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Experimental Study of Flow Analysis in Single Phase Immersion cooling Using Tomographic PIV

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EXPERIMENTAL STUDY OF FLOW ANALYSIS IN SINGLE PHASE IMMERSION COOLING USING TOMOGRAPHIC PIV

by

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THESIS

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Satyam Saini

ABSTRACT

EXPERIMENTAL STUDY OF FLOW ANALYSIS IN SINGLE PHASE IMMERSION COOLING USING TOMOGRAPHIC PIV

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The University of Texas at Arlington, 2024

Supervising Professor: Dereje Agonafer

As data centers evolve to support increasing server densities, the inadequacies of traditional air cooling in managing thermal loads have become evident. This is primarily due to an increased demand for powerful CPU and GPU-based platforms that can run Artificial Intelligence (AI) and Machine Learning (ML) workloads amongst others. Consequently, single-phase immersion cooling has gained prominence as an efficient, sustainable alternative, significantly reducing operational costs and energy consumption. This method has shown a remarkable ability to cut cooling energy by up to 90% and overall data center energy use by 50%. The current investigation uses Particle Image Velocimetry (PIV) to quantify the flow profiles in a functional 1U Coyote Pass server (M50CYP), cooled using an immersion fluid Polyalphaolefin 6 (PAO6), a synthetic hydrocarbon lubricant known for its thermal advantages, to cool a server with an inlet temperature set at 40 degrees Celsius. PG-25 water-based coolant circulates in a coolant distribution unit, coupled with a counterflow heat exchanger to optimize heat dissipation. The cooling system consists of a single-phase immersion-cooled 2U tank filled with PAO as a dielectric fluid.

This study aims to evaluate the effectiveness of single-phase immersion cooling in maintaining optimal server temperatures. The focus is on analyzing the 3D velocity vector field in critical components such as CPUs and heatsinks using Tomographic PIV. Tomographic PIV enables the measurement of fluid velocity by reconstructing a three-dimensional structure from a series of two-dimensional images and tracking the motion of particles suspended in the fluid. Also, this investigation examines the thermal performance of CPUs to gain insights into the cooling system's overall effectiveness.

ACKNOWLEDGEMENT

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I would like to thank my colleagues at the EMNSPC lab for their invaluable support and guidance throughout this project's experimental phase. Their collaborative spirit, expertise, and willingness to share insights have been invaluable in navigating the complexities of the experiment.

I want to thank my parents and friends for always supporting me during my Master’s degree. Their belief in me gave me the strength to finish successfully.

TABLE OF CONTENTS

4 RESULTS

LIST OF FIGURES

Figure Page

LIST OF TABLES

Table Page

CHAPTER 1

INTRODUCTION

1.1 Datacenter

A data center is a division of an organization that consists of many components that offer a secure space to store data. These data centers are a major component of the business and are responsible for most IT operations. With the booming development of information technologies and explosive growth in data processing needs, the large-scale construction of data centers has become an important development strategy for major technological nations [1]. The demand for information technology (IT) applications and services is always rising due to the ever-increasing need for data, which has led to continued expansion and interest in data centers [2]. These services are essential to almost every industry, including banking, healthcare, entertainment, government, and small and medium-sized enterprises [3]. Many large and medium-sized businesses use and store online content on the World Wide Web [4]. Data centers are the heart of the network and daily operations [5]. With the rise of edge computing, 5 G communication, and AI technology, the electrical energy consumption of data centers has increased sharply [6]. Almost 45 % of the power consumption comes from IT devices, 35 % of it comes from cooling systems and 20 % of it comes from other devices [7]. Due to this ongoing demand, data center cooling prices are constantly rising because cooling requires a lot of energy. Almost the entire power feed to the IT equipment is converted into excess heat [8]. Single-phase liquid immersion cooling (Sp-LIC) offers significant advantages when compared to forced convection air cooling such as higher thermal mass, a high percentage of heat dissipation due to direct contact of dielectric fluids with every component, improved reliability due to as the information technology equipment is shielded from the impact of contaminants and harsh environment, reduction in CapEx and energy costs as fans and computer room air handler/computer room air conditioning units might not be required.[9]

Figure 1.1: Datacenter [10]

1.2 Data Center Cooling Methods

Common techniques used for cooling of data centers are:

1. Air cooling.
2. Liquid cooling.

1.2.1 Air Cooling.

This method of cooling datacenters is the most used. Forced air convection over the heat sink is the system used in this method. A type of heat exchanger called a heat sink uses conduction to remove heat from mechanical or electrical equipment and transfer it to a fluid medium [2]. Depending on how hot the IT components are, conditioned air is provided inside the data center. The axial fan controls the airflow in a data center from the intake to the outlet. The task of bringing the air to an appropriate temperature falls on the computer room air conditioning (CRAC) device. As it goes to the hot aisle and enters the CRAC, the air builds up heat from the server components. By use of elevated floor infrastructure, the cold aisle receives the cooled air from CRAC [11]. A fin or other additional attachment is needed to increase the surface area for heat transmission in air since it has a lower heat conductivity than a liquid. Dust and other particulates of dirt enter the facility when using standard air-cooling with airside economization. These dust and dirt particles build up inside the chassis, which causes a mechanical failure [12]. Corrosion difficulties can be brought on by atmospheric humidity.

1.2.2 Immersion Cooling

Heat transfer continuously takes place between dielectric liquid and server. The flow of dielectric liquid is maintained with the help of a flowmeter. The immersion cooling can be classified as:

I. Single-phase immersion cooling

II. Two-phase immersion cooling

Single-Phase Immersion Cooling

Dielectric liquid never changes state in single-phase immersion cooling and keeps its liquid state throughout the server's operating temperature range [5]. Through convection, fluid acts as the working medium to remove heat from the server. Warm fluid is then transferred to a heat exchanger, where it cools by exchanging heat with cold water. Heat exchanger heated water is cooled using a cooling tower [11]. Given the minimal amount of fluid lost through evaporation, it can be used in an open bath situation. Open bath systems are utilized for single phase immersion cooling since there is minimal to no possibility of fluid evaporation [13]. We conducted this study using EC-100 as the fluid. When compared to forced convection air cooling, single-phase liquid immersion cooling (Sp-LIC) has several advantages, including increased thermal mass, a high percentage of heat dissipation since dielectric fluids come into direct touch with every component, and enhanced reliability [9].

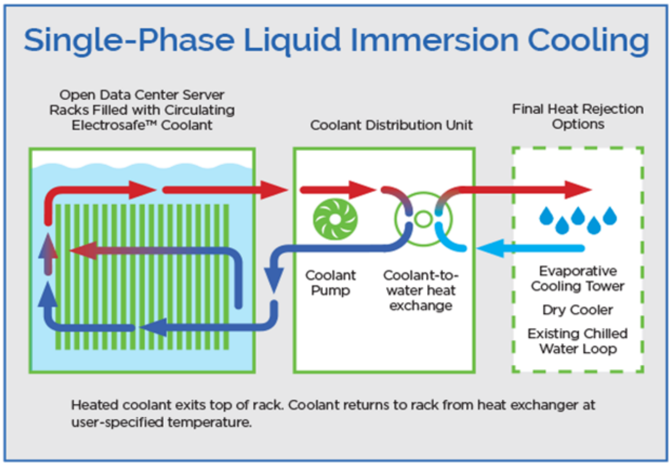


Figure 1.2: Single-Phase Immersion Cooling [14]

Two Phase Immersion Cooling

In a two-phase cooling system, the ICT equipment is completely submerged in the dielectric liquid bath; nucleate boiling occurs on the server surface when the server temperature reaches the boiling temperature of the dielectric liquid [15]. Low-density vapor rises to the top of the tank in relation to liquid. By taking away heat from the vapor, accumulated vapor is condensed using a condenser. This allows the vapor to transform back into a liquid phase and gravitationally return to the liquid sump [16]. The heat transfer efficiency from the boiling and condensation of cooling fluids is increased exponentially by two-phase passive immersion cooling. In an accessible sealed container, electronic components are immersed in a non-conductive liquid bath [4]. Low boiling points and little latent heat are characteristics of the liquid coolants used in two-phase cooling. Two phase immersion cooling systems are more difficult to access and repair if modifications are necessary, and they frequently need additional maintenance. To chill the condenser and remove the accumulated heat, most two-phase cooling systems demand water be supplied directly into the data room. Any time high pressure water is present in a data room, failure is quite likely. Semi-open tubs were necessary for this immersion cooling technique. It indicates that the system is sealed when it is in use to prevent coolant evaporation [13].

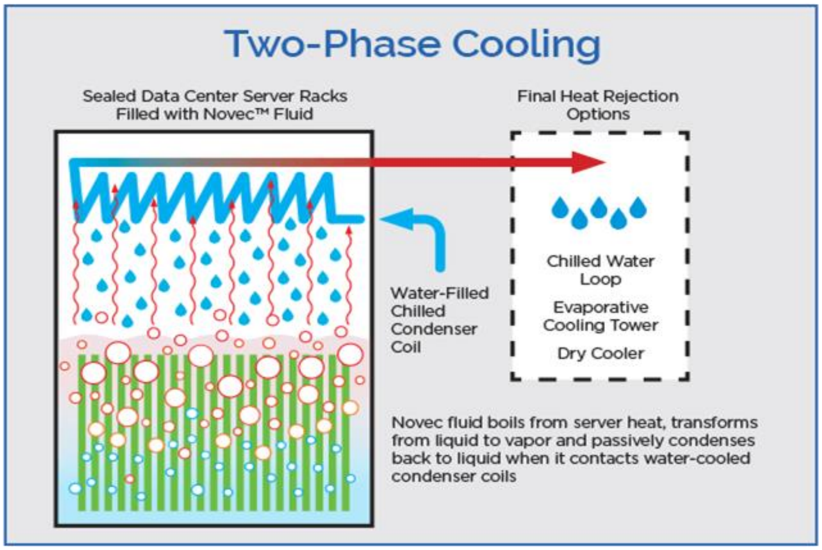


Figure 1.3 Two-Phase Immersion Cooling [14]

CHAPTER 2
EXPERIMENTAL SETUP

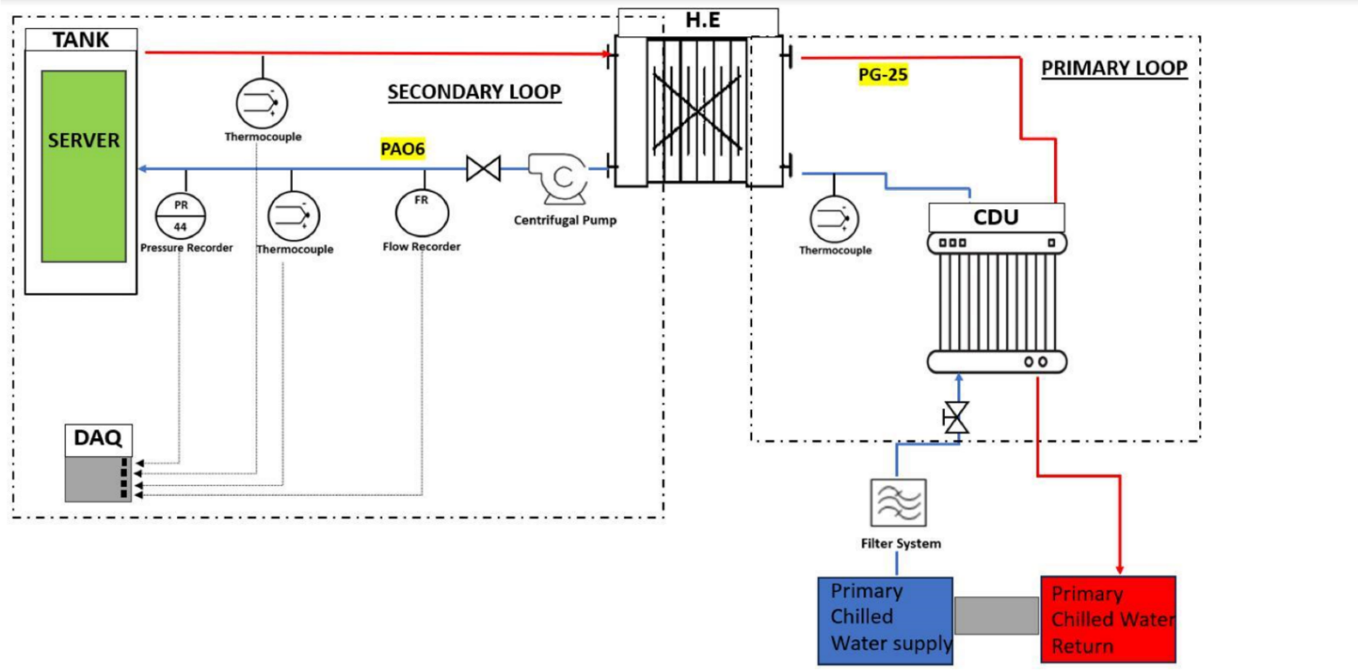


Figure 2.1: Experimental Schematic Diagram

2.1 Primary Loop

- The CDU dissipates heat from the PG25 coolant to chilled water, maintaining optimal operating temperatures within the system. This process of heat rejection ensures that the coolant remains within the desired temperature range.
- Coolant: Propylene Glycol-25 coolant is used in CDU.

Figure 2.2: Coolant Distribution Unit

- CDU- Rack DCLCtm CHx80
- Cool IT coolant: PG-25
- Cooling Capacity: 80 KW
- Maximum Operating pressure: 232 psi
- Maximum Operating flow: 80 lpm
- Operating Temperature (coolant temperature): 0 °C to 70 °C
- Storage Temperature (ambient temperature): -20 °C to 60 °C

2.2 Secondary Loop

- Server**:**1U Coyote Pass Server.
- Tank: Custom-built Single-Phase Immersion Cooled 2U Tank .
- Dielectric Fluid: PAO6.
- Sensors**:** Thermocouples, pressure sensors, and flow sensors are strategically placed within the system to measure the values such as temperature, pressure, and flow rate of the fluid.
- Pump: A centrifugal pump is employed to circulate the fluid in the secondary loop.

- Data Aquisition: The DAQ in a single-phase immersion cooling setup collects data from sensors to monitor system performance in real time.

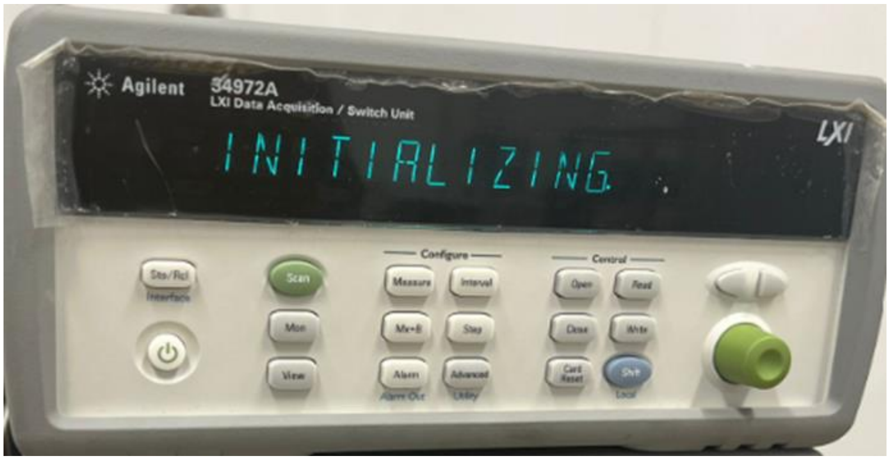


Figure 2.3: Data Acquisition

2.3 Server Description

- 1U Coyote Pass Server.
- Server Dimensions: 436.5 x 38.95 x 781 mm.
- 2 CPUs of 205 W TDP each.
- 32 Dual In – Line Memory Module (DIMM).
- 2 Parallel Plate Heat Sinks.
- Thermal Interface Material (TIM): Indium.
- Heat Sink Dimensions: 78 x 24.7 x 113 mm.
- Heat Sink Base: 4.5 mm.
- Number of Fins: 24.
- Fin Thickness: 0.8 mm.
- Fin Height: 20mm.

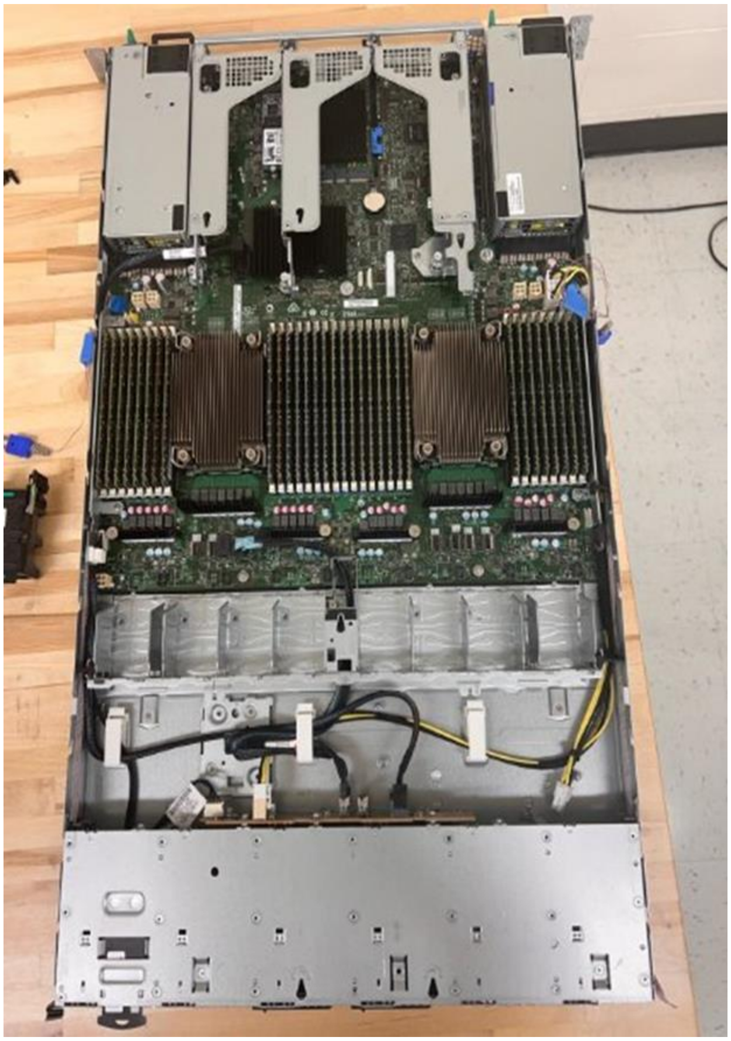


Figure 2.4: Server

2.4 Tank Description

- Single-Phase Liquid Immersion Cooled 2U Tank .
- Dielectric fluid - PAO 6.
- Exterior dimensions: 35” x 29” x 8”.
- Operational coolant capacity: 35 gallons approx.
- Construction Material: Aluminum & Acrylic glass.
- Inlet Fluid temperature- 40 C.

Figure 2.5: Tank Frontside

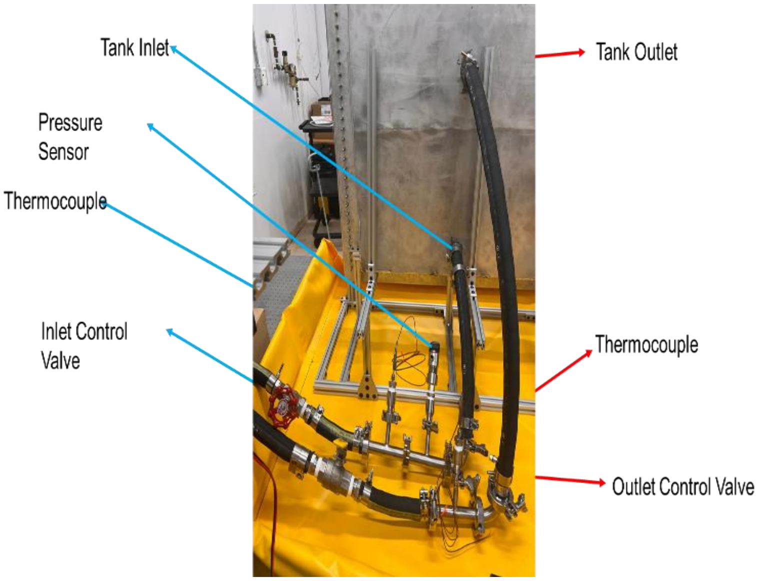


Figure 2.6: Tank Backside

2.5 PAO6 Properties

- Polyalphaolefin 6 (PAO 6) is a type of synthetic hydrocarbon lubricant. It is a colorless, odorless, non-toxic, and non-corrosive liquid.

1. High thermal stability

2. Low pour point.

3. Figure of Merit (FOM) 1: 36.3 [FOM for natural convection (FOM1) = k* ((β*cp*ρ^2)/(μk)) ^0.2813].

Figure of Merit (FOM) 2: 34.6 [FOM for forced convection (FOM2) = k*[(ρ*cp)/k] ^ (1/3)]

Figure of Merit (FOM)3 : 0.026901 [Dynamic Viscosity]

Temperature [C]	Thermal conductivity [W/m.K]	Specific Heat [J/kg.K]	Density [kg/m3]	Viscosity [cSt]	Viscosity [poise]	Vol expansion [1/K]	Thermal diffusivity
0	0.1574	2088.57	835.1	293	2.447	0.0007	9.02438E-08
20	0.156	2153.37	823.1	97.814	0.805	0.0007	8.80143E-08
30	0.1553	2185.77	817.1	49.116	0.401	0.0007	8.69544E-08
40	0.1546	2218.17	811.1	30.127	0.244	0.0007	8.59291E-08
50	0.1539	2250.57	805.1	20.621	0.166	0.0007	8.49369E-08
60	0.1532	2282.97	799.1	15.128	0.121	0.0007	8.39764E-08
70	0.1525	2315.37	793.1	11.642	0.092	0.0007	8.30465E-08
80	0.1518	2347.77	787.1	9.279	0.073	0.0007	8.2146E-08
90	0.1511	2380.17	781.1	7.596	0.059	0.0007	8.12737E-08
100	0.1504	2412.57	775.1	6.351	0.049	0.0007	8.04285E-08

Table 2.1: Fluid Properties

2.6 Sensor Specifications

Pressure sensor-Keyence – GP-M010T

- Rated Pressure 14.5 to +145.0 PSI (–0.1 to +1 MPa)
- Display range of –30.5 to +161.0 PSI (–0.210 to +1.110 MPa).
- Type of pressure: Gauge pressure.
- Fluid type: Liquid or gas.

Flow sensor - Keyence – FD-H47F

- The Keyence FD-H47F is a hose model type.
- Maximum flow rate - 300 L/min,79.3 gal/min.
- Power voltage of 20-30 VDC.

Thermocouple - Omega - 5TC-TT-T-30-36-ROHS

- It is a T type thermocouple.
- Temperature range- 0 to 150 C.
- Wire Gauge: 36AWG

Figure 2.7: Pressure Sensor, Flow Sensor and Thermocouple Specifications.

Heat exhanger -Bell & Gossett – BP410-010

- Maximum Pressure- 435psi
- Brazing Material- Copper
- Maximum Temperature-300 °F

Pump - Pentair Flotec – FP5512

- Maximum Discharge Pressure: 36 psi
- Recommended Breaker: 15 amp on 230v / 15 amp on 115v
- Maximum Water Temperature: (60 °C)
- Horsepower (HP): 1/2

Figure 2.8: Heat Exchanger and Pump Specifications

CHAPTER 3

PIV (PARTICLE IMAGE VELOCIMETRY)

- Particle image velocimetry (PIV) is an optical flow measurement technique used to study fluid flow patterns and velocities.
- The tomographic PIV image recording and analysis is an integrated part of the DaVis software.
- Principle: Tomographic Particle Image Velocimetry (tomo-PIV) involves capturing multiple images of tracer particles from different angles around a fluid volume. These images are then reconstructed into a three-dimensional representation of particle distribution using tomographic techniques. By tracking the motion of these particles across frames, the velocity field of the fluid can be calculated, providing insights into its three-dimensional flow behavior.
- Steps To perform a tomographic PIV:

1. Setup cameras and illumination .
2. Adjust area of interest.
3. Refocus on particles.
4. Perspective calibration.
5. Record particle images.
6. Image preprocessing.
7. Volume self-calibration.
8. Tomographic PIV calculation.

1. setup cameras and illumination -

Required optical component:

The following optical components are required to do a tomographic PIV experiment:

- Cameras: 2 to 6 (or even up to 8) cameras.
- Camera mounts: Camera mounting is very important for volumetric flow measurements. The camera mounts need to be very stiff to maintain such a calibration accuracy over the measurement period.
- Light source: Corresponding to the desired repetition rate of the camera recordings, the light source must be able to deliver light pulses at the desired repetition rate.
- Lens: The focal length of the lens needs to fit to the desired area of interest and the required working distance.
- Laser guiding arm: An optional laser guiding arm is often a very convenient way to deliver the laser light to the required measurement location.
- Seeding particles: As the light budget is often limited for volumetric measurement, choosing the seeding carefully can be crucial for the success of tomographic PIV measurement.
- Seeding Density: There should be about one to three particles in a 4 × 4 pixel area. Over the whole volume, the seeding should be as homogeneous as possible.

- Calibration plate :Since tomographic PIV depends strongly on an accurate calibration, LaVision recommends the newest calibration plates (types 058-5, 106-10, 204-15 or 309-15).

2. adjust area of interest :

- Place the calibration target in the center of the measurement volume.
- Enter the recording dialog and use ’Grab’ to get a live image from the cameras.
- Camera 1 must look at the front side of the calibration plate. The front side is where the type of plate is printed, e.g. 106-10 or 204-15.
- All cameras must see the same area of interest and must have a similar magnification.

3. Refocus on particles :

- Remove the calibration target.
- Setup the volume illumination.
- Seed the volume with particles.
- While using ’Grab’ images with the laser turned on adjust the lens aperture and focus for all cameras, such that all particles are clear and sharp.

4. do perspective calibration: In this step From now on, do not touch the cameras or the camera cables anymore.

5. record particle images

6. do image preprocessing :

- Image preprocessing is often a necessary step before the tomographic PIV calculation and volume self-calibration.

- The purpose of image preprocessing is to remove the camera background and the camera noise and, in this way, to achieve nicely shaped particle images with zero background. Additionally, a ’geometric mask’ can be used to remove noise or reflections inside or outside the desired illuminated particles.

7. do volume self-calibration:
    - The purpose of Volume self-calibration is to remove any residual calibration disparities using recorded particle images.
    - Volume self-calibration requires two steps: 1st: calculation of the disparity vector map and 2nd: correction of the calibration (mapping function).
    - These two steps can be repeated again and again, until the remaining disparity is below 0.1 voxel in all sub volumes.
8. do tomographic PIV calculation
    - After the image preprocessing and volume self-calibration, the next processing step in tomographic PIV is the reconstruction of the particle volume and the velocity vector calculation by 3D correlation of the reconstructed particle volumes.

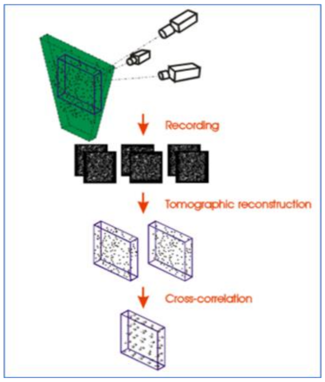


Figure 3.1: Tomographic PIV Principle

3.1 Setup Cameras and Illumination

- Camera: VC-Imager CX-12.
- Laser: Double Pulse YAG laser.
- Focal Length: 12mm.

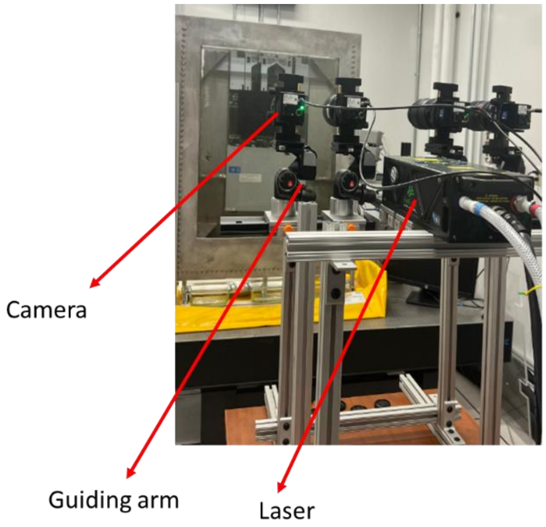


Figure 3.2: PIV Setup

Figure 3.3: Synchronizer

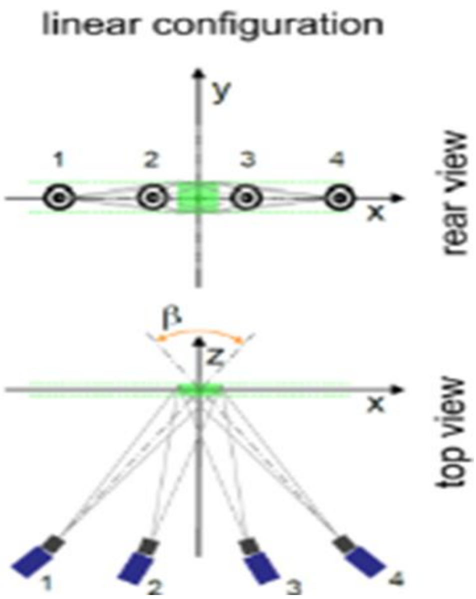


Figure 3.4: Camera Configuration

3.2 Adjust Area of Interest

- Place the calibration target in the center of the measurement volume.
- All cameras must focus on the same area of interest.


Figure 3.5: Area of Interest

Figure 3.6: Calibration Plate

3.3 Seeding Particles

- A good seeding particle is a seeding particle that has non-toxic, non-corrosive, non-abrasive, non-volatile, and chemically inert properties.
- The seeding particles for the experiment: Red Polyethylene Microparticle (compatible with PAO 6)
- Size of particles: 40-47 μm
- Density: 995 kg/m3
- Dosing quantity: 0.85 gms

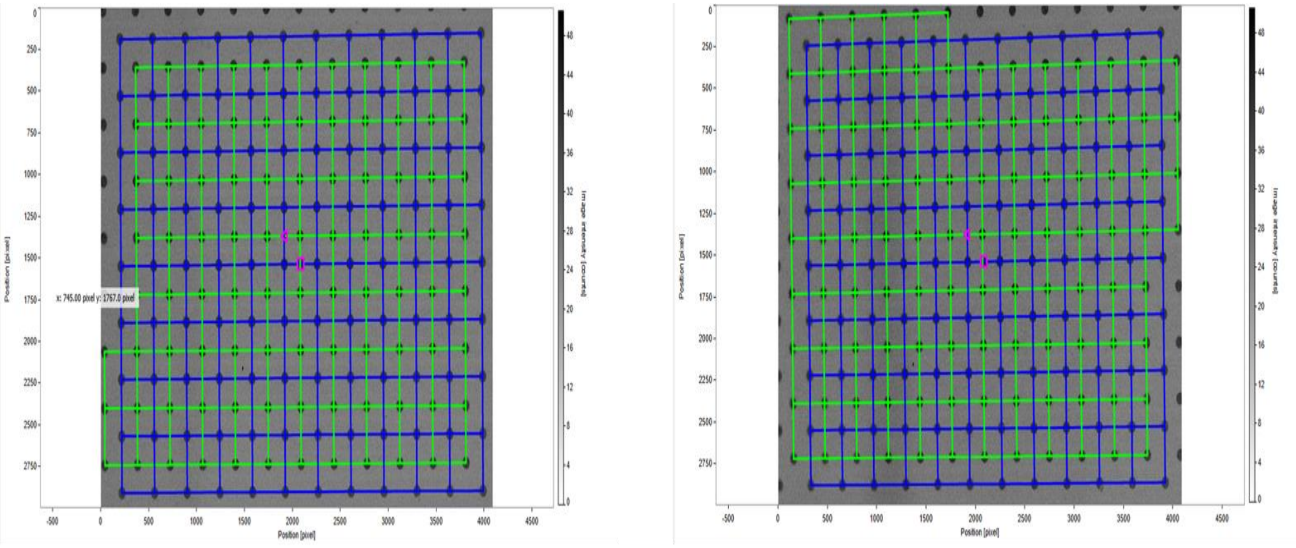
Figure 3.7: Seeding Particles

Figure 3.8: Sonicator

CHAPTER 4

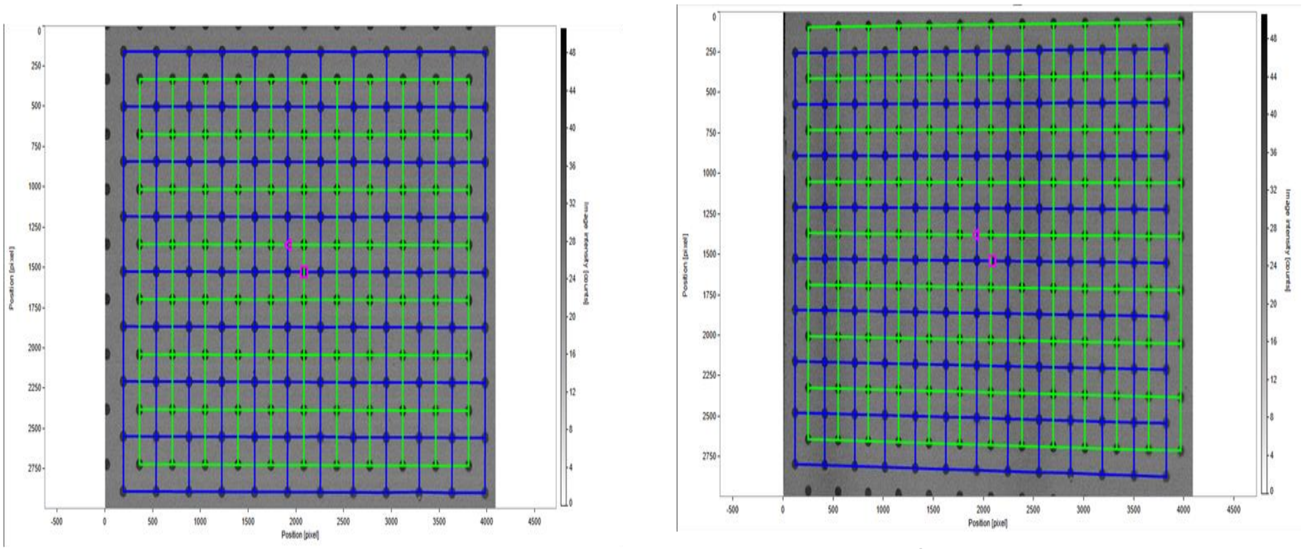
RESULTS

4.1 Calibration Results



Camera 1

Camera 2

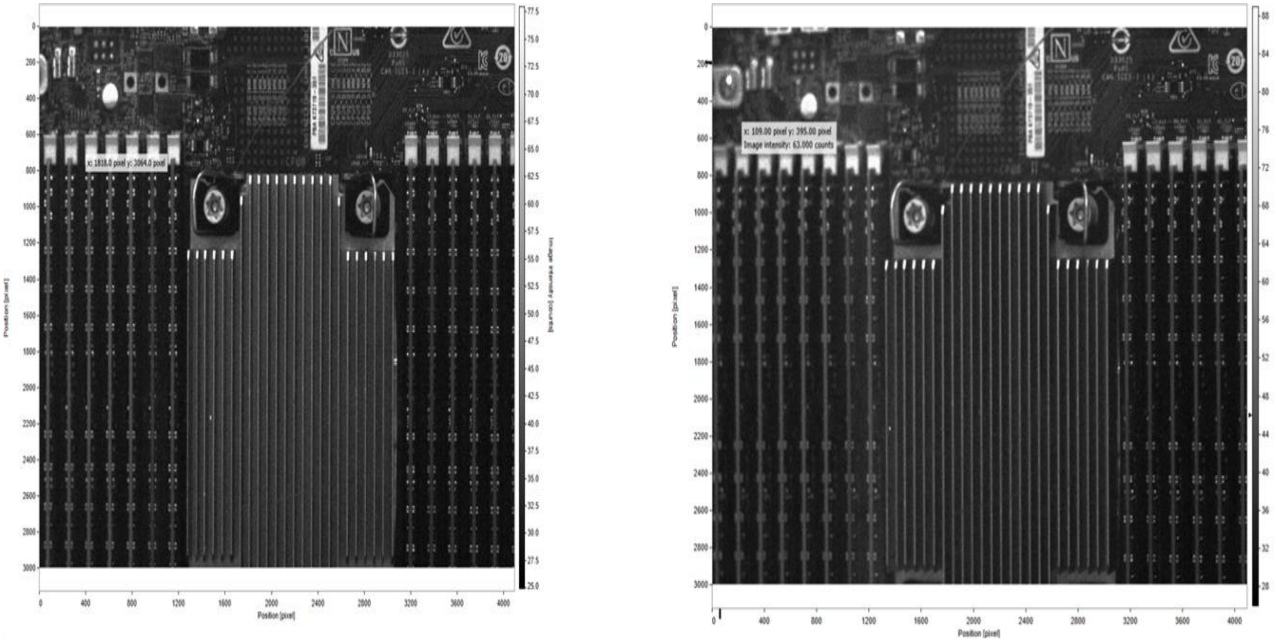


Camera 3

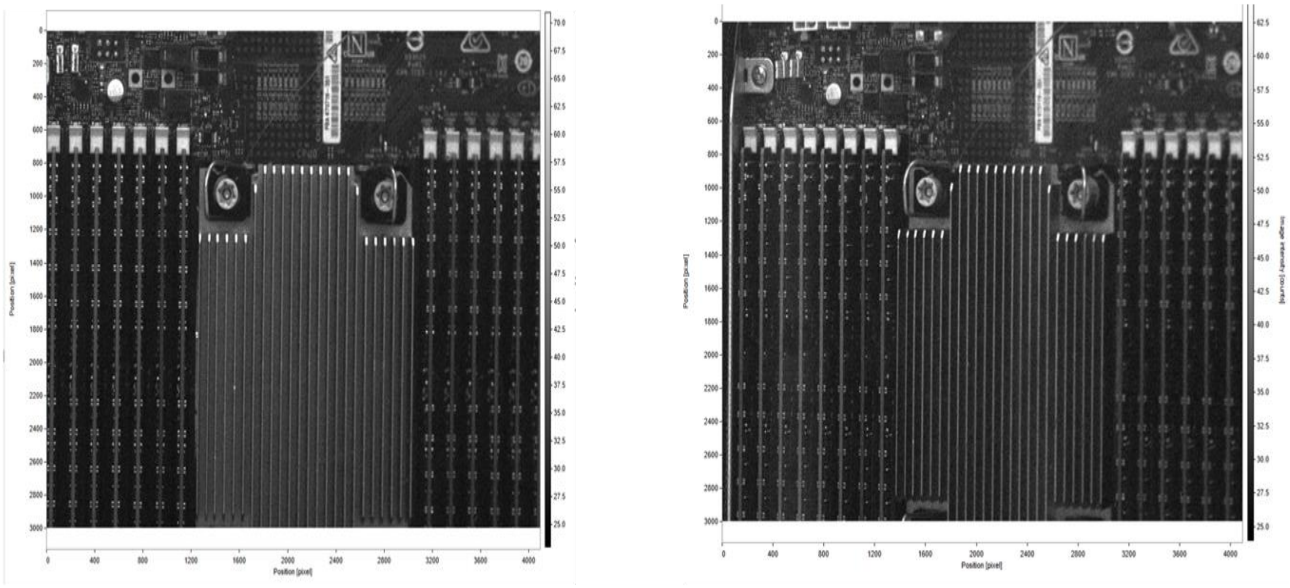
Camera 4

Figure 4.1: Calibration with Plate

4.2 Live Image



Camera 1 Camera 2

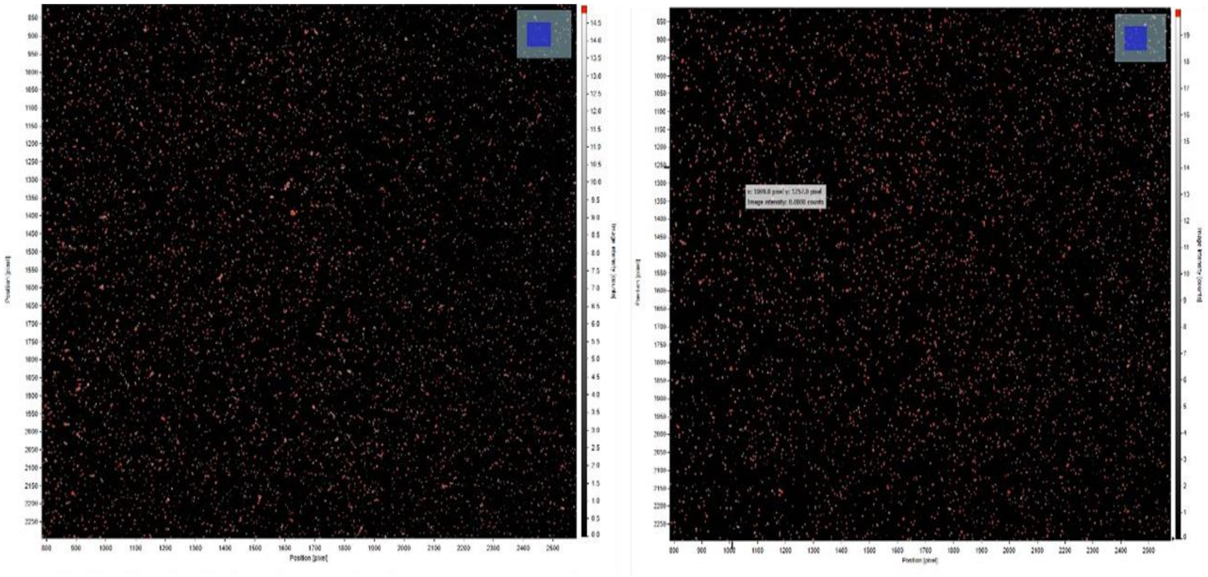


Camera 3 Camera 4

Figure 4.2: Live Image

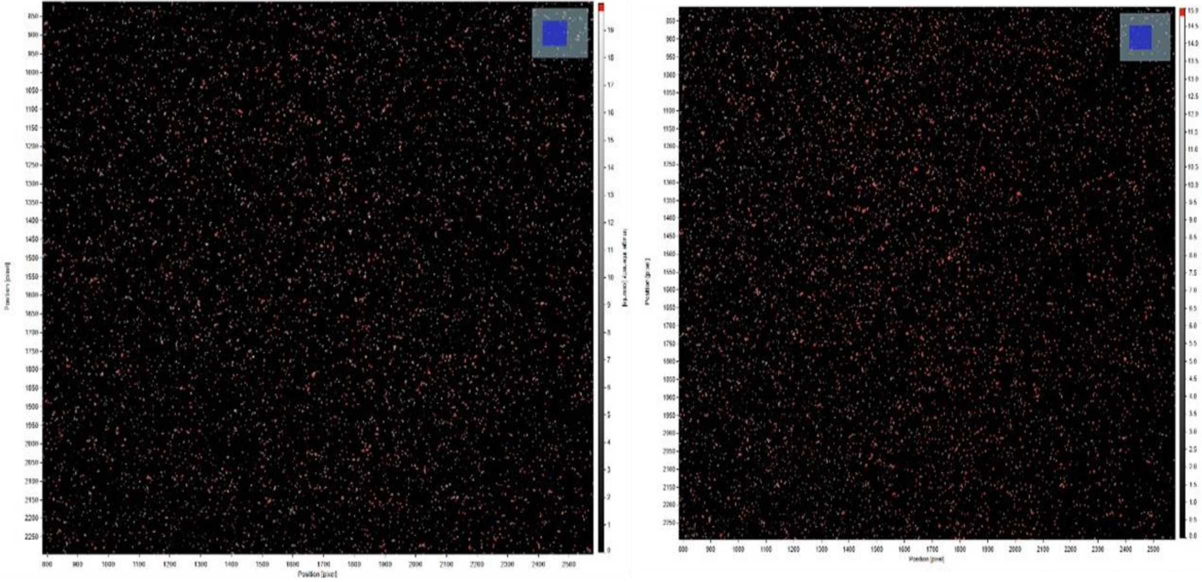
4.3 Image Preprocessing

The purpose of image preprocessing is to remove the camera background and the camera noise and, in this way, to achieve nicely shaped particle images with zero background.



Camera 1

Camera 2



Camera 3

Camera 4

Figure 4.3: Image Preprocessing

4.4 Tank without Server

Objectives	Results
Run the secondary loop (2 hours)	No leakages
Tank Pressure drop	9 to 11 kPa
Minimum and maximum flow rate	Max – 32 LPM, Min – 2 LPM
Check for temperature, pressure and flow sensor readings	Done
Connection to DAQ Units and power supply	Done
Check for correct data logging from all the sensors	Done
Stability	Approximately 5 mins

Table 4.1: Tank without Server

4.5 Tank with Server at Ideal Conditions

Objectives	Results
Run the secondary loop with server – 1 hour	No issues or any leakages
CPU 0 and CPU 1 Temperature	56°C and 57°C approximately
Tank Pressure drop	10-12 kPa
Minimum and maximum flow rate	Max – 32 LPM, Min -2 LPM
Check for temperature, pressure and flow sensor readings	Done
Connection to DAQ Units and power supply	Done
Check for correct data logging from all the sensors	Done
Stability	Approximately 7-8 mins

Table 4.2: Tank with Server

CHAPTER 5

CONCLUSION

The successful commissioning of the single-phase immersion-cooled server and its experimental setup represents a pivotal achievement in our research pursuits. Through the implementation of the Particle Image Velocimetry (PIV) technique, we have constructed a robust framework to meticulously analyze the velocity profile within the immersion cooling system. This comprehensive experimental approach not only ensures the integrity of our findings but also underscores the reliability of immersion cooling technology, evidenced by the absence of leakages observed during the examination of the tank without a server.

Moreover, our investigation into the thermal performance of the server under ideal conditions provides valuable insights into its operational efficacy. With CPU 0 and CPU 1 maintaining temperatures of 56°C and 57°C respectively, our study reaffirms the efficiency of single-phase immersion cooling in maintaining optimal operating conditions. These findings not only contribute to the advancement of server cooling methodologies but also lay a solid groundwork for future research endeavors aimed at enhancing the efficiency and sustainability of data center operations.

CHAPTER 6

FUTURE SCOPE

In future research, we aim to conduct experimental studies exploring various power configurations within our server setup. This includes investigating scenarios with two CPUs, each carrying a power load of 205 watts, as well as configurations featuring two CPUs along with 32 DIMMs (Dual In-line Memory Modules), and further extending to setups incorporating both 32 DIMMs and 4 SSDs (Solid State Drives). Through these experiments, we seek to comprehensively understand the impact of differing power configurations on the performance and thermal behavior of the immersion-cooled server. Furthermore, our future work will involve conducting Particle Image Velocimetry (PIV) analysis on these diverse power configurations. Specifically, we will focus on studying the velocity profiles within the server, with a particular emphasis on analyzing the cooling efficiency and fluid dynamics under varying load conditions. Additionally, we plan to perform component-level studies using a single heat sink for PIV analysis, enabling us to gain deeper insights into the thermal management of individual server components. Alongside these experimental investigations, we intend to complement our findings by conducting Computational Fluid Dynamics (CFD) analysis. By comparing the results obtained from PIV experiments with those derived from CFD simulations, we aim to validate and enhance our understanding of the immersion cooling system's performance across different power configurations, thus paving the way for more efficient and optimized server cooling solutions in the future.

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