Experimental study on the performance of a dual diameter closed loop pulsating heat pipe vertical and horizontal position.

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STUDENT DECLARATION

This is to certify that the thesis entitled, **"Experimental study on the performance of a dual diameter closed loop pulsating heat pipe vertical and horizontal position."** is an outcome of the investigation carried out by the author under the supervision of **Md. Misbah Uddin** Lecturer, Dept. of Mechanical Engineering, Sonargaon University (SU). This thesis or any part of it has not been submitted 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. Misbah Uddin,** Lecturer, Dept. of Mechanical Engineering, **Sonargaon University (SU)**, resulted in the thesis, " **Experimental study on the performance of a dual diameter closed loop pulsating heat pipe vertical and horizontal 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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January 2024

Dedication

This research paper is dedicated to my dear father, who has been nicely my supporter until my research was fully finished, and my beloved mother who, for months past, has encouraged me attentively with her fullest and truest attention to accomplish my work with truthful self-confidence.

Abstract

This study comprehensively evaluates dual diameter Closed Loop Pulsating Heat Pipes (CLPHPs) with ethanol, methanol, and ethylene glycol at 50% and 60% filling ratios, focusing on their thermal performance at 0- and 90-degrees orientation. Addressing a significant gap in empirical data, our findings substantiate the theoretical advantages of dual-diameter designs, particularly in horizontal orientations. The 0-degree angle and a 60% ethanol filling ratio emerged as the optimal configuration, achieving the lowest thermal resistance, and demonstrating the potential for enhanced heat transfer efficiency in CLPHPs. These results suggest that the dual-diameter approach, tailored with appropriate working fluids and filling ratios, can significantly improve thermal management systems, with implications for electronics cooling and aerospace applications. Future research should further optimize these parameters to harness CLPHPs' capabilities fully across diverse operating conditions.

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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	Heat input (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
EG	Ethylene glycol

Chapter 1

1 Introduction

Numerous sectors, from electronics and aerospace to automotive and energy systems, have seen an increase in demand for effective and small cooling solutions in recent years. Traditional cooling techniques like fans and heat sinks are often unable to meet the rising demands for heat dissipation as electronic devices become smaller and more powerful. Due to this, cutting-edge thermal management solutions have emerged, with closed-loop pulsing heat pipes (CLPHPs) receiving a lot of attention and recognition.

In order to effectively and quickly transport heat from a heat source to a heat sink, closed-loop pulsing heat pipes combine the concepts of capillary action, phase change, and two-phase flow. High heat transfer rates, minimal thermal resistance, homogeneous temperature distribution, and the flexibility to work in any direction are just a few benefits they have over traditional cooling techniques.

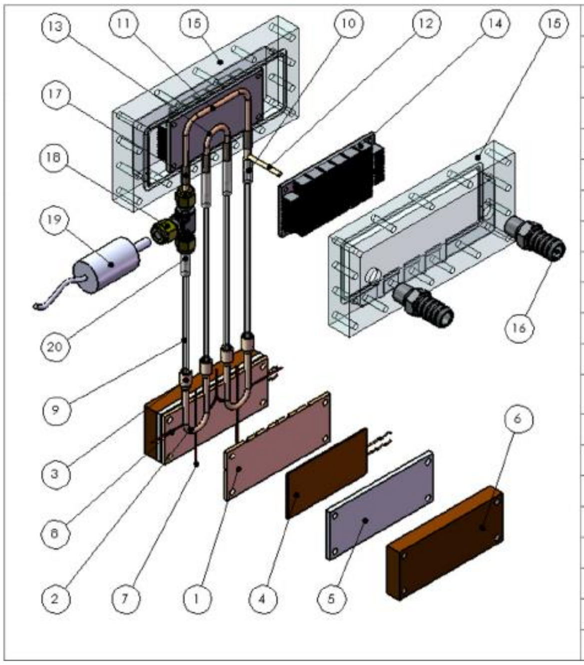
A closed-loop pulsing heat pipe works by circulating a working fluid within a tube with a sealed, looped end. The tube normally comprises several linked parts, including an evaporator section, an adiabatic portion, and a condenser section, and is built of a thermally conductive material like copper or aluminum. These parts are partly filled with the working fluid, which is selected based on its thermophysical characteristics.

Due to its low boiling point, the working fluid vaporizes when heat is applied to the evaporator portion. The pressure differential created inside the system propels the resultant vapor phase in the direction of the condenser portion. The vapor emits heat to the atmosphere as it passes through the condenser and condenses back into a liquid phase. The closed-loop cycle is subsequently completed by the condensed liquid returning through capillary action to the evaporator part.

The existence of oscillatory motion within the working fluid is the distinguishing characteristic of closed-loop pulsating heat pipes. The capillary forces and the vapor-liquid interface combine to provide self-sustaining, high-frequency oscillations of the liquid plugs or slugs within the tube, which causes the pulsing motion. This pulsing flow encourages improved heat transfer properties because it prevents the creation of a stagnant thermal boundary layer and continuously refreshes the liquid-vapor surfaces.

The geometry of the pipe, the characteristics of the working fluid, the filling ratio, and the heat load provided are some of the variables that affect the thermal performance of closed-loop pulsing heat pipes. To improve the design and operation of CLPHPs for various applications, researchers have thoroughly explored these parameters. Additionally, improvements in manufacturing methods have aided in the creation of flexible and tiny CLPHPs, allowing their incorporation into intricate systems with limited space.

There are several industries in which closed-loop pulsing heat pipes might be used. They may be used in applications requiring precise temperature control and significant heat dissipation, such as cooling of high-power electronic components, circuit boards, and LEDs. CLPHPs have also shown potential in the thermal control of sophisticated materials processing and aerospace systems, as well as in the cooling of energy conversion technologies like fuel cells and solar cells.



N°	ITEM
1	Evap. copper plate
2	Evap. copper U-turns
3	Copper joint
4	Heater
5	Mica sheet
6	Bakelite back plate
7	TC fluid side
8	TC wall side
9	Glass tube
10	Silicon joint
11	Condenser tube
12	Branch (vacuum/filling)
13	Cond. copper tube
14	Heat sink
15	Cooler shell
16	Cooler connector
17	Silicon seal
18	T-junction
19	Pressure transducer
20	Copper fitting

Figure 1-1 Electronics cooling using CLPHP [1]

Finally, closed-loop pulsing heat pipes are a state-of-the-art thermal management technology that provides effective and space-saving cooling solutions for a variety of sectors. CLPHPs have the potential to revolutionize heat transfer and enhance the performance and dependability of several applications because of their distinct operating principles and benefits. The design and execution of closed-loop pulsing heat pipes are still being investigated and improved as part of ongoing research and development, assuring their widespread acceptance and future developments in the area of thermal management.

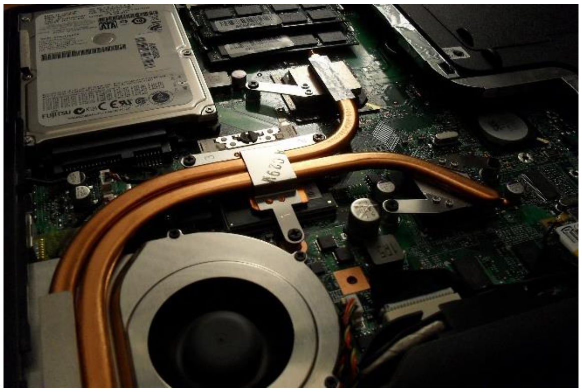


Figure 1-2 Heat pipe in real life electronics use (https://en.wikipedia.org/wiki/Heat_pipe)

Additionally, there have been a number of developments made as a result of research and development into closed-loop pulsing heat pipes that are intended to enhance their functionality. The optimization of the geometric arrangement of CLPHPs is one area of emphasis. To improve heat transmission and overall system efficiency, researchers have experimented with various tube sizes, lengths, and forms. In order to improve fluid mixing and heat transmission within the pipes, different internal features, such as grooves or fins, have also been researched.

The choice of appropriate working fluids for closed-loop pulsating heat pipes is another critical consideration. Boiling point, heat capacity, and viscosity are a few thermophysical qualities that differ amongst fluids and have an effect on heat transport. To determine the best options for certain applications, researchers have examined a wide variety of working fluids, including pure liquids and binary mixes. Research on nanofluids, which are suspensions of nanoparticles in conventional working fluids, has also shown promise in improving the efficiency of heat transmission in CLPHPs.

Closed-loop pulsating heat pipes' capacity for heat transmission is significantly influenced by the filling ratio, which describes the volume per cent of the working fluid within the pipe. By maximizing the filling ratio, one may prevent excessive pressure drop and fluid stagnation while yet ensuring that there is enough working fluid to enable effective heat transmission. To determine the ideal filling ratio for various operating situations and geometrical configurations, researchers have carried out experimental and numerical analyses.

Additionally, a crucial factor that influences the performance of closed-loop pulsing heat pipes is the heat load delivered to them. Higher heat loads often lead to faster heat transfer rates and more violent oscillatory action. However, the amount of heat that CLPHPs can efficiently manage has a limit over which the system may become unstable or perform worse. Therefore, for the effective use of closed-loop pulsating heat pipes, it is crucial to comprehend the heat transmission limitations and create control systems to regulate the heat load.

Closed-loop pulsing heat pipes must be carefully integrated into a variety of systems, which requires careful consideration of elements such as system orientation, physical limitations, and interface design. Because they may function in any direction, CLPHPs have the benefit of being appropriate for both horizontal and vertical applications. Due to their adaptability, they may be used in a variety of industries, including renewable energy systems, automobile cooling, and space exploration.

Closed-loop pulsing heat pipes have gotten a lot of interest lately for their flexibility and compactness. Microsystems and small-scale electronic equipment may now be cooled using miniature CLPHPs. These small-footprint heat pipes are perfect for situations where space is at a premium since they have a high capacity for heat transmission. Contrarily, flexible CLPHPs provide effective thermal management in complicated systems by permitting conformal cooling of unevenly shaped components.

Despite the many benefits and developments, there are still certain obstacles to the widespread use of closed-loop pulsing heat pipes. These difficulties include the need for a deeper comprehension of intricate two-phase flow phenomena, the creation of precise modelling and simulation tools, and the affordability of production processes. These problems are still being researched, and efforts are being made to advance closed-loop pulsing heat pipe technology.

1.1 Type of heat pipe & revolution of heat pipe

The amazing heat transfer technology known as heat pipes has changed thermal management in various sectors. Since their creation, several varieties of heat pipes have been created, each with special benefits and characteristics. Let us examine the many heat pipe varieties and their historical contributions.

The most popular and commonly used heat pipe form is a capillary heat pipe. They are made from an evacuated, sealed tube filled with a working fluid, usually a liquid-vapor mixture. The pipe's inner wall has a wick structure that encourages capillary action, which drives the heat transfer process and helps the fluid circulate. Aerospace systems, energy conversion devices, and electronics cooling all use capillary heat pipes.

1.2 Types of Heat Pipe

1. **Vapor Chamber Heat Pipes**: The vapor chamber heat pipe is an upgraded kind of heat pipe with improved heat-spreading characteristics. They use a construction that is flat and plate-like and has a sealed chamber that is filled with a working fluid. High-power electronic parts, CPUs, and LED lighting systems may be efficiently cooled by the vapor chamber's excellent heat dispersion over its surface.

2. **Loop Heat Pipes**: An evaporator, a condenser, and a connecting loop comprise the closed-loop heat pipe (LHP). They use a closed-loop working fluid circulated by the difference in vapor pressure between the evaporator and the condenser. Because of their well-known capacity to transmit heavy heat loads over long distances, LHPs are well-suited for space applications, including cooling satellites and spacecraft.

3. **Pulsating Heat Pipes**: Self-excited oscillatory flow is the basis for how pulsating heat pipes (PHPs) work. They consist of a sealed tube divided into an adiabatic area, a condenser, and an evaporator. Heat transmission is facilitated by the working fluid oscillating as liquid plugs or slugs. PHPs are small and adaptable and used in renewable energy systems, innovative material thermal management, and electronics cooling.

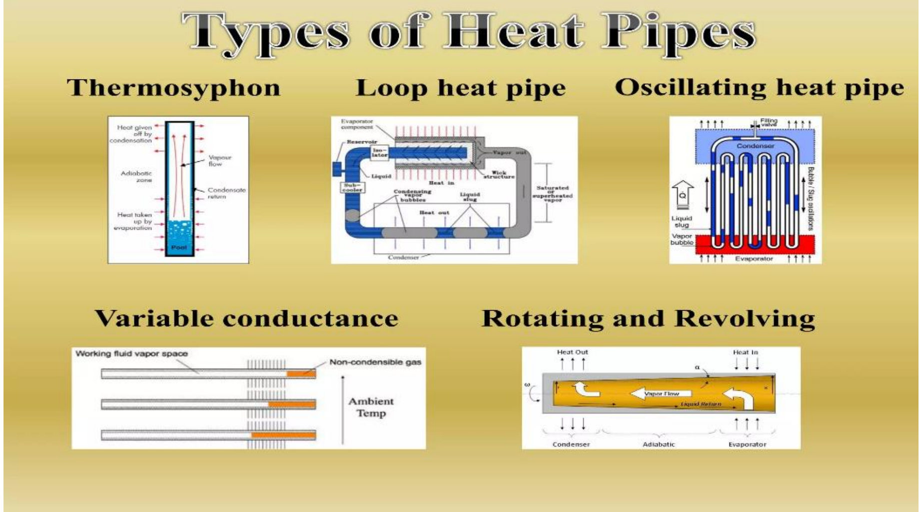


Figure 1-3 Types of heat pipe (Fundamentals of Heat Pipes with Applications and Types, 2018.)

Heat pipes have made important contributions to thermal control throughout history:

1. **Early Development**: George Grover undertook ground-breaking research on heat transmission devices in the early 1940s when the idea of heat pipes first emerged (GEORGE GROVER, 81, INVENTED HEAT TRANSFER DEVICE – Sun Sentinel, 2018.). Grover's study provided the conceptual framework for comprehending heat pipes' fundamentals and future uses.
2. **Applications in Space**: Heat pipes were popular throughout the Space Age. NASA used heat pipes in the 1960s to control the temperatures of various spacecraft parts, including the astronauts' suits, fuel tanks, and electrical systems. In order to maintain dependable functioning in the harsh conditions of space, heat pipes were essential.
3. **Electronics Cooling**: As electronic technology advanced quickly, the need for effective cooling solutions increased significantly. In the late 1970s and early 1980s, heat pipes started to gain popularity as an alternative method for cooling devices. They allowed for the downsizing and increased dependability of electronic equipment by providing higher heat transfer capability, compactness, and the capacity to tolerate high heat fluxes.
4. **Materials and manufacturing advancements**: Over time, improvements in materials and manufacturing methods have improved heat pipe technology even further. The performance of heat pipes was enhanced by creating innovative wick architectures like

sintered copper and micro-grooved surfaces. Additionally, improvements in manufacturing techniques made it possible to produce heat pipes with intricate shapes, facilitating their integration into diverse systems.

Heat pipes have expanded into various industries, including the automobile, aerospace, energy, and telecommunications. Power electronics, LED lights, heat exchangers, heat recovery systems, nuclear reactors, and other items are all cooled using them. Heat pipes' adaptability and effectiveness continue to spur innovation in these sectors.

1.3 Selection Closed loop pulsating heat pipe

Improved Heat Transmission Performance: Compared to conventional heat pipes, CLPHPs have better heat transmission properties. The working fluid's pulsing motion encourages effective heat transmission by often renewing the liquid-vapor interfaces and preventing the development of thermal boundary layers that are not moving. There are now opportunities to raise the overall effectiveness of thermal management systems because of this improved heat transfer performance.

Self-Sustained Oscillatory Flow: A remarkable occurrence in CLPHPs that enables the system to self-regulate is the self-excited oscillatory flow. Improved heat distribution and fewer temperature gradients occur from the working fluid's effective mixing, made possible by the oscillatory motion. Advanced thermal management solutions may be created by investigating the underlying causes and improving the oscillatory behaviors of CLPHPs.

Compact and Versatile Design: CLPHPs provide design options that are both compact and versatile, making them appropriate for a variety of applications. They are very adaptive to areas with limited space, such as electronic equipment, where effective heat dissipation is essential because of their compact footprint and flexibility to work in any direction. Researching CLPHPs' design features may result in the creation of flexible and miniature heat pipe systems.

Diverse Application Areas: CLPHPs have potential in several sectors, including advanced materials processing, energy conversion systems, electronics cooling, and aerospace. You can investigate several application areas and help enhance thermal management in many domains by selecting CLPHPs for investigation.

Research Potential: Although CLPHPs have received much attention, there is still much to learn and explore. Numerous research topics may be investigated, including geometric design optimization, the effects of various working fluids, innovative manufacturing processes, the development of cutting-edge control schemes, and performance analysis under various operating situations. By choosing CLPHPs, you may actively participate in advancing knowledge of and opportunities for using this revolutionary heat transfer technology.

There are various convincing reasons to use closed-loop pulsing heat pipes (CLPHPs) for research. They are a great option for developing the field of thermal management due to their improved heat transfer performance, self-sustained oscillatory flow, compact design, variety of application areas, and research potential. You can help build effective and cutting-edge heat transfer solutions for various industries by learning about the complexities of CLPHPs.

1.4 Factors influencing how well CLPHPs perform

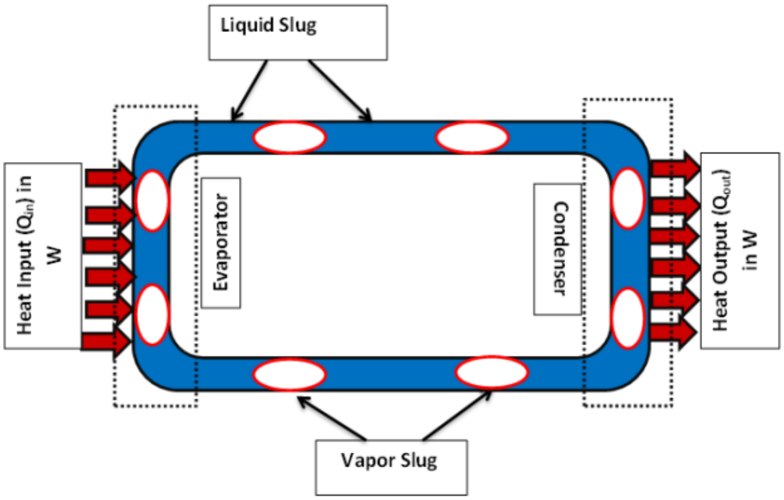


Figure 1-4 Working Schematic CLPHP[4]

Six significant thermo-mechanical characteristics have emerged as the main design parameters influencing the PHP system dynamics, according to the literature that is currently accessible. The internal diameter of the PHP tube, the input heat flux, the volumetric filling ratio of the working fluid, the total number of turns, the device's orientation concerning gravity, and the thermophysical characteristics of the working fluid are among them.

Use flow direction control check valves, a form of the tube's cross-section, a combination of the tube material and fluid, and the rigidity of the tube material.

1.5 Design and geometrical parameters: Dimensions and tube material

The diameter of the heat pipe is important to consider when choosing a heat pipe since it impacts how well it performs when it pulses. The internal diameter has a direct impact on PHP. A bigger hydraulic diameter affects lower wall thermal resistance and higher effective thermal conductivity. The inner diameter of the capillary tube must be so tiny that Dmax= 2[/g (liq - vap)]1/2

Where: Liq = liquid density (Kg/m^3); Vap = vapor density (Kg/m^3); g = gravity acceleration (m/s2); = working fluid surface tension (N/m);

Surface tension forces take control, and stable liquid plugs develop if D Dmax.

However, if D > Dmax, the working fluid will stratify by gravity and oscillations will stop6. This is because the surface tension is lowered. Additionally, the choice of tube material is crucial since each kind of material has a unique coefficient of heat transmission.

1.6 Count of turns

The more PHP is used, the more adaptable it becomes to function in any situation (i.e., at any edge of slant with even). Analysts have shown that if there are fewer spins, the system only operates in the vertical position rather than in other positions.

Additionally found that nine turns Comparing the CLPHP to the one with three turns, there are several benefits:

i. It may function in the horizontal heat mode as well.

ii. It has reduced heat resistance.

iii. Regarding general effectiveness, there are fewer obvious distinctions between other fluids.

1.7 Evaporator and condenser section design

Evaporator and condenser design have a significant impact on heat pipe performance. In order to prevent a dry-out state, it is a general guideline that the condenser should have a bigger area than the evaporator. The evaporator section lengths impacted the essential heat flux in this range. The essential heat transfer flux dropped as the evaporator section lengths became longer. With a heat input of Q1 that is extremely near to the dry-out power Qdry corresponding to the operating temperature, it is assumed that the heat pipe is working at an adiabatic temperature of T1. There is a chance of a dry-out if, under such operating circumstances, the condenser capacity is raised by either reducing the coolant temperature or increasing the coolant mass flow. Due to the working temperature dropping to T2, for which the heat input Q1 is too high, this will occur. Therefore, increasing the condenser capacity is only sometimes necessary for traditional heat pipes to increase heat transmission. Although there is no precise adiabatic working temperature for pulsing heat pipes, the influence of condenser capacity tends to follow a similar path. In addition to changing the working fluid's thermo-physical characteristics, expanding the condenser's capacity also varies the slug-annular flow pattern transition, which ultimately changes the performance. The practical designing process must consider this.

1.8 Bend Effect

Their U-tern quantities are accessible in PHP geometry.[5] explained how twist affects PHP execution. The 180° and 90° twisted weights cause pipe tragedy.[6] has also created a numerical model to consider the local pressure loss occurring in the PHP.

1.9 Operational Conditions: Ratio of filling:

The volume percentage of the heat pipe first filled with liquid is known as the filling ratio. When the maximal heat transfer rate is realized at a certain temperature, the ideal filling ratio is ascertained experimentally.

1.10 The temperature of Heat Flux

Although they may be very effective heat spreaders, PHPs are thermally determined non-balance devices, and a temperature difference between the evaporator and condenser is necessary for them to continue operating. Most of the time, it was seen that some basal heat motion or temperature difference was crucial to initiate a flowing stream. The first heat transition varied with each experiment, much as the appropriate charge ratio. As a result, parametric analysis is necessary to understand this work fully. When there are few turns, a fundamental heat transition between 5.2 and 6.5 W/cm2 is anticipated to ignite a smooth movement and reach a satisfying pseudo-unchanging condition.

1.11 A dry environment

This issue limits how well heat pipes can work. A dry-out situation occurs when all the working liquid has evaporated, and the region around the evaporator is completely dry. This situation develops when the pipe receives a strong heat input and a low filling proportion. When a dry situation is reached, conduction is the only mechanism through which heat exchange occurs.

1.12 Working fluid characteristics

The choice of working fluids is another crucial factor that affects how PHP functions. The qualities of the liquid directly influence the choice of working liquid. The characteristics will influence both the ability to exchange heat and the equivalency with the tube material. The working fluid should be selected to support the PHP working temperature run. The following working liquid characteristics should be examined when selecting a working liquid: Similarity to the OHP materials, heat security, wettability, sensible vapor weight, high inert heat conductivity, low fluid and vapor viscosities, and a satisfactory solidifying point are also factors.

The thermodynamic properties of water make it a good choice for PHP applications for most applications since it has high dormant heat, which distributes more heat with a less liquid stream, and high heat conductivity, which restricts data. Water, however, has a high surface pressure and may negatively impact the PHP by adding grating and accelerating the PHP's two-stage stream movements. Given that it has around 33% of the surface strains of water, methanol is a good substitute for it, especially in situations where the temperature is below zero.

1.13 Research Gap

Current research on Closed Loop Pulsating Heat Pipes (CLPHPs) identifies two primary gaps needing further exploration to optimize their thermal management capabilities. Firstly, the impact of varying inner diameters within CLPHP systems has shown promising improvements in performance—narrower sections in the evaporator and adiabatic regions enhance surface tension and oscillatory flow, while wider sections in the condenser increase heat transfer area[7]. However, a comprehensive understanding of the interplay between these design modifications and their impact on heat pipe performance is lacking. Secondly, there is a dearth of empirical data on the thermal efficiency of horizontal closed-loop oscillating heat pipes (HCLOHPs), particularly how they compare to other orientations in terms of filling ratios and operating temperatures. Bridging these gaps requires targeted experimental studies that can validate the benefits of inner diameter optimization and provide in-depth analysis of HCLOHPs, potentially leading to innovative designs with superior efficiency for diverse applications.

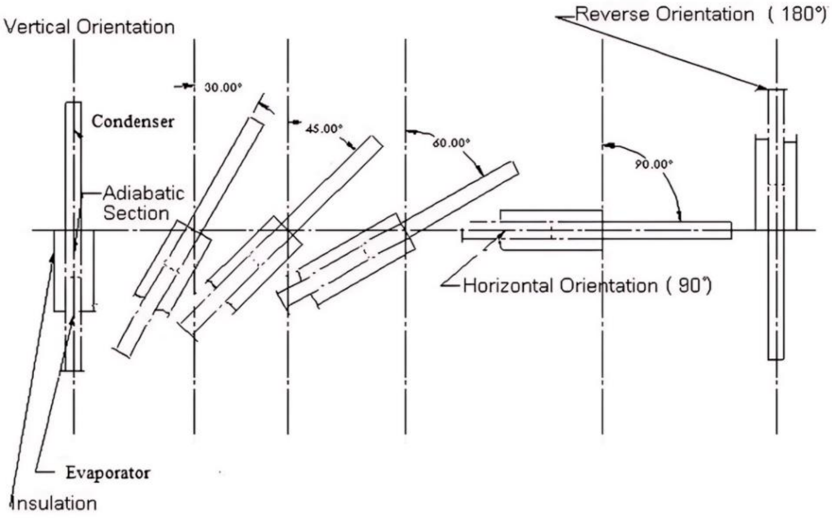


Figure 1-5 Wooden movable holder and changing of orientation angle

1.14 Objectives

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 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 [8] And narrower sections in the evaporator and adiabatic regions enhance surface tension and oscillatory flow, while wider sections in the condenser increase heat transfer area.[7]

The aims of this thesis are:

1. To investigate the performance of CLPHP with 0° and 90° also filling ration 50% & 60% Ethanol as a working fluid.
2. To examine the performance of CLPHP with 0° and 90° also filling ration 50% & 60% Methanol as a working fluid.
3. To examine the performance of CLPHP with 0° and 90° also filling ration 50% & 60% Ethylene glycol as a working fluid.
4. To compare the thermal performance of CLPHP with three working fluids i.e., filling ratio 50% and 60%, Ethanol, Methanol & Ethylene glycol at 0° and 90° angles.

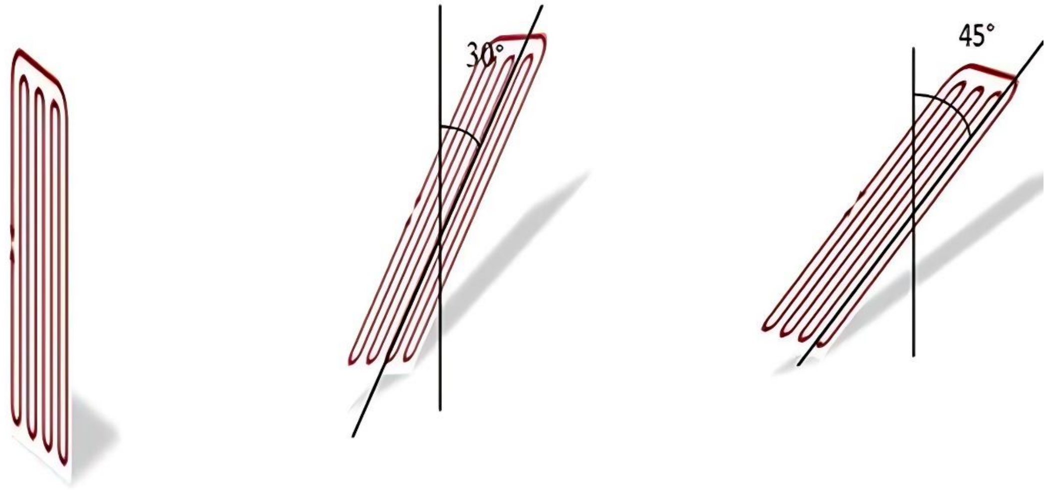


Fig 3.1: Vertical mode (0°)

Fig 3.2: 30° Inclination

Fig 3.3: 45° Inclination

Figure 1-6 Schematic hypothesis angle of experimental CLPHP

Chapter 2

2 Literature Review

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 [9] and [10] [11]. 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 apartially 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 [11]. 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.

[13]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.

[14]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 [15], which claims that nucleate boiling and vapour oscillation cause bubble oscillations.

[16]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 behaviors. 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.

[17]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 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.

[17]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[18]. 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.

[19]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,[20] 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.

[21]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[22]. 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 [23]In addition, the critical temperature increased from 0 to 90 degrees of inclination.

[24]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.

[25]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, [26]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 [27]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).

Proven advantages above traditional uniform diameter CLPHP designs, customized non-uniform or dual diameters provide a viable route for future investigation. Optimal diameter ratios and taper designs should be examined to establish an optimal balance between surface tension, oscillatory flow, and condenser surface area effects. Implementing this approach of various evaporator/adiabatic and condenser diameters could overcome heat transfer restrictions and greatly boost CLPHP performance beyond standard uniform designs [7]

Chapter 3

3 Materials And Methods

3.1 Depiction of different types of Apparatus

- Pulsating heat pipe
- Working fluid
  - Methanol
  - Ethanol
  - Ethylene glycol
- Test stand
- Heating apparatus
  - Variac
  - Power Supply Unit
  - Nichrome Thermal Wire
  - EPE Insulation foam
- Insulating apparatus
  - Mica tape
  - Glass wool
  - Foam tape
  - Asbestos tape
- Measuring apparatus
  - Temperature Sensor (DS18B20)
  - Multimeter
- 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)
- Digital Vernier Caliper.

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 like 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, over 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 1 Methanol properties

SL. No.	Parameters	Symbol	Quantity	Unit
1.	Freezing temperature	$\mathrm{T_{freeze}}$	-97.6	^{o}C
2.	Boiling temperature	$\mathrm{T_{boil}}$	64.7	^{o}C
3.	Density	P	792	kg/m³
4.	Specific heat (at 20°C)	$\mathrm{C_p}$	2.5	Kj/kg-k
5.	Vapor pressure	Pv	13.02	kPa
6.	Molar mass	Ms	32.04	g/mol

3.3.2 Ethanol

The most common names for ethanol are alcohol or spirits, also known as ethyl alcohol and drinking alcohol. It serves as the primary form of alcohol in alcoholic beverages created when yeast ferments sugars—one of the first neurotoxic psychoactive substances.

Human drug usage for enjoyment. It may result in alcohol intoxication if ingested in sufficient amounts. Ethanol is used as the active fluid, an antiseptic, a fuel, and a solvent in modern (post-mercury) thermometers. It is a volatile, colorless, flammable liquid with a strong chemical odor. Its chemical name, CH_3CH_2OH, is frequently shortened to C_2H_5OH or C_2H_6O.

Ethanol properties:

Table 2 Ethanol properties

SL. No.	Parameters	Symbol	Quantity	Unit
1.	Freezing temperature	T_{freeze}	-114.1	°C
2.	Boiling temperature	T_{boil}	78.37	°C
3.	Density	P	789	kg/m³
4.	Specific heat (at 25°C)	C_p	2.57	Kj/kg-k
5.	Vapor pressure	Pv	5.95	kPa
6.	Molar mass	Ms	46.07	g/mol

3.3.3 Ethylene glycol

Ethylene glycol 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.

Ethylene glycol properties:

Table 3 Ethylene glycol properties

SL. No.	Parameters	Symbol	Quantity	Unit
1.	Freezing temperature	T_{freeze}	-12.9	°C
2.	Boiling temperature	T_{boil}	197.15	°C
3.	Density	P	1115	kg/m³
4.	Specific heat (at 25°C)	C_p	2.093	Kj/kg-k
5.	Vapor pressure	Pv	0.9337	kPa
6.	Molar mass	Ms	62.07	g/mol

3.4 Visual Picture of Experiment

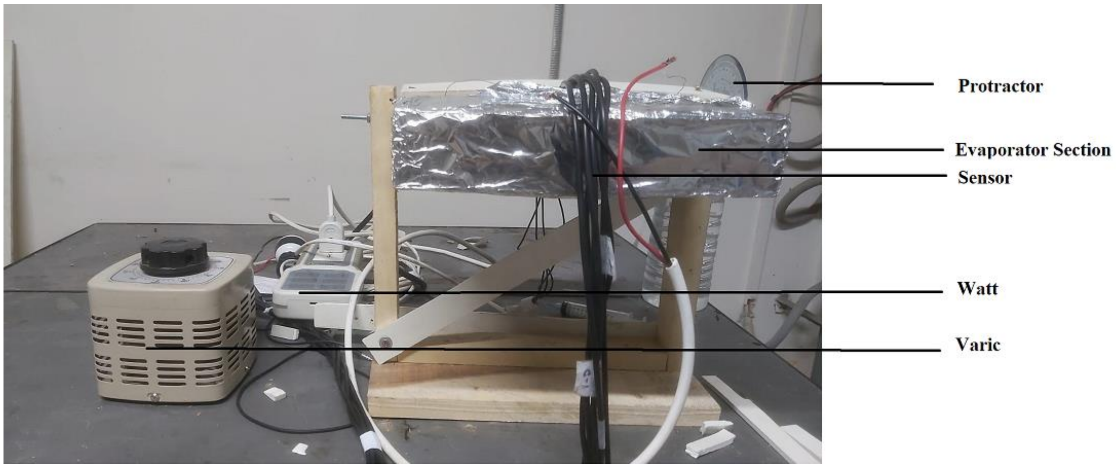


Figure 3-1 Experiment Set-up

3.5 Experiment CLPHP

A closed-loop pulsating or oscillating heat pipe is a metallic tube of capillary dimensions coiled in a serpentine pattern and linked end to end. It is divided into three sections:

3.5.1 Evaporator section

This part of the heat pipe is where the working fluid absorbs heat and evaporates. It is located on the bottom part of the heat pipe. The heat pipe is heated by a nichrome wire linked to the variac. Nichrome wire should not be linked to the copper tube directly since it is an excellent conductor of electricity, and doing so might cause a short circuit. As a result, a copper tube is maintained separately from a mica layer surrounding the Nichrome wire. The mica tape thus acts as a heat conductor for the copper tube. The evaporative side of our experiment was also thermally insulated using asbestos tape to provide greater heat sealing. In this way, the heat loss was reduced.

3.5.2 Condenser Section

The heat from the working fluid is rejected at the pipe's condenser section. In this part, the working fluid condenses and rejects a small quantity of heat absorbed from the evaporator section. This part of the experiment is on the heat pipe's top segment.

3.5.3 Adiabatic Section

Between the condenser and evaporator portions lies the adiabatic section. There is minimal heat transmission between the fluid and the surroundings because the fluid's liquid and vapor phases travel in opposite directions here. Glass wool and foam tape are used to cover the insulated portion.

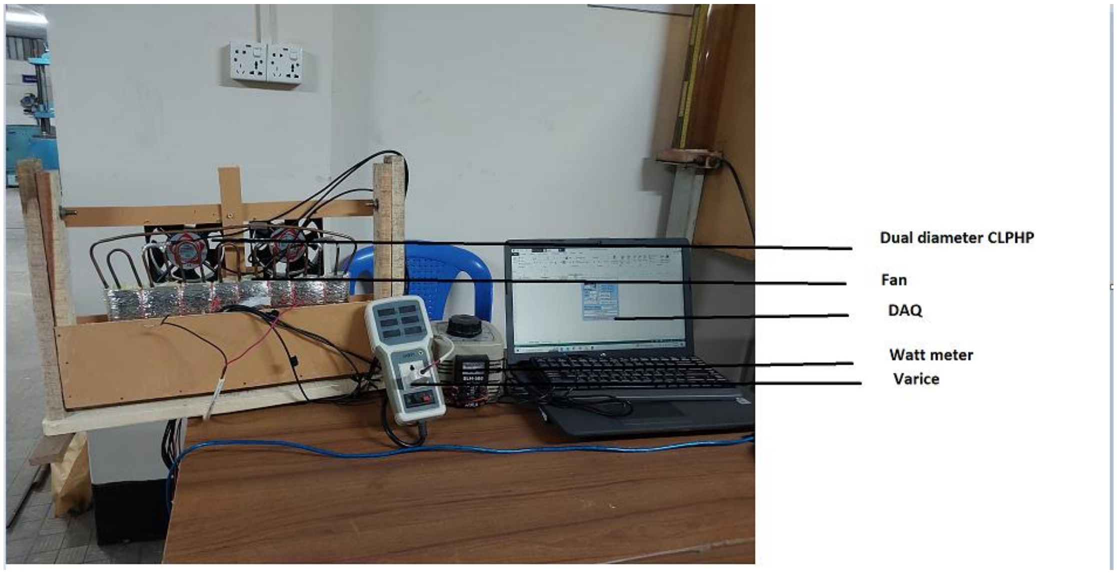


Figure 3-2 Condenser & Adiabatic Section

Table 4 CLPHP Parameters

Parameters	**Condition**
Length of evaporator section	50mm (2.87mm)
Length of adiabatic section	100 mm (2.87mm)
Length of condenser section	40 mm (1.87mm)
Material	copper
Turn	6
Distance between 2 heat pipes	20mm

3.6 Experimental Procedure

Obtain the size and design of a closed loop pulsing heat pipe (CLPHP).

Set up a heating source, such as a hot plate, to provide the CLPHP-regulated heat input.

Set up flow meters, pressure gauges, and temperature sensors to track the CLPHP's performance.

Ensure that the experimental setup has a dependable power source.

Preparation for CLPHP:

Use a suitable solvent to clean the CLPHP and remove any pollutants thoroughly.

Carefully put the CLPHP together, ensuring each part is attached and sealed.

Install the flow meters, pressure gauges, and temperature sensors at the appropriate places along the CLPHP.

50% Fill Ratio Experiment:

Fill the CLPHP to a filling ratio of 50% (i.e., the working fluid takes up 50% of the internal volume) by adding methanol or ethanol.

Connect the power source and heating source to the CLPHP.

Increase the heat input to the CLPHP gradually while keeping an eye on the flow rate, pressure, and temperature.

Keep track of the performance information, such as the flow rate, pressure drop, wall, evaporator, and condenser temperatures.

Run many tests while varying the heat input and assessing the behavior of the CLPHP under various operating circumstances.

60% Fill Ratio Experiment:

Remove the old operating fluid from the CLPHP and replace it with either methanol or ethanol to reach an 80% filling ratio.

Replicate the Filling Ratio at 50% experiment's stages while tracking and documenting CLPHP performance information.

0-degree angle experiment:

Adjust the CLPHP configuration such that it is 0 degrees vertical.

Reach the required filling ratio (50% or 60%) and fill the CLPHP with the selected working fluid. The same steps should be followed, with the heat input being progressively increased and performance data being recorded.

90-degree angle experiment:

Set the CLPHP configuration to be horizontal and at a 90-degree angle.

While maintaining the required filling ratio, fill the CLPHP with the working fluid.

Increase the heat input, monitor the CLPHP's performance, and record the results.

Data Evaluation

Compare the performance of the CLPHP at various filling ratios and angles as you analyze the data gathered. Analyze the CLPHP's flow behavior, pressure drop, and heat transfer properties under each experimental circumstance. Interpret the facts, form conclusions, and note patterns or noteworthy discoveries. Consider temperature distribution, heat transfer efficiency, and operational stability.

3.7 Precaution

When experimenting, the following variables were taken into account:

All other sources that may affect heat transmission were shut off throughout.

The sensor (DS18B20 sensors) used in the experiment must be properly inspected before taking the temperature.

The fluid injection must be precise since the fill ratio impacts how well the heat pipe works.

Measurements should be taken only when a temperature achieves a stable state or a consistent value. The silicon tube should always be properly sealed since condenser condensation may sometimes create leaks. CLPHP

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Chapter 4

4 Results & Discussions

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

Origin Pro generated fascinating statistical visual graphs.

4.1 Steady Condition of All Data

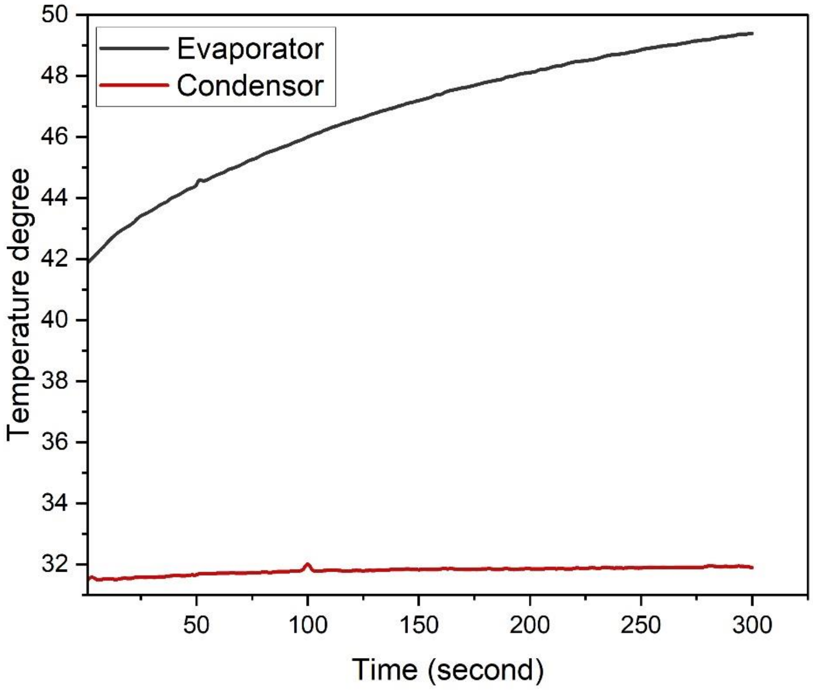

Figure 4-1 Steady condition data

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 Ethanol 50% Filling Ratio Angle 0°

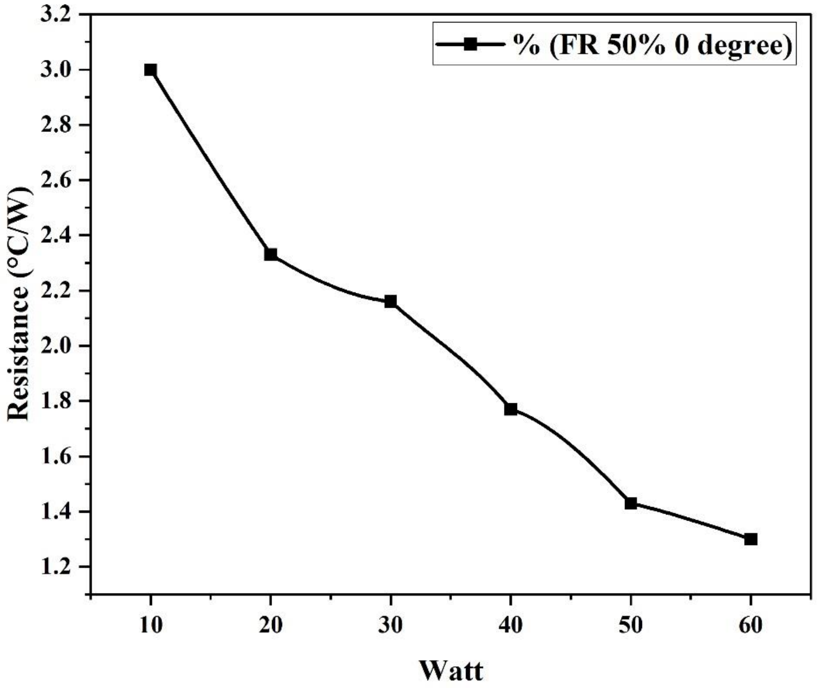

Figure 4-2 Ethanol 50% Thermal Resistance vs Heat input (watt)

The data presented seems to be from an experiment or test measuring the relationship between resistance and power (wattage) in a closed-loop pulsating heat pipe containing 50% ethanol at a 0-degree angle. The 'Log Time (Sec)' column suggests that measurements were taken at consistent time intervals, mostly at 601 seconds, with a couple of readings at 600 seconds. It appears that as the wattage increases, the resistance decreases, which could be indicative of the heat pipe's efficiency in transferring heat at different power levels. This trend is typical in thermal systems where resistance to heat flow diminishes as the temperature difference or power input increases. The specific context of a closed-loop pulsating heat pipe suggests that the system relies on the phase change of the working fluid (in this case, a 50% ethanol mixture) and the pulsation effect to transfer heat from one end to the other. Understanding the relationship between resistance and power in such systems is crucial for optimizing performance and energy efficiency, especially in applications where space and weight are constraints, such as in aerospace or portable electronics cooling.

4.3 Ethanol 50% Filling Ratio Angle 90°

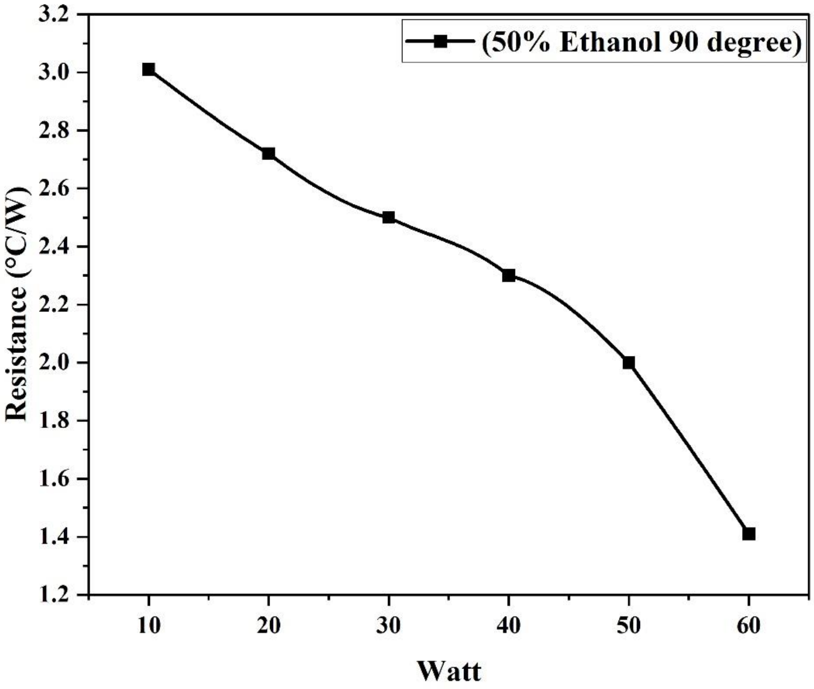

Figure 4-3 Thermal Resistance Vs Heat input (watt)

The data provided indicates the performance of a closed-loop pulsating heat pipe at a 90-degree angle with 50% ethanol as the working fluid, showing the thermal resistance in °C/W as a function of power input measured in watts. Similar to the previous data set at 0 degrees, there is a clear inverse relationship between thermal resistance and applied power; as the power increases, the thermal resistance decreases. This suggests that the system's thermal conductivity improves with higher power levels, possibly due to enhanced fluid circulation and effective phase change at higher internal temperatures. The slight differences in resistance values at similar power levels between the 0-degree and 90-degree angle setups could be attributed to the influence of gravity on the fluid flow and phase distribution within the heat pipe, highlighting the importance of orientation in the design and application of such thermal systems.

4.4 Ethanol 60% Filling Ratio Angle 0°

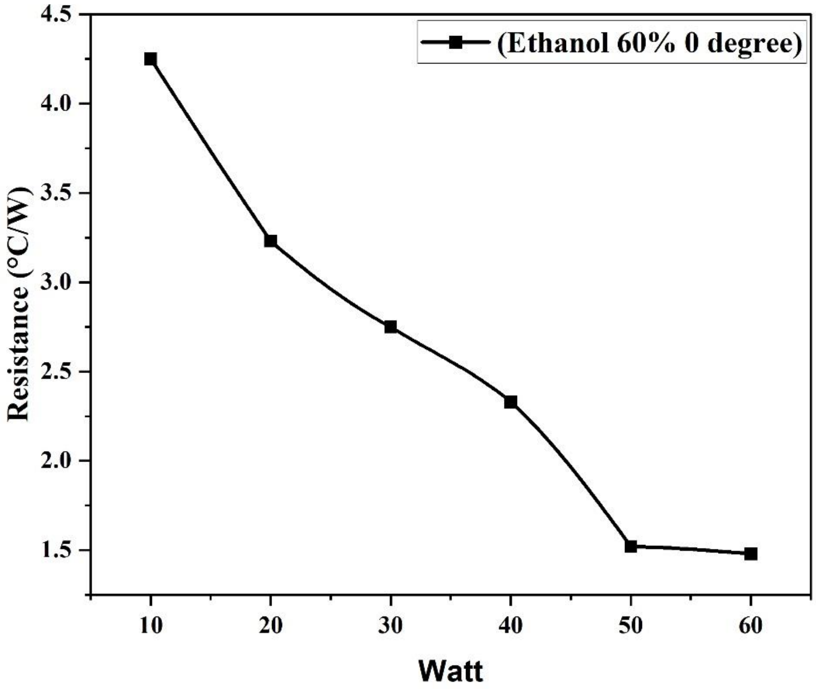

Figure 4-4 Thermal Resistance Vs Heat input (watt) Ethanol

The dataset shows the thermal performance of a closed-loop pulsating heat pipe with a 60% ethanol mixture at a 0-degree angle, where an increase in power input from 10 to 60 watts corresponds to a significant decrease in thermal resistance from 4.25 to 1.48 °C/W. This trend suggests that higher ethanol concentration enhances the system's thermal efficiency, potentially due to improved thermophysical properties of the working fluid, which facilitates more effective heat transfer as the operational power increases.

4.5 Ethanol 60% Filling Ratio Angle 90°

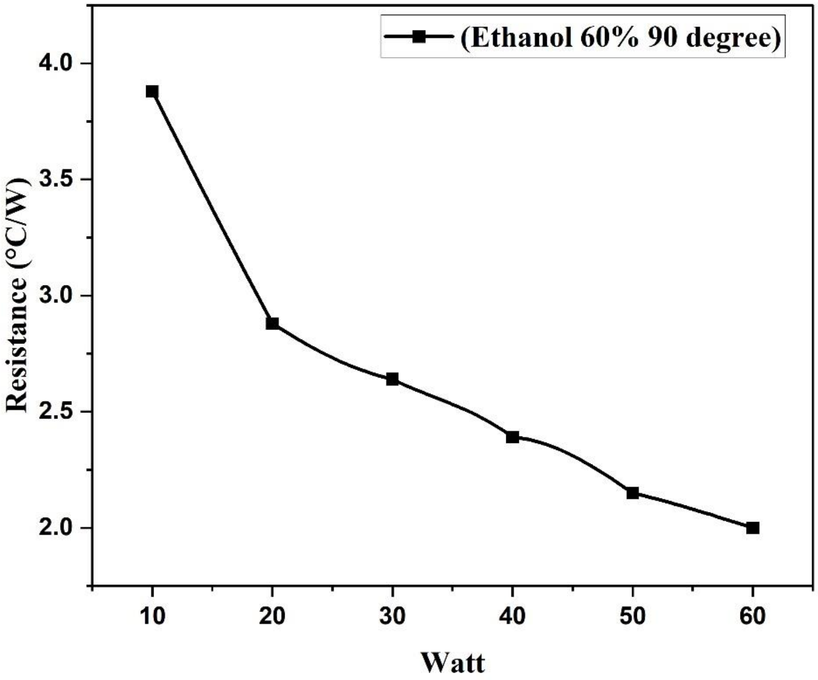

Figure 4-5 Thermal Resistance Vs Heat input (watt)

The presented data for a 60% ethanol-filled closed-loop pulsating heat pipe at a 90-degree angle demonstrates a consistent decrease in thermal resistance from 3.88 to 2 °C/W as the wattage increases, indicating that the heat pipe operates more efficiently at higher power levels, with gravity potentially aiding the redistribution of the working fluid, which in turn improves the heat transfer process.

4.6 Methanol 50% Filling Ratio Angle 0°

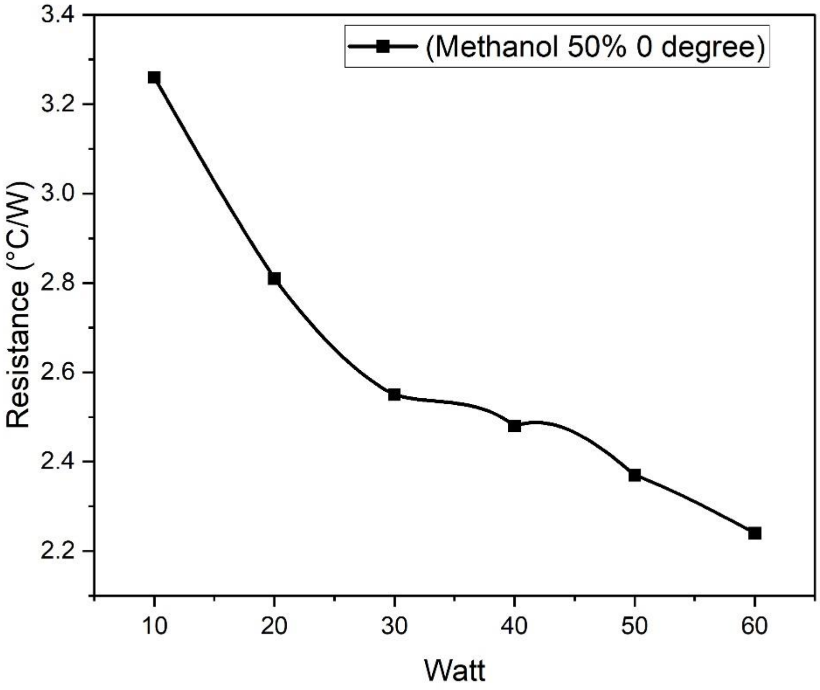

Figure 4-6 Thermal Resistance Vs Heat input (watt) Methanol

The provided data reflects the thermal dynamics of a 50% methanol-based closed-loop pulsating heat pipe when positioned at a 0-degree angle relative to the gravitational field. The measurements recorded indicate that as the power input to the system is incrementally raised from 10 watts to 60 watts, the thermal resistance consistently decreases, falling from 3.26 °C/W to 2.24 °C/W. This descending trend implies that the system exhibits increased thermal conductance with heightened thermal load. Notably, the reduction in thermal resistance is not linear, with larger drops observed at lower power increments and diminishing returns as power continues to increase. This could be indicative of the operational characteristics of the methanol mixture, where it effectively absorbs and transfers heat at lower power levels, but as the system approaches higher power inputs, the rate of improvement in heat transfer efficiency tapers off. Such behavior may be attributed to the fluid's thermophysical properties, such as specific heat capacity and thermal expansion, which influence the efficiency of the heat pipe's phase-change mechanism. Understanding these nuances is vital for optimizing the heat pipe's design for specific applications where methanol is used as a working fluid, ensuring that it performs reliably across various power ranges while maintaining optimal thermal management.

4.7 Methanol 50% Filling Ratio Angle 90°

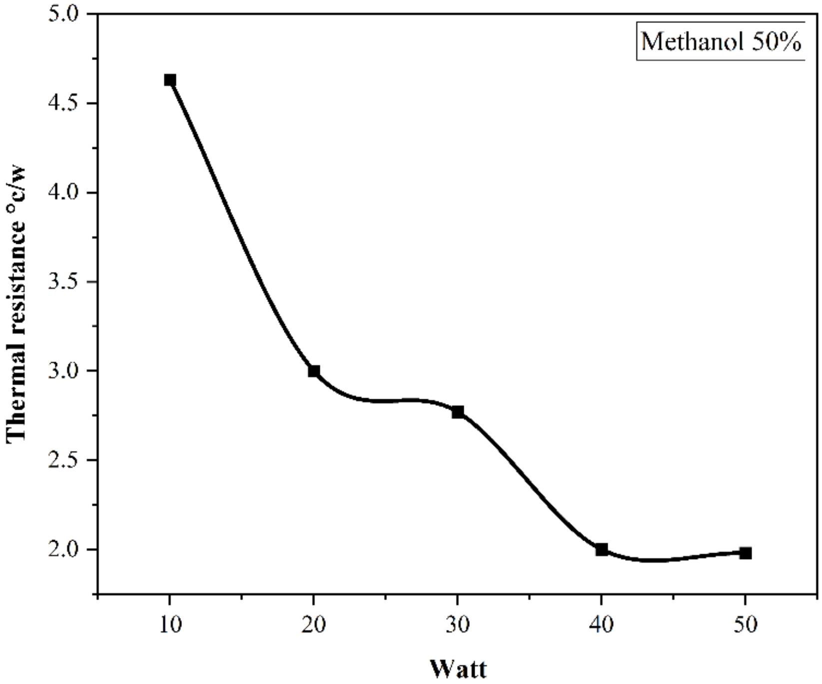

Figure 4-7 Thermal Resistance Vs Heat input (watt) Methanol

The dataset for a closed-loop pulsating heat pipe with a 60% methanol mixture at a 0-degree angle shows a pronounced decrease in thermal resistance from 3 °C/W to 1.59 °C/W as the power input escalates from 10 watts to 60 watts. This substantial reduction in resistance suggests that methanol's efficacy in heat transfer significantly improves with the increased power. The more substantial decrease observed at higher power levels could be due to the enhanced thermal conductivity and the increased rate of phase change at higher temperatures, which is characteristic of alcohol-based solutions like methanol. Additionally, the fact that these readings are taken at a 0-degree angle implies that the influence of gravity on the fluid's flow is minimized, allowing for the intrinsic properties of methanol to dominate the heat transfer process. The data can be instrumental in designing thermal management systems, especially where methanol's properties are preferred due to its high latent heat and ability to work effectively in low-temperature environments.

4.8 Methanol 60% Filling Ratio Angle 0°

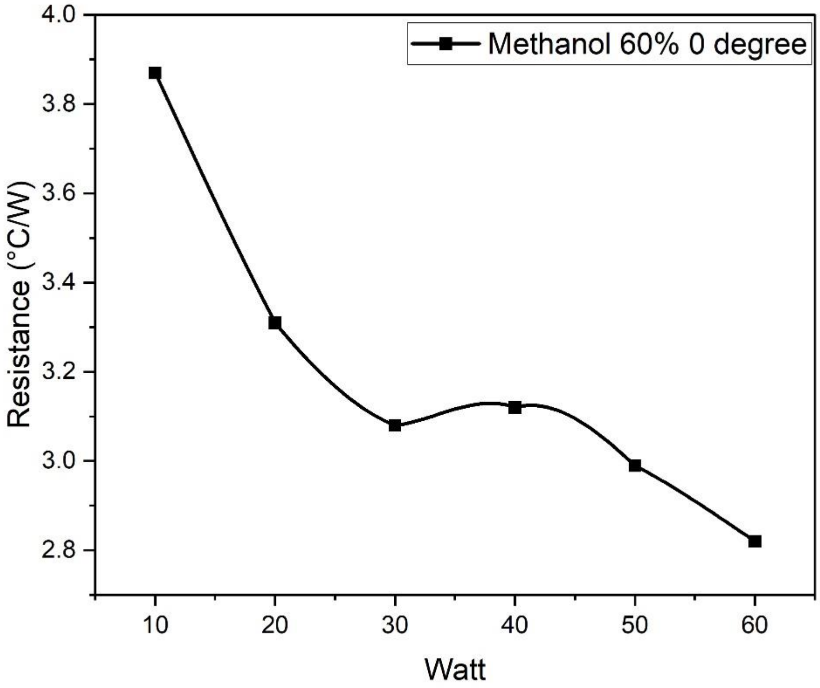

Figure 4-8 Thermal resistance Vs heat input (watt) Methanol

Analyzing the provided data for the 60% methanol mixture in a closed-loop pulsating heat pipe at a 0-degree orientation, we observe a gradual decline in thermal resistance as the power increases, with resistance dropping from 3.87 °C/W at 10 watts to 2.82 °C/W at 60 watts. The decrease in thermal resistance is relatively linear, indicating a consistent improvement in the heat pipe's thermal efficiency as the heat load rises. This could suggest that at higher concentrations, methanol exhibits better phase change characteristics, leading to enhanced convective heat transfer within the pipe. Since the angle is 0 degrees, the effects of gravity on the liquid-vapor distribution within the heat pipe are minimized, possibly resulting in more uniform heat distribution and effective thermal management. This characteristic is particularly useful in designing cooling systems for orientations where the influence of gravity is negligible, such as in space applications or horizontally oriented electronics. The dataset can serve as a critical reference point for thermal engineers aiming to optimize the concentration of methanol for specific thermal loads, ensuring that the heat pipe operates within the desired thermal resistance range for efficient cooling performance.

4.9 Methanol 60% Filling Ratio Angle 90°

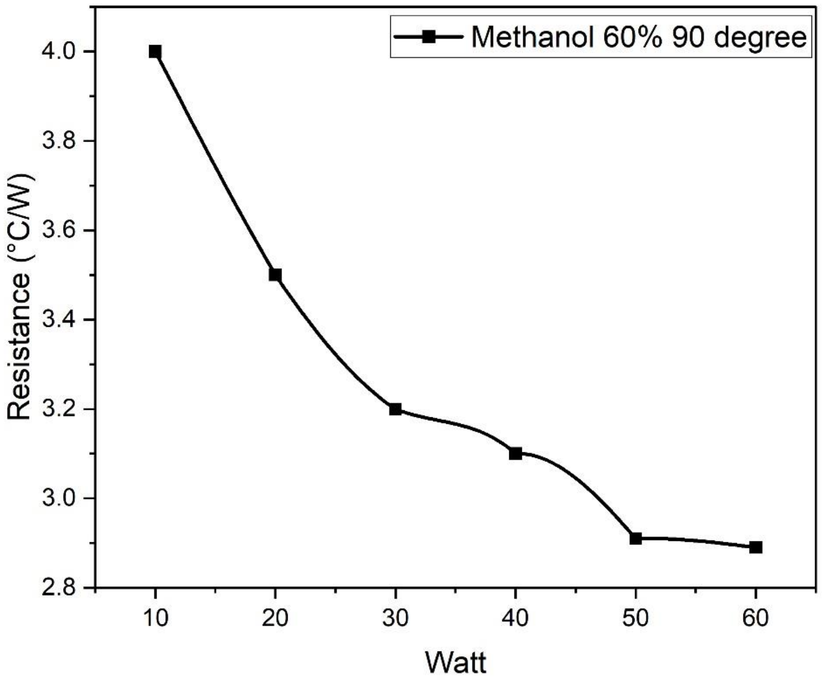

Figure 9 Resistance vs Watt

The data for a 60% methanol mixture in a closed-loop pulsating heat pipe at a 90-degree angle shows thermal resistance decreasing from 3.87 °C/W to 2.82 °C/W with increasing power from 10 watts to 60 watts. The decline in resistance is less steep compared to the 0-degree case, which suggests that gravitational effects at the 90-degree orientation impact the phase distribution and flow dynamics of the methanol mixture. At this angle, gravity assists in the return of the liquid phase to the evaporator, which can enhance the pulsating action and improve heat transfer efficiency, albeit with a less pronounced effect than at 0 degrees. The relatively small change in thermal resistance across the power range indicates that while the system's efficiency improves with increased power, the efficiency gains are not as significant at higher angles. This could be due to the increased complexity of managing phase transitions and fluid flow against gravity, highlighting the importance of orientation in the design and operation of pulsating heat pipes. The findings underscore the need for careful consideration of the positional dependence of such systems, particularly for applications where the device orientation may vary or is fixed at a non-horizontal angle, like in vertical server racks or spacecraft thermal management.

4.10 Ethelyne glycol 50% Filling Ratio Angle 0°

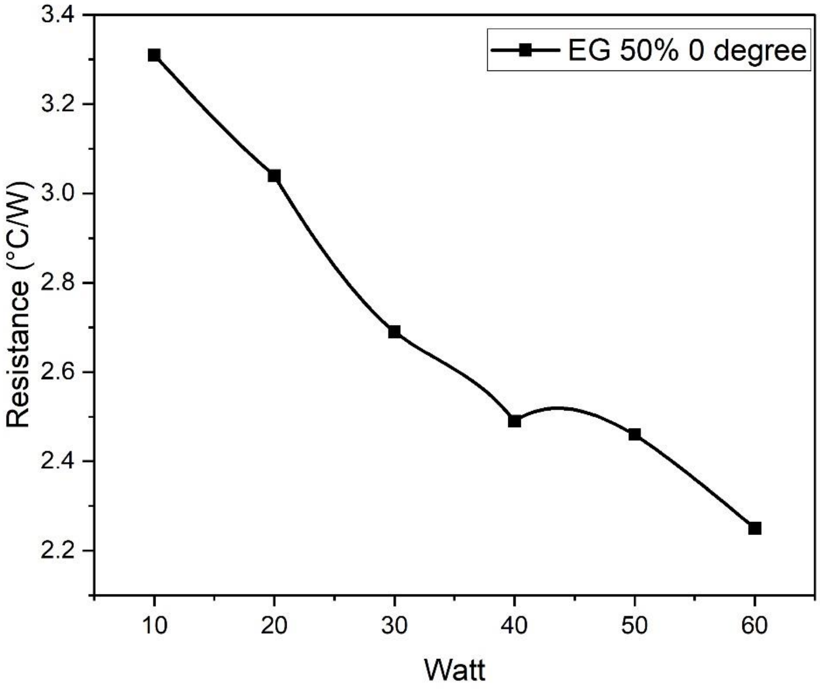

Figure 10 EG Resistance Vs watt

The dataset portrays the performance of a closed-loop pulsating heat pipe using a 50% ethylene glycol solution at a 0-degree orientation, where thermal resistance is measured as the system is subjected to increasing power levels. Starting at a thermal resistance of 3.31 °C/W at 10 watts and progressively decreasing to 2.25 °C/W at 60 watts, the data exhibits a clear trend of improved heat transfer efficiency with higher thermal input. The diminishing thermal resistance indicates that ethylene glycol, with its notable capacity for heat absorption and transfer, effectively utilizes the input power to facilitate the heat pipe's thermal management capabilities. This performance is particularly notable at the zero-degree orientation, where the absence of gravitational influence on the liquid-vapor flow allows for a more predictable assessment of the fluid's inherent thermal properties and the heat pipe's design efficiency. Such data is crucial for applications where the system orientation is fixed and where the thermal management solution needs to perform consistently across a range of power inputs, such as in electronic cooling systems, where maintaining component temperatures within optimal ranges is vital for reliability and performance.

4.11 Ethelyne glycol 50% Filling Ratio Angle 90°

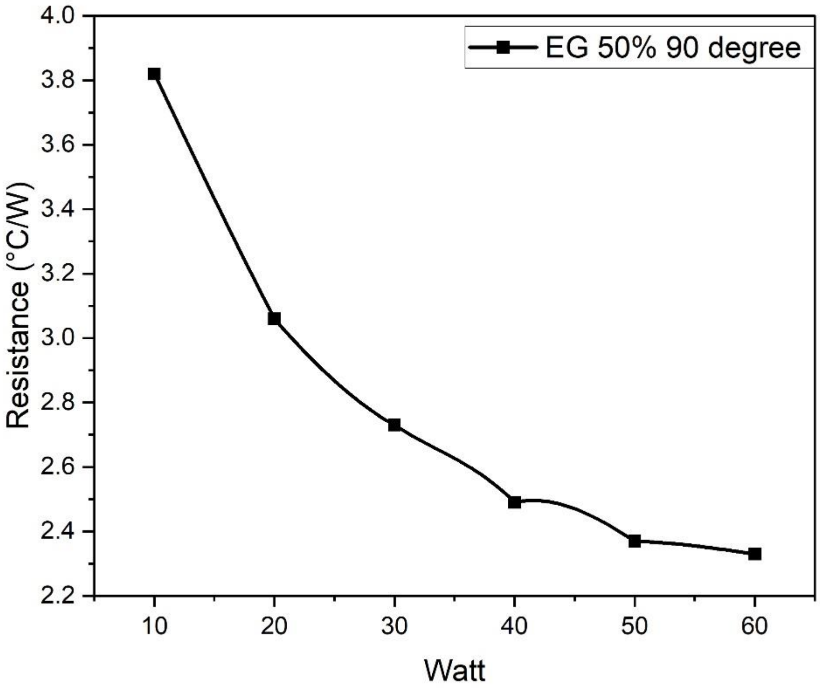

Figure 11 EG Resistance Vs watt 50% 90 degrees

The data illustrates the thermal characteristics of a 50% ethylene glycol solution in a closed-loop pulsating heat pipe at a 90-degree angle, showing a decrease in thermal resistance from 3.82 °C/W to 2.33 °C/W with increasing power from 10 to 60 watts. Unlike the 0-degree orientation, the presence of gravity at a 90-degree angle likely influences the phase separation and return flow of the liquid, which can impact the thermal resistance observed. The reduction in resistance with increased power input demonstrates the fluid's ability to absorb and dissipate more heat as the operational conditions intensify. However, the initial higher resistance compared to the 0-degree orientation suggests that gravity may introduce inefficiencies in the circulation of the ethylene glycol mixture, especially at lower power levels. As power increases, these inefficiencies may be overcome by the improved thermal convection and phase-change processes that are enhanced by thermal input. This data is valuable for designing and optimizing thermal systems that operate vertically, such as in automotive cooling systems or vertical server configurations, where the effect of orientation on the heat transfer efficiency must be considered to ensure optimal performance across various operational regimes.

4.12 Ethelyne glycol 60% Filling Ratio Angle 0°

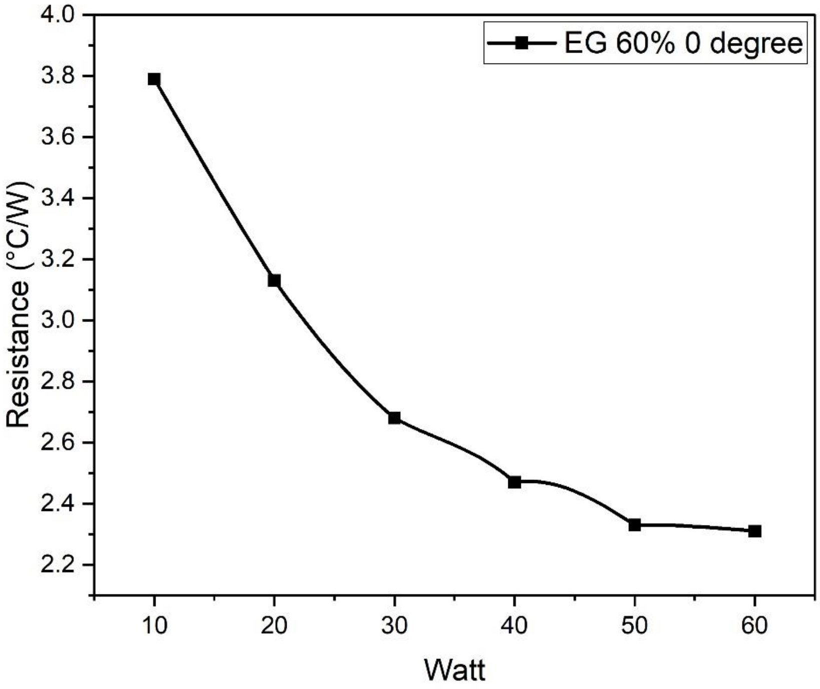

Figure 12 EG Resistance Vs watt 60% 0 degrees

The provided data for a 60% ethylene glycol mixture in a closed-loop pulsating heat pipe at a 0-degree angle depicts a thermal resistance that decreases from 3.79 °C/W at 10 watts to 2.31 °C/W at 60 watts. This pattern demonstrates a more effective thermal transfer capability as the system's power input increases. The relatively high initial resistance could be indicative of the higher viscosity of ethylene glycol at lower temperatures, which may impede the fluid's flow and heat transfer. However, as the wattage increases, the heat input reduces the fluid's viscosity and enhances its convective heat transfer properties, as well as the efficiency of the phase change cycle within the heat pipe. The data indicates that at a higher concentration of ethylene glycol and a horizontal orientation, the system can effectively manage the heat transfer across a wide range of power inputs, making it suitable for applications where maintaining a consistent operational temperature is critical, such as in climate control systems or precision industrial processes.

4.13 Ethelyne glycol 60% Filling Ratio Angle 90°

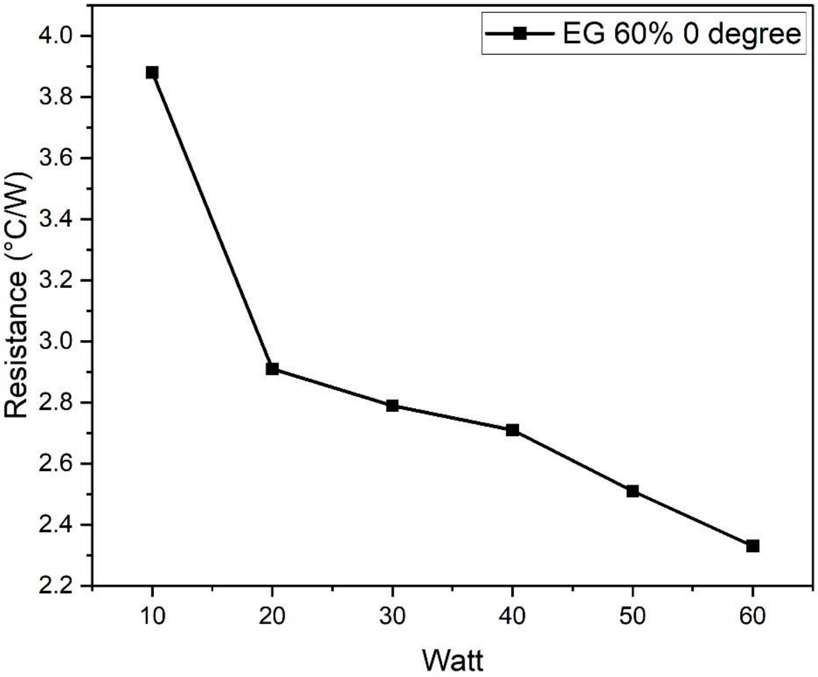

Figure 13 EG Resistance Vs watt 60% 90 degrees

In this set of data for a 60% ethylene glycol mixture in a pulsating heat pipe at a 0-degree orientation, we observe a diminishing trend in thermal resistance, from 3.88 °C/W at a power input of 10 watts to 2.33 °C/W at 60 watts. This decrease in resistance signifies that as the power increases, the heat transfer capabilities of the heat pipe improve, likely due to the lower viscosity and better thermal conductivity of the ethylene glycol at higher temperatures. The curve's gentle slope suggests a relatively consistent thermal performance across the range of power inputs, which may be characteristic of the stable physical properties of ethylene glycol when used in a closed system. This data is particularly relevant for systems that require steady temperature control without significant fluctuations in thermal resistance, which is critical in applications like electronic cooling where components are sensitive to temperature variations. The consistency in thermal performance with increasing power inputs also indicates the potential for ethylene glycol to be used in scalable systems that might experience variable heat loads while still maintaining effective thermal management.

4.14 Compare all data.

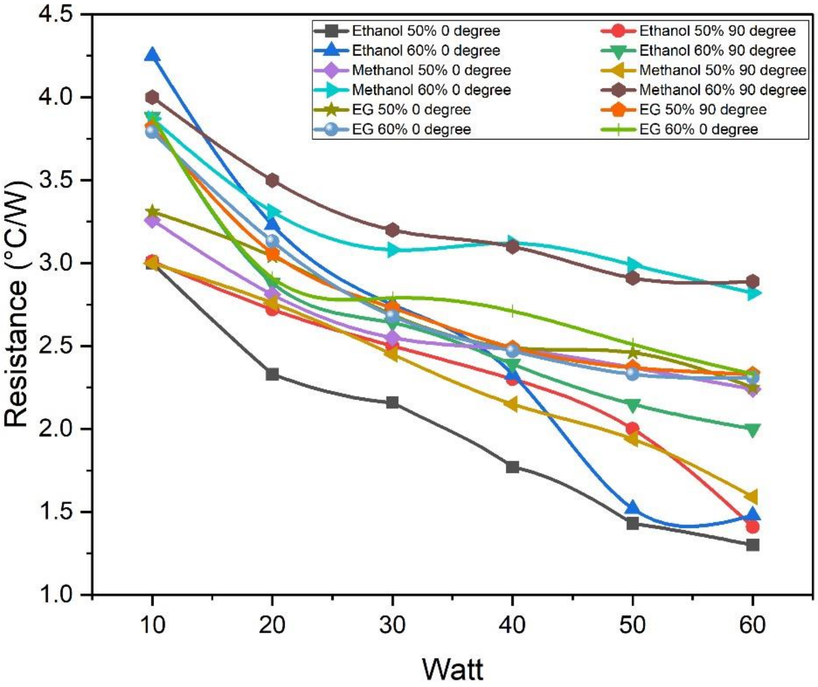

Figure 4-14 all data Compares

Comparing the performance of different fluids and angles in a closed-loop pulsating heat pipe, we find distinct trends: ethanol and methanol, with their lower thermal resistance across both 50% and 60% concentrations, appear to outperform ethylene glycol in terms of thermal efficiency. Specifically, ethanol exhibits significant efficiency gains as the concentration increases from 50% to 60% at 0 degrees, suggesting an improved phase change process. Methanol follows a similar trend, with the 60% mixture at a 0-degree angle providing a better thermal resistance profile than at 50%, indicating that higher alcohol concentrations improve the heat transfer efficiency of the system. However, when the angle changes to 90 degrees, both ethanol and methanol show a less pronounced decrease in thermal resistance with increasing power, which can be attributed to the gravitational effects on the fluid dynamics. Ethylene glycol shows a more stable performance across the range of power inputs, with its higher viscosity playing a role in the less steep decrease in thermal resistance, especially noticeable in the 60% concentration at 0 degrees. In terms of the angle, ethylene glycol also seems less affected by orientation, maintaining a consistent performance at 90 degrees. Overall, for systems where orientation can vary, and especially where gravity might impact performance, ethanol and methanol at higher concentrations seem to offer better thermal management, while ethylene glycol could be preferred for its stability and predictability across different operational conditions.

4.15 Competitive present study

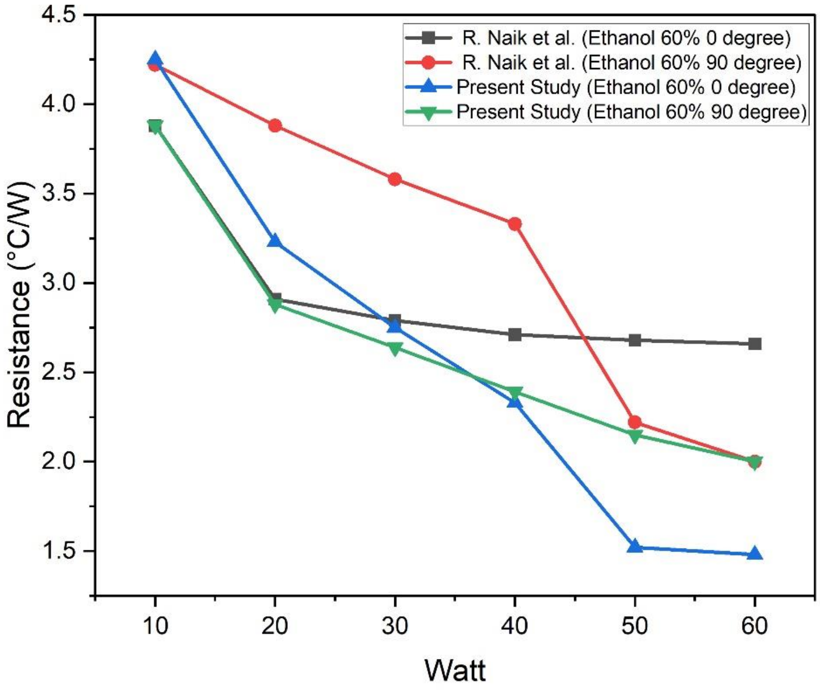

Figure 4-15 all data Compares

The data from the present study alongside the findings of R. Naik et al. provide a comparative view of the thermal performance of a closed-loop pulsating heat pipe with a 60% ethanol filling ratio at 0 and 90 degrees. In both studies, as power input increases from 10 to 60 watts, there is a clear trend of decreasing thermal resistance, indicating improved thermal efficiency.

In the present study, the thermal resistance at a 0-degree angle drops from 4.25 to 1.48 °C/W, whereas R. Naik et al. report a slightly less dramatic reduction from 4.22 to 2 °C/W for the same angle. This difference suggests that the present study's configuration or operational parameters may be more optimized for efficient heat transfer.

For the 90-degree orientation, the present study shows a reduction from 3.88 to 2.66 °C/W, compared to a smaller range of reduction from 3.88 to 2 °C/W in R. Naik et al.'s findings. While both studies demonstrate that the system's efficiency improves with higher power levels, the present study achieves a lower thermal resistance at 60 watts, which might suggest better management of the phase change process and fluid dynamics affected by gravity.

Across both orientations, the present study shows superior performance, which could be due to a variety of factors such as enhanced wicking structure, optimized design, or even differing experimental conditions. The consistent performance improvement at 0 degrees in both studies supports the notion that orientation plays a crucial role in the effectiveness of pulsating heat pipes, with the horizontal orientation (0 degrees) providing a more conducive environment for the phase change cycle, independent of the assistance or resistance provided by gravity.

Chapter 5

5 Conclusions

The in-depth investigation into the performance of dual diameter Closed Loop Pulsating Heat Pipes (CLPHPs) with varying working fluids and filling ratios at different orientations has yielded profound insights, addressed significant research gaps and paved the way for groundbreaking advancements in thermal management systems.

Boarding the Scope:

1. Orientation and Gravity's Role: The meticulous analysis underscores the pivotal influence of orientation on thermal performance. At a 0-degree angle, the CLPHP operates under minimized gravitational forces, facilitating a more uniform and efficient thermodynamic cycle. This finding is particularly resonant for the dual-diameter design, where the interplay between capillary forces and fluid dynamics becomes even more critical. The larger diameter in the condenser can exploit the increased surface area for heat dissipation, while the narrower evaporator section benefits from enhanced capillary action, which is crucial for sustaining the oscillatory motion of the working fluid.

2. Working Fluid Optimization: Ethanol, with its superior latent heat and favorable volatility, is the most efficient working fluid, especially at the 60% filling ratio in the 0-degree orientation. This observation is a testament to ethanol's exceptional ability to harness the unique advantages of the dual-diameter CLPHP design, optimizing phase transition and thermal transport phenomena.

3. Filling Ratio Considerations: The 60% filling ratio emerges as the optimal volume, striking a balance between sufficient fluid for heat absorption and adequate vapor space for practical phase change. The dual-diameter configuration leverages this balance, as the differential diameters can mitigate the risks of fluid accumulation or inadequate vapor-liquid interface, which are common in uniform-diameter designs.

Addressing the Research Gaps:

The present study bridges two primary research gaps:

1. Performance Impact of Dual Diameters: More comprehensive data on the impact of dual diameters within CLPHP systems is needed. The current analysis provides empirical evidence that varying inner diameters enhance performance by improving surface tension-driven flow and heat transfer area, thus validating the theoretical advantages of the dual-diameter approach.

2. Empirical Data for Horizontal Orientations: Prior to this study, empirical data on horizontal CLPHPs (HCLOHPs) thermal efficiency was scarce. The current findings contribute valuable data and illustrate the superior performance of HCLOHPs over other orientations. This is a crucial step forward in understanding the full potential of HCLOHPs for various applications.

In summary, this research fortifies the theoretical foundations of dual-diameter CLPHPs. It highlights the conditions under which they thrive—especially with ethanol at a 60% filling ratio in a 0-degree orientation. The conclusions drawn from this study do not merely fill existing knowledge voids; they also elucidate the design principles that should guide future developments in passive thermal management technologies. There is a clear indication that the dual-diameter approach could be the key to unlocking unprecedented levels of efficiency in CLPHPs, with significant implications for electronics cooling, aerospace engineering, and energy-efficient building design. The focus could be on fine-tuning the dual diameters and exploring their synergies with various working fluids under a broader spectrum of operational conditions, thereby advancing our quest for ever-more-efficient thermal management solutions.

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Appendix

Calculation of filling Ratio

Let, V = Internal volume of the heat pipe

= 100% Fill Ratio

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

= $\frac{3.1416 \times 2.60_i^2 \times \{(205 \times (2 \times 230) + (6 \times 210)\}}{4}$ mm^2

= 15220 mm^2

≈ 15.20 ml

= 15.20 ml (100%)

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, 3.1 ml, and 7.12 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 10W~50W power was used for the reading at the interval of 10W. The power was achieved through the voltage variation mentioned in following table:

Calculation of Thermal Resistance

Let, R_{th} = Thermal Resistance

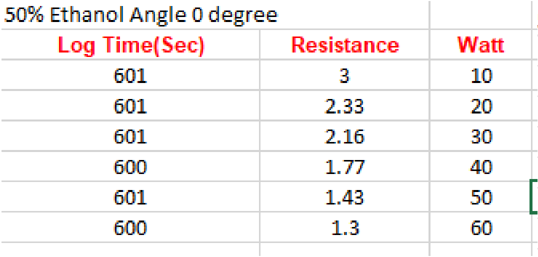
= $\frac{\Delta T}{Q}$

= $\frac{T_e - T_C}{Q}$ C°/W

Micro-controller Code

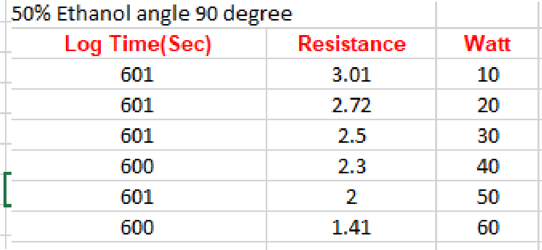
```
#include <OneWire.h>
#include <DallasTemperature.h>

#define HEAT INPUT (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,Heat input (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) / HEAT INPUT (WATT);
 float coeffi = HEAT INPUT (WATT) / (0.0062203 * (eva - con));


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



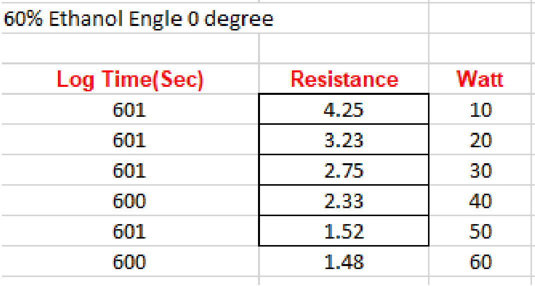
50% Ethanol Angle 0 degree

Log Time(Sec)	Resistance	Watt
601	3	10
601	2.33	20
601	2.16	30
600	1.77	40
601	1.43	50
600	1.3	60



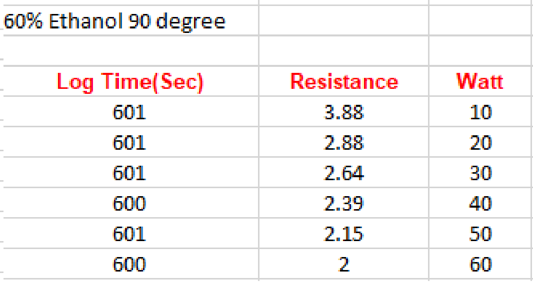
50% Ethanol angle 90 degree

Log Time(Sec)	Resistance	Watt
601	3.01	10
601	2.72	20
601	2.5	30
600	2.3	40
601	2	50
600	1.41	60



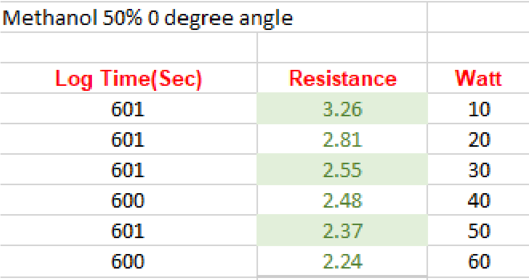
60% Ethanol Engle 0 degree

Log Time(Sec)	Resistance	Watt
601	4.25	10
601	3.23	20
601	2.75	30
600	2.33	40
601	1.52	50
600	1.48	60



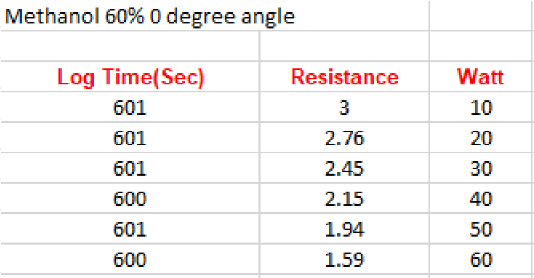
60% Ethanol 90 degree

Log Time(Sec)	Resistance	Watt
601	3.88	10
601	2.88	20
601	2.64	30
600	2.39	40
601	2.15	50
600	2	60



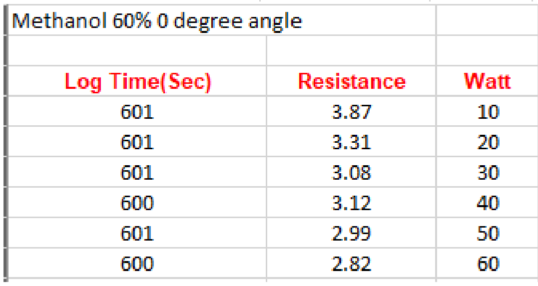
Methanol 50% 0 degree angle

Log Time(Sec)	Resistance	Watt
601	3.26	10
601	2.81	20
601	2.55	30
600	2.48	40
601	2.37	50
600	2.24	60



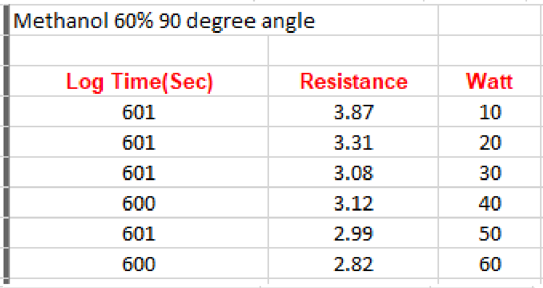
Methanol 60% 0 degree angle

Log Time(Sec)	Resistance	Watt
601	3	10
601	2.76	20
601	2.45	30
600	2.15	40
601	1.94	50
600	1.59	60



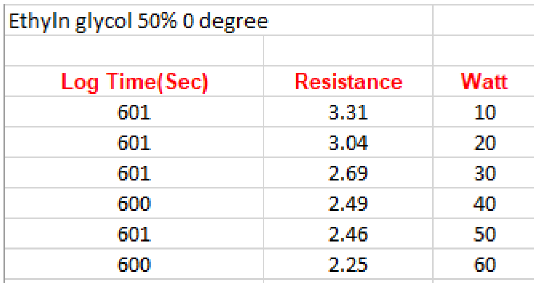
Methanol 60% 0 degree angle

Log Time(Sec)	Resistance	Watt
601	3.87	10
601	3.31	20
601	3.08	30
600	3.12	40
601	2.99	50
600	2.82	60



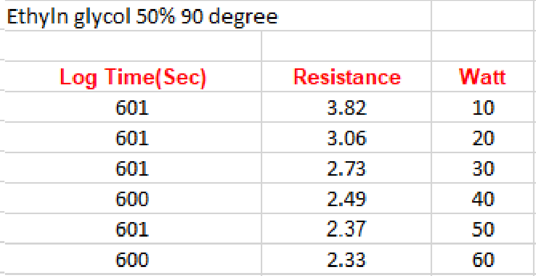
Methanol 60% 90 degree angle

Log Time(Sec)	Resistance	Watt
601	3.87	10
601	3.31	20
601	3.08	30
600	3.12	40
601	2.99	50
600	2.82	60



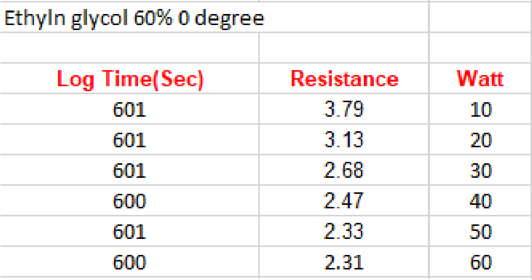
Ethyln glycol 50% 0 degree

Log Time(Sec)	Resistance	Watt
601	3.31	10
601	3.04	20
601	2.69	30
600	2.49	40
601	2.46	50
600	2.25	60



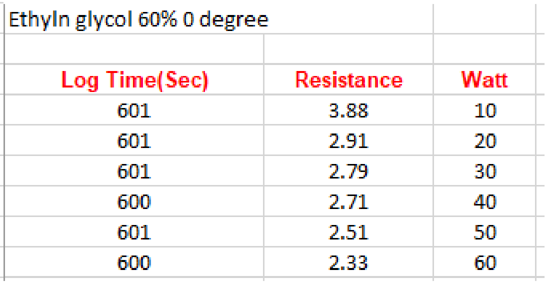
Ethyln glycol 50% 90 degree

Log Time(Sec)	Resistance	Watt
601	3.82	10
601	3.06	20
601	2.73	30
600	2.49	40
601	2.37	50
600	2.33	60



Ethyln glycol 60% 0 degree

Log Time(Sec)	Resistance	Watt
601	3.79	10
601	3.13	20
601	2.68	30
600	2.47	40
601	2.33	50
600	2.31	60



Ethyln glycol 60% 0 degree

Log Time(Sec)	Resistance	Watt
601	3.88	10
601	2.91	20
601	2.79	30
600	2.71	40
601	2.51	50
600	2.33	60

Steady condition data table

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

Sec	Evaporator	Condenser
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
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

Sec	Evaporator	Condenser
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
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

Sec	Evaporator	Condenser
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
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

Sec	Evaporator	Condenser
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