Experimental study on the thermal performance of a closed loop pulsating heat pipe with horizontal and vertical position

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28 May 2023

STUDENT DECLARATION

This is to certify that the thesis entitled, "**Experimental study on the thermal performance of a closed loop pulsating heat pipe with horizontal and vertical position"** is an outcome of the investigation carried out by the author under the supervision of **Md. Sojib Kaisar** Assistant Professor, Dept. of Mechanical Engineering, Sonargaon University (SU). This thesis or any part of it has not been submitted to elsewhere for the award of any other degree or diploma or other similar title or prize.

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This is to certify that the investigation conducted by the author under the guidance of **Md. Sojib Kaisar**, Assistant Professor, Dept. of Mechanical Engineering, **Sonargaon University (SU)**, resulted in the thesis, "**Experimental study on the thermal performance of a closed loop pulsating heat pipe with horizontal and vertical position**." This thesis or any portion of it has not been submitted to another institution for the granting of another degree, diploma, or any title or reward that is identical as well.

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Dedication

To our parents and supervisor, with heartfelt appreciation.

Abstract

This research compares the thermal performance of two working fluids, Methanol, and distilled water, in a closed-loop pulsating heat pipe. The investigation explores the impact of these fluids on the thermal resistance of the system at different heat inputs and configurations. At an initial heat input of 10 watts, Methanol exhibits a higher thermal resistance of 4.8 than distilled water, which records a thermal resistance of 5. However, when considering the overall performance, Methanol outperforms distilled water. The optimal configuration for Methanol is achieved with a 60% filling ratio and a 90-degree inclination angle, resulting in a thermal resistance of 4. Distilled water initially exhibits higher thermal resistance at the 10-watt heat input, but it shows promise when used with a 60% filling ratio and a 90-degree inclination angle, with a thermal resistance of 1.4. However, as the heat input exceeds 40 watts, distilled water with a 60% filling ratio and a 90-degree inclination position outperforms other configurations. Based on the analysis, Methanol is the optimal working fluid in the closed-loop pulsating heat pipe experiment. Although initially demonstrating higher thermal resistance, it achieves the best overall performance with a 60% filling ratio and a 90-degree inclination angle. Distilled water performs less favorably in terms of thermal performance throughout the experiment.

It is important to note that the specific results presented in this research depend on the provided information. The closed-loop pulsating heat pipe's design, size, and experimental conditions can influence its thermal behavior.

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List of Abbreviations

Words/Signs	Abbreviation
C_P	Specific Heat (kJ/Kg-K)
D	Diameter (mm)
D_i	Inner Diameter (mm)
D_o	Outer Diameter (mm)
F_R	Filling Ratio (%)
h	Heat transfer Co-efficient (W/C-m^2)
L	Length (mm)
Q	Heat input (W)
R_{th}	Thermal resistance (K/W)
T_c	Condensation Section Temperature (°C)
T_e	Evaporator Temperature (°C)
ΔT	Temperature difference (°C)
V	Specific Volume (m^3/kg)
W	Watt
CLPHP	Closed Loop Pulsating Heat Pipe
OHP	Oscillating Heat Pipe
PHP	Pulsating Heat Pipe
Fig	Figure
P	Density of water (kg/m^3)
CFD	Computational fluid dynamics
FR	Filling Ratio
D. Water	Distilled Water

Chapter 1

1 Introduction

In many engineering applications, closed-loop pulsing heat pipes (CLPHPs) is an effective and promising thermal control method. They are especially effective in removing heat from electronics, aircraft systems, renewable energy sources, and other heat-producing parts. CLPHPs work on the premise that they may transfer heat across a closed-loop circ using oscillatory flow patterns, phase change processes, and capillary action.

The capacity of CLPHPs to transport heat over long distances with little temperature variations is one of its main advantages. Due to their ability to quickly and uniformly distribute heat throughout the system, they are very effective thermal conductors. Additionally, the self-regulating characteristic of CLPHPs results in optimum performance and the avoidance of overheating by automatically adjusting the heat transfer rate to fit the thermal load.

Numerous studies have been conducted recently to comprehend the complexities better and enhance the efficiency of closed-loop pulsating heat pipes. Studies have concentrated on elements such as channel design, working fluid choice, system size, and operating circumstances to improve their capacity for heat transmission.

The channel shape significantly influences the heat transmission properties of CLPHPs. Various configurations, including circular, rectangular, triangular, and annular channels, have been investigated to accomplish effective fluid flow and heat transmission. The required heat transmission rate, the permitted pressure drops, and the simplicity of manufacturing are only a few examples of the variables that affect the choice of channel shape. Researchers have used models and studies to determine how various channel designs affect the overall effectiveness of CLPHPs.

The choice of an adequate working fluid is another important consideration in the design of CLPHP. Desirable characteristics of the working fluid include a low boiling point, high latent heat of vaporization, low viscosity, and excellent thermal stability. Water, methanol, ethanol, ammonia, and refrigerants like R134a working fluids are often utilized. The operating temperature range, optimum heat transfer efficiency, and safety concerns affect the working fluid choice.

The closed loop's length, diameter, and number of turns all impact how well heat is transferred in CLPHP systems. In-depth research has been done to identify the ideal parameters that maximize heat transfer rates while reducing pressure drop and system size. In addition, researchers have offered helpful insights into the impact of system dimensions on the thermal performance of CLPHPs via experimental studies and computer modeling.

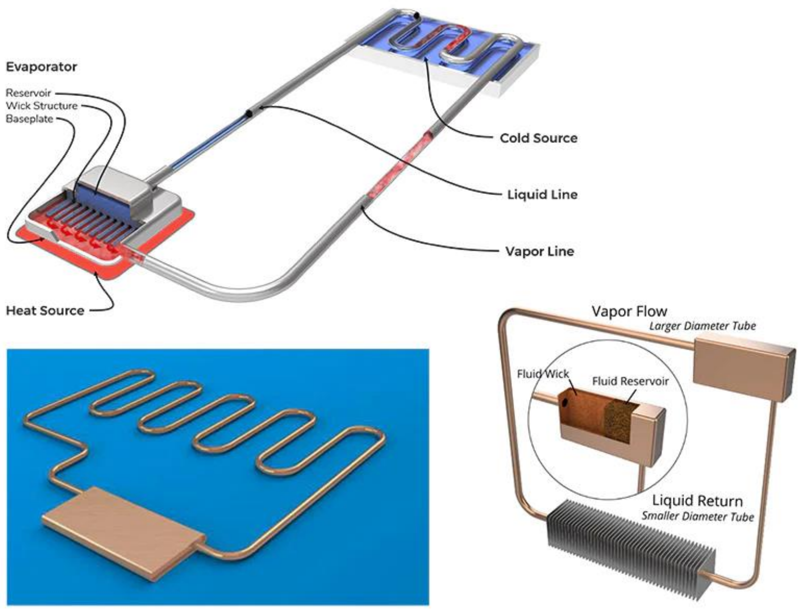

Figure 1-1 Real life application of CLPHP

In order to maximize the performance of CLPHPs, various operating circumstances have been investigated. In addition to channel geometry, working fluid choice, factors like heat input, filling ratio (the percentage of the internal volume occupied by the working fluid), inclination angle, and working fluid temperature to comprehend their influence on heat transfer characteristics have been studied. These studies have offered helpful guidance for maintaining effective heat dissipation and reaching the best operating conditions for various applications.

The progress of closed-loop pulsing heat pipes has also facilitated the creation of novel variants and hybrid systems. Phase change materials, heat sinks, heat exchangers, thermoelectric devices, and other heat transfer technologies have all been investigated concerning CLPHP integration. With the help of these hybrid systems, complicated thermal management situations' particular needs may be addressed while also broadening the operating range and improving overall thermal performance.

Additionally, the behavior of CLPHPs under various operating circumstances has been predicted and simulated using numerical modeling approaches, including computational fluid dynamics (CFD) and finite element analysis (FEA). These modeling tools help engineers improve their designs and reduce the need for lengthy experimental testing by providing insightful information on the fluid flow patterns, temperature distribution, and overall performance of CLPHPs.

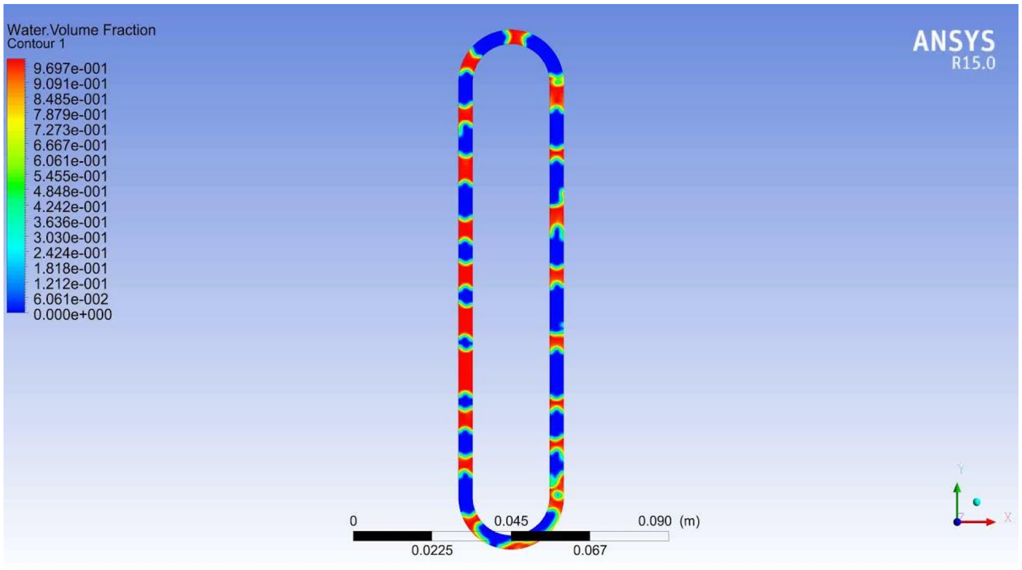

Figure 1-2 CFD Analysis of CLPHP [1]

Closed-loop pulsing heat pipe technology is constantly improving, and this holds tremendous potential for solving the growing thermal management problems in modern engineering applications. Engineers and scientists are always pushing the limits of CLPHPs to improve their effectiveness, dependability, and ability to be applied to various systems sec. Consequently, CLPHPs are anticipated to be widely used in the future, changing the area of thermal management of more dependable and efficient technologies. A working fluid (usually a low-boiling-point liquid) is confined inside a closed loop of linked channels or capillaries for CLPHPs to function. The working fluid absorbs the heat and vaporizes when applied to one or more evaporator portions. The vapor then makes its way to the condenser, condensing lenses into a liquid and turning its heat to the environment. The closed loop is completed when the condensed liquid flows by capillary action or gravity-driven flow back to the evaporator.

Pulsating flow is the distinctive quality that sets CLPHPs apart from traditional heat pipes. The system experiences pulsations due to the interaction of surface tension forces, gravity forces, and pressure differences. These pulsations create oscillating flow patterns that improve the CLPHP's ability to transmit heat. In addition, the working fluid's pulsing motion encourages the evacuation of vapor bubbles from the evaporator, enabling new liquid to come into contact with the heated surface and increasing the area and efficiency of heat transfer.

Two basic configurations are often seen when considering how CLPHPs are oriented: horizontal and vertical angles. The evaporator and condenser parts are positioned at the same height in horizontal CLPHPs but below the condenser in vertical CLPHP each layout has unique benefits and difficulties regarding riding heat transfer efficiency, fluid distribution, and general system duties.

When a horizontal surface is easily accessible for heat dissipation or when space is at a premium, horizontal CLPHPs are an excellent choice. They have a small footprint and are often used in electronic cooling systems because they can fit into confined places in electronic equipment. Because the flow is unaffected by the system's orientation, horizontal CLPHPs also provide improved resistance to gravitational influences. However, with horizontal CLPHPs, maintaining uniform fluid distribution might be more difficult because gravity forces may prevent the working fluid from flowing freely.

Vertical CLPHPs, on the other hand, are beneficial in situations where forced or natural convection cooling is easily accessible. Vertical CLPHPs may use gravity-driven flow to improve fluid circulation by placing the evaporator below the condenser. In order to ensure efficient heat transmission, this structure makes it possible to remove vapor bubbles from the evaporator portion more effectively. In applications like solar thermal systems, where heat may be quickly removed by forced air cooling or natural convection, vertical CLPHPs are often used.

Finally, closed-loop pulsing heat pipes provide a flexible and effective thermal management solution in various technical applications. They are very appealing for resolving issues with heat dissipation because of their quick and even heat transfer and self-regulating nature. Engineers may adapt their design to meet certain application needs by using CLPHPs, which provide special benefits and considerations in horizontal or vertical orientations. Advancements in electronic cooling, aeronautical systems, renewable energy, and other fields have been made possible by CLPHPs thanks to continued research and development.

1.1 Evolution of CLPHP

Closed-loop pulsing heat pipes (CLPHPs) have made great strides in their development. CLPHPs were first presented in the early 1990s and were created as closed-loop passive heat transfer devices with a network of linked channels and a working fluid. These gadgets have developed into effective, adaptable thermal management solutions for various applications.

Early CLPHP designs were primarily concerned with comprehending the underlying theories and essential traits of pulsing flow and heat transfer inside the system. Researchers experimented with various channel arrangements, dimensions, and orientations to improve performance. Simple planar geometries and rectangular channels were used in the early prototypes.

As research developed, increasingly complex designs with curved and meandering channels arose, improving heat transmission efficiency. In addition, capillary structures were added within the channels, further enhancing the thermal and fluid properties and allowing for effective functioning in various orientations and gravitational fields.

CLPHPs have evolved due to improved fabrication methods, including microfabrication and additive manufacturing. These methods have made it possible to produce intricate and tiny geometries, which has improved the devices' thermal efficiency and compactness.

Furthermore, CLPHPs now have more options because of the advancement of working fluids, such as phase change materials and nanofluids. With their superior thermal conductivity and heat capacity, these cutting-edge fluids enable faster heat transfer rates and better system performance.

Additionally, recent developments in control and optimization techniques have enabled the use of CLPHPs in several applications, including renewable energy systems, aeronautical systems, and electronics cooling. The CLPHPs' applicability and flexibility to various thermal management needs have increased because of their ability to control and regulate the pulsing flow inside them actively.

Ongoing research, technical breakthroughs, and the need for effective thermal management solutions have fueled the development of closed-loop pulsing heat pipes. Future developments in heat transfer efficiency, downsizing, and integration into various applications are anticipated due to the devices' continued research and optimization.

1.2 Types of pulsating heat pipe

Both closed-loop pulsing heat pipes (CLPHPs) use phase change phenomena and capillary action to transmit heat. They are closed systems with interconnecting pipes or tubes stuffed with a working fluid. As heat is transported, the working fluid experiences phase shifts (vaporization and condensation), which causes pulsing motion within the pipes. Several varieties of CLPHPs may be distinguished according to their setups and features:

Single-channel CLPHP: The working fluid runs via a single channel or pipe in this design. It has a reasonably simple design and is often utilized in small-scale applications.

Multi-channel CLPHP: This kind employs several parallel channels to improve the capacity for heat transmission. Compared to single-channel CLPHPs, it offers improved thermal performance and is appropriate for applications demanding more heat dissipation.

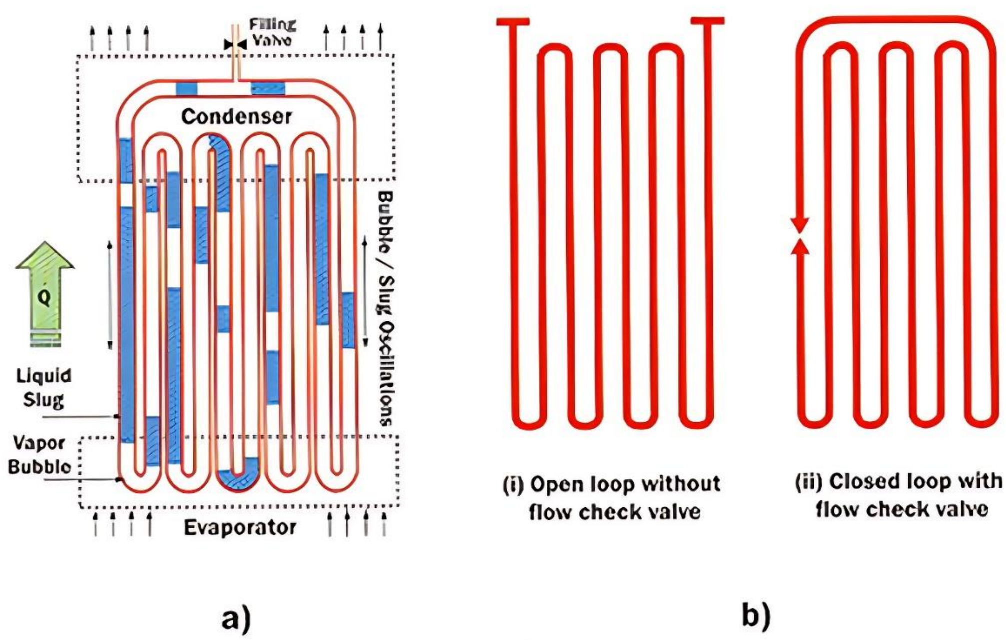

Figure 1-3 Types of CLPHP

1.3 Parameter effect the CLPHP

CLPHPs having a tree-like configuration: These CLPHPs feature a central evaporator and several branches. This design is excellent for applications with non-uniform heat sources because it improves the dispersion of the working fluid and heat transmission.

Loop heat pipe (LHP): LHPs are a particular kind of CLPHP in which a wick structure manages the working fluid flow. The evaporator, adiabatic section, condenser, and compensating chamber make up the majority of them. LHPs are suited for severe thermal management applications because of their excellent heat transmission capacity and dependability.

Several factors, such as the following, affect how well CLPHPs perform:

1) **Working fluid:** The working fluid choice impacts the CLPHP's thermal performance, heat transfer properties, and operating temperature range. The different boiling points, latent heat of vaporization, and thermal conductivities of the various fluids impact the total effectiveness of the system.
2) **Fill ratio:** The fill ratio describes the percentage of the working fluid-filled CLPHP's internal volume. It impacts the capillary flow behavior and the accessible surface area for heat transmission. Therefore, the fill ratio must be ideal to accomplish effective heat transmission.

Dimensions of the channels or pipes in the CLPHP: such as their diameter and length, influence the flow resistance, pressure drop, and heat transfer properties. Therefore, the channel's diameter and length must be properly planned to balance the performance of heat transmission and fluid flow resistance.

Temperature and power of the heat source: The heat input into the CLPHP is influenced by the temperature and power of the heat source. Higher heat source temperatures and powers may impact the system's thermal resistance, vaporization, and condensation rates.

1) **Ambient temperature:** The area where the CLPHP is located impacts how much heat it can dissipate. A greater ambient temperature may result in less efficient heat transfer and impact the system's overall thermal performance.
2) **Wick structure and design:** In CLPHPs with wick structures, the wick's design and material properties influence the capillary flow and liquid transport. Wick characteristics, including pore size, porosity, and permeability, influence the CLPHP's overall performance.

3) **Orientation and gravity:** The flow patterns and heat transfer characteristics within the system are influenced by the CLPHP's orientation (vertical, horizontal, or inclined), as well as by the effects of gravity. In applications involving microgravity or space, the effects of gravity become crucial.

To ensure effective and dependable heat transmission, these factors and others must be considered when designing and optimizing closed-loop pulsating heat pipes.

1.4 Limitation of CLPHP

There are several benefits to using closed-loop pulsing heat pipes (CLPHPs) for thermal control and heat transmission. They do, however, have certain restrictions that must be taken into account. Their sensitivity to direction is one drawback. In locations where the orientation is continually changing or when gravity is drastically changed, CLPHPs may operate differently than when correctly aligned with the gravitational field. Furthermore, CLPHPs' total size may be a drawback. The capillary forces that propel fluid circulation within pipes may be less effective as the system's size shrinks, resulting in less efficient heat transmission.

CLPHPs may be vulnerable to fluid leakage, particularly if they are put under high working pressures or vibrations. This may lead to a loss of working fluid and a reduction in the effectiveness of heat transmission. Lastly, CLPHPs must be carefully designed and optimized to provide the best performance for certain applications, which may take more time and resources. Nevertheless, closed-loop pulsing heat pipes continue to be a viable technology for many thermal management applications despite these drawbacks, and continuing research strives to solve these drawbacks and enhance their general performance.

Examines how thermal performance and performance limits are impacted by operating orientation, inner diameter, filling ratio, and heat input flux. According to the research, orientation hardly affects CLPHPs with a 1 mm inner diameter. For both CLPHPs, a filling ratio of 50% is optimal in all orientations. The CLPHPs were run until they reached a performance threshold marked by severe evaporator overheating (dry-out), and a significant variety of heat loads could be handled. Gravity has a modest or negligible impact on thermal performance when the inner tube diameter decreases. The study offers useful information regarding the performance thresholds of CLPHPs, which may help develop and improve these devices.[2]

1.5 Research Gap

In order [3] to get reliable results for the thermal performance of a horizontal closed-loop oscillating heat pipe (HCLOHP), this paper explains the necessity for further testing to support alternative theoretical models. The study indicates that the results for horizontal orientation are less significant than those for bottom heat mode, and it should have considered the impacts of the filling ratio and operating temperature. To close this knowledge gap, the authors suggest more experimental investigations on an HCLOHP's thermal performance under normal operating conditions.

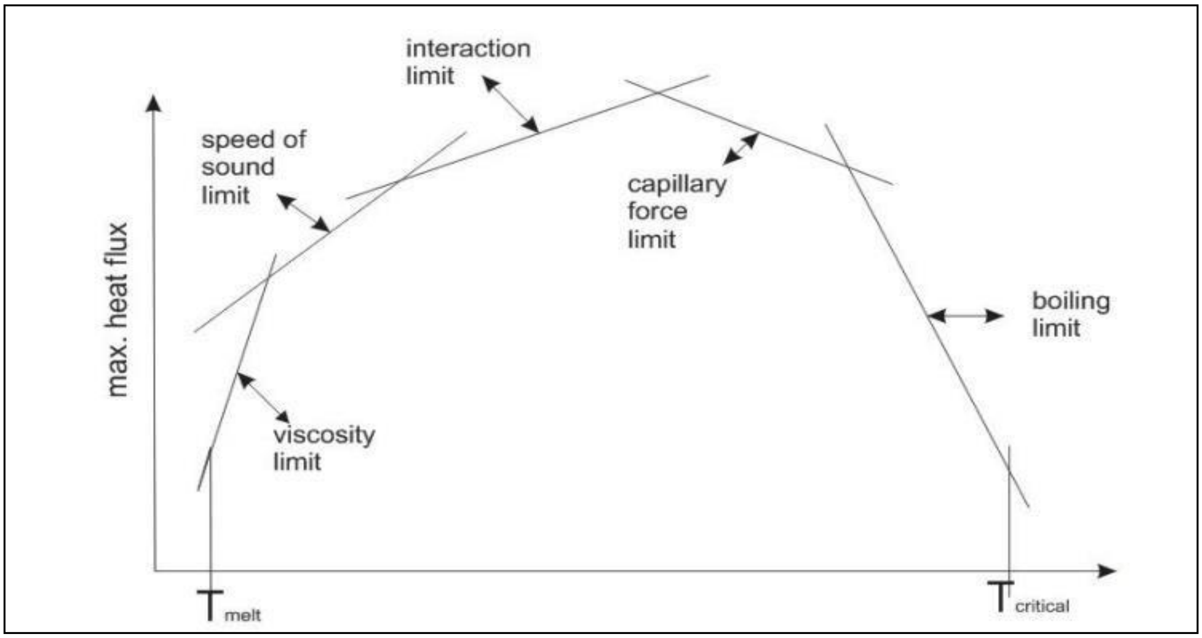

Figure 1-4 Limitation of CLPHP[2]

1.6 Objective

1. To examine the performance of CLPHP with 90° and 180° and filling ratios of 50% and 60% Methanol as a working fluid.

2. To evaluate the performance of the CLPHP at 90° and 180° with a working fluid filling ratio of 50% and 80% Distilled water.

3. To examine the thermal performance of the CLPHP with two working fluids—methanol and distilled water—at 90° and 180° angles, respectively, with filling ratios of 50% and 60%.

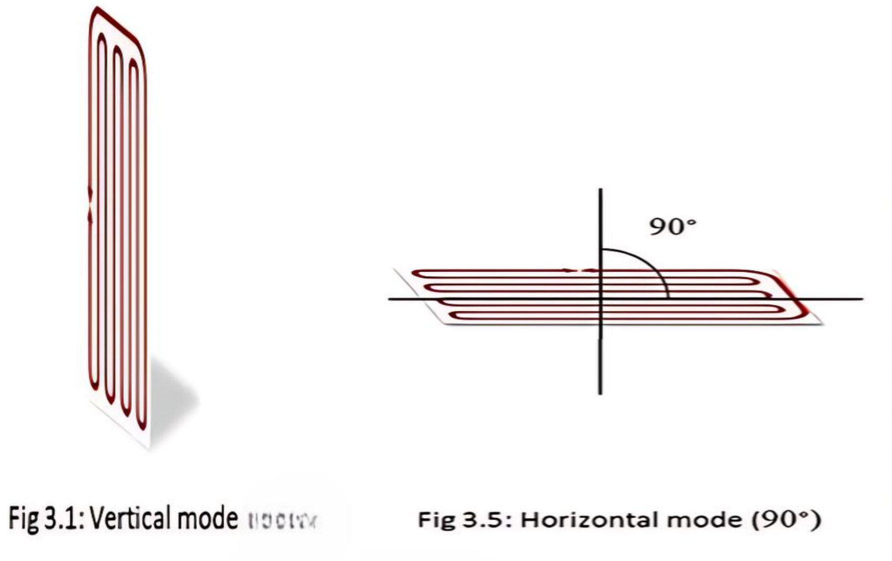

Figure 1-5 Angles hypothesis define origin in vertical plan

Chapter 2

2 Literature Review

Similar to traditional heat pipes, pulsating heat pipes are closed, two-phase devices that may transfer heat without the need of extra electricity. However, they significantly vary from traditional heat pipes in a number of important aspects. A typical PHP is a tiny, meandering tube holding a fluid that is only half functional. The tube's ends may either be pinched off and left open or they can be welded together to make a closed loop. The tube rotates back and forth while being parallel to itself. Researchers found that the closed-loop PHP performs better in terms of heat transmission. The majority of experimental work employs closed-loop PHPs as a result. Heat transfer is improved in the closed-loop PHP because the working fluid may also be circulated in addition to the oscillatory flow. The ability of the PHPs to carry heat may be increased by installing a check valve, which directs the working fluid in a certain direction. However, doing so is challenging and costly. Using PHP structures that are closed-loop and lack a check valve is the best option.

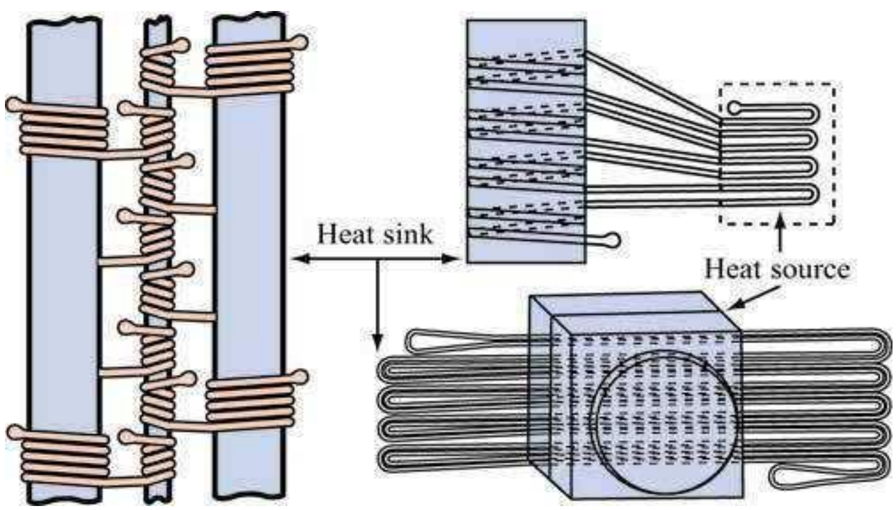

Figure 2-1 Heat pipe by Akachi [3]

2.1 Closed loop pulsating heat pipe

Pulsating heat pipes are closed, two-phase systems that, like conventional heat pipes, may convey heat without needing additional power. However, they differ dramatically from conventional heat pipes in several critical ways. A typical PHP is a very small, meandering tube containing a partially working fluid. The ends of the tube may be welded together to form a closed loop, or they can be pinched off and left open. The tube is parallel to itself and rotated back and forth. The closed-loop PHP works better in terms of heat transfer, according to researchers. Because of this, the bulk of experimental work uses closed-loop PHPs. In the closed-loop PHP, the working fluid may also be circulated in addition to the oscillatory flow, which enhances heat transfer. Installing a check valve may improve the PHPs' capacity to transport heat by making the working fluid flow in a certain direction. However, doing so is difficult and expensive. The ideal choice is to use PHP structures that are closed-loop and do not have a check valve.

Recently, PHPs were prototyped and examined utilizing a sintered metal wick by Holley and Faghri [3] and [4] [5]. The wick should help with both liquid dispersion and heat transfer. A PHP must have at least one heated area and one cooled space. The evaporators and condensers are often located at the bends of the capillary tube. After emptying, a working fluid is initially partially injected into the tube. The liquid and its vapor will spread throughout the pipe as it slugs and bubbles. As the PHP heats up, the vapor pressure in the bubbles in the evaporator part will increase. This forces the liquid slug toward the condenser part of the heat pipe. As the vapor bubbles approach the condenser, they will begin to condense. When a vapor changes phases, the vapor pressure decreases, which causes the liquid to return to the condenser end. The PHP is set up to have a continuous oscillating flow in this way. Boiling the working fluid will also cause fresh vapor bubbles to form. PHP research is divided into two categories: theoretical and experimental. Regarding the experimental study, the focus has been on characterizing the heat transfer or illustrating the flow pattern in PHPs.

Theoretical studies attempt to mimic the heat transfer and fluid dynamics associated with oscillating two-phase flow numerically and analytically. A thermo-hydraulic coupling strongly controls the performance of a sophisticated heat transfer mechanism called a PHP. It operates as a non-equilibrium heat transfer mechanism. The success of the device's functioning depends on continuously maintaining or sustaining these non-equilibrium conditions within the system. Slugs of liquid and vapor are transferred due to the pressure pulsations generated in the system. The device's inherent architecture thermally drives these pressure pulsations. Therefore, no additional mechanical power source is required for the fluid transfer.

2.2 Emergence of Pulsating Heat Pipe

Conventional heat pipes (CHP) began to gain popularity in the 1960s, and various new geometries, working fluids, and wick structures have been proposed since then [5]. In addition, to address some of the shortcomings of conventional heat pipes, new heat pipe shapes, such as capillary pumped loops and loop heat pipes, have been created during the last 20 years by separating the liquid and vapor fluxes.

The pulsating or oscillating heat pipe (PHP or OHP) is a new kind of heat pipe developed by Akachi et al. in the 1990s & Khandekar et al., 2002. . PHP is often employed in electronics cooling because it can disperse the enormous heat fluxes required by next-generation devices. Pumping water or heating air are some other potential applications for PHPs. This review article will describe the operation of pulsating heat pipes, outline recent research and development, and discuss any outstanding issues.

[7]derived the wave equation of pressure oscillation in a PHP based on self-excited oscillation and assuming reciprocal excitation between pressure oscillation and void percentage. By solving the wave equation, they obtained a closed-form solution for the wave propagation velocity.

[8]conducted an experimental analysis of the oscillatory flow in the PHP and found the wave velocity reasonably consistent with Akachi et al. in the 1990s prediction.

The departure of small bubbles is considered the normal flow pattern at the evaporator and adiabatic section, respectively, according to [9], which claims that nucleate boiling and vapour oscillation cause bubble oscillations.

[10]conducted several tests using various PHP settings. He looked at how several factors (such as filling ratio, heat input, number of turns, and orientation) influenced their behaviour. His experiments gave him a better understanding of the heat and fluid dynamics of PHPs. He stressed the need to select a tube diameter permitting flow oscillations.

[11]also performed some flow visualizations while a PHP was active. They discovered four operating modes that resemble the PHP operating curve, representing the heat pipe's total thermal resistance as a function of input power. The oscillations' amplitude is confined at low heat input, and as heat input rises, the thermal resistance somewhat decreases. A more severe decline in

thermal resistance with higher heat input leads to a slug flow pattern. Nevertheless, a preferred flow direction eventually becomes apparent as the heat input rises. The desired flow direction must be chosen, and the flow pattern must be circular rather than slug-like for the thermal.

Little opposition exists, and there is a plateau. However, due to the thermal resistance rapidly increasing as the heat input increases, the evaporator dries up when there is a considerable heat flow.

[11]provided further details in their research using ethanol, water, and R-123. The critical diameter for ethanol and water was substantially larger than the tube diameter, in contrast to the latter, when it was equal to (or even slightly below) the tube diameter. According to their study, the filling ratio and orientation of the PHPs affect how bubbles affect the two-phase oscillating flow that develops at the PHPs' extreme operating limits (i.e., when the PHP is empty or filled with liquid). At high filling ratios (like 95% of liquid) and favorable orientations (like evaporator at the bottom, condenser at the top), the bubbles tend to limit the movement of the two-phase fluid. Even for water at modest filling ratios (approximately 20% to 70%, which really causes oscillations) or even for a critical diameter considerably bigger than the tube diameter (very constrained condition), gravity was a problem. The PHP was discovered to work with R-123 despite having a crucial diameter that was a little bit less than the tube diameter. These results were all explained by accounting for the influence of bubbles on the two-phase flow.

In their article[12]. discusses the effects of CLPHP on them.

Several variables impact HP's thermal performance, including the device's inclination angle, working fluid, the number of turns, and internal tube diameter. The findings of this experiment demonstrated that buoyancy forces affect bubble shape, the internal diameter must be selected with a crucial Bond number within the limit, and performance may be improved by boosting ID and meandering turn numbers. In addition, the performance of CLPHP is significantly impacted by gravity. Finally, different fluids are favorable depending on the working conditions, latent and sensible heat proportions, and flow properties.

[13]examined the spread of vapor plugs in a meandering closed-loop heat transfer system. They observed that a simple flow pattern emerged at high liquid volume percentages. Only two vapor plugs can be located independently in neighboring rounds under these conditions, and one starts

to constrict as the other starts to grow. A streamlined numerical solution was also performed, removing any conceivable liquid coating between the tube wall and the vapor stopper under several critical assumptions.

From several angles and with various working fluids,[14] evaluated an open-loop PHP. He evaluated the thermal efficiency of a PHP using working fluids such as water, ethanol, propanol, methanol, and acetone. Under his test conditions, methanol and acetone generated the greatest thermal performance, whereas water produced the worst. Additionally, he discovered that the PHP oscillations are stronger and more frequent when methanol is used in place of water. The low latent heat of methanol, which promotes boiling and nucleation and, as a consequence, fluid flow instability, was thought to be the cause. Finally, he found that horizontal orientation outperformed vertical orientation regarding thermal performance. However, the importance

Unlike ethanol and methanol, water's thermal performance is almost fully independent of orientation, where the ratio of thermal resistances in horizontal and vertical orientation is more than two.

[15]used a high-speed video to observe the oscillatory flow in a closed-loop PHP. For methanol and water, several oscillation modes were discovered. The working fluid was water, which highlighted the processes of vapor plug break-up and coalescence, particularly near tube U-bends. They concluded that the capillary pressure is not constant in the bends, leading to a localized buildup of liquid based on an analytical model. They further said the methanol used as the working fluid's low surface tension prevents coalescence or break-up. When compared to water, the liquid plugs are, therefore, longer.

In their article published at[16]. offer an experimental study on the operational restrictions of closed-loop pulsing heat pipes (CLPHPs). The three operational orientations looked at were vertical bottom heated, horizontal heated, and vertical top heated. The effects of inner diameter, operating orientation, filling ratio, and heat input flux on thermal performance and performance limits were examined. The CLPHPs were operated until a performance threshold was achieved, indicated by extreme evaporator overheating (dry-out). After that, rather high heat loads may be managed. An experimental examination on two closed-loop pulsing heat pipes (CLPHPs) examined the effects of inner diameter, filling ratio, operational orientation, and heat load on thermal performance and performance limitation in the form of evaporator dry-out. CLPHPs have their best thermal performance and maximum performance limit in the vertical bottom heat mode with a 50% filling ratio. As the inner diameter decreases, performance changes brought on by different heat modes (i.e., the gravity effect) become extremely slight or insignificant.

This work examined the operational limit of closed-loop oscillating heat pipes with check valves (CLOHP/CV) concerning the inner diameter and inclination angles. Using copper tubes with an ID of 1.77 and 2.03 mm and ten turns, R123 was used as the working fluid. Five equal lengths with inclination angles of 0, 20, 40, 60, 80, and 90° comprised the evaporator, adiabatic, and condenser sections. The critical temperature increased when the inner diameter changed from 1.77 to 2.03 mm, according to [17]In addition, the critical temperature increased from 0 to 90 degrees of inclination.

[18]quantitatively investigated oscillatory flow and heat transfer in a small U-shaped channel. The U-shaped tube's two sealed ends served as the heating components. The condenser part was located in the middle of the U-shaped canal. The U-shaped duct was placed vertically, with two sealed ends (heating parts) at the top. The impact of several non-dimensional factors on PHP performance was also investigated. Empirical correlations were found between the oscillation's amplitude and circular frequency.

[19]found that heat transmission in a PHP is primarily brought about by the interchange of heat, with sensible heat accounting for over 90% of the heat transfer from the evaporator to the condenser. The oscillation of liquid slugs was the primary effect of evaporation and condensation on the performance of PHPs. At the same time, latent heat had less effect on the overall quantity of heat transfer.

In an experiment, [20]showed that with an input power of 30–50W at the same charge volume, the temperature difference between silver Nano-fluids and DI-water decreased by 0.56–0.65°C.

Base water and spherical Al2O3 particles with a diameter of 56 nm were used in an experiment by [21]The highest thermal resistance was reduced by 0.14 °C/W (or 32.5%) compared to pure water when the power input was 58.8W at a 70% filling ratio and 0.9% mass fraction.

The current use of heat pipe technology has significantly advanced due to heat pipes being reduced in size. The American and Japanese heat pipe industries have conducted research on the use of heat pipes, even with a diameter of 2 mm, for cooling the laptop PC and CPU.

The small heat pipe has recently shown a startling effect when used to disperse heat and keep computers and other electrical gadgets at a consistent temperature. Therefore, a thorough investigation is crucial for the little heat pipe's further growth and performance improvement.

Using a full-sized PHP, this article will first assess some experimental data. The impacts of fluid and tube sizes, as well as orientation, will get particular emphasis. We will then discuss the results of an experimental investigation of the oscillating flow in a single tube of a single liquid plug under adiabatic conditions (purely hydrodynamic aspect) and under non-adiabatic conditions to help us analyze the results obtained at the system scale (thermal effects due to heating of the test-section).

Chapter 3

3 Experimental set-up and test procedure

Usually, components are required. The following are some prerequisites to running a CPL:

Evaporator: The part of the CPL where heat is provided is the evaporator. Usually, thermal energy is created by a heated surface or component. The working fluid evaporates with the aid of the evaporator, commencing the heat transfer process.

Condenser: The condenser discharges the heat that the evaporator's working fluid has absorbed. It is frequently positioned in a cooler section of the CPL and assists with vapor condensation, distributing heat into the surroundings.

Capillary Structure: A CPL's capillary structure is vital because it lets the working fluid flow freely throughout the loop. It comprises microscopic capillaries or channels that support capillary action, which allows the fluid to flow against gravity. The CPL's capillary structure contributes to maintaining continuous circulation.

Working Fluid: This fluid changes phases from liquid to vapor to liquid again, filling the closed-loop system. Working fluids that are typically employed in CPLs include alcohol, water, or their mixtures. The needed operating temperature range, heat transfer efficacy, and system compatibility are just a few of the aspects determining the working fluid choice.

The closed-loop pulsating heat pipe is produced using pipes or tubes constructed of a thermally conductive material, such as copper or aluminum. The pipes combine the evaporator and condenser components to produce a closed circuit or network. In addition, they provide a route for the working fluid, letting heat travel between different areas of the CPL.

Heat Source: A heat source is needed to offer the evaporator part the required thermal energy. This may comprise an indirect heat transfer from a separate component or a direct heat input from an external source.

Insulating: To prevent heat loss from the CPL system and maintain a more efficient heat transfer mechanism, insulating material may be employed. Insulation is typically placed on the CPL's outer surfaces to decrease heat losses to the environment.

3.1 Common peripheral devices

- Pulsating heat pipe
- Other Equipment
  - AC fan
  - Adapter circuit
  - Arduino Mega
  - Arduino 1.5.2 Compiler
  - Glue Gun
  - Super Glue
  - Electric Wire
  - Copper Wire 0.9mm (Insert)
  - Aluminum Wire 0.9mm (Insert)

Table 1 Working apparatus

Working fluid	**Test stand**	**Insulating apparatus**
Methanol	**Heating apparatus**	Mica tape
Ethanol	Variac.	Glass wool
Distilled Water	Power Supply Unit.	Foam tape
Acetone	Nichrome Wire	Asbestos tape
	EPE Insulation foam	

3.2 Description of Different types of Apparatus

3.3 Working Fluid

3.3.1 Methanol

Methanol, commonly known as methyl alcohol, wood alcohol, wood naphtha, or wood spirits (sometimes abbreviated MeOH), has the chemical formula CH_3OH. Methanol was originally known as "wood alcohol" because it was predominantly generated as a byproduct of the destructive distillation from wood. Modern methanol is produced directly from hydrogen, carbon dioxide, and monoxide in an industrial catalytic process.

Methanol, the most basic form of alcohol, is a colorless, light, flammable liquid with a characteristic odor similar to that of ethanol (drinking alcohol). In contrast to ethanol, methanol is poisonous and not recommended for human intake. It is a denaturant for ethanol used as an antifreeze, solvent, fuel, and polar liquid at room temperature. It is also utilized in the transesterification process that produces biodiesel.

Methanol is naturally formed in the anaerobic metabolism of many bacterial species and is usually present in the environment at trace levels. Methanol vapor is thus only very little present in the environment. However, for many days, sunshine breaks down the methanol in the atmosphere into carbon dioxide and water.

Methanol burns when exposed to oxygen, even in the open air, producing carbon dioxide and water:

$$2\ CH_3OH + 3\ O_2 \rightarrow 2\ CO_2 + 4H_2O$$

Methanol properties:

Table 2 Methanol properties

SL. No.	Parameters	Symbol	Quantity	Unit
1.	Freezing temperature	T_{freeze}	-97.6	^oC
2.	Boiling temperature	T_{boil}	64.7	^oC
3.	Density	P	792	kg/m^3
4.	Specific heat (at 20°C)	C_p	2.5	Kj/kg-k
5.	Vapor pressure	Pv	13.02	kPa
6.	Molar mass	Ms	32.04	g/mol

3.3.2 Distilled Water

Distilled water is water that has been heated into a vapor and then condensed back into liquid in a separate container. Any contaminants in the original water that do not boil at or below the boiling point of water are still present in the original container. So, distilled water is one kind of purified water.

Distilled Water properties:

Table 3 Distilled water properties

SL. No.	Parameters	Symbol	Quantity	Unit
1.	Freezing temperature	T_{freeze}	0	°C
2.	Boiling temperature	T_{boil}	100	°C
3.	Density	P	997	kg/m³
4.	Specific heat (at 25°C)	C_p	4.187	Kj/kg-k
5.	Vapor pressure	Pv	3.157/25 °C	kPa
6.	Molar mass	Ms	18.01528	g/mol

3.4 Experiment Set-up

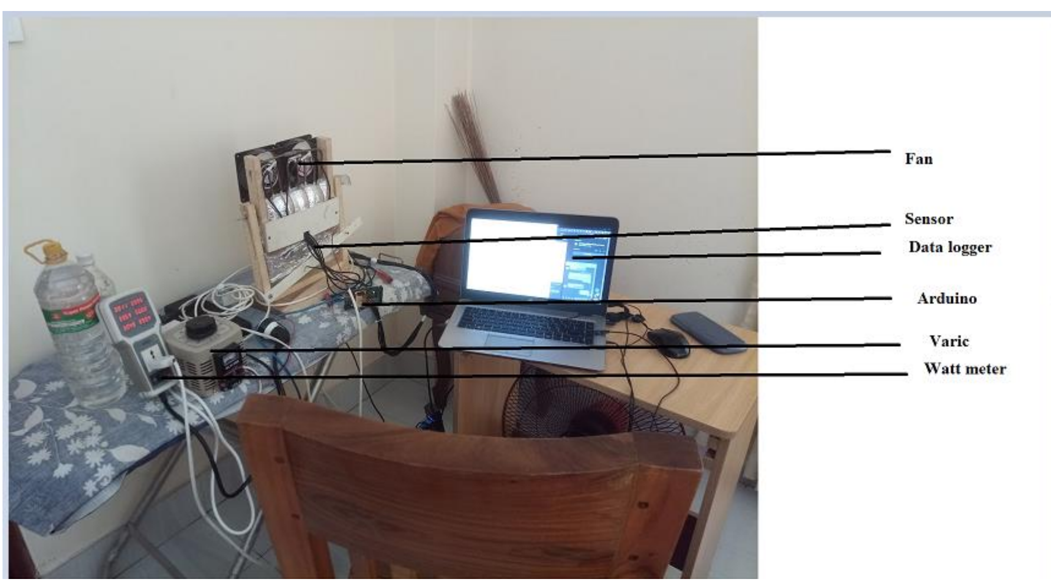

Figure 3-1 Experiment Set-up

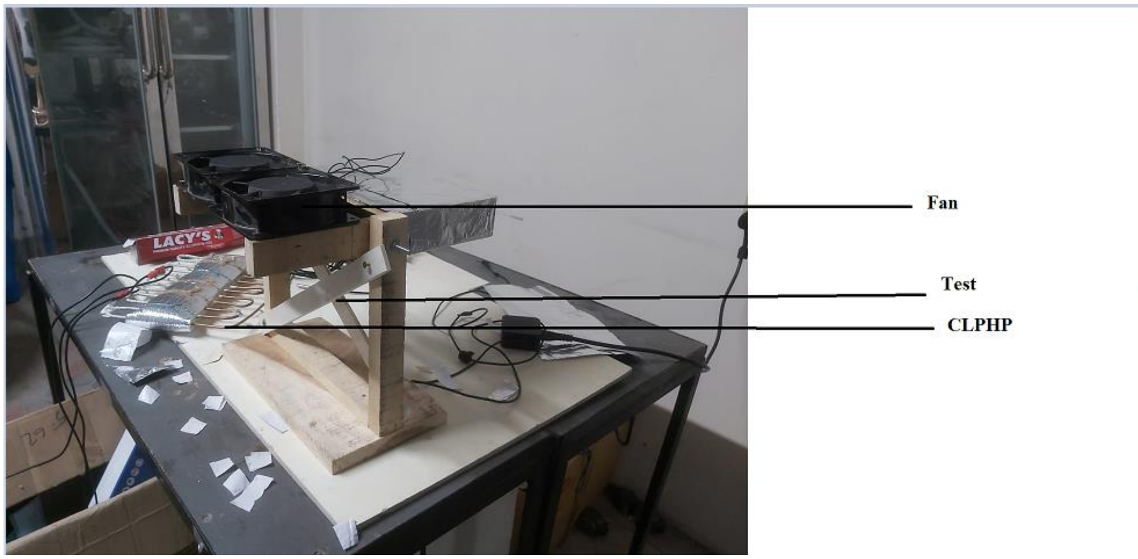

Figure 3-2 Test Stand with Apparatus

Parameters	**Condition**
Length of evaporator section	50mm
Length of adiabatic section	100 mm
Length of condenser section	60 mm
Material	copper
Turn	4
Distance Between two pipes	20mm

3.5 Experimental Methodology

Identify the closed loop pulsing heat pipe's (CLPHP) dimensions and configuration.

Set up a hot plate or another heating source to provide the CLPHP-regulated heat input.

To monitor the functioning of the CLPHP, install flow meters, pressure gauges, and temperature sensors. Make sure there is a reliable power supply for the experimental setup.

CLPHP preparation:

Clean the CLPHP thoroughly and eliminate any impurities using an appropriate solvent. Make sure that each component of the CLPHP is joined and sealed before assembling it.

Install the temperature sensors, pressure gauges, and flow meters where they go along the CLPHP.

3.6 Experiment using a 50% Fill Ratio:

By adding methanol or ethanol, fill the CLPHP to a filling ratio of 50% (i.e., the working fluid occupies 50% of the internal volume).

Connect the CLPHP to the power supply and the heating source.

As you progressively increase the heat input to the CLPHP, pay attention to the flow rate, pressure, and temperature.

Record the flow rate, pressure drop, wall, evaporator, condenser temperatures, and other performance data.

Run many tests while adjusting the heat input and evaluating the CLPHP's performance under different operating conditions.

Experiment using an 60% Fill Ratio:

To fill the CLPHP to 60% of its capacity, drain the previous working fluid and swap it out with either methanol or ethanol.

Track and record CLPHP performance data while replicating the Filling Ratio at 50% experiment's stages.

3.7 At 90° position experiment

Make the CLPHP configuration 90 degrees above the horizontal by adjusting it.

Fill the CLPHP with the chosen working fluid until the appropriate filling ratio (usually 50% or 80%).

The same procedures should be followed, and performance data should be documented as the heat input is gradually raised.

3.8 Experiment using a 180-degree angle:

Set the CLPHP setting to 180 degrees off the vertical.

Fill the CLPHP with the working fluid while keeping the necessary filling ratio. Increase the heat input, monitor the CLPHP's operation, and note the outcomes. Data Analysis the collected data and compare the performance of the CLPHP at different filling ratios and orientations. Examine the flow behavior, pressure drop, and heat transfer characteristics of the CLPHP under each experimental situation. Analyze the data, draw conclusions, and identify trends. Observations that need mention. Think about heat transmission effectiveness, temperature distribution, and operational stability.

3.9 Precaution

The following factors were considered throughout the experiment: All other sources impeding heat transfer were turned off throughout the process. Before taking the temperature, the sensor (DS18B20 sensors) utilized in the experiment has to be thoroughly examined. The fluid injection must be accurate since the fill ratio affects how efficiently the heat pipe functions. Only when a temperature reaches a stable condition or a consistent value can measurements be conducted. Since condenser condensation might sometimes result in leaks, the silicon tube should always be adequately sealed. CLPHP Trying to blast the liquid out of your mouth is never a good idea. If you do, blisters will form on your lips. Sealing Methods Efficient sealing methods are essential to stop pressure leakage in CLPHPs. High-quality seals or joints should be utilized at the connections between various heat pipe parts, such as the evaporator, condenser, and various portions of the loop. The seals must be strong enough to resist the operating pressures and temperature variations encountered inside the system.

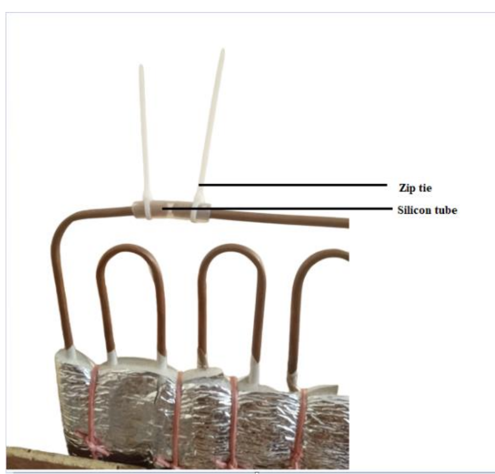

Figure 3-3 Sealing Ensure by Zip tie & Silicon tube

Chapter 4

4 Results & Discussions

In this chapter, we will illustrate our findings visually and briefly explain the effect.

Excel & Origin Pro generated fascinating statistical visual graphs.

4.1 Steady Condition of All Data

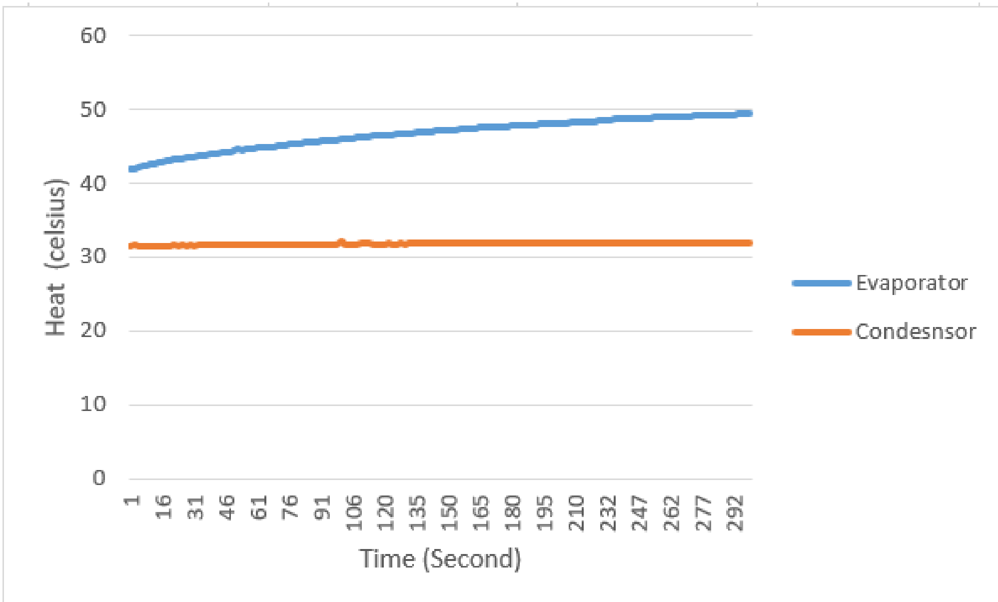

Figure 4-1 Heat vs Second Steady condition data

In this graph representing that the steady condition archive in our experiment. To examine the behavior of the CLPHP, data collection entails monitoring numerous parameters, including temperature, pressure, flow rate, and heat transfer coefficient. Ensuring the instrument enters a stable condition before collecting any measurements is essential to acquire reliable and precise data. Achieving a steady state in a CLPHP entails that the flow rate, temperature, and pressure of the working fluid have stabilized and that there has been little change over time. As a result, the heat transfer process is more predictable, and the device's performance is easier to analyze when the CLPHP is in a steady state. Data that are consistent and reliable may be obtained when the CLPHP is not in a stable state during data collection. For instance, getting precise and important data could be challenging because of the large fluctuations in the observed temperatures, pressures, and flow rates. A steady state must be established and maintained to collect data in a closed-loop pulsating heat pipe.

4.2 Methanol

4.2.1 50% filling ratio position 90 degree

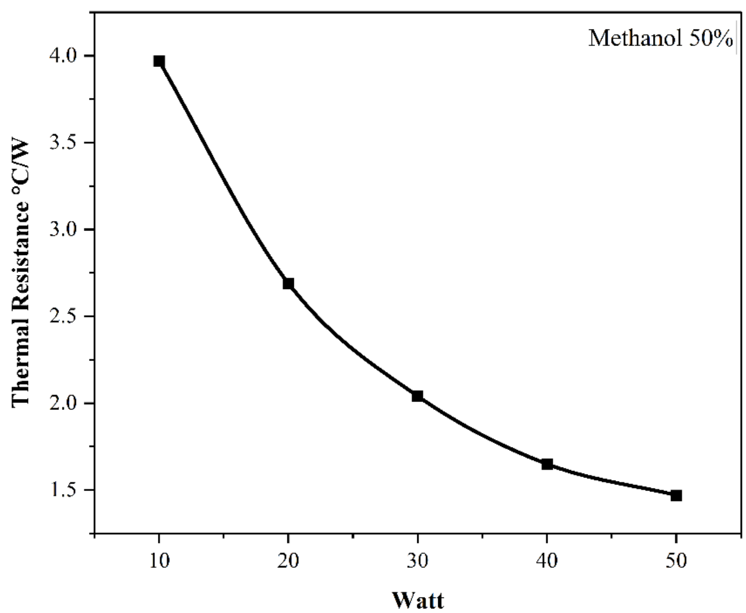

Figure 4-2 Thermal resistance vs heat input (Watt) 50% FR Position 90 degree

Power input is represented by the graph's x-axis, which has two data points: 10 watts and 50 watts. The y-axis displays thermal resistance, and the equivalent values for the two power inputs are 4.00 and 1.5, respectively.

The thermal resistance reduces from 10 watts to 50 watts of power input in the specified range. This suggests that greater power inputs cause the closed pulsating heat pipe's thermal resistance to decrease.

The graph's slope indicates thermal resistance decreases significantly as power input increases. The difference is most noticeable between 10 and 50 watts.

The graph illustrates an inverse connection between thermal resistance and power input. Thermal resistance reduces as power input rises.

These findings allow us to conclude that the closed pulsating heat pipe performs better thermally at larger power inputs. This behavior is advantageous for situations where effective heat dissipation is needed to avoid overheating.

4.2.2 50% filling ratio position 180 degree

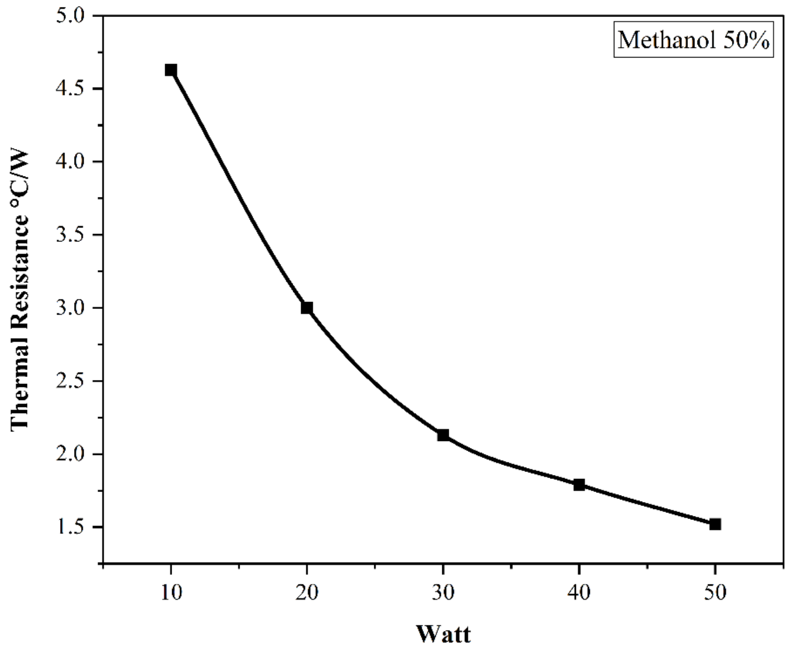

Figure 4-3 Thermal resistance vs heat input (Watt) 50% FR position 180 degree

Power input is represented by the graph's x-axis, which has two data. The thermal resistance falls as the power input rises from 10 watts to 50 watts. According to this, a closed pulsing heat pipe's thermal resistance decreases as power input increases.

The graph's slope shows a modest reduction in thermal resistance as the power input rises. However, the difference is less noticeable compared to the preceding instance.

Thermal resistance and power input continue to be inversely correlated. The thermal resistance decreases as the power input increases.

These data lead us to the conclusion that the closed pulsing heat pipe performs better thermally at larger power inputs. In contrast to the earlier research, the magnitude of the thermal resistance decrease is less substantial.

The actual thermal resistance values (4.6 and 1.6) might be interpreted differently based on the units employed and the properties of the closed pulsing heat pipe under study.

4.2.3 60% filling ratio position 90 degree

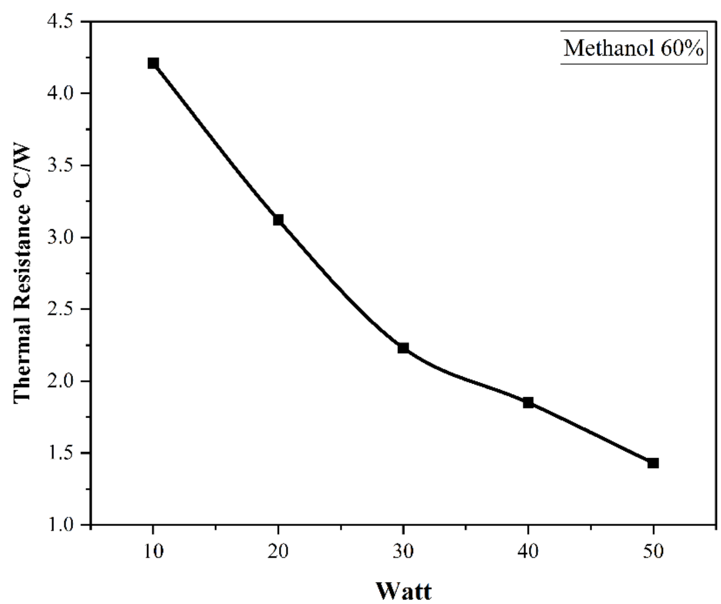

Figure 4-4 Thermal Resistance vs heat input (Watts) 60% FR position 90 degree

The graph shows that the thermal resistance reduces from 10 to 50 watts of power input. This demonstrates that larger power inputs produce decreased thermal resistance in the closed pulsating heat pipe.

The graph's slope indicates a significant drop in thermal resistance as the power input rises. Compared to the earlier assessments, this suggests a more substantial decrease in heat resistance.

Thermal resistance and power input have an inverse connection that is valid. This is because the thermal resistance reduces as the power input rises.

These findings lead us to the conclusion that the closed pulsating heat pipe performs better thermally at larger power inputs. Furthermore, according to the graph, thermal resistance significantly decreases as power input rises, indicating that the system effectively dissipates heat.

It is crucial to remember that the precise thermal resistance values (4.3 and 1.3) may vary depending on the units employed and the properties of the closed pulsating heat pipe under study.

4.2.4 60% filling ratio position 180 degree

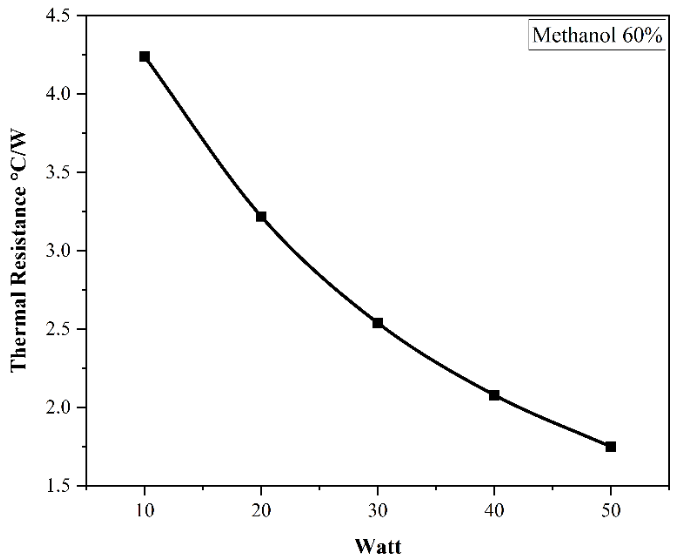

Figure 4-5 Thermal resistance vs heat input (Watt) FR 60% position 180 degree

The graph demonstrates that the thermal resistance reduces from 10 to 50 watts of power input This demonstrates that larger power inputs produce decreased thermal resistance in the closed pulsating heat pipe.

The graph's slope indicates thermal resistance steadily decreases as power input rises. This suggests that the decrease in heat resistance is predictable and constant.

Higher power inputs correspond with lower thermal resistance, demonstrating the inverse connection between power input and thermal resistance.

These findings lead us to the conclusion that the closed pulsating heat pipe performs better thermally with greater power inputs. Furthermore, the graph's thermal resistance is decreasing steadily and predictably, indicating that the system is effectively dissipating heat.

4.2.5 Compare methanol all

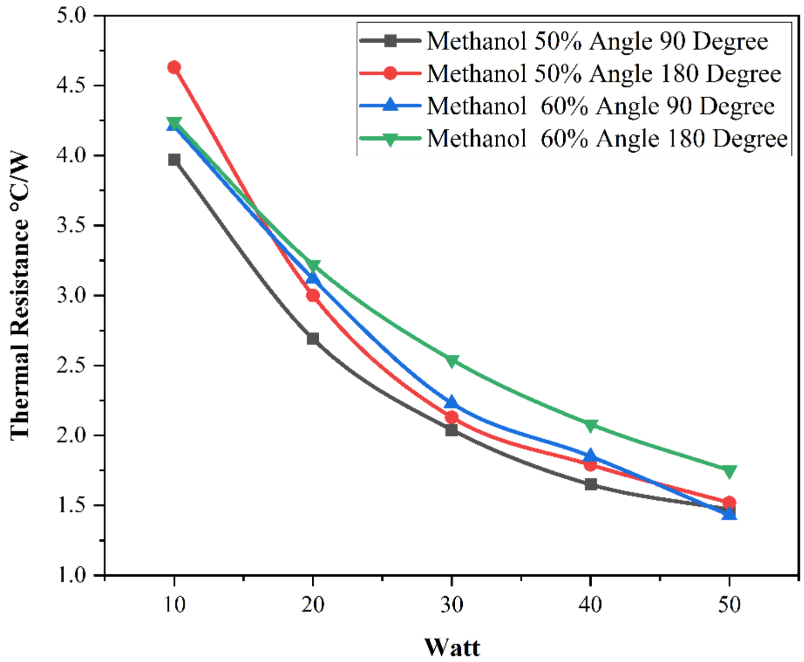

Figure 4-6 Thermal resistance vs Heat input (Watt) Methanol all

The heat resistance, which measures 4.6 at 10 watts and a 50% methanol filling ratio, is quite high. This suggests that the heat pipe's capacity to disperse heat effectively is constrained under certain circumstances.

The graph shows a consistent decrease in thermal resistance when power input exceeds 10 watts. According to this, a closed pulsating heat pipe's thermal resistance decreases, and heat dispersion improves with larger power inputs.

However, the reduction in heat resistance progresses extremely slowly when the methanol filling ratio is raised to 60%. This shows improved heat dissipation diminishes when the methanol filling percentage is over 50%. The lowest point of heat resistance is attained at 40 watts, corresponding to a 60% methanol filling ratio and a 90-degree angle. This suggests that the closed pulsing heat pipe displays the lowest thermal resistance and reaches its maximum heat dissipation under these circumstances. These findings lead us to conclude that the closed pulsing heat pipe exhibits strong thermal resistance at 10 watts and a 50% methanol filling ratio. However, thermal resistance continuously decreases as power input rises, suggesting improved heat dissipation. However, the graph shows that improving heat dissipation by raising the methanol filling ratio over 50% may be ineffective. Additionally, at 40 watts, a 60% methanol filling ratio and a 90-degree position result in maximum heat dissipation.

4.3 Distilled water

4.3.1 50% filling ratio position 90 degree

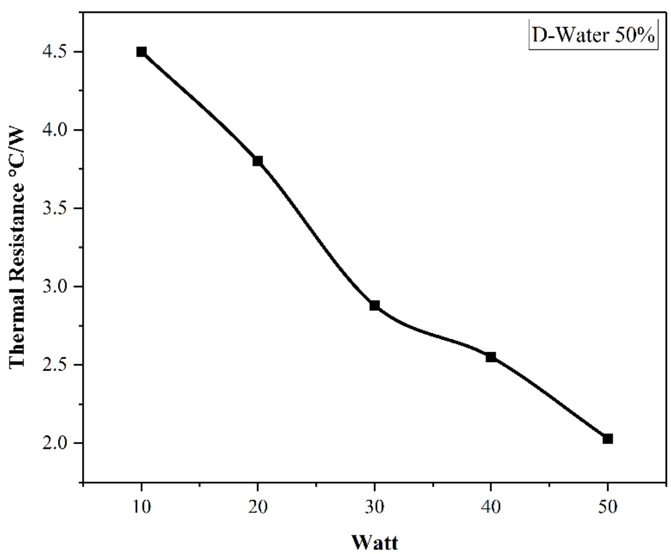

Figure 4-7 Thermal resistance vs heat input (watt) FR 50% position 90-degree D. water

The graph demonstrates that the thermal resistance rises as the power input rises from 10 watts to 50 watts. This suggests that increased power inputs cause the closed pulsating heat pipe's thermal resistance to increase.

The graph's slope indicates a particularly sharp rise in thermal resistance as power input rises. This shows that the heat pipe's thermal performance decreases noticeably when the power input increases.

However, there is a noticeable decrease in heat resistance at 30 watts. This shows that heat dissipation has significantly improved at this power level.

Unfortunately, the graph shows that the reduction in thermal resistance becomes continuous beyond 40 watts. This indicates that increasing the power intake does not further increase heat dissipation beyond a certain point. The heat pipe's capacity to effectively disperse heat hits a limit.

These findings lead us to the conclusion that when the power input rises, the closed pulsing heat pipe first suffers an increase in thermal resistance. Although there is a positive decrease in thermal resistance at 30 watts, this suggests increased heat dissipation. However, the thermal resistance stays the same at 40 watts, suggesting that the heat pipe's thermal performance has peaked and that adding more power would not result in further advantages.

4.3.2 50% filling ratio position 180 degree

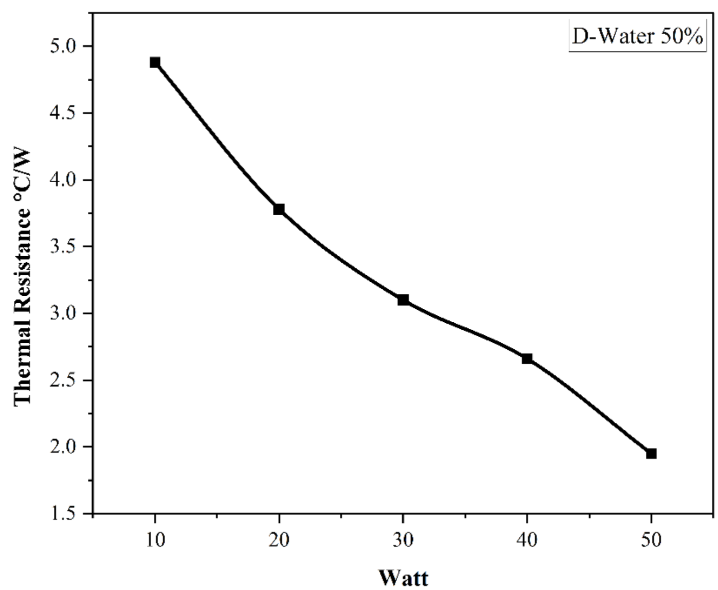

Figure 4-8 Thermal resistance vs heat input (Watt) methanol FR 50% position 180

The graph shows that the thermal resistance reduces from 10 to 50 watts of power input. This demonstrates that larger power inputs produce decreased thermal resistance in the closed pulsating heat pipe. The graph's slope suggests thermal resistance decreases significantly as power input rises. This shows that greater power inputs significantly enhance the heat pipe's thermal performance. Thermal resistance shows a good decrease at 30 watts. This suggests that the closed pulsing heat pipe dissipates heat effectively at this power level. However, the graph demonstrates that the drop in thermal resistance becomes continuous beyond 40 watts. This shows that power input increases beyond this amount do not result in further improvements in heat dissipation. The thermal resistance is constant when the heat pipe is in an equilibrium condition. These findings lead us to the conclusion that at 10 watts, the closed pulsing heat pipe initially exhibits substantial thermal resistance. However, thermal resistance significantly decreases as power input rises, suggesting improved heat dissipation. At 30 watts, the most encouraging improvement is shown. However, the thermal resistance is constant at 40 watts, indicating that the heat pipe's thermal performance reaches a maximum.

4.3.3 60% filling ratio position 90 degree

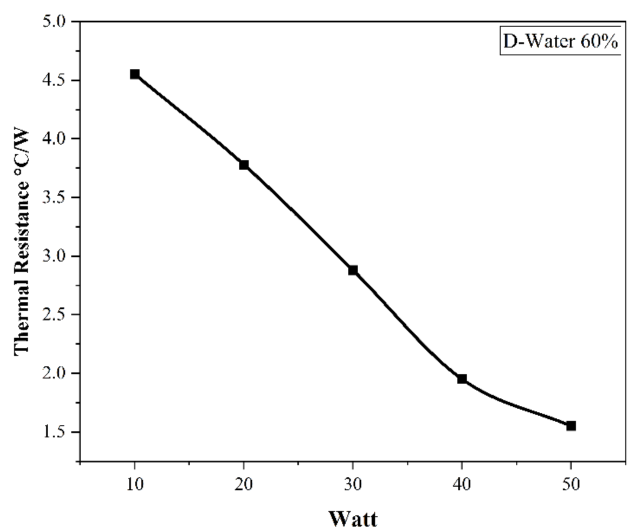

Figure 4-9 Thermal resistance vs heat input (Watt) FR 60% position 90 degree

The graph demonstrates that the thermal resistance reduces from 10 to 50 watts of power input. This demonstrates that larger power inputs produce decreased thermal resistance in the closed pulsating heat pipe.

The graph's slope indicates thermal resistance will significantly reduce as power input rises. This shows that greater power inputs significantly increase the heat pipe's thermal performance.

There is a promising decrease in thermal resistance at 40 watts. This shows that at this power level, the closed pulsing heat pipe demonstrates effective heat dissipation, significantly decreasing thermal resistance. However, the graph demonstrates that the drop in thermal resistance becomes continuous beyond 40 watts. This suggests that power input increases beyond this limit do not result in further improvements in heat dissipation. The heat pipe reaches a stage where the thermal resistance is largely constant when the thermal resistance hits a plateau. These findings lead us to the conclusion that at 10 watts, the closed pulsing heat pipe initially exhibits substantial thermal resistance. The thermal resistance, however, significantly decreases as the power input rises, suggesting increased heat dissipation. Finally, at 40 watts, the most encouraging improvement is shown. Beyond this threshold, the thermal resistance stays constant, proving that increased power input does not further enhance the heat pipe's thermal performance.

4.3.4 60% filling ratio position 180 degree

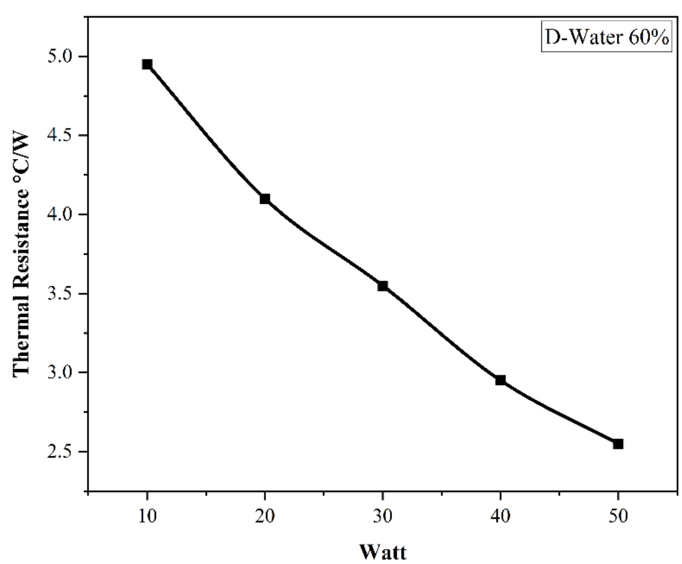

Figure 4-10 Thermal resistance vs heat input (Watt) FR 60% position 180 degree

The graph demonstrates that the thermal resistance reduces from 10 to 50 watts of power input. This demonstrates that larger power inputs produce decreased thermal resistance in the closed pulsating heat pipe.

The graph's slope indicates thermal resistance will significantly reduce as power input rises. This suggests that greater power inputs significantly enhance the heat pipe's thermal performance.

The thermal resistance is rather high at 10 watts, measuring at 5.0. The thermal resistance, however, drops to 2.5 when the power input rises to 50 watts.

These findings lead us to conclude that at 10 watts, the closed pulsing heat pipe initially displays a high thermal resistance. However, the thermal resistance considerably drops at 50 watts of power input, suggesting enhanced heat dissipation. According to the graph, the closed pulsing heat pipe efficiently lowers thermal resistance as power input rises.

4.3.5 Distilled water compares

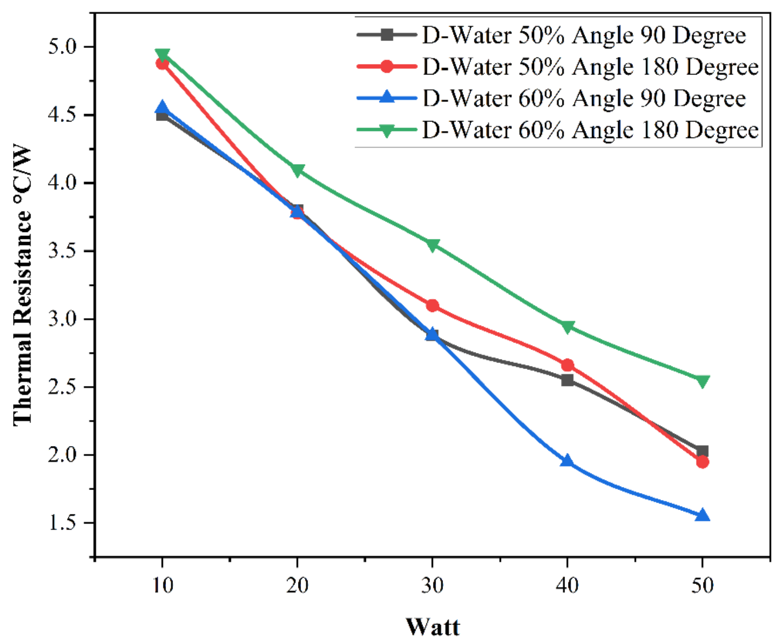

Figure 4-11 Thermal resistance vs heat input (watt) D. water all

The graph shows that using distilled water with a 60% filling ratio and a position of 180 degrees results in poor thermal performance. In addition, the thermal resistance is high, indicating inefficient heat dissipation.

However, when the filling ratio remains at 60%, but the position changes to 90 degrees, the thermal performance significantly improves. In addition, the thermal resistance decreases to a value of 1.5, indicating effective heat dissipation.

Notably, at an position of 90 degrees, both the 50% and 60% filling ratios exhibit better thermal performance compared to the 180-degree angle. This suggests that the orientation of the heat pipe has a significant impact on its thermal behavior.

Based on these observations, at an initial power input of 10 watts, the closed-loop pulsating heat pipe shows the poor thermal performance when using distilled water with a 60% filling ratio at a 180-degree angle. However, shifting to a 90-degree position significantly improves thermal performance, with the lowest thermal resistance recorded at 1.5. Additionally, the 50% and 60% filling ratios perform better at the 90-degree position than the 180-degree angle.

It is important to note that the specific values and trends in thermal resistance may vary depending on the units used and the specific characteristics of the closed-loop pulsating heat pipe being analyzed.

Chapter 5

5 Conclusions

The working fluid used in a closed-loop pulsating heat pipe research significantly impacts the thermal performance of the device. Therefore, the performance of Methanol and distilled water as working fluids is the main topic of this investigation.

At an input heat power of 10 watts, the working fluid, Methanol, initially displays a greater thermal resistance than purified water. Methanol has a thermal resistance of 4.8, whereas distilled water has a somewhat greater thermal resistance of 5. This suggests that at the first stage, Methanol hinders heat dissipation more than pure water.

Methanol, however, performs better when the performance as a whole is considered. When using Methanol with a filling ratio of 60% and a 90° inclination angle, the lowest and best thermal resistance of 4 is attained. The closed-loop pulsing heat pipe performs optimally and efficiently thanks to its particular arrangement.

Distilled water, on the other hand, performs far worse than Methanol. It first displays more thermal resistance with a 10-watt heat input (measured 5), but it begins to show promise when utilized with a 60% filling ratio and a 90-degree inclination angle. The thermal resistance reduces to 1.4 with this arrangement, indicating greater heat dissipation. However, the performance of distilled water with a 60% filling ratio and a 90-degree inclination position outperforms other setups if the heat input approaches 40 watts.

Based on the investigation, Methanol is the best working fluid in the closed-loop pulsating heat pipe experiment. Although it originally showed greater heat resistance, it performs best overall when utilized with a 60% filling ratio and a 90° inclination angle. Distilled water, however, performs less well thermally throughout the trial.

It is crucial to remember that the precise figures in this analysis depend on the information at hand. The design, size, and testing settings all impact the closed-loop pulsing heat pipe's performance and characteristics. Further research and testing are required to develop a more thorough knowledge of the thermal behavior of various working fluids in closed-loop pulsing heat pipe systems.

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Appendix

Mathematical Equations and Calculations

Calculation of filling Ratio

Let, V = Internal volume of the heat pipe

= 100% Fill Ratio

Now, V = $\frac{\pi \times D_i^2 \times L}{4}\, mm^2$

= $\frac{3.1416 \times 2.60_i^2 \times \{(205+(2\times230)+(6\times210)\}}{4}$ mm^2

=10220 mm^2

≈10.20 ml

= 10.20 ml

The complete internal volume of the pipe is taken into consideration to be the system's maximum capacity as there isn't a separate container for working fluid in the test configuration. For instance, 5.1 ml, and 6.12 ml of working fluids were employed to evaluate the properties of heat transfer, yielding respective ratios of 50%, and 60%.

Calculation of Heat Input

Let, Q = Power Input (Heat Input)

= V.I. Cos θ

In our experiment 20W∼50W power was used for the reading at the interval of 10W.

Calculation of Thermal Resistance

Let, R_{th} = Thermal Resistance

= $\frac{\Delta T}{Q}$

= $\frac{T_e - T_C}{Q}$ °C/W

Micro-controller Code

```
#include <OneWire.h>
#include <DallasTemperature.h>
```

```
#define WATT 10.0

#define ONE_WIRE_BUS 10
OneWire oneWire(ONE_WIRE_BUS);
DallasTemperature sensors(&oneWire);

float temp[6];
long recordTime;

void setup() {
  Serial.begin(9600);
  sensors.begin();

  // set excel top row label
  Serial.println("CLEARSHEET");
  Serial.println("LABEL,Log Time(Sec),Resistance,Co-efficient,Watt");
  delay(500);
}

void loop() {
  sensors.requestTemperatures();
  for (byte i = 0; i < 6; i++) {
    float tempC = sensors.getTempCByIndex(i);
    if (tempC != DEVICE_DISCONNECTED_C) temp[i] = tempC;
Serial.print((String)temp[i] + ",");
  }
Serial.println();
```

```
  recordTime = millis() / 1000;
  float eva = temp[0] + temp[1] + temp[2] / 3.0;
  float con = temp[3] + temp[4] + temp[5] / 3.0;
  float resist = (eva - con) / WATT;
  float coeffi = WATT / (0.0062203 * (eva - con));

  Serial.println((String)"DATA," + recordTime + "," + resist + "," + coeffi + "," + WATT);
  delay(1000);
}
```

Data

50% Filling Ratio Angle 90 Degree

Steady condition

Watt	Evaporator (1)	Evaporator (2)	Evaporator (3)	Condensor (1)	Condensor (2)	Condensor (3)	Eva-Con/Watt
10	47.19	49.88	47.56	32.38	32.44	32.85	**3.97**
20	58.25	63.15	53.81	32.69	32.88	34.06	**2.69**
30	70.13	77.88	62.06	32.56	33.13	34.75	**2.04**
40	82.38	92.5	72.63	32.69	33.44	35.56	**1.65**
50	93	101.06	81.56	33.19	33.81	36.13	**1.47**

Methanol

50% Filling Ratio Angle 180 Degree

Steady condition

Watt	Evaporator (1)	Evaporator (2)	Evaporator (3)	Condens[illegible]	[illegible]ensor (2)	Condensor (3)	Eva-Con/Watt
10	47.94	50.81	50.44	32.81	32.75	33.25	**4.63**
20	59.06	64.31	63.25	32.81	33	33.56	**3**
30	72	80.25	77.06	32.94	33.38	34.13	**2.13**
40	85.13	95.81	89.44	33.13	33.75	93	**1.79**
50	100.56	114.81	102.56	33.38	34.19	35.75	**1.52**

Methanol

60% Filling Ratio Angle 90 Degree

Steady condition

Watt	Evaporator (1)	Evaporator (2)	Evaporator (3)	Condensor (1)	Condensor (2)	Condensor (3)	Eva-Con/Watt
10	48.06	50.31	49.81	32.25	31.19	32.25	**4.21**
20	63.63	64.19	[illegible]	32.94	32.81	33.31	**3.12**
30	72.56	72.5	[illegible]	33.69	35.44	35	**2.23**
40	77.75	77.38	78.31	34.44	39.69	37	**1.85**
50	52.75	53.88	51.56	33.31	32.88	33.69	**1.43**

Methanol

60% Filling Ratio Angle 180 Degree

Steady condition

Watt	Evaporator (1)	Evaporator (2)	Evaporator (3)	Condensor (1)	Condensor (2)	Condensor (3)	Eva-Con/Watt
10	55.13	56.44	53.5	33.44	32.88	33.81	**4.24**
20	65.38	67.63	65	33.38	33.81	34.44	**3.22**
30	75.5	75.69	74.19	33.94	34.44	36.06	**2.54**
40	79	[illegible] Chart Area	84.13	35.06	36.63	35.88	**2.08**
50	82.25	83.13	85.88	37.81	48	38	**1.75**

50% Filling Ratio Angle 90 Degree

Steady condition

Watt	Evaporator (1)	Evaporator (2)	Evaporator (3)	Condensor (1)	Condensor (2)	Condensor (3)	Eva-Con/Watt
10	46.25	48.75	46.25	32.06	32.06	32.44	**4.5**
20	58.75	63.94	58.75	32.06	32.31	32.81	**3.8**
30	70.81	78.13	66	32.25	32.69	33.88	**2.88**
40	83.56	93	75.5	32	32.56	34.25	**2.55**
50	94.13	103.88	81.13	32.19	32.88	34.44	**2.03**

D-Water

50% Filling Ratio Angle 180 Degree

Steady condition

Watt	Evaporator (1)	Evaporator (2)	Evaporator (3)	Condensor (1)	Condensor (2)	Condensor (3)	Eva-Con/Watt
10	47.81	50.75	47.81	31	31.13	31.56	**4.88**
20	58.69	64.69	58.69	31.44	31.56	32.06	**3.78**
30	70.31	78.56	75.44	31.56	31.75	32.31	**3.1**
40	83	92.75	87.44	31.81	32.19	32.94	**2.66**
50	96.13	108.81	96.13	31.75	32.44	33.69	**1.95**

D-Water

60% Filling Ratio Angle 90 Degree

Steady condition

Watt	Evaporator (1)	Evaporator (2)	Evaporator (3)	Condensor (1)	Condensor (2)	Condensor (3)	Eva-Con/Watt
10	48.63	51.88	48.63	30.69	31	31.56	**4.55**
20	61.69	67.25	61.69	30.75	31.19	31.81	**3.78**
30	77.38	84.88	77.38	31.13	32.06	32.94	**2.88**
40	88.44	97.56	81.5	31.13	33.19	34.88	**1.95**
50	103.38	103.5	103.38	31.38	36	35.5	**1.55**

D-Water

60% Filling Ratio Angle 180 Degree

Steady condition

Watt	Evaporator (1)	Evaporator (2)	Evaporator (3)	Condensor (1)	Condensor (2)	Condensor (3)	Eva-Con/Watt
10	51.06	54.31	51.06	30.56	30.69	31.31	**4.95**
20	64.69	70.5	64.69	30.94	31.13	31.69	**4.1**
30	78.56	86.5	82.13	30.81	31.81	31.88	**3.55**
40	92.94	100.63	92.94	31.13	32.56	32.69	**2.95**
50	106.63	107.75	106.63	31.75	38.44	35.06	**2.55**

Steady condition data table

Sec	Evaporator	Condenser
1	41.88	31.49
3	42.02	31.63
5	42.17	31.48

Sec	Evaporator	Condenser
7	42.32	31.5
9	42.46	31.54
10	42.56	31.52
12	42.71	31.52
14	42.83	31.5
16	42.94	31.54
18	43.02	31.56
20	43.1	31.52
22	43.21	31.58
23	43.31	31.56
25	43.43	31.6
27	43.48	31.56
29	43.56	31.6
31	43.64	31.56
33	43.75	31.6
35	43.83	31.58
37	43.88	31.62
38	43.98	31.62
40	44.04	31.64
42	44.1	31.64
44	44.19	31.62
46	44.29	31.64
48	44.33	31.66
50	44.39	31.64
51	44.64	31.71
53	44.54	31.69
55	44.6	31.69
57	44.69	31.69
59	44.75	31.71
61	44.81	31.71
63	44.85	31.71
64	44.94	31.71
66	44.96	31.73
68	45.02	31.71
70	45.08	31.71
72	45.16	31.71
74	45.25	31.73
76	45.27	31.73
78	45.35	31.71
79	45.39	31.75
81	45.46	31.75
83	45.52	31.73

Sec	Evaporator	Condenser
85	45.56	31.75
87	45.62	31.77
89	45.68	31.77
91	45.72	31.77
92	45.75	31.77
94	45.83	31.79
96	45.87	31.79
98	45.93	31.79
100	46	32.12
102	46.06	31.77
104	46.12	31.79
106	46.15	31.79
107	46.21	31.79
109	46.25	31.81
111	46.33	31.81
113	46.35	31.81
115	46.42	31.79
117	46.46	31.79
119	46.5	31.79
120	46.54	31.79
122	46.58	31.81
124	46.62	31.79
126	46.66	31.79
128	46.73	31.81
130	46.77	31.79
132	46.81	31.83
133	46.85	31.81
135	46.87	31.81
137	46.93	31.83
139	46.95	31.83
141	47.02	31.83
143	47.04	31.83
145	47.12	31.87
147	47.12	31.81
148	47.16	31.85
150	47.19	31.81
152	47.23	31.85
154	47.27	31.83
156	47.31	31.83
158	47.4	31.83
160	47.38	31.85
161	47.44	31.87

Sec	Evaporator	Condenser
163	47.5	31.85
165	47.54	31.87
167	47.56	31.83
169	47.6	31.85
171	47.62	31.83
173	47.65	31.83
175	47.69	31.85
176	47.71	31.83
178	47.75	31.85
180	47.79	31.85
182	47.81	31.87
184	47.85	31.83
186	47.87	31.83
188	47.89	31.85
189	47.96	31.87
191	47.98	31.85
193	48	31.83
195	48.06	31.85
197	48.08	31.85
199	48.1	31.87
201	48.12	31.85
203	48.14	31.85
204	48.21	31.85
206	48.21	31.85
208	48.23	31.87
210	48.29	31.87
212	48.33	31.85
214	48.33	31.87
216	48.37	31.85
217	48.41	31.85
219	48.44	31.85
221	48.48	31.89
223	48.48	31.87
225	48.5	31.85
227	48,54	31.89
229	48.54	31.89
231	48.58	31.85
232	48.6	31.89
234	48.65	31.91
236	48.69	31.89
238	48.69	31.87
240	48.71	31.89

Sec	Evaporator	Condenser
242	48.73	31.87
244	48.75	31.89
245	48.79	31.89
247	48.79	31.89
249	48.83	31.87
251	48.88	31.9
253	48.9	31.9
255	48.92	31.91
257	48.94	31.89
258	48.96	31.89
260	48.98	31.91
262	49	31.89
264	49.01	31.89
266	49.02	31.91
268	49.06	31.91
270	49.08	31.91
272	49.1	31.91
273	49.14	31.91
275	49.14	31.91
277	49.17	31.91
279	49.17	31.91
281	49.19	31.98
283	49.23	31.93
285	49.25	31.93
286	49.29	31.91
288	49.27	31.95
290	49.31	31.91
292	49.31	31.93
294	49.37	31.95
296	49.37	31.93
298	49.37	31.93
300	49.39	31.89