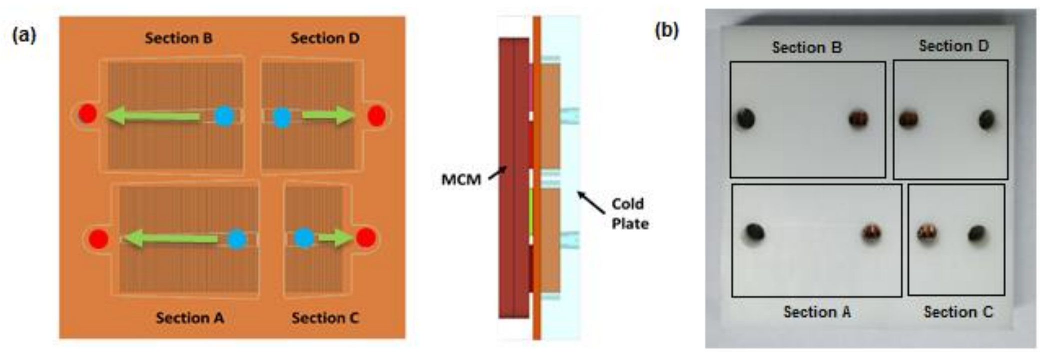

Figure 6 (a) CAD model of dynamic cold plate (b) Manufactured dynamic cold plate

CHAPTER 4

Components for Experimental Testing

The control scheme was designed in labVIEW to test both original and proposed cold plates available with electromagnetically commutated pumps used as external FCDs. In addition, since a functioning MCM was not available and thermal test vehicles (TTV) are monetarily unfeasible, a mock MCM TTV was designed and fabricated for experimental testing. Details of a liquid cooling test bench are also finalized and previewed. Finally, series of tests are conducted on both cold plates and resultant parameters of interest are outlined.

4.1 The MCM TTV

A thermal test vehicle, dimensionally identical to the MCM as well as capable of independent power dissipation within heat generating components is required for experimental testing. Figure 7 shows details of the mock MCM designed to serve this purpose. Thick film heaters (12.7mm x 12.7mm) soldered to the base of copper blocks (accurate footprints) simulate the ASICs and FPGA. A hole was drilled midway into the side of each block such that the attached thermocouple measures temperature 1mm below the center of the top surface. These measurements are intended to represent case temperatures of ASICs and the FPGA.

The base of the MCM was machined from acrylic and has two parts. The top half ensures that installed copper blocks only extend 0.8mm above the base (similar to component heights). The bottom half prevents blocks from moving when either cold plate is attached with applied pressure. In addition, holes in the bottom half of the base facilitate exit of heater leads and thermocouples from each individual block.

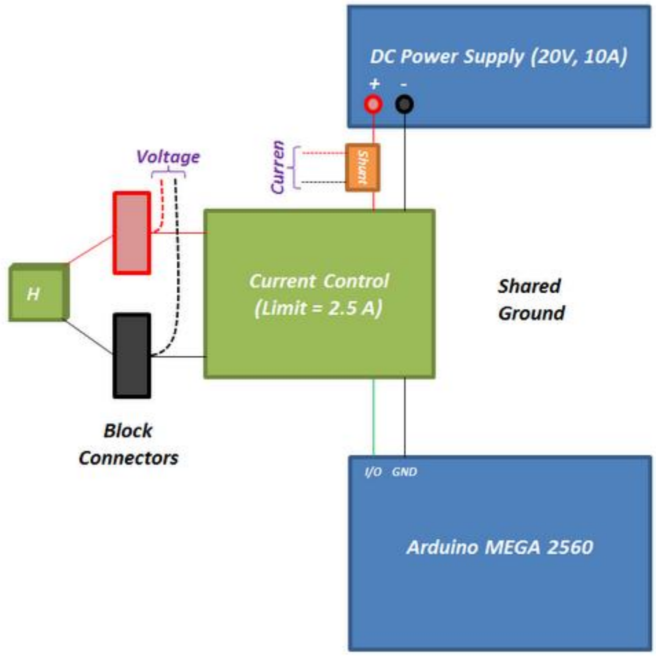

Figure 7 Block diagram of a single heater control circuit

Controlling power dissipation of each heater is achieved similar to details in figure 7. A shunt resistor measures current drawn by the heater based on voltage drop readings through the data acquisition (DAQ) unit. In addition, an NPN BJT modulates current flowing through the circuit based on a PWM signal from the Arduino. Additional leads at the terminal connectors measure the voltage across the resistive heater for power measurement. Two boards with thirteen individual circuits were assembled for blocks in sections A, B, C and D.

4.2 Pump as FCD

The selected Swiftech MCP50X pump has pulse width modulated (PWM) control so it can be used to control the flowrate of distilled water (coolant) and there no need for an extra component as pump itself act as flow control device (FCD). It has a smaller footprint and higher pressure head capacity with low power requirement. It works on centrifugal pumping mechanism and operates at really low noise. It has 4-wired connector for PWM control and SATA cable for DC power supply. The pump has attached reservoir with standard G1/4” ports which are compatible with large assortment of fittings. Variable speed control via PWM through the Arduino has range from 1200 rpm for completely silent operation to 4500 rpm for ultra-high flow performance.

Figure 8 Swiftech MCP50X pump [20]

4.3 Pressure sensor

The pressure sensors selected is Honeywell MLH050PGL06E which works on silicon Piezo-resistive pressure sensing principle. The pressure sensor is equipped with four piezo-resistors suppressed in a chemically- etched silicon diaphragm. This diaphragm is being flexed together with the suppressed resistors whenever there is a change in pressure that induces stress. This results to an electrical output when the resistor value changes in proportion to the stress applied. These sensors were selected as they are small, more reliable and cheap. They report maximum repeatability, precision and reliability under different conditions. Also, they are highly consistent with regard to operating characteristics and interchanges without recalibration.

Figure 9 Honeywell MHL series pressure sensor [21]

4.4 Flowmeter

The Omega FTB 421 flowmeter was selected as it has range of operation from 0.1 to 2.5 LPM. It has accuracy of ± 3% of reading normal range and repeatability of 0.5% FS normal range. The flowmeter accuracy and repeatability was checked by recalibrating the flowmeter frequently. The lightweight turbine ensures fast startup and can mount in any orientation.

Figure 10 Omega FTB421 Flowmeter [22]

4.5 Thermocouple Probe

The thermocouple probes from OMEGA are selected as they have quick disconnect with miniature connectors. The glass filled nylon connector is rated for temperatures up to 220°C. The diameter of thermocouple probe is 3.0mm. These thermocouple probes are fitted into stainless steel vacuum fitting as shown in figure 11 (b). The vacuum fittings are then fitted into fluid line by use of Tee joint.

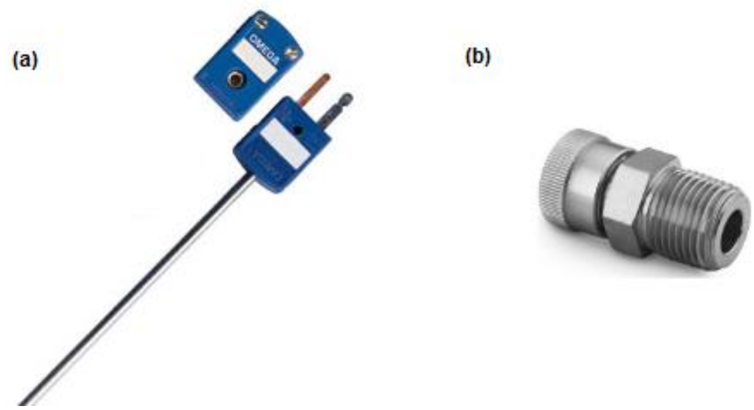

Figure 11(a) Thermocouple probe (b) vacuum fitting [22, 23]

4.6 Reducer and barb fittings at inlet and outlet of DCP

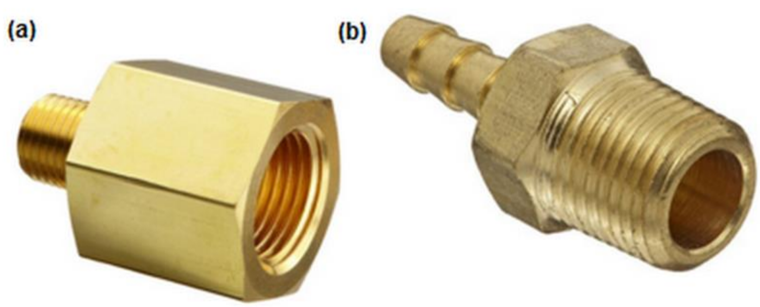

Figure 12 Reducer and barb fittings at inlet and outlet of DCP [24]

There major change in design of DCP was the increase in number of inlet and outlets to overcome with space and dimension constraints a reducing adapter, 1/8" NPT female x 1/16" NPT male, and hose fitting adapter, 1/4" barb x 1/8" NPT male pipe, were used at the inlet and outlet. Heat resistant silicone tubing was connected to the hose adapter which are easily detachable and flexible than most of the other tubing and hoses.

CHAPTER 5

Liquid Cooling Test Bench

A simplified sketch of the test bench setup to evaluate both cold plates is depicted in Figure 10. A Kinetics RS33AO11 recirculating chiller drives flow through the external loop and cools the plate heat exchanger (HEX). The chiller is equipped with a positive displacement pump capable of pumping up to 1.6gpm of coolant at 100psi and a temperature range of -15°C to 75°C. As these units are known to drift (variation in temperature), the HEX provides substantial thermal capacitance to prevent transmission to subsequent loops. A DC 4-wire pump drives flow of distilled water through the two HEXs in the intermediate loop. Similarly, a separate pump controls flow of distilled water through all components in the internal loop. Turbine flow-meters measure the flow rate of water cooled by the plate HEX. Temperature and pressure differences across the cold plate are measured using T-type thermocouple probes and pressure transducers. The pump in the internal loop is primarily responsible for maintaining a fixed flow rate during testing. The pump in the intermediate loop controls the inlet temperature of water to the cold plate by modulating flow rate between the two HEXs. Temperature and flow rate readings are input to the LabVIEW code that in-turn controls both pumps by sending PWM signal through Arduino. Inlet temperatures to the cold plate is relatively high (35°C) to test for warm water cooling. Water and glycol mixture (50/50) is employed in external loops to have effective running of chiller. The Agilent 34970A Data Acquisition/Switch Unit is used to sense temperature, pressure, flow, voltage and current by compiling a LabVIEW program. There are thirteen case temperature readings measured from the MCM as mentioned in section 4.1 through the labVIEW program. Agilent E3632A 120W power supply is used to power the pressure sensor, flowmeter. An Antec Basiq BP350 power supply unit is used to power the 4-wired DC pumps since they have a SATA cable.

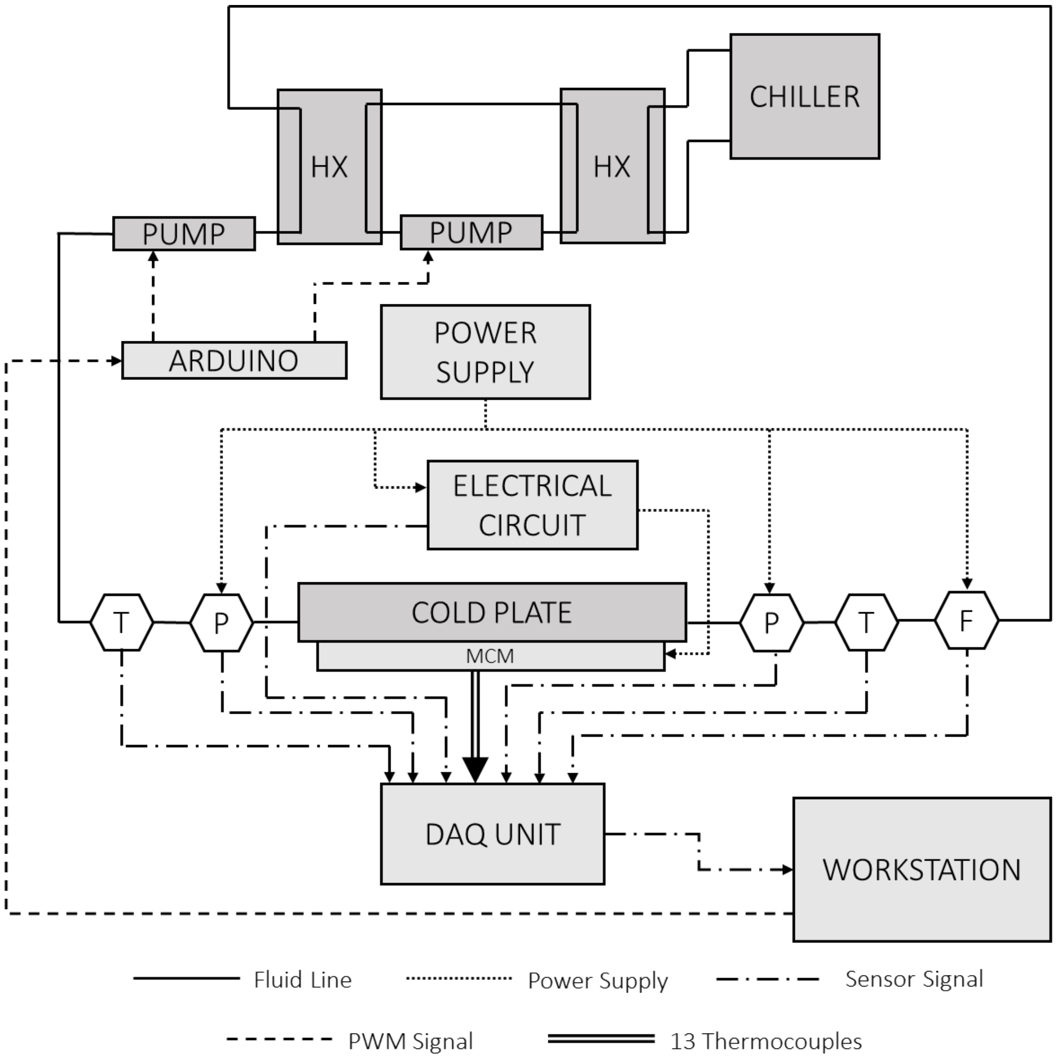

Figure 13 Schematic of liquid cooling test bench

5.1 Experimental testing of OCP

The experiment test matrix was operated at higher inlet temperature (35º C) to investigate warm water cooling. The W4 zone (2º C – 45º C) promotes warm water cooling and ensures chiller-less operation. The MCM TTV was subjected to uniform and non-uniform loading conditions during testing both the liquid cold plates (OCP and DCP). There were five cases of uniform loading considered were all twelve ASIC were subjected to uniform loads 5W, 10W, 20W, 30W and 40W whereas the FPGA was idling at 5W. There were twelve cases of non-uniform loading were a single block of ASIC was subjected to maximum load of 40W and rest all were set at idling power of 5W. All seventeen loading cases were studied at four different flow rates viz. 0.5lpm, 1lpm, 1.5lpm and 2lpm in the internal loop. Two flowmeters were used in parallel to make sure the flowmeter operates in its working range. The pressure drop across the OCP is measured and utilized to calculate the pumping power.

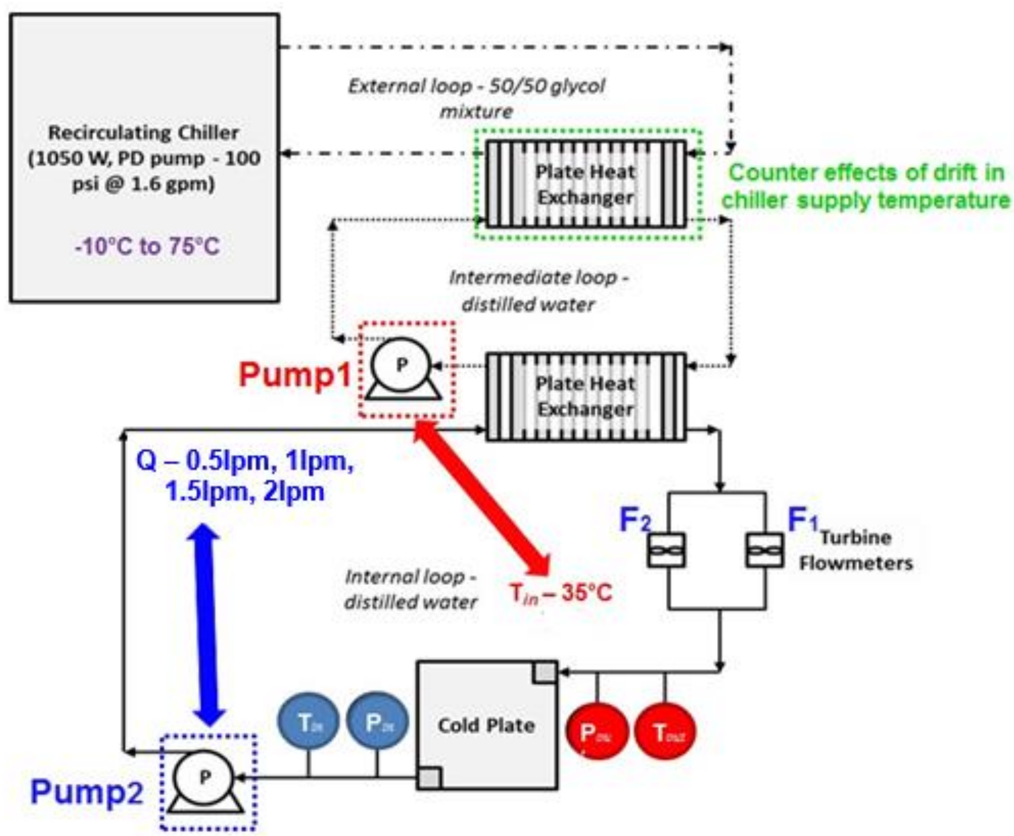

Figure 14 Schematic of hydraulic loop of OCP testing

We could see the labVIEW panel programmed for testing OCP in Figure 14. The waveform graph to the left shows the measured pressure drop across the OCP. The waveform graph on the right-side of front panel shows the flowrate through the OCP measured using flowmeters. The dead band control for the inlet water temperature control is just below the flowrate waveform graph. The dead band control for maintaining the flowrate in the internal loop is to the right of dead band control of inlet water temperature control. There are thirteen temperature readings measured from twelve ASIC's and a FBGA at the bottom right of the front panel.

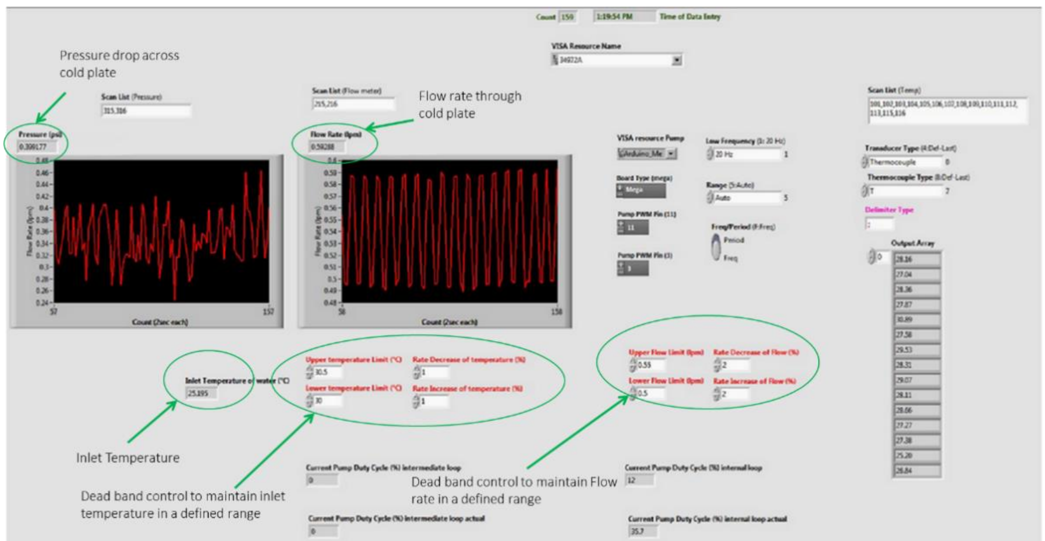

Figure 15 Front Panel of LabVIEW for OCP testing

5.2 Experimental testing of DCP

The Figure 15 shows the hydraulic loop of DCP testing. As mentioned in section 3.3 there are four sections in the DCP where each section has its own pump which is used as FCD. The flowmeters gives the flowrate of each individual section. The pressure drop across the DCP is measured across each section and the impedance curve for each section is determined. Variation of device temperatures with individual section flow rates are obtained from the experimental testing. These device temperatures are then compared with the device temperatures during OCP testing.

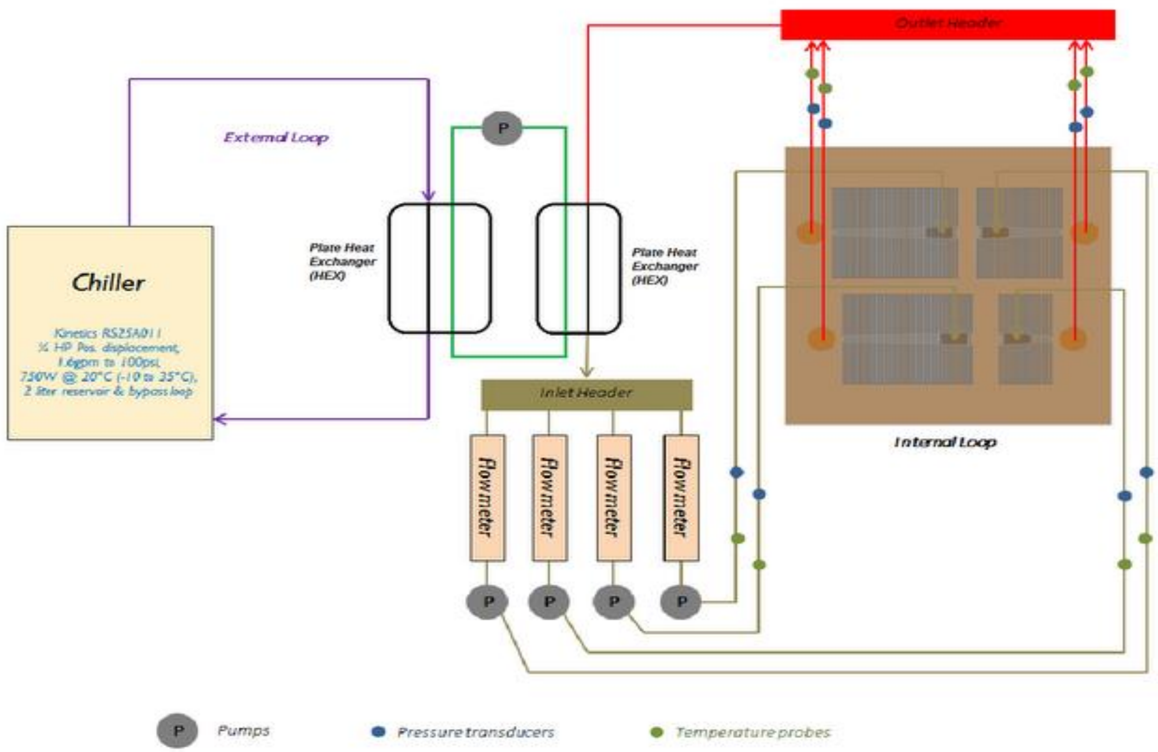

Figure 16 Schematic of hydraulic loop of DCP testing

CHAPTER 6

Results

6.1 Results of Original cold Plate

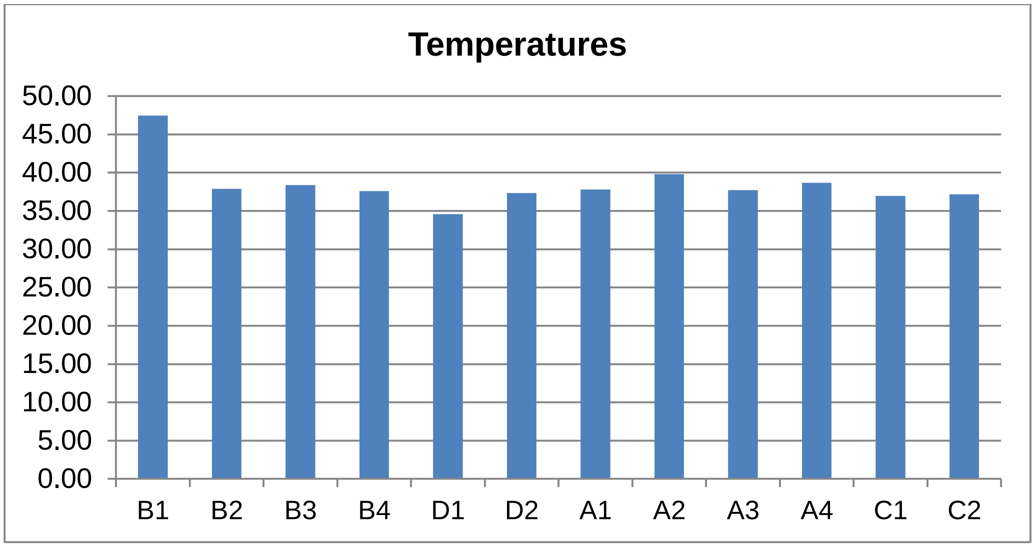

Figure 17 Temperature variation across the MCM

The variation in die temperature across module is 12.87° C at 2 lpm. The inlet temperature of water is 35°C and ASIC B1 is at 40 W (i.e. maximum power) whereas rest of ASIC's are at 5W (i.e. idle). The temperature variation across the MCM increases as we decrease the flowrate through the liquid cold plate. It was 18.08°C at 0.5 lpm for non-uniform power distribution.

Impedance of OCP increases as flow-rate increases the increase as we can see from figure 17. There is no significant difference in the pressure drop for uniform and non-uniform loading conditions.

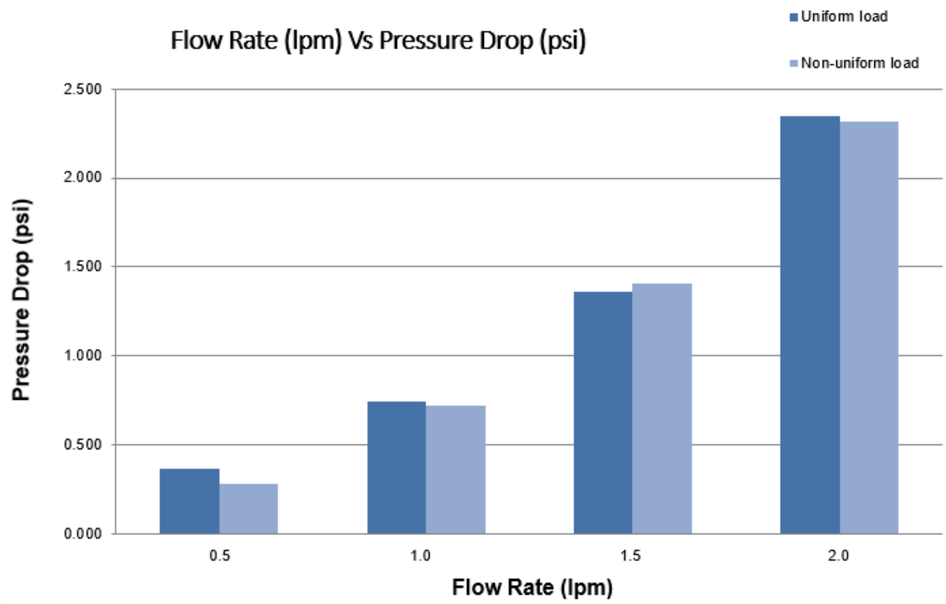

Figure 18 Impedance of OCP under uniform and non-uniform loading

The graph of pumping power verses flowrate shown in figure 18 signifies the increase to be third degree polynomial function for curve fitting of R^2=1.

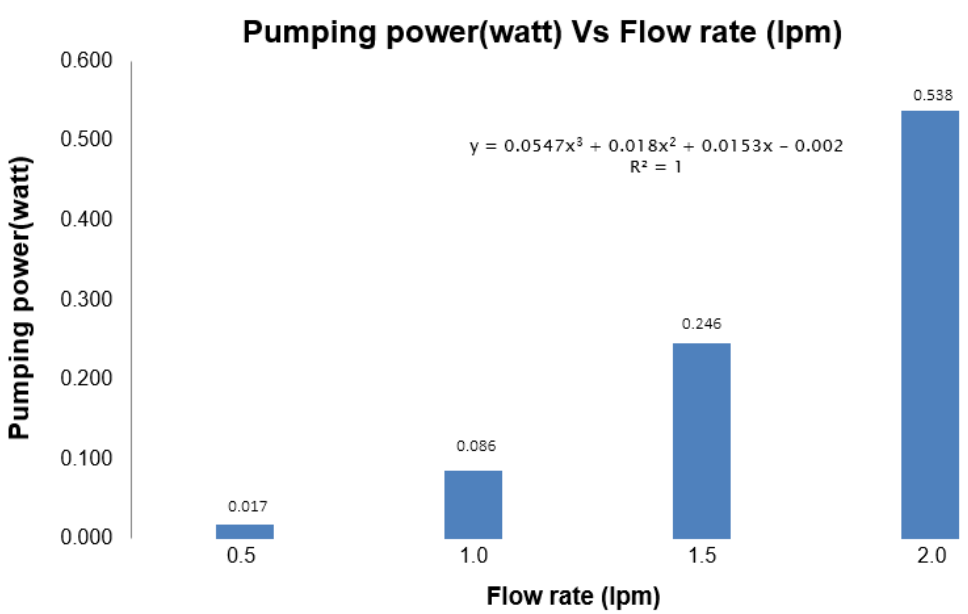

Figure 19 Pumping power (W) vs Flowrate (lpm)

6.2 Results of Dynamic cold Plate

The variation in die temperature across module is 6.13^{o} C at 2 lpm. The inlet temperature of water is 35^{o}C and ASIC B1 is at 40 W (i.e. maximum power) whereas rest of ASIC's are at 5W (i.e. idle).

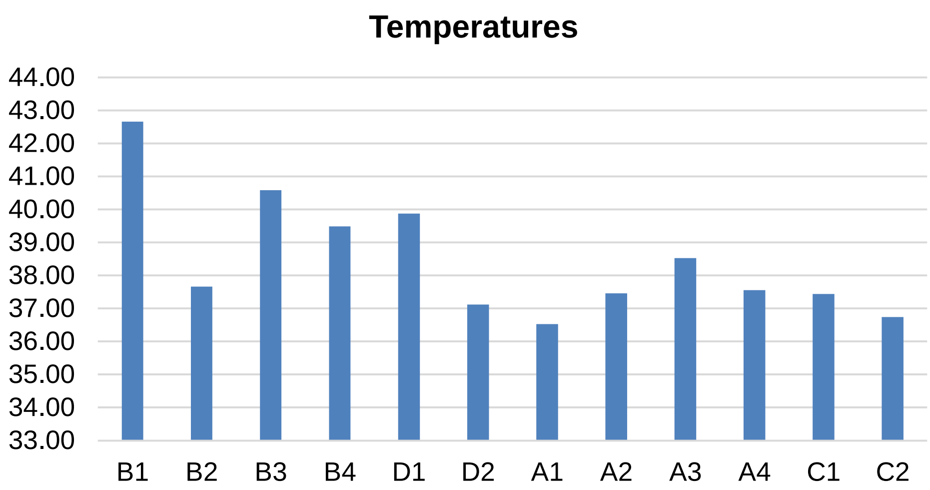

Figure 20 Temperature profile for DCP

CHAPTER 7

Conclusions

The concept for a dynamic cold plate which works on segregating flow control of cooling resources based on requirement for thermal management of high power devices was introduced. A multichip module(MCM) with 485Watt thermal design power was selected as the reference platform for designing such a solution. Performance parameters of the original cold plate were experimentally evaluated and provided a baseline regarding the extent of savings available based on experimental analysis of the dynamic counterpart. The major manufacture challenge was to have inlet ports so close to each other and to account for the hose fittings. The 1/16" NTP fitting with 1/4" hose reducer was used for all the inlet and outlet port. Specifics for cost-effective design and fabrication of a mock MCM thermal test vehicle were outlined. Control circuits that enabled automation of testing through modulation of heaters and cooling systems were demonstrated with a simplified test setup. Details of the liquid cooling test bench for evaluation of both original and dynamic cold plates are included. The experimental analysis of the cold plate assembled with the MCM reported moderate operating temperatures of components with low impedance to flow in individual sections. Specifically, the variation in the temperature across the MCM for non-uniform loading showed significant improvements of the designed dynamic cold plate over the original solution.

CHAPTER 8

Future Work

With the increase in number of cores in processors a dynamic cold plate for such devices will serve as efficient cooling solution. A survey of available flow control valve can be done to help to build a dynamic cooling solution with miniaturized flow control valve can be utilized for commercial applications. Integration of miniaturized flow control valve in cold plate itself can be studied to have a better dynamic control.

Appendix A

Supplementary Figures

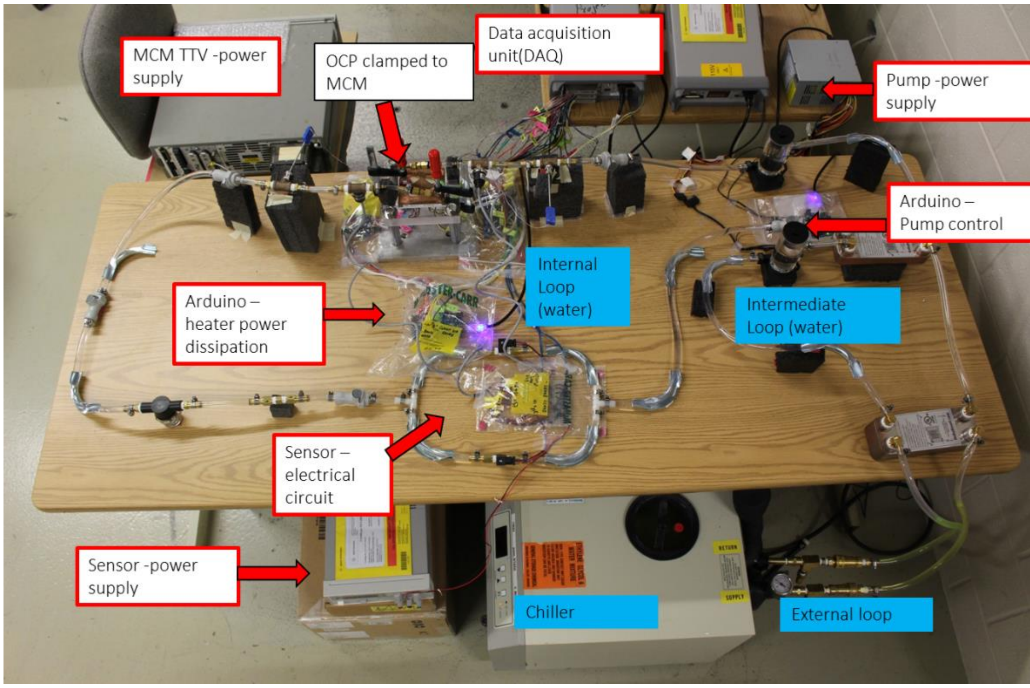

Figure 21 Experimental setup of OCP

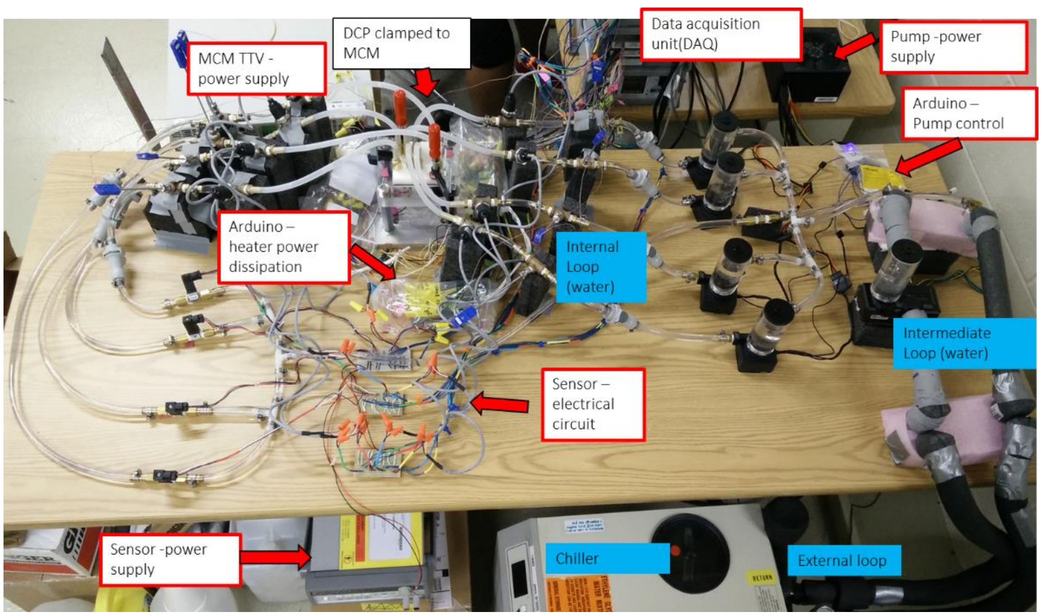

Figure 22 Experimental setup of DCP

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