INVESTIGATION OF IMMERSION COOLED ARM-BASED COMPUTER CLUSTERS
FOR LOW-COST, HIGH-PERFORMANCE COMPUTING

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This study aimed to investigate performance of ARM-based computer clusters using two-phase immersion cooling approach, and demonstrate its potential benefits over the air-based natural and forced convection approaches. ARM-based clusters were created using Raspberry Pi model 2 and 3, a commodity-level, single-board computer. Immersion cooling mode utilized two types of dielectric liquids, HFE-7000 and HFE-7100. Experiments involved running benchmarking tests Sysbench high performance linpack (HPL), and the combination of both in order to quantify the key parameters of device junction temperature, frequency, execution time, computing performance, and energy consumption. Results indicated that the device core temperature has direct effects on the computing performance and energy consumption. In the reference, natural convection cooling mode, as the temperature raised, the cluster started to decease its operating frequency to save the internal cores from damage. This resulted in decline of computing performance and increase of execution time, further leading to increase of energy consumption. In more extreme cases, performance of the cluster dropped by 4X, while the energy consumption increased by 220%. This study therefore demonstrated that two-phase immersion cooling method with its near-isothermal, high heat transfer capability would enable fast, energy efficient, and reliable operation, particularly benefiting high performance computing applications where conventional air-based cooling methods would fail.
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By

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# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACKNOWLEDGMENTS</td>
<td>iii</td>
</tr>
<tr>
<td>LIST OF TABLES</td>
<td>vi</td>
</tr>
<tr>
<td>LIST OF FIGURES</td>
<td>vii</td>
</tr>
<tr>
<td><strong>CHAPTER 1. INTRODUCTION</strong></td>
<td>1</td>
</tr>
<tr>
<td>1.1 Motivation</td>
<td>1</td>
</tr>
<tr>
<td>1.2 Objectives</td>
<td>3</td>
</tr>
<tr>
<td>1.3 Technical Approach</td>
<td>4</td>
</tr>
<tr>
<td><strong>CHAPTER 2. LITERATURE REVIEW</strong></td>
<td>6</td>
</tr>
<tr>
<td>2.1 Need for Cooling</td>
<td>6</td>
</tr>
<tr>
<td>2.1.1 Effect of Temperature on Performance of a Microprocessor</td>
<td>6</td>
</tr>
<tr>
<td>2.1.2 Effect of Temperature on Power consumption of a Microprocessor</td>
<td>7</td>
</tr>
<tr>
<td>2.1.3 Effect of Temperature on Lifetime Reliability of a Microprocessor</td>
<td>9</td>
</tr>
<tr>
<td>2.2 A Detailed Review of Immersion Cooling</td>
<td>10</td>
</tr>
<tr>
<td>2.2.1 Boiling Process</td>
<td>14</td>
</tr>
<tr>
<td>2.3 Factors Affecting the Boiling Process</td>
<td>15</td>
</tr>
<tr>
<td>2.3.1 Orientation</td>
<td>15</td>
</tr>
<tr>
<td>2.3.2 Surface Roughness</td>
<td>18</td>
</tr>
<tr>
<td>2.3.3 Fluid Selection</td>
<td>19</td>
</tr>
<tr>
<td>2.4 Non-Thermal Design Considerations for Two-Phase Immersion Cooling</td>
<td>20</td>
</tr>
<tr>
<td>2.4.1 Electrical Properties</td>
<td>20</td>
</tr>
<tr>
<td>2.4.2 Material Compatibility</td>
<td>20</td>
</tr>
<tr>
<td>2.4.3 Effect of Non-Condensable Gases (Air)</td>
<td>21</td>
</tr>
<tr>
<td>2.4.4 Effect of Water</td>
<td>21</td>
</tr>
<tr>
<td>2.5 Implementation of Two-Phase Immersion Cooling in Servers</td>
<td>21</td>
</tr>
<tr>
<td><strong>CHAPTER 3. EXPERIMENTAL SETUP AND PROCEDURE</strong></td>
<td>24</td>
</tr>
<tr>
<td>3.1 Construction of ARM-Based Cluster</td>
<td>24</td>
</tr>
<tr>
<td>3.1.1 Configuring and Installing</td>
<td>24</td>
</tr>
<tr>
<td>3.1.2 Setting up the Network</td>
<td>26</td>
</tr>
</tbody>
</table>
# LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Table 1.1: Comparison of Common Cooling Methods [3]</td>
<td>3</td>
</tr>
<tr>
<td>Table 2.1: Thermophysical Properties of Dielectric Fluids and Water at 1 atm and 25 °C [20]</td>
<td>19</td>
</tr>
<tr>
<td>Table 3.1: Fluid Selection [27]</td>
<td>35</td>
</tr>
<tr>
<td>Table 3.2: Test Matrix</td>
<td>36</td>
</tr>
<tr>
<td>Figure</td>
<td>Description</td>
</tr>
<tr>
<td>--------</td>
<td>-----------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Figure 2.1</td>
<td>Effect of Temperature on Performance and Operating Frequency [5]</td>
</tr>
<tr>
<td>Figure 2.2</td>
<td>Temperature Dependence of Subthreshold Leakage Current [7]</td>
</tr>
<tr>
<td>Figure 2.3</td>
<td>Power Consumption with Respect to Temperature [8]</td>
</tr>
<tr>
<td>Figure 2.4</td>
<td>Distribution of Heat Flux and Temperature [9]</td>
</tr>
<tr>
<td>Figure 2.5</td>
<td>Boiling Curve [15]</td>
</tr>
<tr>
<td>Figure 2.6</td>
<td>Schematic of the Typical Boiling Curve of Dielectric Liquids [17]</td>
</tr>
<tr>
<td>Figure 2.7</td>
<td>Effects of Surface Inclination on Saturation CHF of HFE-7100 and FC-72 Dielectric Liquids on Various Surfaces [17]</td>
</tr>
<tr>
<td>Figure 2.8</td>
<td>Thin Heater Pool Boiling Photograph at CHF – for Various Surface Orientations [19]</td>
</tr>
<tr>
<td>Figure 2.9</td>
<td>Open Bath Immersion Concept. Junction-to-Fluid Performance [23]</td>
</tr>
<tr>
<td>Figure 3.1</td>
<td>Overclock Config File</td>
</tr>
<tr>
<td>Figure 3.2</td>
<td>Schematic Diagram of Cluster</td>
</tr>
<tr>
<td>Figure 3.3</td>
<td>Forced Air-Cooled Cluster</td>
</tr>
<tr>
<td>Figure 3.4</td>
<td>Isometric View of Filler Structure to Accommodate Cluster</td>
</tr>
<tr>
<td>Figure 3.5</td>
<td>Assembled View of the Cluster</td>
</tr>
<tr>
<td>Figure 3.6</td>
<td>Initiation of Boiling</td>
</tr>
<tr>
<td>Figure 3.7</td>
<td>Fully Developed Boiling</td>
</tr>
<tr>
<td>Figure 3.8</td>
<td>Cluster Under Immersion Cooling System</td>
</tr>
<tr>
<td>Figure 4.1</td>
<td>Sysbench (100K Iterations) Test on Rpi3 and Rpi2 Cluster under Natural Air Convection</td>
</tr>
<tr>
<td>Figure 4.2</td>
<td>Sysbench (100K Iterations) Test on Rpi3 and Rpi2 Cluster under Forced Air Convection</td>
</tr>
<tr>
<td>Figure 4.3</td>
<td>Sysbench (100K Iterations) Test on Rpi3 and Rpi2 Cluster under Immersion Cooling with HFE7100</td>
</tr>
</tbody>
</table>
Figure 4.4: Sysbench (100K Iterations) Test on Rpi3 and Rpi2 Cluster by Immersion Cooling using HFE 7000 ................................................................. 44

Figure 4.5: HPL Test on Rpi3 and Rpi2 Cluster under Natural Air Convection .......... 45

Figure 4.6: HPL Test on Rpi3 and Rpi2 Cluster under Forced Air Convection .......... 46

Figure 4.7: HPL test on Rpi3 and Rpi2 Cluster under Immersion Cooling with HFE7100 ........................................................................................................ 47

Figure 4.8: HPL Test on Rpi3 and Rpi2 Cluster under Immersion Cooling with HFE7000. ........................................................................................................ 48

Figure 4.9: Combine Sysbench (200K Iterations) + HPL Test on Rpi3 and Rpi2 Cluster under Natural Air Convection ................................................. 49

Figure 4.10: Combine Sysbench (200K Iterations) + HPL Test on Rpi3 and Rpi2 Cluster under Forced Air Convection ...................................................... 50

Figure 4.11: Combine Sysbench (200K Iterations) + HPL Test on Rpi3 and Rpi2 Cluster under Immersion Cooling with HFE7100 .............................................. 51

Figure 4.12: Combine Sysbench (200K Iterations) + HPL Test on Rpi3 and Rpi2 cluster under Immersion Cooling with HFE7000 ................................................ 52

Figure 4.13: Overall Comparison of the Clusters under Sysbench Test .................. 54

Figure 4.14: Overall Comparison of Clusters under HPL Test ............................... 56

Figure 4.15: Combined Sysbench and HPL Test on Clusters ............................... 58
CHAPTER 1
INTRODUCTION

The present work is an experimental approach to study the effect of Two-phase immersion cooling on ARM-based computer clusters for improved performance over conventional cooling methods. This chapter starts with the motivation of the research, outlines the objectives, and finally describes the technical approach to achieve the objectives.

1.1 Motivation

Advancements in high performance of microprocessors have been a major area of research for decades. Millions of transistors are embedded into the processors to achieve higher processing speeds but higher efficiency is still a challenging task to do. One of the main reasons for lagging performance is thermal load. The increase in number of transistors has increased the amount of heat flux. This heat flux is causing the gate delays in the transistors resulting in reduced performance. Hence, efficient cooling is one of the prime factors in order to attain higher efficiencies from the microprocessors.

In the case of supercomputers, where the microprocessors work under heavy loads for extended periods, they tend to generate more heat. Ineffective cooling in such cases can result in significant losses as well as faulty results. Currently, most of the supercomputers are cooled by “air based technologies.” Due to poor efficiency of such air-cooling systems, cooling cost accounts major portion of the datacenter operating cost. In a typical system a series of racks house the clusters and cool air is circulated through them to take away the heat generated. This circulating air transfers heat into
cold water in a chiller, which operates on vapor compression cycle and ultimately rejects heat to the ambient air (atmosphere). The major drawbacks of this technology are thermal cyclic loads on the processor, high carbon footprint, large space requirement, and inefficient cooling. According to a survey, a supercomputer named “Tianhe-1A” consumes around 4.04 MW of electricity and the cost of cooling is about $400 per hour or about $3.5 million per year [1-2].

An alternative to the conventional forced air cooling technology is liquid cooling technology that provides significantly higher heat transfer coefficient (HTC). Table 1 provides a comparison between the heat transfer capabilities of various cooling techniques. Due to its appealing performance characteristics, immersion cooling has grabbed increased attention over the past decade. Immersion cooling takes the advantage of direct contact between the device and the coolant to minimize the thermal resistance between the heat sink and source, and utilizes latent heat of vaporization to extract higher amounts of heat from the surface. In addition, this cooling technology maintains nearly-uniform temperatures due to phase change process, and allows packaging large number of processors close to each other in a compact envelope due to direct liquid contact and high HTC. The working principle of this technique is rather simple. Usually the component or chip to be cooled is immersed in a dielectric liquid, and as the device operates and the surface temperature exceeds the boiling point, the dielectric liquid in contact with this surface starts to nucleate and change its phase from liquid to vapor. The bubbles on the surface grow, detach, and rise to the upper section of a closed, sealed chamber. As the vapor passes over a condenser, it cools down, gets back to liquid state, and drops into the pool. Immersion cooling is considered as a
passive system since it does not require any energy to drive the vapor or to condense it as general facility water can be used in condenser for cooling.

Table 1.1: Comparison of Common Cooling Methods [3]

<table>
<thead>
<tr>
<th></th>
<th>Natural convection</th>
<th>Forced air cooling</th>
<th>Water cooling (recirculating cooling)</th>
<th>Immersion cooling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat transfer coefficient</td>
<td>h = 5 - 30 W/m²K</td>
<td>h = 20 - 400 W/m²K</td>
<td>h = 100 - 1600 W/m²K</td>
<td>h = 800 - 10000 W/m²K</td>
</tr>
<tr>
<td>Q</td>
<td>2 - 9 W</td>
<td>6 - 120 W</td>
<td>30 - 480 W</td>
<td>240 - 3000W</td>
</tr>
<tr>
<td>- Free convection</td>
<td>- Free convection</td>
<td>- Free + forced convection</td>
<td>- Forced convection</td>
<td>- Free convection</td>
</tr>
</tbody>
</table>

Manufacturers of the specialized dielectric coolants (e.g., 3M) has been conducting extensive research to advance this technology and demonstrate its potential benefits. A recent research found that the computing power per square meter in air cooled facility would be 10 kW, while immersion cooling technology can harvest 100 kW of computing power for every square meter due to tighter packing of the electronic devices, resulting in 10 times the lesser floor space when compared to general air cooling system. In addition, the cost on energy consumption can be reduced by 95% when compared to an air cooling facility. Being a passive system with no moving parts, its maintenance cost and operating costs are also lower [4].

1.2 Objectives

Based on the defined motivation, primary objective of this research was to investigate the performance of ARM-based computer clusters using two-phase immersion cooling approach. Different immersion cooling liquids were used to track variation in performance and ultimately the results were compared to those from reference, air-cooled cluster. Secondary objective of this study was to find the variation
In energy consumption with respect to the temperature. Reliability of the system is further studied by running the cluster for extended period.

1.3 Technical Approach

In the current research, objectives were achieved by a three stage technical approach. In the first stage an ARM-based cluster was created using Raspberry Pi (RPi) model 2 and 3. The Raspberry Pi is a small, ARM-based, single-board computer equipped with 1.0-1.2 GHz processor. Three boards of Raspberry Pi are used to form a cluster using the concepts of parallel computing and Message Passing Interface (MPI). Each Raspberry Pi board is addressed as a node in the cluster. Once the cluster is built, a complex problem can be solved by dividing it into bits and executing them at the same time on different nodes. This prototype depicts a supercomputer in a datacenter facility.

In the second stage, an experimental setup was designed to accommodate the cluster and the liquid immersion cooling system. Since one of the dielectric liquids used in this study has a low boiling point (34°C), it was crucial to design a leak proof enclosure to avoid vapor leakage. A 3D printed structure was designed to accommodate all the peripherals of the cluster and to reduce the amount of liquid to be used in the system. Since all the components were placed inside the enclosure, including power supply and network switch, the number of connectors going into the chamber was kept to a minimum.

In the final stage, different benchmarking tests were conducted on the cluster to determine the performance under different cooling methods. Data were acquired in different cooling technologies and compared against the baseline, natural convection.
cooling mode. The measured parameters included junction and ambient temperatures, frequency, computing performance (GFLOPS), and energy consumption.
CHAPTER 2
LITERATURE REVIEW

The main aim of this chapter is to discuss the earlier research done in immersion cooling and its implementation for CPU thermal management, which will act as a base for understanding the science behind our experimental model and to make critical decisions in selecting the input parameters for the test. This chapter begins with a brief introduction to the need for cooling of processors; followed by a detailed overview of immersion cooling and design considerations for two-phase immersion cooling and later focuses on the current research in this field.

2.1 Need for Cooling

2.1.1 Effect of Temperature on Performance of a Microprocessor

Temperature has a direct effect on the performance of a transistor; if the temperature is low, the gate delay is low resulting in higher speeds. Researchers at Intel conducted a study with an i7-4790 processor cooled by a Gelid Silent Spirit Rev. 2 CPU cooler connected to a PWM fan speed controller [5]. The processing speed at different intervals was measured by running a Linpack benchmark and controlling the temperature.

Figure 2.1 shows the effect of temperature on clock speed (MHz) and the performance of the processor (GFLOPS). The frequency dropped by more than 100% when the processor ran for an extended period at a temperature higher than 99°C, resulting in the reduction of performance to its half.
2.1.2 Effect of Temperature on Power consumption of a Microprocessor

Leakage current is the gradual loss of energy from the transistors, which is also considered static power consumption. As the transistors are scaled to nano sizes, the tendency of leakage is becoming higher. A recent study states that the leakage accounts for 40% of the total power consumption for high-performance microprocessors [6]. Leakage current is exponentially dependent on temperature. In general, the leakage current doubles for every 10°C rise in temperature [7].

Figure 2.2 shows the increase in sub threshold leakage current $I_{sub}$, with the increase in temperature. Another factor for the increase in leakage current is the size of the transistor. At constant temperature, since the size of the device decreases the magnitude of leakage current increases.
In order to understand the effect of temperature on power consumption, a test was conducted by using the current high-performance microprocessor i7-2600K, running it at an optimal frequency of 3GHz and varying the operating temperature by controlling the cooling mechanism. As shown in Figure 2.3, as the operating temperature increased from 60°C to 100°C the power consumption also increased by 30W [8].
2.1.3 Effect of Temperature on Lifetime Reliability of a Microprocessor

The increase in the level of integration, reduction in size and increase in clock speeds of processors has resulted in overheating of the device. High temperature has a serious effect on the lifetime reliability of the system. The addition of multiple units like GPU, processor, etc. on the chip has led to the formation of high heat flux zones in certain areas of the chip, while the remaining part has a low heat flux which results in formation of hot spot. Figure 2.4 shows the distribution of heat flux and temperature on the surface of microprocessor. A hot spot is a region with exceptional high temperature in the processor, which results in damage to internal cores, system instability and the weakening of soldered joints. In general, the reliability of a transistor is exponentially dependent on junction temperature. A difference in ten to fifteen degree of junction temperature can cause the system lifespan to differ by ~2X [9].

![Figure 2.4: Distribution of Heat Flux and Temperature [9]](image)

In order to mitigate the effect of thermal cycling and hot-spot zone, efforts have been made in both design and software architecture areas. The initial step was to simulate the effect of thermal load on a processor by considering the different workload
undergoes throughout its lifetime. Many analytical simulation models have been
developed to analyze the effect of temperature and voltage in the lifetime reliability but
not all of them consider all the working constraints a processor handles during its
working life.

In a research conducted by Huang Lin & Xu [10] on the reliability of
microprocessor, he has developed a simulation framework named as “Agesim.” The
concept of this framework is to study the repetitive workloads running on a processor
which will be consistent for its lifetime. Information like temperature and voltage values
are recorded to plot the usage strategy of a processor. If we find a quantity named
aging rate, it can capture the impact of processor’s usage strategy on its aging effect
and simultaneously the aging rate will be independent of time. In other words, reliability
will be a function of aging rate and time. Finally, reliability can be calculated by using
arbitrary failure distribution at any time in the service life of the CPU [10].

2.2 A Detailed Review of Immersion Cooling

Considering the effect of temperature on the overall efficiency of the system, it is
important to effectively cool the CPU. The conventional way is Natural air convection,
where the extended surface is attached to the source to remove heat by increasing
contact surface area. As this is a passive technique, the heat transfer coefficient is not
adequate to effectively remove the heat from high heat flux sources. Forced convection
is one of the most frequently used cooling technique; the key concept is to blow the air
over the surface to increase the heat transfer coefficient. The application of this system
differs with respect to the magnitude of heat. When applied to something like a data
center, a chiller or vapor compression system is employed to supply cool air. This makes the system expensive and has a high carbon footprint.

Immersion cooling is another technique, where the heat source is immersed in a liquid bath. Single-phase immersion cooling proves to be an ineffective method, as the fluid thermal properties are quite low. Whereas Two-phase immersion cooling seems to be the promising one. In the latter method as the liquid in contact with the hot surface turns into vapor this transition requires high heat energy which results in higher heat removal. Since the system is passive it requires very less amount of energy to operate when compared to the forced air convection system. A Large number of CPU’s can be kept side by side reducing the size of the facility. In Addition to that, the junction-to-fluid thermal resistance can be maintained less than 0.06°C/W at 200W enabling very tight junction-to-water thermal coupling.

In order to understand the mechanism and physic behind the functioning of two-phase immersion cooling system, we have to know the fundamentals of boiling and the factors that contribute to its efficient operation.

Immersion cooling is the process of cooling a heat generating device by completely immersing it in a thermally conductive liquid to remove the heat with the help of passive phenomena’s like natural convection and latent heat of vaporization. The use of immersion cooling is found in different sectors including solar farms, nuclear medicine imaging applications and electronics cooling [11-12].

To understand how an immersion cooling mechanism works, and the factors that contribute to its efficient operation, we will have to understand the boiling process. The significance of boiling in a heat transfer mechanism was first studied in 1756 when
Leidenfrost [13] discovered a varying number of drops of water into the bowl of heavy metal spoon heated to different temperatures. A slightly heated spoon when dipped in a cup of water had bubbles on its surface as the temperature of the spoon was slightly higher than the normal boiling point of water, but when the spoon was red-hot, the water would pull into spherical drops and vibrate in the spoon and then convert into steam after about a minute. This stood as a base for further research by different scientists to understand boiling process and its contribution to heat transfer.

A study conducted by Nukiyama [14] in the year 1934 is considered the first modern boiling transition curve. He used a horizontal wire as both a heater and a resistance thermometer through which he measured the heat flux $q''$ and the wall superheat ($\Delta T$). First, the wall superheat raised a little when the heat flux was very high, then it rapidly increased to a thousand degrees following that when the heat flux was reduced to a lesser value the wall superheat remained the same. Finally, the wall superheat dropped back to a negligible value. The graph was plotted for $\Delta T$ vs $q''$.

Later in 1937, Drew and Mueller [15] did a qualitative experiment in which they approximated a controlled surface temperature situation. Their strategy involved heating a copper tube from inside with a condensing steam and boiling more volatile liquid outside by this they were successful at running the test at a saturated temperature and atmospheric pressure and plotted the graph for boiling curve by interchanging the axis $q''$ vs $\Delta T$.

There are five different regions in this curve, which are as follows

1. Natural convection

   Nucleate boiling which is further classified into two regions:

2. Region of isolated bubbles at lower heat flux
3. Region of columns of bubbles at high heat flux
4. Transition boiling region
5. Film boiling regime

Figure 2.5 represents a graph drawn showing the boiling curve of water at 1 atmospheric pressure, with heat flux \( q \) against wall superheat \( \Delta T = T_{\text{surface}} - T_{\text{sat}} \). The heater is submerged in the liquid, as the temperature of the heater rises the liquid around the surface becomes less dense causing it to move upwards resulting in natural convection.

Further increasing the heat flux bubbles start to develop on the surface of the heater, which represents the first phase of nucleate boiling. As the heat flux increases bubbles start to appear throughout the surface, on the further rise of heat flux the number of bubbles forming from a single pore increase to an extent that the series of bubbles moving up combine to look like a jet or column which represents the second phase of nucleate boiling. The end of this stage is marked as Critical Heat Flux (CHF), it is the point that represents the system can function without failure under fully developed nucleate boiling.

Once the CHF mark is reached the value of heat flux decreases with increase in wall superheat. As the \( \Delta T \) value further increases the surface gets totally covered by the vapor and due which the heat flux drops to a minimum value shown by \( q_{\text{min}} \) on the graph. On further increasing the \( \Delta T \) a stable layer of vapor is formed that results in an increment of heat flux this stage is called represented as film boiling as the vapor film acts as a barrier to heat transfer.
2.2.1 Boiling Process

The key factors like the bubble generation, departure diameter, departure frequency and the active nucleation site density of the bubbles produced on the heated surface play important role in heat transfer. These parameters depend on a number of variables like applied heat flux, wall superheat, bulk liquid temperature, system pressure, heater conditions like orientation, geometry, surface characteristics and liquid properties [16].

Mostly, surfaces seem to be smooth to the human eye but there are always tiny grooves on the surfaces created by chattering and pitching of tools during machining. This sometimes also results in the formation of microscale holes on the surface. When a liquid is brought into contact with the surface tiny holes or pores stay dry as the surface
tension of the liquid does not allow it to enter the holes resulting in the formation of vapor pockets. Thus the superheated liquid layer above the surface grows sufficiently thick to cause the vapor or gas trapped in the cavity or crack to overcome the surface tension force and grow. As the bubble nucleates, it grows through evaporation of liquid at the liquid-vapor interface.

Figure 2.6 shows a graph drawn against heat flux and surface temperature. Different stages of bubbles and their effect in the electronic cooling is shown. NC represents the inclined line for natural convection, which results in temperature overshoot at very low heat flux. Region-1 is discrete-bubbles region shows the beginning of active nucleation sites, due to increase in surface temperature the nucleate boiling heat transfer coefficient increases. Region-2 shows the fully developed boiling region, the density of active nucleation site and heat transfer coefficient is high, this can be said because of steep slope of curve. The maximum nucleate boiling heat transfer coefficient occurs at the end of this region. At region-3 bubble coalesce near the surface resulting in increased temperature and heat transfer resistance. [17]

2.3 Factors Affecting the Boiling Process

2.3.1 Orientation

Orientation of the heat source in a pool has a significant effect on the critical heat flux. Large amount of research has been done in this area to interrelate the angle of inclination and CHF, Ishigai et al[18]. are one of the first investigators to work on the orientation effects in pool boiling CHF. In their research, they found that CHF value is minimum when the heated surface is oriented in the horizontal, downward-facing position (180°) because the vapor accumulates and prevents liquid access to the
heated surface. Additionally, he found that CHF decreased with increase in the heater area when the heater to the surrounding insulation surface area ratio was held constant.

Mohamed S. El-Genk [17], has worked to check the effect of inclination on CHF, he conducted tests with two different immersion cooling fluids FC-72 and HFE-7100 on different types of metals with different sizes.

The inclination angles from horizontal (upward facing) to 180° with downward facing. By looking at the graph above, we can figure out that different metals with different sizes
have different values of CHF, under different dielectric liquids. One thing that remains common is the CHF value slowly decreases from 0° to vertical facing of 90°, but from 90° to 180° the value of CHF drastically decreases. Ultimately, CHF is high if heat surface is horizontal facing upwards and low when it faces downwards.

Figure 2.8 shows rising of bubbles at different angle of inclinations. First comes the upward facing orientation which includes 0° and 30°. Here the vapor moves vertically off the surface by buoyancy. The second stage is the near-vertical region, containing surface orientations at three different angles say 90°, 120°, and 150°. The vapor travels along the surface and instabilities cause the liquid-vapor interface to be wavy. Finally, at orientations near 180° stratification of the vapor along the heated surface occurs. This third region is the downward-facing region [19].

Figure 2.8: Thin Heater Pool Boiling Photograph at CHF – for Various Surface Orientations [19].
2.3.2 Surface Roughness

Surface roughness is a critical criterion in formation of a nucleation site and ultimately in high heat transfer. Thus, many surface enhancement strategies with the intention to increase the boiling heat transfer under different dielectric fluids have been developed. These surfaces can be broadly classified into three categories.

- Coated surfaces – surface features are directly coated onto the substrate surfaces for example electrochemical deposition, chemical vapor deposition and direct powder sintering.

- Intrinsic surfaces – surface features that are intrinsically part of the material’s surface like surfaces developed using MEMS/NEMS technologies, CNC machining, additive manufacturing (AM) and other advanced manufacturing techniques.

- Hybrid surfaces – surface features that consist of combinations of coated and intrinsic surfaces. [20]

In an surface enhancement experiment conducted by Rainey and You [21] on epoxy binding technique by using diamond particles of size 8-12 μm on copper substrate was tested under pool boiling. The test was conducted at atmospheric pressure with working fluid as FC-72. It was found that the heat transfer coefficient (h) increased by 300% at 0° surface orientation, while the value of CHF was increased by 64% with reference to plane surface.

In another experiment conducted by Guglielmini et al. [22] on enhanced surface with array of copper pin fins of square cross section was itched using EDM. The width of pin fin was 0.4 to 1.0 mm, and the length being 3 mm while spacing between adjacent pin fin were 1.2 mm. Under saturated pool boiling under atmospheric pressure with FC-72 as working fluid. It was found that the overall heat transfer coefficient (h) increased by 12,000 W/m².K.
2.3.3 Fluid Selection

Fluid selected for immersion cooling plays a vital role in heat transfer coefficient. Although, thermal conductivity is a critical factor in liquid selection but other properties like electrical inertness, surface tension and dynamic viscosity should be considered for efficient operation and reduced risks. As the coolant fluids are in direct contact with the electronic heat sources, dielectric fluids such as fluorocarbon fluids (FC-72, FC-87 and PF-5060) and hydrofluoroethers (HFE-7000, HFE-7100, HFE-7300) are often the fluids of choice due to their chemical compatibility and high dielectric strength. In addition, due to their low boiling points, dielectric fluids are also highly desirable for boiling heat transfer applications to preserve the die temperatures within the recommended range of 80°C to 130°C. However, the low surface tension and high-wetting nature of these fluids which enable the fluids to penetrate deep into the cavity sites, have resulted in noticeably higher incipient superheats as compared to conventional fluids such as water. [20]

Table 2.1: Thermophysical Properties of Dielectric Fluids and Water at 1 atm and 25 °C [20]

<table>
<thead>
<tr>
<th></th>
<th>FC-72</th>
<th>FC-87</th>
<th>HFE-7000</th>
<th>HFE-7100</th>
<th>HFE-7300</th>
<th>Water</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boiling point (°C)</td>
<td>56</td>
<td>30</td>
<td>34</td>
<td>61</td>
<td>98</td>
<td>100</td>
</tr>
<tr>
<td>Liquid density (kg/m³)</td>
<td>1680</td>
<td>1650</td>
<td>1400</td>
<td>1510</td>
<td>1660</td>
<td>997</td>
</tr>
<tr>
<td>Liquid dynamic viscosity (kg/m·s)</td>
<td>6.4×10⁻⁴</td>
<td>4.5×10⁻⁴</td>
<td>4.5×10⁻⁴</td>
<td>5.8×10⁻⁴</td>
<td>11.8×10⁻⁴</td>
<td>8.9×10⁻⁴</td>
</tr>
<tr>
<td>Liquid specific heat (J/kg·K)</td>
<td>1100</td>
<td>1100</td>
<td>1300</td>
<td>1183</td>
<td>1140</td>
<td>4182</td>
</tr>
<tr>
<td>Liquid thermal conductivity(W/m·K)</td>
<td>0.057</td>
<td>0.056</td>
<td>0.075</td>
<td>0.069</td>
<td>0.063</td>
<td>0.61</td>
</tr>
</tbody>
</table>
2.4 Non-Thermal Design Considerations for Two-Phase Immersion Cooling

2.4.1 Electrical Properties

CPUs and the PCBs are designed to function in air, a medium which has its own dielectric constant. Whereas in the case of two-phase immersion cooling mechanism the whole system is completely immersed in a bath, this will have an impact on the dielectric constant of the liquid. The movement of vapor bubbles within the liquid will cause transient spatial discontinuities in dielectric properties of the fluid. These properties depend upon the frequency the system operates. A study on “performance of passive 2-phase immersion cooling of server hardware” [23], has found that there was significant effect on insertion losses above few GHz in a bath of HFE fluid, which makes it unsuitable for high frequency applications.

2.4.2 Material Compatibility

Many PVC based materials contain oily plasticizers, which are added to aid the manufacturing processes but are not needed in the end use application. These materials release oils into the fluid while in operation. These oils will coat the fluid surface impending heat transfer. It will also fill nucleation sites on the heat source leading to subsequent problems with boiling incipience. An experiment was conducted by dipping the Asus KFSN5-D motherboard in HFE placed in Soxhlet extractor, the duration of experiment was for 10 days. After evaporation of HFE 0.01g of greenish solid residue was remained. The residue was found to contain components of aromatic...
carboxamide, ester and carboxylic acid functional group. In order to mitigate the effect of oils in the bath small amount of perforated sachet of activated carbon can be added to clean the fluid. While it is mandatory to clean the system and all materials using vapor degreasing process [23].

2.4.3 Effect of Non-Condensable Gases (Air)

Air has a significant impact on the condensation heat transfer resulting in higher operation temperatures when compared to optimal temperature. In case of systems that eject air will result in loss of fluid as the volume of air that is released contains some amount of fluid vapor. Even if the air accommodates on the upper end system leaving the liquid oxygen free, which will cause corrosion of the metallic components and may exacerbate thermal decomposition of HFE fluids operating at very high temperature.

There are many ways to minimize air infiltration. The first one is to use a volatile fluid so the system pressure will not fall below the atmospheric pressure. Other strategies include use of bellows and degas techniques. While in case of datacom equipment’s it is advised to operate the system at very near to atmospheric pressure.

2.4.4 Effect of Water

Water dissolved in the fluid or the vapor in the headspace of the system does not have a significant effect on the system. However, the presence of water in the HFE fluids operating at very high temperatures can result in thermal decomposition of the fluids. Water solvates the breakdown products and becomes corrosive [23].

2.5 Implementation of Two-Phase Immersion Cooling in Servers

Phillip E, Tuma [24], has done a research on the Open bath immersion cooling concept (OBI), a concept named for immersion cooling of servers in a datacenter. Here
servers are immersed side-by-side in open baths of a volatile dielectric fluid operating at atmospheric pressure. As the servers generate heat, fluid around it takes it and changes its phase. The vapor generated rises up, which is then cooled by a condenser and the fluid falls back into the container. These system has advantages like reliability, power consumption and easy maintenance. Isothermal operation and fire protection are intrinsic to the technology.

His research also included system thermal performance. He divided this into two parts. Chip-to-fluid performance, which talks about the ability of a heat transfer from the origin of heat to the fluid. A typical CPU package with 100μm integrated heat spreader coated with boiling enhancement coating has a heat transfer coefficient of \( h > 10 \text{ W/cm}^2\text{-K} \) at heat fluxes exceeding 30W/cm².

![Figure 2.9: Open Bath Immersion Concept. Junction-to-Fluid Performance [23]](image)

The chip-to-fluid thermal resistance of passive immersion is about 0.015°C/W higher than that achievable with a water microchannel cooler. The other one is fluid-to-water performance; in this case the heat transfer efficiency from outside condenser water and the vapor is studied to design a suitable condenser.
Power density is the next concerning factor, when considered an air-cooled system. The density of a typical air-cooled server chassis is 0.04 Kw/l. although immersion cooled server with a PCB carrying 20X14 heaters each 200W were able to be placed in adjacent to another PCB with a gap of 4 mm. This system could handle a heat flux of 11.7W/cm² when compared to Cray X1E spray-cooled supercomputer having heat flux of 1.7W/cm². [24]

Fluid loss is a major drawback of this system as it effects both the economy and the life of human beings working around it, but a good understanding of the loss mechanism we can reduce it. As perfectly sealed container can reduce higher amount of losses. By trapping the vapor, most of the fluid can be condensed and sent back to the container. Based on some assumptions a calculation is done to predict the quantity and cost incurred in fluid loss, for a 80kW bath cost of $123/yr. of fluid loss.
CHAPTER 3
EXPERIMENTAL SETUP AND PROCEDURE

The following chapter describes the experimental setup and procedure used to conduct this research. Detailed description of construction of ARM-based cluster, selection of working fluids, and experimental setup design is presented. Finally the chapter ends with the overview of the types of tests conducted.

3.1 Construction of ARM-Based Cluster

The main base of this experiment is to test the operation and performance of an ARM-based cluster, which comprises four processors connected using MPI so that they can solve a larger arithmetic problem by dividing in bits and solving it simultaneously.

Raspberry Pi model 2 and 3 are used to form a cluster. These are commodity grade, single-board computers equipped with a 1.0 - 1.2GHz 64-bit quad-core ARM v8 processor and 1GB of RAM. An SD card is used to store the operating system and also serves as hard drive.

Construction of cluster is done in four steps, which are as follows.

3.1.1 Configuring and Installing

Raspberry Pi comes with default configuration, as to test the high end performance the CPU has to be overclocked so that we can drive the processor to its core limit. After testing the CPU with a benchmarking program with different input configuration parameters, a set of optimal working parameters are considered. Figure 3.1 shows overclocking parameters with their values.
Along with overclocking the processor, there are different packages that has to be installed in order to operate the server and support another programs. As Raspberry Pi runs upon Linux operating system, it is easy to use the terminal window to install all the required software’s, the command to install a package is “sudo apt-get install <package name>.” Term ‘sudo’ gives the administrator permission to make modification to the system.

The first package is “build-essential manpages-dev” which downloads a ‘C’ language based compiler and library in order to write and execute programs. “gfortran” is the other GNU Fortran based compiler for gcc.

The key component in functioning of a cluster is to share the file or directories with others in the network. With the help of NFS (Network file system) every system can access file on the every other system without any delay. The package to install is “nfs-common nfs-kernel- server.” Similarly, “openssh-server” is another tool to control and transfer files across systems. MPI is the other critical tool to transfer data, it acts as an interface between the system. The command “openmpi-bin libopenmpi-dev open mpi-doc” will install the software as well as the libraries required to run the software.
3.1.2 Setting up the Network

The first step in setting up the network is to create a local network using the master node. The processes is simple, initially software is required to create the network are installed. The commonly used software is "DNSMASQ." Once the software is installed, the device should be disconnected from the main server and the 'dhcpd.conf' file is to be edited. A 'static ip address' and 'netmask id' is selected, most commonly used once are 192.168.0.1 and 255.255.255.0 respectively written at the bottom of the file. Next step is to configure the DHCP server software 'dnsmasq' this can be done by following commands.

// cd /etc
// sudo mv dnsmasq.conf dnsmasq.default
// sudo nano dnsmasq.conf

The first command is to change the directory, while the second command will move the dnsmasq.conf file and make it default. The third command will open the file in editable mode where the instructions are given to listen to the dhcp on the Ethernet port of the pi, and range of IP address are specified over the local network. Finally a command 'dnsmasq restart' will reboot the server and new devices can be added to the local network by simply plugging in to the network switch.

All the devices connected to the network are assigned with a static IP-address, and all of them has to have the list of devices in the network with their name and IP-address in the 'hosts' file of every device. This will allow them to interact and transfer data among the network. In order to check the functionality the SSH function is used to access other system in network in remote mode.
3.1.3 Creating a User Account and Mounting Drives

Raspberry pi usually runs with administrator settings all the time. In the case of parallel computing all the devices on the network access files on the master node, due to administrator settings there is a feasibility for the slave nodes to modify the files. To avoid this a user account is created on all the nodes which will be used to run the parallel computing programs. The command “useradd” will create the account and password and other preferences can be made to this account. Once all the accounts are created a key is generated which will allow the device to access all other devices without permission.

Since the master node is the place where the parallel processing programs are executed a directory is created in the user account, which will store all the programs and allow other slave nodes to access during execution. Once the directory is created all the slave nodes are mounted to the master node. This is done with the help of “rpcbind” and “nfs-kernel-server.” Once activated all the slaves nodes on the network will automatically mount the drive and directories.

To check the functionality to this mounting system a dummy program is saved in the directory of the master node. As all the drives are set to automatic mounting the program will reflect in all the slave nodes.

3.1.4 Testing the MPI

Finally the cluster is ready to run the program simultaneously on all the cores. To test the working of a cluster, let’s shoot a basic C-program to print the value of “π.” The program to be executed is saved in the directory of the master node.

```
// mpicc -o pi_c pi.c
// mpiexec -n 4 rpi0,rpi1,rpi2,rpi3 pi.c
```
The first command will compile the program for errors, as no errors are detected an executable is saved in the same directory. The second command will execute the file on all the cores mentioned. Input parameters like number of core to run is given as four, and their names are specified as rpi0, rpi1, rpi2 and rpi3. This will allow the program to be execute on all the four cores.

3.2 Benchmarking Programs

There are several benchmarking programs to test different aspects of a processor. To get the overall performance and following the standards set in testing the top 500 supercomputers following programs were selected.

3.2.1 Sysbench

SysBench is a modular, cross-platform and multi-threaded benchmark tool for evaluating OS parameters like CPU performance, memory, file I/O, and multithread performance. [24] The program is coded to find the largest prime number in a given range of numbers. As a very high range is given as input say 200,000, it requires the processor to operate at higher clock speeds. Since it is a simple arithmetic problem, it can easily be divided in bits so that all cores can work simultaneously.

Following are the parameters that can be tested by sysbench.

- File I/O performance
- Memory allocation and transfer speed
- POSIX threads implementation performance [25]

3.2.2 HPL

HPL stands for high performance linpack, one of the most widely used benchmarking program for cluster computing. A software package solves a dense linear
system in double precision (64 bits) arithmetic on distributed-memory computers. The HPL package provides a testing and timing program to quantify the accuracy of the obtained solution as well as the time it took to compute it. [26]

The performance of this software depends upon large number of factors, some of them include interconnection network, and memory allocation. The algorithm of this program is written in such a way that it is scalable while the parallel efficiency is maintained constant in accordance to the processor memory.

HPL calculates linear system of equations of order n. The input parameters like the problem size N, (P * Q) size of grid which is equal to the number of processors the cluster has, and the block size in the grid NB. The result is calculated in terms of Giga floating point operations per second (GFLOPS) and time measure in seconds.

3.3 Measurement Technique

The objective of this study is to calculate the performance, power consumption, and reliability of the system under different cooling mechanisms. In order to measure the performance of the system, two different units are considered. The first one is GFLOPS, and the second one is by measuring the time consumed to execute the program and errors in the output. As the junction temperature has a direct impact on the performance, it is recorded at an interval of every 10 seconds during the program execution. Finally, the frequency at which the CPU operates is recorded which majorly depends upon the load and temperature.

In this study the selected benchmarking programs give the output in terms of GFLOPS and time (sec), while temperature is measured by operating device itself.
There is a built-in sensor, which monitors the junction temperature. A simple command will record the temperature at a given interval.

In order to calculate the power consumption (W), which is the product of voltage (V), and current (mA), a USB multimeter is used to record the supply and fluctuations. Other factors such as the ambient temperature in case of natural convection, the surrounding temperature is measured by a K-type thermocouple. While in the case of forced convection, the same thermocouple is used to measure the temperature of air, while the velocity of air passing over the heat sink is measured with the help of anemometer. To measure the pressure and temperature in the case of Two-phase immersion cooling, a sensor module ‘sense hat’ is used by attaching it to a Raspberry Pi.

3.4 Experimental Setup

The setup consists of three Raspberry Pi boards. They are stacked one upon another using threaded columns to form a cluster. The distance between two consecutive boards is maintained as 10 mm. All the Raspberry Pi boards are attached with Aluminum-based heat sink to their SoC’s to increase the contact surface area. A USB power supply unit is used to supply 5 V of electric charge consistently to all units. In order to form virtual connection among all the Raspberry Pi’s, a 10/100 Mbps five port network switch and Cat5e cables are used. Figure 3.2 shows the schematic diagram of the setup in the case of natural air-cooling.

3.4.1 Forced Air-Cooled Setup

In case of forced air-cooling all the connections and orientation remains similar to the natural convection, only difference is a fan provided to blow air on to the heat sink parallel to the surface of SoC. Anemometer is used to measure the velocity of air over
the fin. The velocities over the surface of top, middle, and bottom Raspberry Pi’s were 2 m/s, 1.3 m/s, and 1.5 m/s respectively.

Figure 3.2: Schematic Diagram of Cluster

Figure 3.3: Forced Air-Cooled Cluster
3.4.2 Liquid Cooled Setup

The name two-phase immersion cooling itself represents that the mechanism has a phase change process. Since the liquid phase of coolant changes to vapor the experiment should be conducted in an enclosed chamber with minimal openings to the atmosphere. A transparent acrylic container is selected as a housing to the mechanism.

There are few design constraints to be considered in order to efficiently operate the setup. Firstly, as there is high possibility for the vapor to leak because of the number of wired connections into the chamber. In order to reduce the opening created by the wires all the peripherals required to operate the cluster are to be placed inside the container. This has reduced the number of wires going in to the chamber by 95%, ultimately resulting in reduced gap for leakage.

The second constraint is the amount of liquid used to operate the cluster. HFE is an expensive dielectric fluid, and one of the reasons of the higher cost incurred in this type of cooling technique is the fluid cost. To reduce the quantity of fluid consumed and to accommodate all the equipment’s in rigid manner a filler is designed that will support all the parts, simultaneously reduce the fluid quantity. Figures 3.4 and 3.5 show the 3D design of filler and the 3D printed model.

Finally, parts for condensation system are to be carefully selected to efficiently cool the vapor in order to avoid increase in system pressure. A copper heat sink capable of handling 95 W of heat load was selected as a condenser. The finned part of the sink is placed facing the vapor in the chamber while the flat part is attached to aluminum heat sink facing the atmosphere. A fan is used in case of excessive load to increase the heat transfer coefficient.
Figure 3.4: Isometric View of Filler Structure to Accommodate Cluster

Figure 3.5: Assembled View of the Cluster
Figure 3.6: Initiation of Boiling

Figure 3.7: Fully Developed Boiling
3.5 Coolant Properties

Two fluids are considered in the present work to implement two-phase immersion cooling, namely HFE 7100 and HFE 7000. The chemical name for HFE 7100 is methoxyperfluorobutane, it has low global warming potential (GWP) and it is a non-flammable liquid. The HFE 7000 chemical name is methoxyheptafluoropropane. The boiling point of this fluid is 34°C at atmospheric pressure [27].

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Boiling point (°C)</td>
<td>100</td>
<td>34</td>
<td>61</td>
</tr>
<tr>
<td>Liquid density (kg/m3)</td>
<td>997</td>
<td>1400</td>
<td>1510</td>
</tr>
<tr>
<td>Liquid dynamic viscosity (kg/m-s)</td>
<td>8.9×10⁻⁴</td>
<td>4.5×10⁻⁴</td>
<td>5.8×10⁻⁴</td>
</tr>
<tr>
<td>Liquid specific heat (J/kg·K)</td>
<td>4182</td>
<td>1300</td>
<td>1183</td>
</tr>
<tr>
<td>Liquid thermal conductivity (W/m·K)</td>
<td>0.61</td>
<td>0.075</td>
<td>0.069</td>
</tr>
<tr>
<td>-----------------------------------</td>
<td>------</td>
<td>-------</td>
<td>-------</td>
</tr>
<tr>
<td>Latent heat of vaporization (kJ/kg)</td>
<td>2257</td>
<td>142</td>
<td>112</td>
</tr>
<tr>
<td>Liquid surface tension (mN/m)</td>
<td>72</td>
<td>12.4</td>
<td>13.6</td>
</tr>
<tr>
<td>Flash point</td>
<td>No flammability</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td>Toxicity</td>
<td>No</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>ODP</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>GWP</td>
<td>0</td>
<td>530</td>
<td>320</td>
</tr>
<tr>
<td>Freezing point, °C at atm. pressure</td>
<td>0</td>
<td>−122.5</td>
<td>−135</td>
</tr>
<tr>
<td>Boiling point, °C at atm. pressure</td>
<td>99.98</td>
<td>34</td>
<td>61</td>
</tr>
<tr>
<td>Critical temperature, °C</td>
<td>373.94</td>
<td>165</td>
<td>195.3</td>
</tr>
<tr>
<td>Critical pressure, MPa</td>
<td>22.06</td>
<td>2.48</td>
<td>2.23</td>
</tr>
</tbody>
</table>

Table 3.2: Test Matrix

<table>
<thead>
<tr>
<th>Device Model</th>
<th>Cooling Mode / Coolant</th>
<th>Benchmarking Tests</th>
</tr>
</thead>
<tbody>
<tr>
<td>RPI 3 (3 - pi's)</td>
<td>NC / air</td>
<td>Sysbench (100K itr.)</td>
</tr>
<tr>
<td></td>
<td>FC / air</td>
<td>Test-1</td>
</tr>
<tr>
<td></td>
<td>IC / HFE-7100</td>
<td>Test-2</td>
</tr>
<tr>
<td></td>
<td>IC / HFE-7000</td>
<td>Test-3</td>
</tr>
<tr>
<td>RPI 2 (3 - pi's)</td>
<td>NC / air</td>
<td>Test-4</td>
</tr>
<tr>
<td></td>
<td>FC / air</td>
<td>Test-5</td>
</tr>
<tr>
<td></td>
<td>IC / HFE-7100</td>
<td>Test-6</td>
</tr>
<tr>
<td></td>
<td>IC / HFE-7000</td>
<td>Test-7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Test-8</td>
</tr>
</tbody>
</table>

NC: natural convection, FC: forced convection, IC: immersion cooling
CHAPTER 4

RESULTS AND DISCUSSION

4.1 Sysbench (100K Iterations)

Figures 4.1 to 4.4 include results from Sysbench (100K iteration) tests with both clusters of Raspberry Pi model 2 and 3, in terms of core temperature and frequency as a function of time. A quick comparison of data reviles that the raspberry pi 3 cluster takes almost same amount of time to execute the program under different cooling methods except Natural convection mode. The reason for this consistent execution time is that the temperature is kept below the critical temperature limit set on the processor. Unless the processor reaches the core temperature limit, it operates at same performance level. Since the average junction temperature reaches beyond the preset limit in case of Natural convection the execution time increases by 40%.

In case of Raspberry Pi 2 cluster, a more consistent execution time is noticed with respect to the average junction temperature. The variation in time consumption is minute but it clearly shows that a slight difference in operating temperature of the cluster directly impacts the cluster performance. On comparing two clusters of model 2 and 3, difference in the time required to execute a program is seen by 35%, which is mainly because the clusters operate at different frequency levels.

In addition to execution time, the overall energy consumption shows significant variation with respect to the temperature. Raspberry pi 3 cluster cooled by natural convection cooling mode shows the higher amount of energy consumption. Since no external cooling is provided to the cluster, the operation temperature reaches higher limits resulting the cluster to draw more power, and at the same time the processing
speed of cluster decreases due to increase in temperature. Further, both high power consumption and extended operation time results in higher energy consumption.

In all the other cases, the energy consumed by the cluster remains almost same. Only the external cooling consumption by the fan varies. In Immersion cooling mode where HFE7000 fluid is used, the liquid boiling point is 34°C. With HFE7000 boiling point is low, $\Delta T$ with ambient air is low, and that requires higher air flow rate to condense. While in the case of HFE7100, the boiling point of the fluid is 61°C, $\Delta T$ is higher; you need less air flow rate to reject the same heat.

On comparing the cooling methods like Liquid cooling v/s Air cooling, a major damaging phenomena is noticed. In case of Immersion cooling the cluster steadily increases the temperature once the program is started and has a steady decrease on the compilation. On the other hand, temperature abruptly changes on the beginning and end of the program, which will cause thermal cycling and it leads to weakening of solder joints and lower reliability of the system.

4.2 Tests with High Performance Linpack (HPL)

Figures 4.5 to 4.8 include results from HPL tests with both clusters of Raspberry Pi 2 and 3, in terms of core temperature, frequency as a function of computing performance. The important factor that is measured in this test is the performance of cluster, which is measured in terms of GFLOPS. On comparing the results of Raspberry Pi 3 cluster under different cooling methods, it is clear that performance varies with temperature.
In the worst case scenario, i.e, natural convection mode all the nodes in the cluster crash on implementing the HPL test as the temperature starts to build up and reaches its critical operation limit.

Raspberry pi 3 cluster operates at 20% higher frequency when compared to the Raspberry Pi model 2 cluster. Even though the difference in operating frequency between both the clusters is 20%, the computing performance of the RPi3 cluster shows as 4X greater to that of RPi2. Similar to previous tests, this test also shows a direct relation of execution time with respect to operating temperature. The execution time increases with increase in temperature. While it increases with the decrease in frequency.

4.3 Combined Sysbench (200K Iterations) and HPL

Figures 4.9 to 4.12 include results from combined Sysbench test with 200K iterations and HPL tests with both clusters of Raspberry Pi 2 and 3, in terms of core temperature, frequency as a function of computing performance and execution time. To simulate the extreme or peak load conditions the clusters are tested with both the benchmarking tests at the same time. The Sysbench program is first started to calculate first 200K prime numbers. This would provide enough load on to the processors and simultaneously they run for extended period, as the number of iterations are large.

When the cluster is half way to execute the Sysbench, another program HPL is started to check the performance of cluster under extreme load. Simultaneously, this approach allows to study the increase in energy consumption and reliability of the system.

The time taken to execute the sysbench program increases about 35% when compared to running the sysbench test with 200K iterations alone. The variation in this time consumption under the influence of FC and IC modes is minimal. On the other
hand, the performance of the cluster drops by more than 176% compared to running the HPL alone, since both programs are running at the same time. A maximum increase of 221% is recorded in overall energy consumption. From these data, it can be summarized that the energy consumption increases when the cluster process high loads, due to increase in operation time. On analyzing the plots, I found that Immersion cooling technology was efficient at maintaining the temperatures that reduces thermal cycling and further providing higher reliability to the system.

Test – 17 is avoided in order to save the processor from permanent damage in case of Raspberry Pi model 3 natural convection cooled cluster. Since the temperatures exceeded the working limit in Test – 9 and caused the cluster to shut down. As this test is the combination of both programs there is high feasibility for the system to permanently crash due to extreme temperatures for higher amount of time.

4.4 Overall Effects of Cooling Mode on Cluster Performance and Energy Consumption

Figure 4.13 presents results of Sysbench test for two clusters, and illustrates the effect of cooling mode on execution time, total energy consumption, and max junction temperature. The RPi3 cluster takes about same time to execute in all cooling systems except the natural convection mode. The temperatures in this mode go beyond processors optimal working limit resulting in decreased frequency and increased execution time. On the other hand, RPi2 cluster has minor fluctuations in execution time with respect to the temperature.
Figure 4.1: Sysbench (100K Iterations) Test on Rpi3 and Rpi2 Cluster under Natural Air Convection
Figure 4.2: Sysbench (100K Iterations) Test on Rpi3 and Rpi2 Cluster under Forced Air Convection
Figure 4.3: Sysbench (100K Iterations) Test on Rpi3 and Rpi2 Cluster under Immersion Cooling with HFE7100
Figure 4.4: Sysbench (100K Iterations) Test on Rpi3 and Rpi2 Cluster by Immersion Cooling using HFE 7000
Figure 4.5: HPL Test on Rpi3 and Rpi2 Cluster under Natural Air Convection
Figure 4.6: HPL Test on Rpi3 and Rpi2 Cluster under Forced Air Convection
Figure 4.7: HPL test on Rpi3 and Rpi2 Cluster under Immersion Cooling with HFE7100
Figure 4.8: HPL Test on Rpi3 and Rpi2 Cluster under Immersion Cooling with HFE7000.
Test – 17

Experiment not conducted to avoid the cluster from failing.

Test - 21

Figure 4.9: Combine Sysbench (200K Iterations) + HPL Test on Rpi3 and Rpi2 Cluster under Natural Air Convection
Figure 4.10: Combine Sysbench (200K Iterations) + HPL Test on Rpi3 and Rpi2 Cluster under Forced Air Convection
Figure 4.11: Combine Sysbench (200K Iterations) + HPL Test on Rpi3 and Rpi2 Cluster under Immersion Cooling with HFE7100
Energy consumption depends on three main factors, i) Execution time, ii) operating temperature and iii) energy consumed by the cooling system i.e, fan. It is clear that RPi3 cluster in natural convection mode consumes significantly large amount of energy due to high operating temperature and execution time. While in other cooling technologies, a variation is recorded even though the execution time is constant due to
operating temperature. The RPi2 cluster operates at comparable temperature but consumes equal amount of energy as that of RPi3 cluster due to increased execution time.

Figure 4.14 shows the overall effects on both the clusters when HPL benchmark program was implemented. A huge difference in system performance is noted in different model clusters. RPi3 cluster performance was 4X larger than that of RPi2 cluster within quarter of time when compared to RPi2 cluster. Max. Junction temperatures of RPi3 cluster were 125 – 150% high when compared to RPi2 cluster. Because of higher execution time the RPi2 cluster has higher amounts of energy consumption.

Figure 4.15 shows the implementation of both the benchmarking programs at the same time to check the performance of cluster under heavy loads. Initially the Sysbench test is started with 200K iterations and during the middle of execution, HPL test is performed. Technically, on a RPi3 cluster Sysbench test should take about 2100 s to execute but due to added load in middle the program execution time increases by 36%. While, the RPi2 cluster showed 26% increase in execution time.

The performance of the cluster with respect to running the HPL benchmark alone decreased by 150-170%. As the RPi3 cluster managed to run on 7.1 GFLOPS while RPi2 cluster could not cross 2.5 GFLOPS. In addition, the overall energy consumption increased when two program were executed at the same time. On RPi3 cluster energy consumption increased from 165 – 221% depending on the operating temperature. While, RPi2 cluster showed 90% increase.
Figure 4.13: Overall Comparison of the Clusters under Sysbench Test
Figure 4.14: Overall Comparison of Clusters under HPL Test
Figure 4.15: Combined Sysbench and HPL Test on Clusters
CHAPTER 5
CONCLUSIONS AND RECOMMENDATIONS

The following chapter starts with the conclusion remarks, then highlights the contribution of this research to the literature and finally outlines some recommendations for future research.

5.1 Concluding Remarks

This study investigated the performance of ARM-based computer cluster using two-phase immersion cooling under two different dielectric liquids HFE-7100 and HFE-7000. The performance of cluster under air-based natural and forced convection approach was used as a reference to compare the difference between liquid and air-based cooling methods. Benchmarking programs Sysbench and HPL were used to quantify the parameters such as computing performance, frequency, execution time, junction temperature, and energy consumption. After analyzing the results following conclusions were drawn.

- High junction temperature in the case of natural air convection cooled RPi3 cluster increased the execution time by 40%, while the operating frequency dropped from 1.26 GHz to 0.8 GHz.
- In general, RPi2 cluster took 35% more time to execute the Sysbench test when compared to RPi3 cluster.
- Energy consumption increased with increase in junction temperature and execution time. The RPi3 cluster under natural air convection approach consumed about 200% more energy when compared to IC with HFE-7100.
• On implementing HPL test on both the clusters the computing performance of RPi3 cluster was 4X higher than that of RPi2 cluster under IC with HFE-7000.

• Due to high load, the combined Sysbench and HPL program reduced the computing performance of the RPi3 cluster by 3X when compared to running the cluster on HPL program alone. The execution time increased by 170% while the energy consumption increased by 220% on comparing with the single program execution.

5.2 Recommendations

The following topics can be recommended for future research directions that will expand the current study:

• Computing performance of GPU cluster can be studied under two-phase immersion cooling approach.

• Boiling enhancement technologies can be used on the surface of the processor to promote heat transfer and further increase the performance.
REFERENCES


[25]. https://launchpad.net/sysbench (Last viewed on 4/26/17)
