# Experimental study on the thermal performance of a novel dual diameter closed loop pulsating heat pipe.

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**147/I, GREEN ROAD, PANTHAPATH, TEJGAON, DHAKA**

**January 2024**

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“This document is a graduation exercise submitted to the Department of Mechanical Engineering as part of the requirements for obtaining a Bachelor of Science degree in Mechanical Engineering.”

DEPARTMENT OF MECHANICAL ENGINEERING

SONARGAON UNIVERSITY (SU)

147/I, GREEN ROAD, PANTHAPATH, TEJGAON, DHAKA

January 11, 2024

**STUDENT DECLARATION**

This document confirms that the thesis titled **"Experimental study on the thermal performance of a novel dual diameter closed loop pulsating heat pipe"** is the result of research conducted by the author under the guidance of **Md. Mostofa Hossain** is a professor and head of the Department of Mechanical Engineering at Sonargaon University (SU). This thesis, in its whole or any portion thereof, has not been previously presented to obtain any other academic degree, certificate, or comparable distinction.

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## SUPERVISOR'S DECLARATION

I Hereby declare that I have checked this project in my opinion this project is satisfactory in terms of and quality for the award of the degree of Bachelor of Science in Mechanical Engineering.

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**The Authors**

**January 2024**

# Dedication

**To our parents and supervisor, with heartfelt appreciation.**

# Abstract

This study on closed-loop pulsating heat pipes (CLPHP) with a dual-diameter design aimed to enhance heat pipe efficiency by investigating the performance of Methanol, Ethanol, and Ethylene Glycol as working fluids. The research began with understanding the critical role of steady-state conditions in CLPHPs for reliable data collection, emphasizing the importance of consistent flow rates and temperatures. The objective was to assess how different fluids affect the thermal resistance and overall efficiency of CLPHPs, especially under varying power loads. The experiment involved meticulous testing across a power range of 10W to 60W, focusing on observing changes in thermal resistance. Results showed that Methanol exhibited the highest performance, achieving a 70% reduction in thermal resistance between 10W and 60W, thus proving most effective in high heat flux conditions. Ethylene Glycol, on the other hand, demonstrated superior efficiency at lower loads, particularly under 30W. These findings highlighted the effectiveness of the dual-diameter design in enhancing internal circulation and preventing dry-out at higher power levels. The study establishes that a dual-diameter closed-loop pulsating heat pipe can significantly improve heat dissipation when paired with an appropriate working fluid like Methanol. This combination presents a potential solution for managing even higher thermal loads, offering a customizable balance between peak performance and efficiency at varying power ranges. The dual-diameter structure's contribution to reducing thermal resistance and enhancing capillary forces was a key takeaway, suggesting broader applicability in thermal management systems.

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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 |
| EG | Ethylene glycol |

# Chapter 1

# Introduction

In many engineering applications, closed-loop pulsing heat pipes (CLPHPs) are an effective and promising thermal management approach. They are highly useful in eliminating heat from electronics, aviation systems, renewable energy sources, and other heat-producing elements. CLPHPs function on the idea that they may transmit heat over a closed loop by utilizing oscillatory flow patterns, phase change processes, and capillary action.

The potential of CLPHPs to carry heat over long distances with low-temperature changes is one of its key features. Due to their capacity to swiftly and evenly transmit heat throughout the system, they are particularly effective thermal conductors. Additionally, the self-regulating nature of CLPHPs results in optimal performance and the prevention of overheating by automatically modifying the heat transfer rate to match the thermal load.

Numerous investigations have been undertaken lately to appreciate the complexity better and boost the effectiveness of closed-loop pulsating heat pipes. Studies have emphasized variables such as channel design, working fluid choice, system size, and operating situations to increase their capability for heat transfer.

The channel form substantially affects the heat transmission capabilities of CLPHPs. Various shapes, including circular, rectangular, triangular, and annular channels, have been examined to achieve efficient fluid flow and heat transfer. The needed heat transfer rate, the permissible pressure dips, and the ease of manufacture are just a few examples of the factors that determine the choice of channel form. Researchers have utilized models and investigations to assess how different channel configurations impact the overall efficacy of CLPHPs.

The choice of an acceptable working fluid is another key aspect in the design of CLPHP. Desirable features of the working fluid include a low boiling point, high latent heat of vaporization, low viscosity, and great thermal stability. Water, methanol, ethanol, ammonia, and refrigerants like R134a working fluids are widely employed. The operating temperature range, optimal heat transfer efficiency, and safety issues determine the working fluid choice. The closed loop's length, diameter, and number of turns affect how successfully heat is transmitted in CLPHP systems. An in-depth study has been done to discover the appropriate settings that increase heat transfer rates while lowering pressure drop and system size. In addition, researchers have supplied significant insights into the influence of system dimensions on the thermal performance of CLPHPs through experimental experiments and computer modelling.

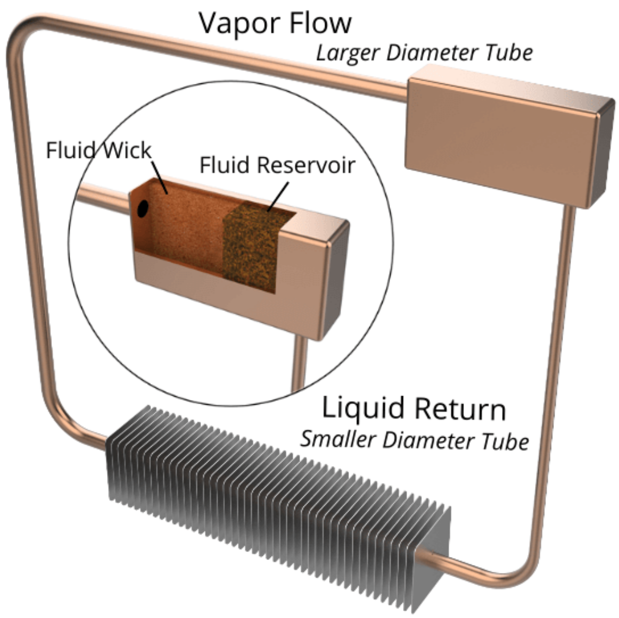


Figure 0-1 Real life application of CLPHP

To optimize the performance of CLPHPs, several operating settings have been examined. In addition to channel shape and working fluid choice, elements including heat input, filling ratio (the proportion of the internal volume occupied by the working fluid), inclination angle, and working fluid temperature have been researched to appreciate their impact on heat transfer characteristics. The advancement of closed-loop pulsating heat pipes has also permitted the design of unique variations and hybrid systems. Phase change materials, heat sinks, heat exchangers, thermoelectric devices, and other heat transfer technologies have all been researched concerning CLPHP integration. With the aid of these hybrid systems, the special demands of challenging thermal management scenarios may be met while simultaneously widening the working range and enhancing overall thermal performance.

Additionally, the behavior of CLPHPs under different operating settings has been anticipated and simulated using numerical modelling methodologies, including computational fluid dynamics (CFD) and finite element analysis (FEA). These modelling tools assist engineers in optimizing their designs and avoiding the need for long experimental testing by giving relevant information on the fluid flow patterns, temperature distribution, and overall performance of CLPHPs.

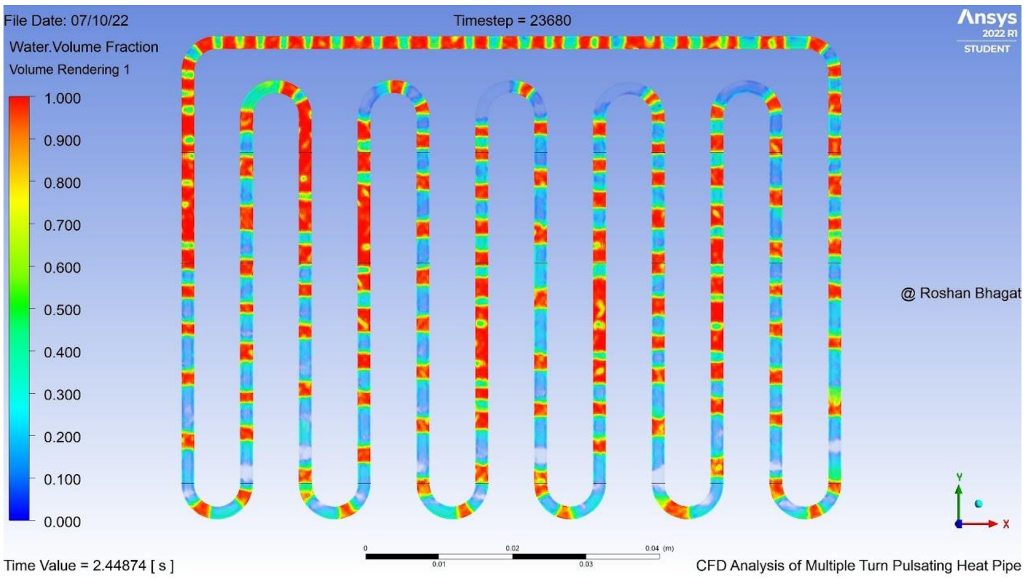


Figure 0-2 CFD Analysis of CLPHP [1]

Closed-loop pulsing heat pipe technology is continually developing, and this has significant promise for overcoming the expanding thermal management difficulties in current engineering applications. Engineers and scientists continually push the boundaries of CLPHPs to increase their usefulness, reliability, and ability to be applied to diverse systems sec. Consequently, CLPHPs are projected to be extensively employed in the future, transforming the domain of thermal management with more reliable and efficient technologies. A working fluid (typically a low-boiling-point liquid) is contained within a closed loop of connected channels or capillaries for CLPHPs to operate. The working fluid absorbs the heat and vaporizes when applied to one or more evaporator sections. The vapor then finds its way to the condenser, condensing lenses into a liquid and turning its heat to the environment. The closed loop occurs when the condensed liquid flows by capillary action or gravity-driven flow back to the evaporator.

Pulsating flow is the characteristic attribute distinguishing CLPHPs from typical heat pipes. The system suffers pulsations owing to the interplay of surface tension forces, gravity forces, and pressure differences. These pulsations produce undulating flow patterns that boost the CLPHP's capacity to transport heat. In addition, the working fluid's pulsating motion facilitates the evacuation of vapor bubbles from the evaporator, allowing fresh liquid to contact the heated surface and enhance the area and efficiency of heat transfer.

Two main combinations are typically noticed when evaluating how CLPHPs are oriented: horizontal and vertical angles. The evaporator and condenser sections are positioned at the same height in horizontal CLPHPs but below the condenser in vertical CLPHPs. Each configuration offers distinct advantages and issues pertaining to riding heat transfer efficiency, fluid distribution, and general system tasks.

When a horizontal surface is readily accessible for heat dissipation or when space is at a premium, horizontal CLPHPs are an ideal alternative. They have a compact footprint and are commonly used in electronic cooling systems because they can fit into limited locations in electronic equipment. Because the flow is unaffected by the system's orientation, horizontal CLPHPs offer superior resistance to gravitational effects. However, with horizontal CLPHPs, ensuring equal fluid distribution could be more challenging because gravity forces may hinder the working fluid from flowing smoothly.

Vertical CLPHPs, on the other hand, are advantageous in circumstances where forced or natural convection cooling is readily available. Vertical CLPHPs may leverage gravity-driven flow to increase fluid circulation by positioning the evaporator below the condenser. In order to guarantee efficient heat transfer, this structure makes it feasible to eliminate vapor bubbles from the evaporator area more efficiently. In applications like solar thermal systems, where heat may be swiftly evacuated by forced air cooling or natural convection, vertical CLPHPs are typically employed.

Finally, closed-loop pulsating heat pipes give a versatile and efficient thermal control solution in numerous technological applications. They are highly tempting for addressing difficulties with heat dissipation because of their rapid and even heat transmission and self-regulating nature. Engineers may alter their design to satisfy application demands by employing CLPHPs, which give unique advantages and considerations in horizontal or vertical orientations. Advancements in electronic cooling, aviation systems, renewable energy, and other disciplines have been made feasible by CLPHPs owing to continuing research and development.

## 1.1 Evolution of CLPHP

Closed-loop pulsating heat pipes (CLPHPs) have made considerable gains in their development. CLPHPs were originally exhibited in the early 1990s and were constructed as closed-loop passive heat transfer devices with a network of connected channels and a working fluid. These devices have matured into useful, adaptive heat management solutions for numerous applications.

Early CLPHP designs were largely focused on knowing the underlying ideas and important aspects of pulsating flow and heat transfer within the system. Researchers experimented with different channel configurations, diameters, and orientations to increase performance. Simple planar geometries and rectangular channels were employed in the early prototypes.

More complicated designs with curved and meandering channels appeared as research expanded, boosting heat transfer efficiency. In addition, capillary structures were placed inside the channels, further increasing the thermal and fluid characteristics, and enabling successful functioning in diverse orientations and gravitational fields.

CLPHPs have developed because of better fabrication technologies, including microfabrication and additive manufacturing. These approaches have made it feasible to construct complicated and microscopic geometries, which has enhanced the devices' thermal efficiency and compactness.

Furthermore, CLPHPs now have more alternatives due to the progress of working fluids, such as phase change materials and nanofluids. With their enhanced thermal conductivity and heat capacity, these cutting-edge fluids offer quicker heat transfer rates and greater system performance.

Additionally, recent improvements in control and optimization approaches have permitted CLPHPs in numerous applications, including renewable energy systems, aviation systems, and electronics cooling. The CLPHPs' applicability and versatility to varied thermal management demands have risen due to their capacity to dynamically control and regulate the pulse flow within them.

Ongoing research, technological discoveries, and the demand for efficient thermal management solutions have fueled the development of closed-loop pulsating heat pipes. Future advancements in heat transfer efficiency, downsizing, and integration into numerous applications are predicted owing to the devices' continuing study 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.

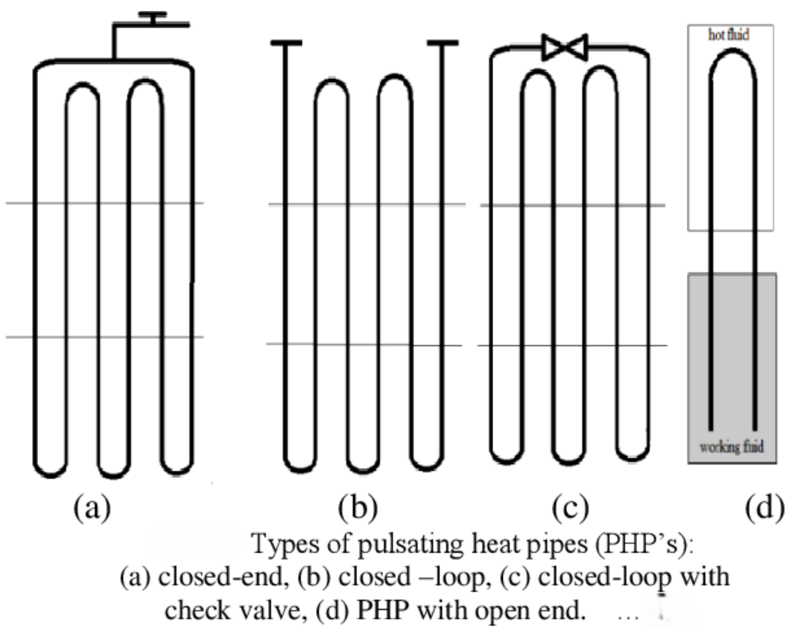


Figure 0-3 Types of CLPHP (https://peregrinecorp.com/pulsating-heat-pipes/)

## 1.3 Parameter effect the CLPHP.

CLPHPs have a tree-like configuration: These CLPHPs have a central evaporator and numerous

branches. This design is suitable for applications with non-uniform heat sources because it enhances the dispersion of the working fluid and heat transfer.
Loop heat pipe (LHP): LHPs are a special sort of CLPHP in which a wick structure governs the working fluid flow. Most of them comprise the evaporator, adiabatic section, condenser, and compensatory chamber. LHPs are appropriate for demanding thermal management applications because of their outstanding heat transfer capability and durability.

Several variables, such as the following, determine how effectively CLPHPs perform:
1) **Working fluid:** The working fluid choice affects the CLPHP's thermal performance, heat transfer qualities, and operating temperature range. The varying boiling points, latent heat of vaporization, and thermal conductivities of the various fluids influence the system's overall efficacy.
2) **Fill ratio:** The fill ratio specifies the proportion of the working fluid filled CLPHP's internal volume. It affects the capillary flow behavior and the available surface area for heat transfer. Therefore, the fill ratio must be optimum to perform good heat transfer.

**Dimension:** The dimensions of the channels or pipes in the CLPHP, such as their diameter and length, determine the flow resistance, pressure drop, and heat transfer qualities. Therefore, the channel's diameter and length must be correctly designed to balance the performance of heat transfer and fluid flow resistance.
Temperature and power of the heat source: The heat input into the CLPHP is affected by the temperature and power of the heat source. Higher heat source temperatures and powers may affect the system's thermal resistance, vaporization, and condensation rates.

**Ambient temperature:** The region where the CLPHP is positioned determines how much heat it can dissipate. A larger ambient temperature may result in less effective heat transfer and influence the system's overall thermal efficiency.
**Wick structure and design:** In CLPHPs with wick structures, the wick's design and material qualities impact the capillary flow and liquid transport. Wick properties, including pore size, porosity, and permeability, determine the CLPHP's overall performance.

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

To guarantee efficient and reliable heat transfer, these parameters and others must be addressed while constructing and optimizing closed-loop pulsing heat pipes.

### 1.4 Limitation of CLPHP

Employing closed-loop pulsating heat pipes (CLPHPs) for thermal management and heat transfer has various advantages. They do, however, have some constraints that must be taken into mind. Their sensitivity to direction is one downside. In areas where the orientation is frequently changing or when gravity is substantially modified, CLPHPs may perform differently than when perfectly aligned with the gravitational field. Furthermore, the overall size of CLPHPs may be negative. The capillary forces that accelerate fluid circulation inside pipes may be less effective as the system's size reduces, resulting in less efficient heat transfer.

CLPHPs may be subject to fluid leakage, especially if placed under high operating pressures or vibrations. This may lead to a loss of working fluid and a decline in the efficacy of heat transfer. Lastly, CLPHPs must be carefully built and tuned to deliver the greatest performance for various applications, which may involve more time and resources. Nevertheless, closed-loop pulsating heat pipes continue to be a viable technology for many thermal management applications despite these shortcomings, and current research attempts to overcome these drawbacks and increase their overall performance.

Examines how operating orientation, inner diameter, filling ratio, and heat input flux influence thermal performance and performance limitations. According to the study, orientation scarcely impacts CLPHPs with a 1 mm inner diameter. For both CLPHPs, a filling ratio of 50% is optimum in all orientations. The CLPHPs were operated until they hit a performance barrier defined by severe evaporator overheating (dry-out), and a large diversity of heat loads could be managed. Gravity has a small or insignificant influence on thermal performance as the inner tube diameter decreases. The research presents significant information on the performance thresholds of CLPHPs, which may assist in developing and enhancing these devices.[2]

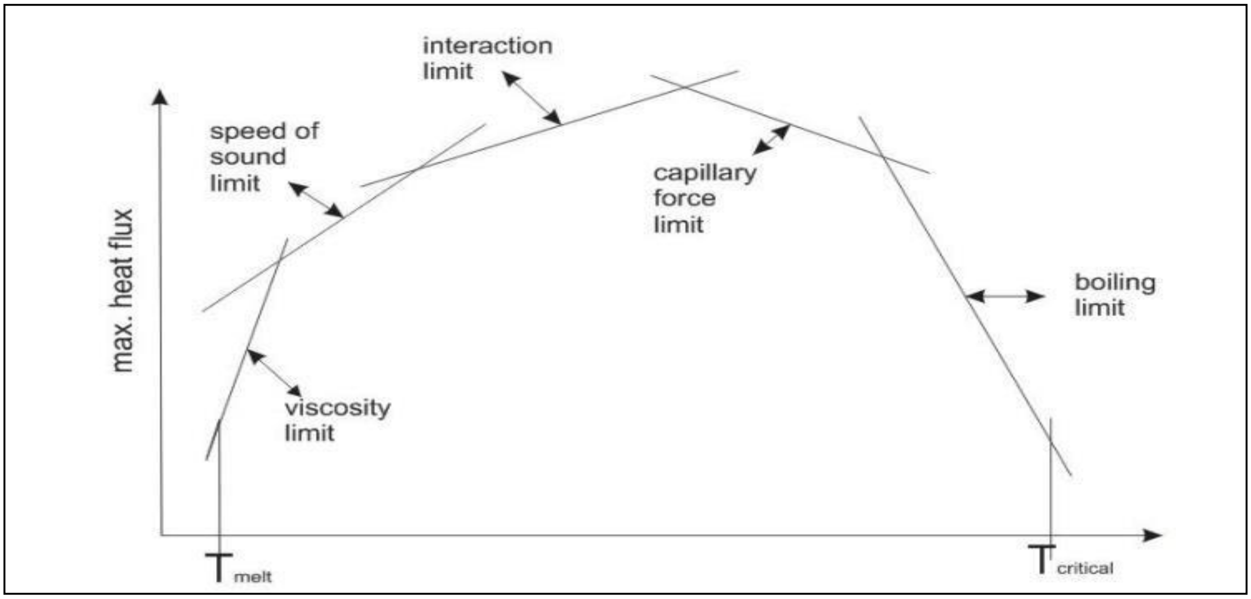


Figure 0-4 Limitation of CLPHP[2]

## 1.5 Research gap:

Existing closed-loop pulsing heat pipes (CLPHPs) usually employ consistent pipe diameters throughout the evaporator, adiabatic portion, and condenser. However, the recent study "A novel energy storage system for latent heat recovery in solar still using phase change material and pulsating heat pipe [3]" demonstrated that reducing the inner diameter in the evaporator and adiabatic sections while increasing the inner diameter in the condenser improved performance. This shows the possibility of enhancing CLPHP performance by carefully altering the inner pipe widths.

The smaller diameters in the evaporator and adiabatic sections boost surface tension forces, possibly increasing liquid slug generation and oscillatory flow. The wider diameter in the condenser portion offers more surface area, facilitating heat transfer like a fin or heat sink. This condenser diameter effect is akin to the Joule-Thomson effect.

There is a study gap in understanding how strategically tapering CLPHP pipe widths may raise surface tension forces in the evaporator, accelerate oscillatory flows, and boost surface area in the condenser to optimize heat transfer. This might lead to more efficient CLPHP designs compared to employing uniform pipe sizes.

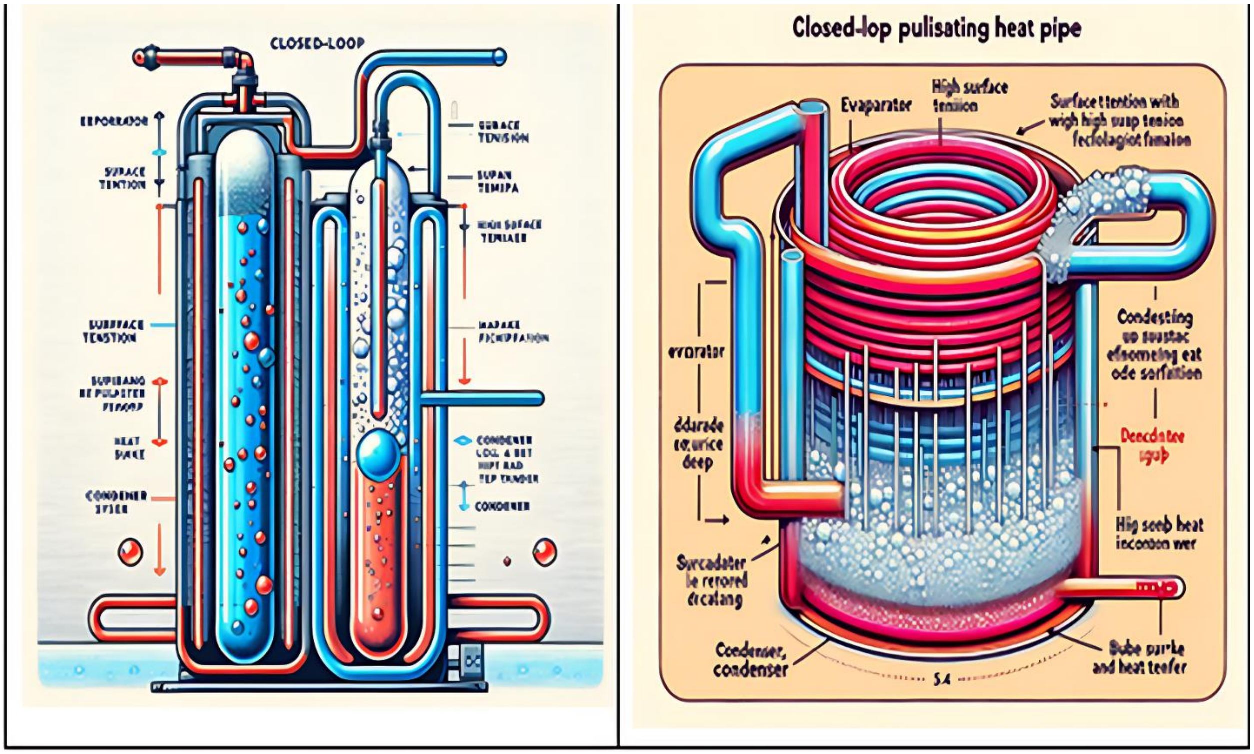


Figure 5 Conceptual hypothesis illustration from Dall-e AI

## 1.6 Objective

1. To examine the performance of CLPHP filling ratios of 50% & 60% Ethanol as a working fluid.

2. To evaluate the performance of the CLPHP filling ratios of 50% & 50% Methanol as a working fluid.

3. To evaluate the performance of the CLPHP filling ratios of 50% & 60% Ethylene glycol as a working fluid.

4. To compare the performance of the CLPHP filling ratios of 50% & 60% Ethanol, Methanol and Ethyle glycol as working fluid.

# Chapter 2

# Literature Review

Like regular heat pipes, pulsing heat pipes are closed, two-phase devices that may transport heat without requiring supplementary energy. However, they drastically differ from standard heat pipes in several essential features. A typical PHP is a small, meandering tube containing a fluid that is only half-functioning. The tube's ends may either be pinched off and left open or welded together to produce a closed loop. The tube spins back and forth while being parallel to itself. Researchers observed that the closed-loop PHP works better in terms of heat transfer.

Therefore, the bulk of experimental work utilizes closed-loop PHPs. Heat transfer is enhanced in the closed-loop PHP because the working fluid may circulate in addition to the oscillatory flow. The capacity of the PHPs to transport heat may be boosted by placing a check valve, which directs the working fluid in each direction. However, doing so is tough and expensive. The best solution is to use closed-loop PHP structures that lack a check valve.

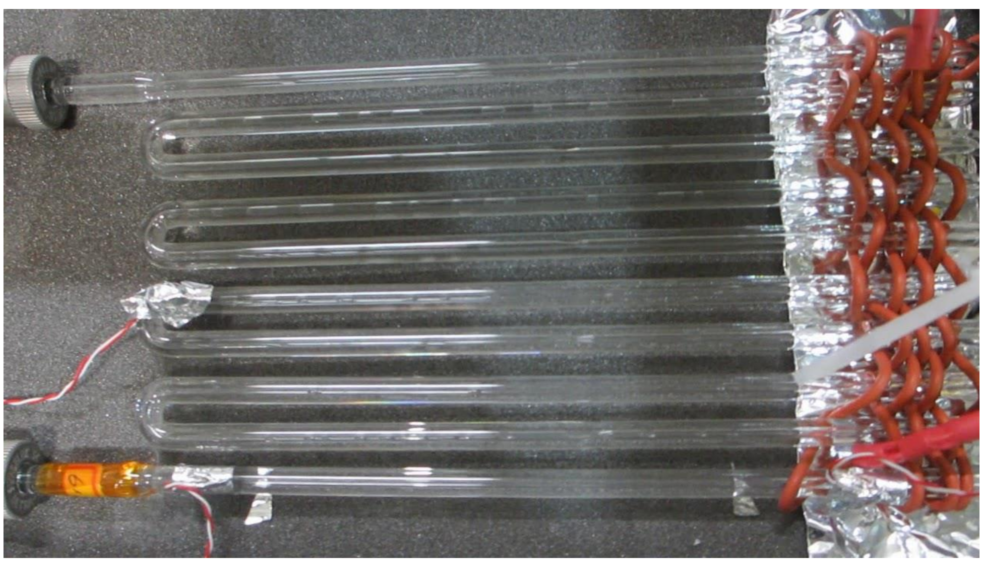

Figure 0-1 Glass view of CLPHP [3]

## 1.7 Closed loop pulsating heat pipe.

Pulsating heat pipes are closed, two-phase systems that, like ordinary heat pipes, may transmit heat without requiring extra power. However, they vary drastically from traditional heat pipes in numerous crucial areas. A typical PHP is a tiny, meandering tube with a partly functioning fluid. The ends of the tube may be welded together to produce a closed loop, or they may be pinched off and left open. The tube is parallel to itself and rotates back and forth. The closed-loop PHP performs better in terms of heat transmission, according to researchers. Because of this, most experimental work employs closed-loop PHPs. In the closed-loop PHP, the working fluid may circulate in addition to the oscillatory flow, which increases heat transfer. Installing a check valve may boost the PHPs' ability to transmit heat by making the working fluid flow in each direction. However, doing so is complicated and costly. The optimal alternative is to employ PHP structures that are closed loop and do not have a check valve.

Recently, PHPs were prototyped and evaluated with a sintered metal wick by Holley and Fakhri [4] and [5] [6]. The wick should aid with both liquid dispersion and heat transmission. A PHP must have at least one heated section and one cooled zone. The evaporators and condensers are commonly situated at the bends of the capillary tube. After emptying, a working fluid is first partly pumped into the tube. The liquid and its vapor will spread throughout the pipe as it slugs and bubbles. As the PHP warms up, the vapor pressure in the bubbles in the evaporator section will grow. This drives the liquid slug toward the condenser section of the heat pipe. As the vapor bubbles reach the condenser, they will begin to condense. When a vapor changes phases, the pressure lowers, forcing the liquid to return to the condenser end. The PHP is set up to have a continual oscillating flow in this fashion. Boiling the working fluid will also cause new vapour bubbles to develop. PHP research is separated into two categories: theoretical and experimental. Regarding the experimental work, the emphasis has been on defining the heat transfer or demonstrating the flow pattern in PHPs.

Theoretical studies aim to simulate the heat transfer and fluid dynamics associated with oscillating two-phase flow computationally and analytically. A thermo-hydraulic coupling greatly regulates the functioning of a complex heat transfer mechanism termed a PHP. It functions as a non-equilibrium heat transfer process. The success of the device's operation hinges on continually maintaining or preserving these non-equilibrium situations inside the system. Slugs of liquid and vapor are transmitted owing to the pressure pulsations induced in the system. The device's fundamental design thermally produces these pressure pulsations. Therefore, no extra mechanical power source is necessary for the fluid transmission.

## 1.8 Emergence of Pulsating Heat Pipe

Conventional heat pipes (CHP) started to gain popularity in the 1960s, and several novel geometries, working fluids, and wick architectures have been developed since then [4]. In addition, to solve some of the drawbacks of traditional heat pipes, innovative heat pipe designs, such as capillary pumped loops and loop heat pipes, have been invented within the past 20 years by separating the liquid and vapor fluxes.

The pulsing or oscillating heat pipe (PHP or OHP) is a novel heat pipe created by Akachi et al. in the 1990s (Khandekar et al., 2002.). PHP is commonly applied in electronics cooling because it can disperse the massive heat fluxes needed by next-generation devices. Pumping water or heating air are some additional possible uses for PHPs. This review article will define the functioning of pulsing heat pipes, highlight current research and development, and analyze any unresolved difficulties.

[6] 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 found a closed-form solution for the wave propagation velocity.

[7] conducted an experimental examination of the oscillatory flow in the PHP and found the wave velocity compatible with Akachi et al.'s forecast in the 1990s.

The departure of tiny bubbles is regarded as the usual flow pattern at the evaporator and adiabatic section, respectively, according to [8], which states that nucleate boiling and vapor oscillation induce bubble oscillations.

[9] conducted multiple experiments utilizing different PHP settings. He studied how numerous elements (such as filling ratio, heat input, number of turns, and orientation) impacted their behavior. His investigations offered him a better knowledge of the heat and fluid dynamics of PHPs. He underlined the necessity to pick a tube diameter tolerating flow oscillations.

[10] also conducted some flow visualizations when a PHP was executing. They observed four operating modes that approximate the PHP operating curve, depicting the heat pipe's total thermal resistance as a function of input power. The oscillations' amplitude is restricted at low heat input, and as heat input grows, the thermal resistance considerably lowers. A more severe fall in thermal

resistance with increasing heat input leads to a slug flow pattern. Nevertheless, a preferred flow direction soon becomes obvious as the heat input accumulates. The desired flow direction must be specified, and the flow pattern must be circular rather than slug-like for thermal.

Little opposition exists, and there is a plateau. However, owing to the thermal resistance quickly rising as the heat input rises, the evaporator dries up when there is a large heat flow.

[10] provided greater information in their investigation employing ethanol, water, and R-123. The critical diameter for ethanol and water was much higher than the tube diameter, in contrast to the latter, when it was equal to (or even slightly below) the tube diameter. According to their research, the filling ratio and orientation of the PHPs determine how bubbles affect the two-phase oscillating flow that emerges at the PHPs' extreme operational limits (i.e. when the PHP is empty or loaded with liquid). The bubbles impede the flow of the two-phase fluid at high filling ratios (like 95% of liquid) and advantageous orientations (like evaporator at the bottom, condenser at the top). Gravity was an issue even for water at moderate filling ratios (about 20% to 70%, which truly creates oscillations) or even for a critical diameter much greater than the tube diameter (highly limited situation). The PHP was found to function with R-123 despite having a critical diameter smaller than the tube diameter. These findings were all explained by accounting for the impact of bubbles on the two-phase flow.

In their article [11]. Addresses the impacts of CLPHP on them.

Several factors affect HP's thermal performance, including the device's inclination angle, working fluid, the number of turns, and internal tube diameter. The outcomes of this experiment indicated that buoyancy forces impact bubble shape, the internal diameter must be set with a key Bond number within the limit, and performance may be enhanced by raising ID and meandering turn numbers. In addition, the performance of CLPHP is strongly influenced by gravity. Finally, various fluids are desirable based on the working circumstances, latent and sensible heat fractions, and flow qualities.

[12] examined the propagation of vapor plugs in a meandering closed-loop heat transfer system. They discovered that a simple flow pattern evolved at large liquid volume percentages. Only two vapor plugs can be identified independently in adjoining rounds under these circumstances, and one begins to constrict as the other starts to develop. A streamlined numerical solution was also

produced, eliminating any hypothetical liquid coating between the tube wall and the vapor stopper under certain important assumptions.

From numerous viewpoints and with various working fluids,[13] examined an open-loop PHP. He examined the thermal efficiency of a PHP using working fluids such as water, ethanol, propanol, methanol, and acetone. Under his test circumstances, methanol and acetone created the highest thermal performance, whilst water produced the lowest. Additionally, he observed that the PHP oscillations are stronger and more frequent when methanol is used instead of water. The low latent heat of methanol, which facilitates boiling and nucleation and, as a result, fluid flow instability, was assumed to be the reason. Finally, he observed that horizontal orientation outperformed vertical orientation for thermal performance. However, the significance

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

[14] used a high-speed video to investigate the oscillatory flow in a closed-loop PHP. For methanol and water, multiple oscillation modes were observed. The working fluid was water, emphasizing the vapor plug break-up and coalescence processes, especially at tube U-bends. They determined that the capillary pressure is not constant in the bends, resulting in a localized liquid deposit based on an analytical model. They noted that the methanol utilized as the working fluid's low surface tension avoids coalescence or break-up. When compared to water, the liquid plugs are, thus, longer.

In their publication published at [15]. Provide an experimental investigation on the operating constraints of closed-loop pulsating heat pipes (CLPHPs). The three operating 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 limitations were explored. The CLPHPs were run until a performance threshold was attained, which was characterized by excessive evaporator overheating (dry-out). After that, relatively substantial heat loads may be controlled. An experimental study on two closed-loop pulsing heat pipes (CLPHPs) studied the effects of inner diameter, filling ratio, operational orientation, and heat load on thermal performance and performance restriction in the form of evaporator dry-out. CLPHPs have optimum thermal performance and maximum performance limit in the vertical bottom heat mode with a 50% filling ratio. As the inner diameter lowers, performance differences brought on by distinct heat modes (i.e., the gravity effect) become exceedingly modest or inconsequential.

This study studied 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 twists, R123 was employed as the working fluid. Five equal lengths with inclination degrees of 0, 20, 40, 60, 80, and 90° formed the evaporator, adiabatic, and condenser sections. The critical temperature rose when the inner diameter changed from 1.77 to 2.03 mm, according to [16]. In addition, the critical temperature rose from 0 to 90 degrees of inclination.

[17] quantitatively examined oscillatory flow and heat transport in a tiny U-shaped channel. The U-shaped tube's two sealed ends acted as the heating components. The condenser section was positioned in the center of the U-shaped canal. The U-shaped duct was positioned vertically, with two sealed ends (heating sections) at the top. The influence of numerous non-dimensional parameters on PHP performance was also explored. Empirical relationships were observed between the oscillation's amplitude and circular frequency.

[18] Heat transmission in a PHP is predominantly carried out by heat exchange, with sensible heat contributing to over 90% of the heat transfer from the evaporator to the condenser. The oscillation of liquid slugs was the principal impact of evaporation and condensation on the performance of PHPs. At the same time, latent heat had less influence on the total amount of heat transmission.

In an experiment, [19] showed that with an input power of 30–50W at the same charge volume, the temperature difference between silver Nano-fluids and DI-water dropped by 0.56–0.65°C.

Base water and spherical $Al_2O_3$ particles with a diameter of 56 nm were employed in an experiment by [20]. The maximum thermal resistance was lowered 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 present utilization of heat pipe technology has substantially evolved owing to heat pipes being lowered in size. The American and Japanese heat pipe manufacturers have researched heat pipes, even with a diameter of 2 mm, for cooling the laptop PC and CPU.

The little heat pipe has demonstrated a remarkable impact when used to spread heat and maintain computers and other electrical devices at a steady temperature. Therefore, a comprehensive examination is important for the tiny heat pipe's continued development and performance enhancement.

Using a full-sized PHP, this post will first analyze some experimental data. The implications of fluid and tube diameters, as well as orientation, will gain special focus. 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.[3]

# Chapter 3

## Experimental set-up and test procedure

Usually, components are necessary. The following are some conditions for operating a CPL:

**Evaporator:** The section of the CPL where heat is delivered is the evaporator. Usually, thermal energy is generated by a heated surface or component. The working fluid evaporates with the assistance of the evaporator, initiating the heat transfer process.

**Condenser:** The condenser releases the heat that the evaporator's working fluid has absorbed. It is often positioned in a cooler region of the CPL and aids with vapor condensation, spreading heat into the surroundings.

**Capillary Structure:** A CPL's capillary structure is crucial because it enables the working fluid to flow freely throughout the loop. It contains small capillaries or channels that promote capillary action, which permits the fluid to flow against gravity. The CPL's capillary structure aids in sustaining continuous circulation.

**Working Fluid:** This fluid changes phases from liquid to vapor to liquid again, filling the closed-loop system. Working fluids that are usually utilized in CPLs include alcohol, water, or their mixes. The essential operating temperature range, heat transfer effectiveness, and system compatibility are only a few of the elements affecting the working fluid choice.

The closed-loop pulsing heat pipe is manufactured utilizing pipes or tubes composed of a thermally conductive material, such as copper or aluminum. The pipes unite the evaporator and condenser components to make a closed circuit or network. In addition, they offer a pathway for the working fluid, helping heat transfer between various sections of the CPL.

**Heat Source:** A heat source is needed to supply the evaporator section with the appropriate thermal energy. This may contain an indirect heat transfer from a separate component or a direct heat input from an external source.

Insulating: To reduce heat loss from the CPL system and maintain a more effective heat transfer mechanism, insulating material may be applied. Insulation is generally put on the CPL's outside surfaces to reduce heat losses to the surroundings.

## 1.9 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
    - K Type thermocouple

Table 1 Working apparatus.

| **Working fluid** | **Test stand** | **Insulating apparatus** |
|---|---|---|
| Ethanol<br>Methanol<br>Ethylene glycol | **Heating apparatus**<br>Variac.<br>Power Supply Unit.<br>Nichrome Wire<br>EPE Insulation foam | Mica tape<br>Glass wool<br>Foam tape |

## 1.10 Description of Different types of Apparatus

## 1.11 Working Fluid

### 1.11.1 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 (postmercury) 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 |

### 1.11.2 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, 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 3 Methanol properties

| SL. No. | Parameters | Symbol | Quantity | Unit |
|---|---|---|---|---|
| 1. | Freezing temperature | $T_{freeze}$ | -97.6 | °C |
| 2. | Boiling temperature | $T_{boil}$ | 64.7 | °C |
| 3. | Density | P | 792 | kg/m³ |
| 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 |

### 1.11.3 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 4 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 |

| SL. No. | Parameters | Symbol | Quantity | Unit |
|---|---|---|---|---|
| 5. | Vapor pressure | Pv | 0.9337 | kPa |
| 6. | Molar mass | Ms | 62.07 | g/mol |

### 1.12 Experiment Set-up

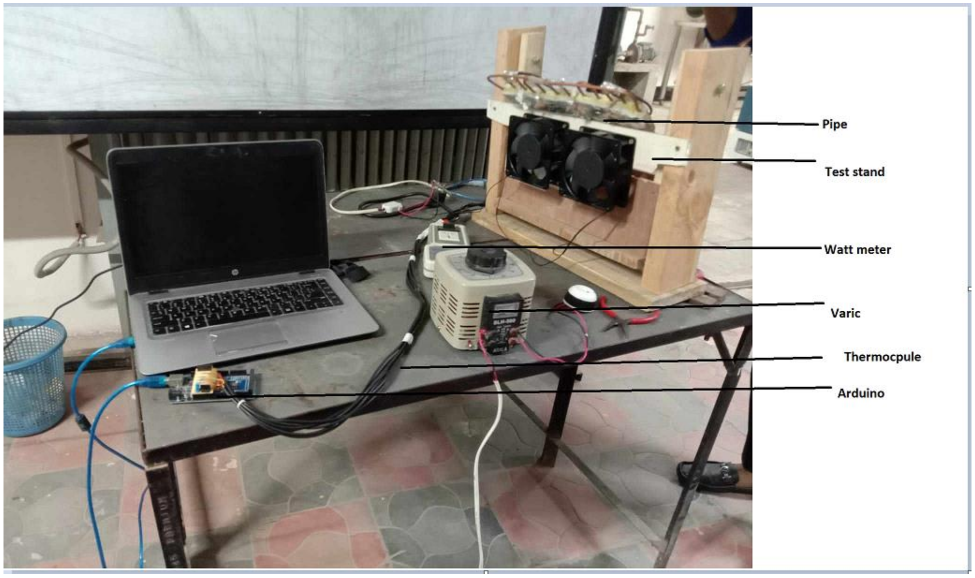


Figure 0-1 Experiment Set-up

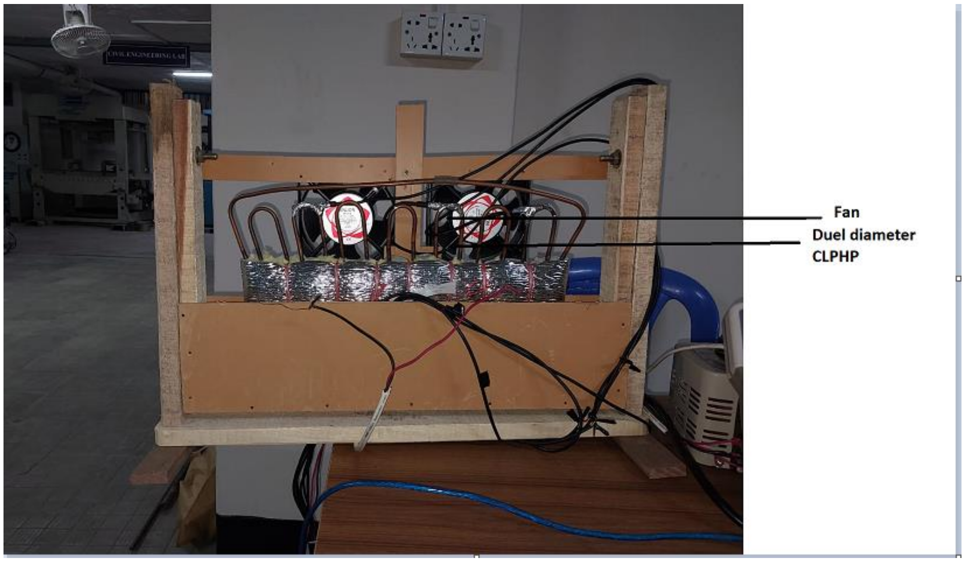


Figure 0-2 Test Stand with Apparatus

Table 5 Pipe Schematic Information

| **Parameters** | **Condition** |
|---|---|
| Length of evaporator section | 50mm (1.87 inner diameter) |
| Length of adiabatic section | 100 mm (1.87 inner diameter) |
| Length of condenser section | 40 mm (2.87 inner diameter) |
| Material | copper |
| Turn | 8 |
| Distance Between two pipes | 20mm |


Figure 3 Dual diameter pipe view

## 1.13 Experimental Methodology

The experiment intends to evaluate the thermal performance of a closed loop pulsing heat pipe (CLPHP) at two different loading ratios - 50% and 60%. The CLPHP is heated at the evaporator part using a Nichrome wire coiled uniformly around it, controlled by a variable voltage supply using a wattmeter. Temperatures are monitored throughout the CLPHP length using thermocouples coupled to a data recorder.

The working fluid is filled to 50% of CLPHP capacity, and heat input is changed from 10W to 60W in stages, leaving ample time for a steady state before jotting down the data. This is repeated for a 60% filling ratio. The temperatures, pressures and flow rates at varied heat inputs are utilized to examine thermal performance and assess the best fill ratio and operating circumstances.

### 1.14 Working Procedure:

- Prepare the CLPHP by cleaning and sealing all components carefully. Install temperature sensors along the evaporator and condenser.
- Fill the CLPHP with methanol/ethanol to 50% of internal capacity (filling ratio 0.5).
- Insulate the evaporator portion with glass wool. Provide heating using a Nichrome wire coiled along the evaporator and link it to a variable voltage source using a wattmeter.
- Seal the adiabatic area with glass wool and thermocol insulation.
- Provide cooling in the condenser area using a fan. Further, insulate using tape.
- Connect the CLPHP setup to the data recording system to capture temperatures, pressures, and flow rates.
- Start with a heat input of 10W and steadily raise it to 60W in increments, leaving adequate time for a steady state at each step.
- Record temperatures and flow rate data once a steady state is established at each heat input.
- After finishing the experiment at 50% filling ratio, drain the CLPHP and refill with working fluid to 60% of the internal capacity.

### 1.15 Precaution

The following criteria were evaluated during the experiment: All other sources obstructing heat transmission were switched off during the operation. Before measuring the temperature, the sensor (K-type sensors) employed in the experiment must be properly inspected. The fluid injection must be exact, as the fill ratio impacts the heat pipe's performance. Only when a temperature achieves a stable state, or a constant value can measurements be done. Since condenser condensation could sometimes result in leaks, the silicon tube should always be properly sealed. CLPHP: Trying to blow the liquid out of your mouth is never a brilliant idea. If you do, blisters will grow on your lips. Sealing Methods Efficient sealing solutions are necessary to stop pressure leakage in CLPHPs. High-quality seals or joints should be applied to connect different heat pipe sections, such as the evaporator, condenser, and various loop segments. The seals must be robust enough to endure the operating pressures and temperature fluctuations found within the system.

# Chapter 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.

### 1.16 Steady Condition of All Data

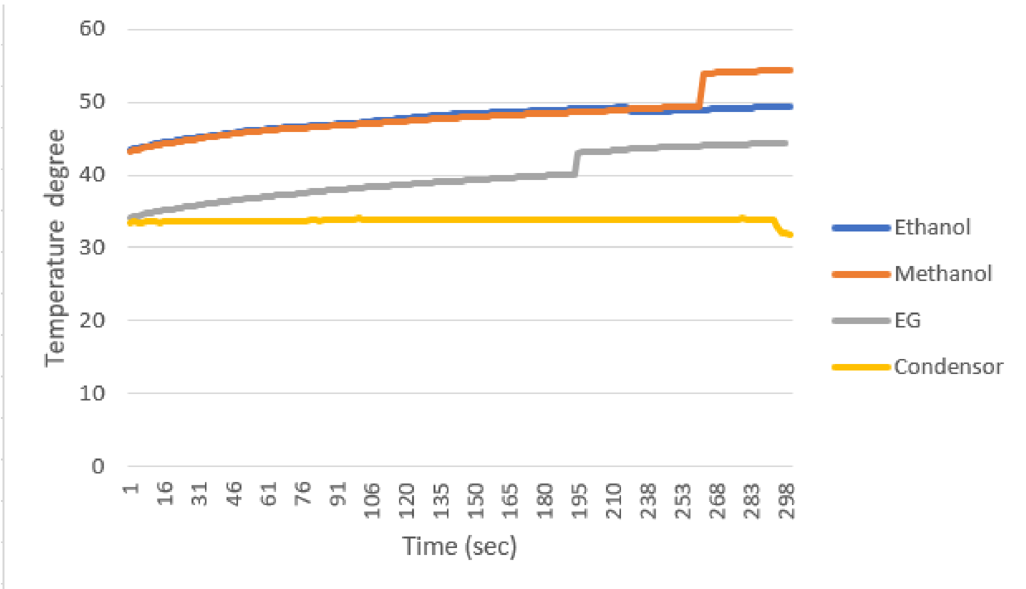


Figure 0-1 Heat vs Second Steady condition data

This graph indicates that a stable condition is achieved in our experiment. To evaluate the behaviour of the CLPHP, data gathering requires monitoring various parameters, including temperature, pressure, flow rate, and heat transfer coefficient. Ensuring the equipment is stable before taking any measurements is critical to gathering accurate and exact data. Achieving a steady state in a CLPHP means that the flow rate, temperature, and pressure of the working fluid have stabilized and that there has been minimal variation over time. Consequently, the heat transfer process is more predictable, and the device's performance is more straightforward to examine while the CLPHP is steady. Consistent and trustworthy data may be produced when the CLPHP is not in a stable condition during data collection. For instance, acquiring exact and essential data might be problematic due to the considerable changes in the measured temperatures, pressures, and flow rates. A steady state must be generated and maintained to gather data in a closed-loop pulsing heat pipe.

## 1.17 Ethanol

### 1.17.1 50% filling ratio

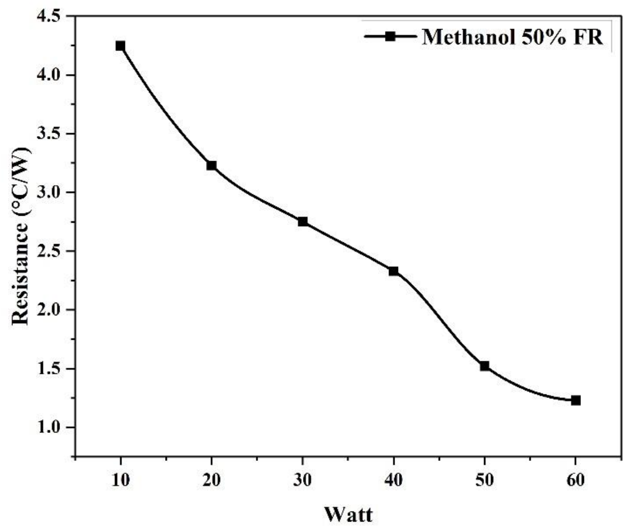


Figure 0-2 Thermal resistance vs heat input (Watt) 50% FR Ethanol

Below is an examination of the graph of thermal resistance vs power for a closed loop pulsing heat pipe dual diameter with a 50% filling ratio:

As the power grows from 10W to 60W, the thermal resistance reduces. This suggests that the heat pipe is more effective at transmitting heat at more significant power inputs.

There is a substantial fall in thermal resistance from 10W to 30W, with the resistance reducing from 3.06 to 2.5. This shows there is a considerable increase in performance in this power range.

From 30W to 60W, the drop in thermal resistance begins to taper off, decreasing from 2.5 at 30W to 1.43 at 60W. This means the heat pipe is beginning to exceed its practical limitations for transporting heat at the 50% filled ratio.

Based on the pattern, we may anticipate the thermal resistance to continue falling, albeit slower and slower, as the power rose above 60W.

The lowest thermal resistance obtained is 1.43 at the most significant power level of 60W. This is the best heat transfer capability observed for this heat pipe design and fluid filling arrangement.

The graph indicates that increasing the input power increases considerably in lowering thermal resistance up to 30W, with declining but still noticeable benefits up to 60W and perhaps beyond. The 50% fluid filling ratio looks effective, particularly at higher power levels over 40-50W.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.

### 1.17.2 60% filling ratio

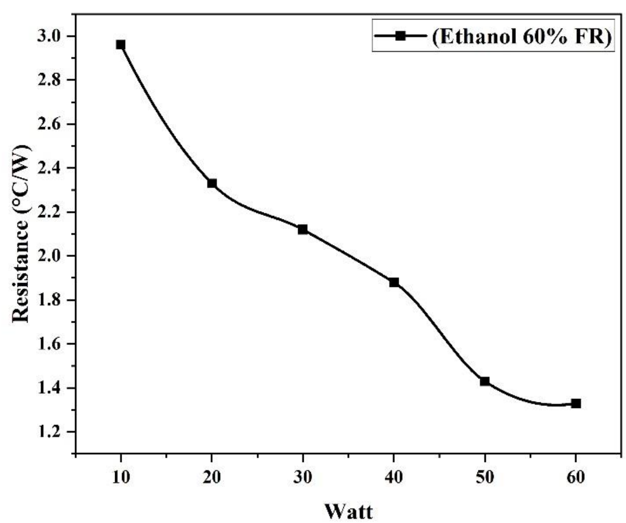


Figure 0-3 Thermal resistance vs heat input (Watt) 60% FR Ethanol

Based on the additional data points, here is a revised analysis:

As previously, there is a diminishing trend in thermal resistance as power rises from 10W to 60W. This demonstrates that increased power levels result in better heat transfer capabilities. Specifically, the thermal resistance lowers from 2.96 at 10W to 1.33 at 60W. That is nearly a 55% decrease throughout this power spectrum. The resistance reduction rate does fall somewhat as power rises, but not as substantially as the first data set showed. The sharpest drop is noted in the 10W to 30W range. Resistance lowers over 34% from 2.96 to 1.96 in this portion. From 30W to 60W, the drop-off is less dramatic but still considerable at roughly 30% (from 2.12 to 1.33). This shows the heat pipe continues to demonstrate considerable increases in heat transfer efficiency even up to more significant power inputs with this 50% fluid filling arrangement.

Although the performance advantages fall off at higher powers, the heat pipe can efficiently use greater power to minimize thermal resistance over the tested 10W to 60W range. Based on the pattern, there may be future increases at powers over 60W.

### 1.17.3 Compare Ethanol all.

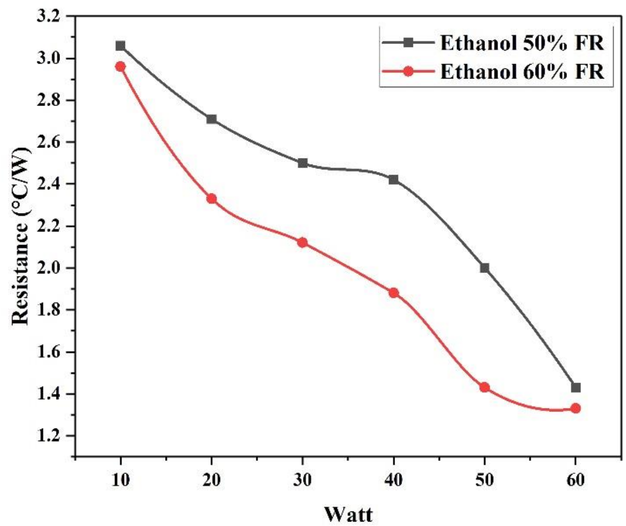


Figure 0-4 Thermal resistance vs Heat input (Watt) Ethanol all

Here is a comparison study and conclusion based on the two data sets:

Comparing the two data sets, the general pattern of decreasing thermal resistance with increased power is constant. However, the earlier data set revealed a steeper fall in the improvement rate after 30W, whereas the second set exhibits a more progressive tapering off in resistance reduction up to 60W.

Specifically, in the first data, the resistance reduced from 3.06 at 10W to 2.5 at 30W, an 18.3% decline. From 30W to 60W, the decline was substantially less - from 2.5 to 1.43, a 12.8% reduction.

However, the second set shows a 32.4% reduction from 2.96 at 10W to 1.96 at 30W, followed by a 28.6% drop from 1.96 to 1.33 as power climbed from 30W to 60W.

The new data reveals more consistent and considerable heat transfer efficiency increases over the tested 10W to 60W power range. The heat pipe continues to exhibit the capacity to employ more significant power levels to yield considerably reduced thermal resistance, with a 55% drop from 2.96 at 10W to 1.33 at 60W.

Based on the new data, this specific heat pipe design and working fluid fill ratio of 50% may effectively exploit increased power inputs to enhance heat dissipation performance throughout a broad range. The falling off in resistance reduction is more gradual, enabling more oversized heat loads to be controlled successfully. Further testing over 60W would indicate whether this pattern persists at even higher power levels.

## 1.18 Methanol

### 1.18.1 50% filling ratio

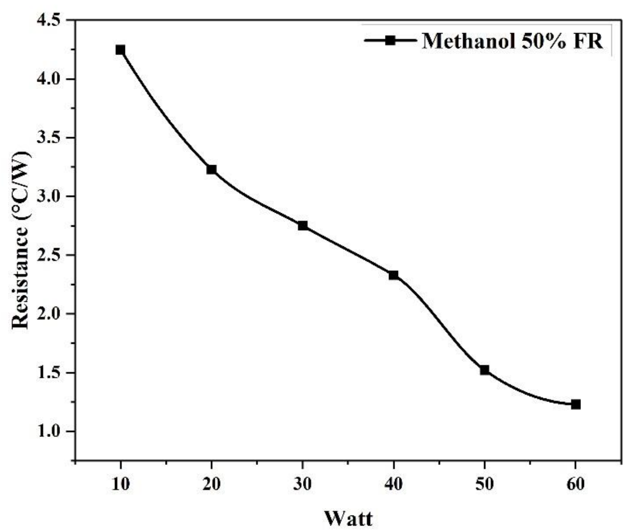


Figure 0-5 Thermal resistance vs heat input (watt) FR 50% position Methanol

Here is a study of the closed loop pulsing heat pipe with 50% methanol filling:

Once again, we witness the thermal resistance reducing as the power input rises from 10W to 60W. Using methanol results in more excellent total thermal resistance ratings.

The resistance drops from 4.25 at 10W to 1.23 at 60W. This is nearly a 70% decline, showing tremendous advances in heat transfer efficiency with increased power.

The most striking drop is from 50W to 60W, with resistance reducing from 1.52 to 1.23 - roughly a 19% decrease.

In the 10W to 40W zone, the resistance gradually reduces at a consistent pace of approximately 18-25%. This shows that employing methanol as the working fluid hinders performance marginally across lower power levels compared to earlier data sets.

However, with more significant power inputs of 50W-60W, the methanol-based arrangement shows substantial benefits, eventually outperforming preceding setups in heat transfer capabilities.

A 50% methanol-filled pulsing heat pipe arrangement needs more significant power inputs to optimize its heat transfer capability. However, based on the presented data, it can equal or outperform the performance of other choices at 50W and above. Further testing over 60W might reveal optimum operating settings.

### 1.18.2 60% filling ratio

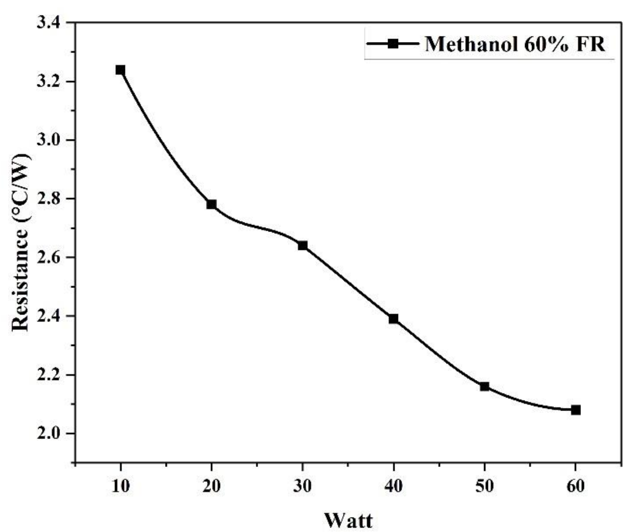


Figure 0-6 Thermal resistance vs heat input (Watt) methanol FR 60%

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.

### 1.18.3 Methanol compares.

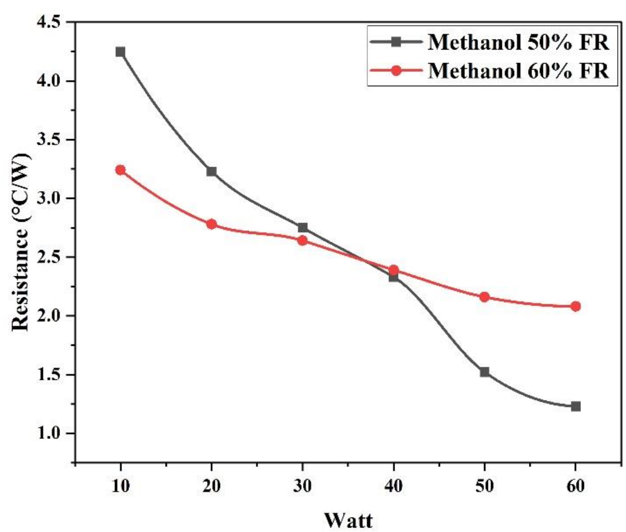


Figure 0-7 Thermal resistance vs heat input (watt) Methanol all

Both observe the general lowering thermal resistance with increasing power input from 10W to 60W, showing enhanced heat transfer capabilities. The first study reveals a tapering off increases above 30W, whereas the second suggests more continuous improvements up to 60W. The first covers ideal methanol performance at 50W+ levels, whereas the second does not compare working fluids. Only the second study reveals 30W and 40W as probable transition points in the performance curve. While the two studies exhibit similar general patterns about the negative connection between input power and thermal resistance, the second study adds more detailed technical insights. It measures the decreases in thermal resistance along the power range, indicating a 70% drop from 10W to 60W. This underlines the considerable advantages gained. It emphasizes that the most significant decrease occurs between 50W and 60W (19%), offering a more nuanced assessment. It compares the methanol results to earlier working fluids, illustrating the relative underperformance at low power inputs but advantages above 50W. It determines probable ideal operating locations at 30W and 40W power levels based on variations in the slope of the performance curve. Whilst both methods accurately depict the increase in heat transfer efficiency with increasing input power, the second study gives more detailed quantitative evaluations of the decreases in thermal resistance. It directly compares performance across working fluids and power levels. This permits the extraction of more precise ideal operating conditions.

## 1.19 Ethylene glycol

### 1.19.1 50% Filling ratio

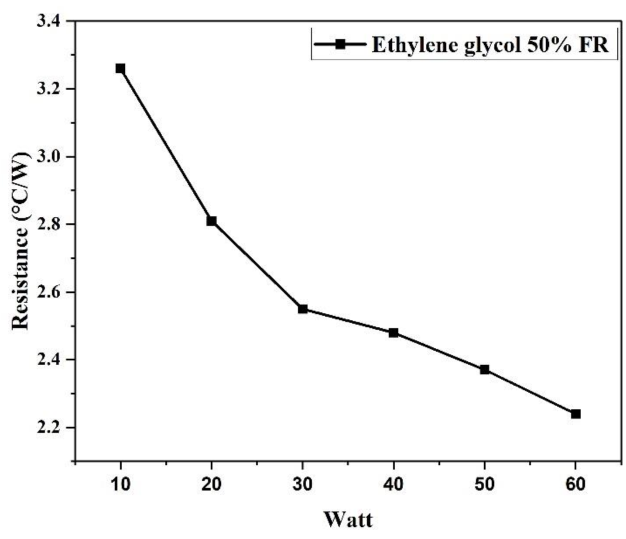


Figure 8 Thermal resistance vs heat input (Watt) Ethylene glycol FR 50%

Here is a concise analysis of the thermal performance graph for the closed loop pulsating heat pipe with 60% ethylene glycol filling: As observed previously, thermal resistance reduces as power input rises from 10W to 60W, indicating better heat transfer at higher powers.

Resistance declines from 3.26 at 10W to 2.24 at 60W, showing a 31% drop across the range. This signals good improvement.

The steepest descent is in the 10W to 30W band, with resistance falling by 22%. This suggests that the most significant gains come from lower powers. Beyond 40W, the slope flattens noticeably, with only a 9% decrease from 40W to 60W. This implies diminishing enhancements at higher inputs.

At the 60% ethylene glycol fill ratio, maximum heat transfer potential peaks between 50W and 60W based on the trend flattening.

Increasing power assists heat transfer initially, but benefits taper off after 40W. The resistance trend points to peak thermal performance in the 50-60W input range with the 60% ethylene glycol configuration.

### 1.19.2 60% Filling ratio

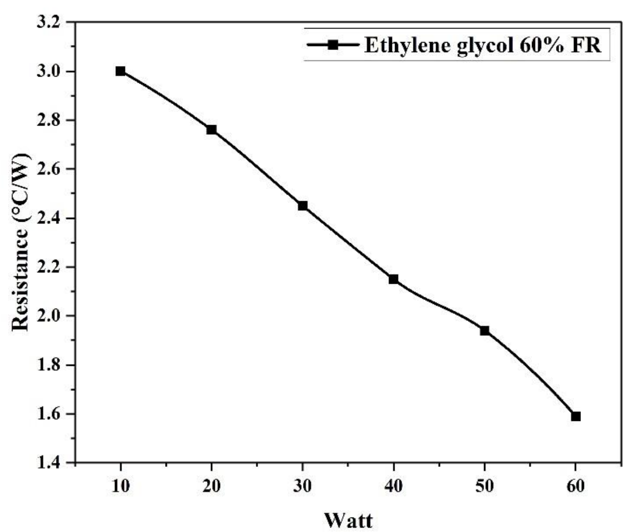


Figure 9 Thermal resistance vs heat input (Watt) Ethylene glycol FR 60%

Here is a concise analysis of the thermal resistance vs heat input graph for the closed loop pulsating heat pipe with 60% ethylene glycol filling ratio:

Thermal resistance reduces considerably from 3 at 10W to 1.59 at 60W as power rises, a 47% decrease. This signifies substantial improvements in heat transfer.

The slope is steepest between 10W and 30W, with resistance dropping by 18%. This implies that the most significant gains in efficiency occur in the lower power range.

Beyond 30W, the reduction rate begins to taper off, falling 14% from 30W to 60W. This suggests incremental benefits start diminishing at higher inputs.

At 60W input, the thermal resistance levels off at 1.59, likely indicating the maximum heat transfer potential for the 60% ethylene glycol configuration.

Increasing power input results in considerably reduced thermal resistance and better dissipation. However, gains above 30W start diminishing, with peak efficiency reached at the 60W point based on trend flattening.

### 1.19.3 Compare Ethylene glycol.

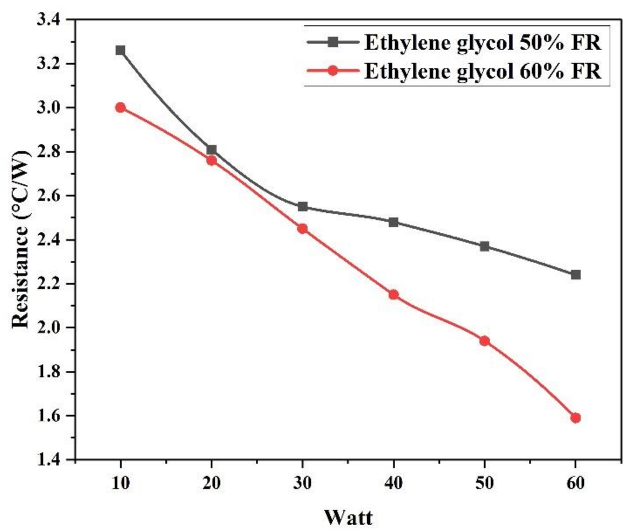


Figure 10 Thermal resistance vs heat input (watt) Ethylene glycol all

Here is a concise analysis of the thermal resistance vs heat input graph for the closed loop pulsating heat pipe with 60% ethylene glycol filling ratio:

Thermal resistance reduces considerably from 3 at 10W to 1.59 at 60W as power rises, a 47% decrease. This signifies substantial improvements in heat transfer.

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Increasing power input results in considerably reduced thermal resistance and better dissipation. However, gains above 30W start diminishing, with peak efficiency reached at the 60W point based on trend flattening.

### 1.20 Comparison all data

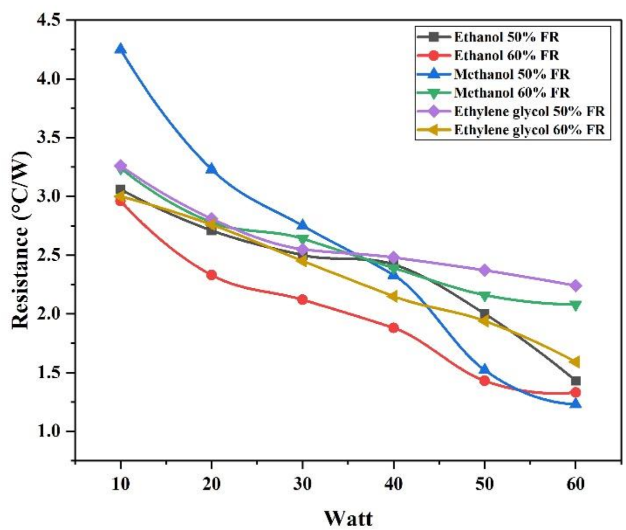


Figure 11 Thermal resistance Vs Watt all FR ratio comparison

Here is a combined analysis incorporating the key findings:

**Working Fluid Comparison**

The methanol (50% fill) configuration achieves superior peak heat transfer capabilities, evidenced by the lowest thermal resistance of 1.23 at 60W input power. It also demonstrates the highest relative improvement from 10W to 60W - over a 70% drop in resistance.

Meanwhile, the ethylene glycol (60%) fill shows lower absolute resistance values across most power inputs, with a 47% reduction from 10W to 60W. It also optimizes performance in the 10-30W range based on its steeper slope.

These tradeoffs indicate ethylene glycol works better for lower power applications, while methanol is advantageous for dissipating high heat loads. This confirms proper working fluid selection depends on the target operating range.

**Dual Diameter Closed Loop Design**

The decreasing thermal resistance from 10W to 60W input power signifies the dual diameter pulsating structure spreads heat effectively at higher loads.

The taper in resistance reduction after 40W suggests the dual configuration reaches its heat transfer capacity threshold around 50-60W. But a 55% resistance decrease is still achieved up to the 60W point.

The steepest slope in the 10-30W range points to the greatest efficiency gains at lower inputs. This aligns with the ethylene glycol fluid performance range.

In summary, adopting a dual diameter closed loop enables substantial heat transfer improvements from 10W up to 60W power, with the flexibility to optimize working fluids based on expected load levels. Further testing beyond 60W would reveal the ultimate potential.

# Chapter 5

## 2 Conclusions

Based on all the facts and studies offered, below is an enlarged consolidated conclusion on the closed-loop pulsing heat pipe performance:

Working Fluids Comparison: Testing demonstrated a performance hierarchy across the working fluids:

Methanol provided the greatest overall resistance decline from 10W to 60W of almost 70%, combined with the lowest peak resistance of 1.23 at 60W. It optimized high heat flux circumstances.

Ethanol displayed high resistance but had a reasonably constant 55% drop from 10W to 60W. Its performance profile was in between methanol and ethylene glycol.

Ethylene glycol gave the best resistance under 30W power, with its steeper slope in that range. However, its overall decline by 60W was just 47%, and resistance tapered off. It was best appropriate for low-medium heat loads.

Closed Loop Design Benefits: The constant decrease of thermal resistance from 10W up to 60W verifies that the two-diameter loop arrangement helped disperse heat efficiently at increasingly more significant inputs without drying out.

The absence of any observed dry-out implies the dual diameters boosted internal liquid/vapour circulation and surface tension, allowing smooth, continuous operation.

Optimal Configuration: The methanol fluid paired with the dual-diameter closed loop construction gave the most significant benefits - over 70% resistance decrease and no tapering trend through 60W.

This combination is suitable for high heat flux circumstances up to at least 60W, with the theoretical ability to disperse even higher loads. It successfully exploits the dual diameter looping to increase methanol's thermal efficiency.

In summary, using a closed loop dual diameter pulsing heat pipe with methanol working fluid delivers good resistance reductions throughout a wide power range. It also provides customizable adjustment between peak performance and low-medium load economy.

# References

[1] Mr. M. A. ul Haque, Dr. M. Azizuddin, and Mr. M. K. Rehman, “CFD and Volume Fraction Analysis of Closed Loop Pulsating Heat Pipe (CLPHP),” *IOSR Journal of Mechanical and Civil Engineering*, vol. 13, no. 05, pp. 88–94, May 2016, doi: 10.9790/1684-1305048894.

[2] H. Yang, S. Khandekar, and M. Groll, “Operational limit of closed loop pulsating heat pipes,” *Appl Therm Eng*, vol. 28, no. 1, pp. 49–59, Jan. 2008, doi: 10.1016/J.APPLTHERMALENG.2007.01.033.

[3] P. Khalilmoghadam, A. Rajabi-Ghahnavieh, and M. B. Shafii, “A novel energy storage system for latent heat recovery in solar still using phase change material and pulsating heat pipe,” *Renew Energy*, vol. 163, pp. 2115–2127, Jan. 2021, doi: 10.1016/J.RENENE.2020.10.073.

[4] Mr. M. A. ul Haque, Dr. M. Azizuddin, and Mr. M. K. Rehman, “CFD and Volume Fraction Analysis of Closed Loop Pulsating Heat Pipe (CLPHP),” *IOSR Journal of Mechanical and Civil Engineering*, vol. 13, no. 05, pp. 88–94, May 2016, doi: 10.9790/1684-1305048894.

[5] H. Yang, S. Khandekar, and M. Groll, “Operational limit of closed loop pulsating heat pipes,” *Appl Therm Eng*, vol. 28, no. 1, pp. 49–59, Jan. 2008, doi: 10.1016/J.APPLTHERMALENG.2007.01.033.

[6] A. Faghri, “Review and advances in heat pipe science and technology,” *J Heat Transfer*, vol. 134, no. 12, Dec. 2012, doi: 10.1115/1.4007407/365832.

[7] *Author index*. in ITHERM 2000. The Seventh Intersociety Conference on Thermal and Thermomechanical Phenomena in Electronic Systems (Cat. No.00CH37069). Institute of Electrical and Electronics Engineers (IEEE), 2000. doi: 10.1109/ITHERM.2000.866221.

[8] J. Qu and H. Wu, “Silicon-based micro pulsating heat pipe for cooling electronics,” *Adv Mat Res*, vol. 403–408, pp. 4260–4265, 2012, doi: 10.4028/WWW.SCIENTIFIC.NET/AMR.403-408.4260.

[9] S. Khandekar, M. Groll, P. Charoensawan, P. Terdtoon, and ¡¢¤£¦¥¨), “Pulsating Heat Pipes: Thermo-fluidic Characteristics and Comparative Study with Single Phase Thermosyphon.”

[10] R. Naik, L. Pinto, K. Rama Narasimhak, and G. Pundarika, “Theoretical studies on the application of pulsating heat pipe in vapour compression refrigeration system,” *Applied Mechanics and Materials*, vol. 592–594, pp. 1801–1806, 2014, doi: 10.4028/WWW.SCIENTIFIC.NET/AMM.592-594.1801.

[11] F. Mobadersani, S. Jafarmadar, and A. Rezavand, “Modeling of A Single Turn Pulsating Heat Pipe based on Flow Boiling and Condensation Phenomena,” *International Journal of Engineering*, vol. 32, no. 4, pp. 569–579, Apr. 2019, doi: 10.5829/IJE.2019.32.04A.15.

[12] J. S. Kim, N. H. Bui, J. W. Kim, J. H. Kim, and H. S. Jung, “Flow visualization of oscillation characteristics of liquid and vapor flow in the oscillating capillary tube heat pipe,” *KSME International Journal*, vol. 17, no. 10, pp. 1507–1519, 2003, doi: 10.1007/BF02982330/METRICS.

[13] S. Khandekar, “Thermo-hydrodynamics of closed loop pulsating heat pipes,” Feb. 2014, doi: 10.18419/OPUS-1637.

[14] S. Khandekar, P. Charoensawan, M. Groll, and P. Terdtoon, “Closed loop pulsating heat pipes - Part B: Visualization and semi-empirical modeling,” *Appl Therm Eng*, vol. 23, no. 16, pp. 2021–2033, Nov. 2003, doi: 10.1016/S1359-4311(03)00168-6.

[15] P. R. Pachghare and A. M. Mahalle, “THERMAL PERFORMANCE OF CLOSED LOOP PULSATING HEAT PIPE USING PURE AND BINARY WORKING FLUIDS,” *Frontiers in Heat Pipes*, vol. 3, no. 3, Jan. 2013, doi: 10.5098/FHP.V3.3.3002.

[16] M. B. Shafii, A. Faghri, and Y. Zhang, “Thermal Modeling of Unlooped and Looped Pulsating Heat Pipes,” *J Heat Transfer*, vol. 123, no. 6, pp. 1159–1172, Dec. 2001, doi: 10.1115/1.1409266.

[17] M. L. Rahman, T. Afrose, H. K. Tahmina, R. P. Rinky, and M. Ali, “Effect of using acetone and distilled water on the performance of open loop pulsating heat pipe (OLPHP) with

different filling ratios," *AIP Conf Proc*, vol. 1754, no. 1, p. 50015, Jul. 2016, doi: 10.1063/1.4958406/586918.

[18] Y. Sriudom, S. Rittidech, and T. Chompookham, "The Helical Oscillating Heat Pipe: Flow Pattern Behaviour Study," *https://doi.org/10.1155/2014/194374*, vol. 7, no. 1, Dec. 2014, doi: 10.1155/2014/194374.

[19] J. Choi and Y. Zhang, "Numerical simulation of oscillatory flow and heat transfer in pulsating heat pipes with multi-turns using OpenFOAM," *Numeri Heat Transf A Appl*, vol. 77, no. 8, pp. 761–781, Apr. 2020, doi: 10.1080/10407782.2020.1717202.

[20] P. Meena, S. Rittidech, and P. Tammasaeng, "Effect of Inner Diameter and Inclination Angles on Operation Limit of Closed-Loop Oscillating Heat-Pipes with Check Valves," *American Journal of Engineering and Applied Sciences*, vol. 1, no. 2, pp. 100–103, Jun. 2008, doi: 10.3844/AJEASSP.2008.100.103.

[21] H. Sayevand and R. Nemati, "Numerical Solution of the Effect of Increasing the Wall Temperature on Flow and Heat Transfer in Pulsating Heat Pipe," *Journal of Modeling in Engineering*, vol. 18, no. 60, pp. 13–25, May 2020, doi: 10.22075/JME.2019.15523.1542.

[22] B. Verma, V. L. Yadav, and K. K. Srivastava, "Experimental Studies on Thermal Performance of a Pulsating Heat Pipe with Methanol/DI Water," *Journal of Electronics Cooling and Thermal Control*, vol. 03, no. 01, pp. 27–34, 2013, doi: 10.4236/JECTC.2013.31004.

[23] T. Parametthanuwat, S. Rittidech, A. Pattiya, Y. Ding, and S. Witharana, "Application of silver nanofluid containing oleic acid surfactant in a thermosyphon economizer," *Nanoscale Res Lett*, vol. 6, no. 1, pp. 1–10, Apr. 2011, doi: 10.1186/1556-276X-6-315/FIGURES/11.

[24] J. Qu, H. ying Wu, and P. Cheng, "Thermal performance of an oscillating heat pipe with Al2O3-water nanofluids," *International Communications in Heat and Mass Transfer*, vol. 37, no. 2, pp. 111–115, Feb. 2010, doi: 10.1016/j.icheatmasstransfer.2009.10.001.

# Appendix

## Mathematical Equations and Calculations

### Calculation of filling Ratio

Let, V = Internal volume of the heat pipe

= 100% Fill Ratio

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

= $\frac{3.1416 \times 2.60_i^2 \times \{(205+(2\times230)+(8\times210\}}{4}$ $\mathrm{mm}^2$

=17220 $mm^2$

≈17.20 ml

= 17.20 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 sheet**

50% Ethanol

| Log Time(Sec) | Resistance | Watt |
|---|---|---|
| 601 | 3.06 | 10 |
| 601 | 2.71 | 20 |
| 601 | 2.5 | 30 |
| 600 | 2.42 | 40 |
| 601 | 2 | 50 |
| 600 | 1.43 | 60 |

60% Ethanol

| Log Time(Sec) | Resistance | Watt |
|---|---|---|
| 601 | 2.96 | 10 |
| 601 | 2.33 | 20 |
| 601 | 2.12 | 30 |
| 600 | 1.88 | 40 |
| 601 | 1.43 | 50 |
| 600 | 1.33 | 60 |

60% Methanol

| Log Time(Sec) | Resistance | Watt |
|---|---|---|
| 601 | 3.24 | 10 |
| 601 | 2.78 | 20 |
| 601 | 2.64 | 30 |
| 600 | 2.39 | 40 |
| 601 | 2.16 | 50 |
| 600 | 2.08 | 60 |

Ethylene glycol 50%

| 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 |

Ethylene glycol 60%

| 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 |

| Sec | Evaporator | Evaporator | Evaporator | Condensor |
|---|---|---|---|---|
| 1 | 43.41 | 43.22 | 34.11 | 33.49 |
| 3 | 43.55 | 43.36 | 34.25 | 33.63 |
| 5 | 43.7 | 43.51 | 34.4 | 33.48 |
| 7 | 43.85 | 43.66 | 34.55 | 33.5 |
| 9 | 43.99 | 43.8 | 34.69 | 33.54 |
| 10 | 44.09 | 43.9 | 34.79 | 33.52 |
| 12 | 44.24 | 44.05 | 34.94 | 33.52 |
| 14 | 44.36 | 44.17 | 35.06 | 33.5 |
| 16 | 44.47 | 44.28 | 35.17 | 33.54 |
| 18 | 44.55 | 44.36 | 35.25 | 33.56 |
| 20 | 44.63 | 44.44 | 35.33 | 33.52 |
| 22 | 44.74 | 44.55 | 35.44 | 33.58 |
| 23 | 44.84 | 44.65 | 35.54 | 33.56 |
| 25 | 44.96 | 44.77 | 35.66 | 33.6 |
| 27 | 45.01 | 44.82 | 35.71 | 33.56 |
| 29 | 45.09 | 44.9 | 35.79 | 33.6 |
| 31 | 45.17 | 44.98 | 35.87 | 33.56 |
| 33 | 45.28 | 45.09 | 35.98 | 33.6 |
| 35 | 45.36 | 45.17 | 36.06 | 33.58 |
| 37 | 45.41 | 45.22 | 36.11 | 33.62 |
| 38 | 45.51 | 45.32 | 36.21 | 33.62 |
| 40 | 45.57 | 45.38 | 36.27 | 33.64 |
| 42 | 45.63 | 45.44 | 36.33 | 33.64 |
| 44 | 45.72 | 45.53 | 36.42 | 33.62 |
| 46 | 45.82 | 45.63 | 36.52 | 33.64 |
| 48 | 45.86 | 45.67 | 36.56 | 33.66 |
| 50 | 45.92 | 45.73 | 36.62 | 33.64 |
| 51 | 46.17 | 45.98 | 36.87 | 33.71 |
| 53 | 46.07 | 45.88 | 36.77 | 33.69 |
| 55 | 46.13 | 45.94 | 36.83 | 33.69 |
| 57 | 46.22 | 46.03 | 36.92 | 33.69 |
| 59 | 46.28 | 46.09 | 36.98 | 33.71 |
| 61 | 46.34 | 46.15 | 37.04 | 33.71 |
| 63 | 46.38 | 46.19 | 37.08 | 33.71 |
| 64 | 46.47 | 46.28 | 37.17 | 33.71 |
| 66 | 46.49 | 46.3 | 37.19 | 33.73 |
| 68 | 46.55 | 46.36 | 37.25 | 33.71 |
| 70 | 46.55 | 46.36 | 37.31 | 33.71 |
| 72 | 46.59 | 46.4 | 37.39 | 33.71 |

| Sec | Evaporator | Evaporator | Evaporator | Condenser |
|---|---|---|---|---|
| 74 | 46.62 | 46.43 | 37.48 | 33.73 |
| 76 | 46.66 | 46.47 | 37.5 | 33.73 |
| 78 | 46.7 | 46.51 | 37.58 | 33.71 |
| 79 | 46.74 | 46.55 | 37.62 | 33.75 |
| 81 | 46.78 | 46.59 | 37.69 | 33.75 |
| 83 | 46.82 | 46.63 | 37.75 | 33.73 |
| 85 | 46.86 | 46.67 | 37.79 | 33.75 |
| 87 | 46.9 | 46.71 | 37.85 | 33.77 |
| 89 | 46.94 | 46.75 | 37.91 | 33.77 |
| 91 | 46.98 | 46.79 | 37.95 | 33.77 |
| 92 | 47.02 | 46.83 | 37.98 | 33.77 |
| 94 | 47.06 | 46.87 | 38.06 | 33.79 |
| 96 | 47.1 | 46.91 | 38.1 | 33.79 |
| 98 | 47.17 | 46.95 | 38.16 | 33.79 |
| 100 | 47.19 | 46.99 | 38.23 | 34.12 |
| 102 | 47.27 | 47.06 | 38.27 | 33.77 |
| 104 | 47.31 | 47.08 | 38.31 | 33.79 |
| 106 | 47.38 | 47.16 | 38.35 | 33.79 |
| 107 | 47.44 | 47.16 | 38.39 | 33.79 |
| 109 | 47.48 | 47.19 | 38.43 | 33.81 |
| 111 | 47.54 | 47.22 | 38.47 | 33.81 |
| 113 | 47.6 | 47.26 | 38.51 | 33.81 |
| 115 | 47.64 | 47.3 | 38.55 | 33.79 |
| 117 | 47.67 | 47.34 | 38.59 | 33.79 |
| 119 | 47.75 | 47.38 | 38.63 | 33.79 |
| 120 | 47.79 | 47.42 | 38.71 | 33.79 |
| 122 | 47.85 | 47.46 | 38.75 | 33.81 |
| 124 | 47.92 | 47.5 | 38.79 | 33.79 |
| 126 | 47.99 | 47.54 | 38.83 | 33.79 |
| 128 | 48.05 | 47.58 | 38.85 | 33.81 |
| 130 | 48.08 | 47.62 | 38.91 | 33.79 |
| 132 | 48.14 | 47.66 | 38.93 | 33.83 |
| 133 | 48.18 | 47.68 | 39 | 33.81 |
| 135 | 48.26 | 47.71 | 39.02 | 33.81 |
| 137 | 48.26 | 47.75 | 39.1 | 33.83 |
| 139 | 48.28 | 47.79 | 39.1 | 33.83 |
| 141 | 48.34 | 47.83 | 39.13 | 33.83 |
| 143 | 48.38 | 47.87 | 39.16 | 33.83 |
| 145 | 48.38 | 47.91 | 39.2 | 33.87 |
| 147 | 48.42 | 47.95 | 39.24 | 33.81 |

| Sec | Evaporator | Evaporator | Evaporator | Condenser |
|---|---|---|---|---|
| 148 | 48.46 | 47.99 | 39.28 | 33.85 |
| 150 | 48.49 | 48.02 | 39.31 | 33.81 |
| 152 | 48.53 | 48.03 | 39.35 | 33.85 |
| 154 | 48.53 | 48.06 | 39.44 | 33.83 |
| 156 | 48.55 | 48.1 | 39.41 | 33.83 |
| 158 | 48.59 | 48.12 | 39.47 | 33.83 |
| 160 | 48.59 | 48.14 | 39.53 | 33.85 |
| 161 | 48.63 | 48.18 | 39.57 | 33.87 |
| 163 | 48.65 | 48.18 | 39.59 | 33.85 |
| 165 | 48.7 | 48.2 | 39.63 | 33.87 |
| 167 | 48.74 | 48.26 | 39.65 | 33.83 |
| 169 | 48.74 | 48.3 | 39.68 | 33.85 |
| 171 | 48.76 | 48.3 | 39.72 | 33.83 |
| 173 | 48.78 | 48.34 | 39.74 | 33.83 |
| 175 | 48.8 | 48.38 | 39.78 | 33.85 |
| 176 | 48.84 | 48.41 | 39.82 | 33.83 |
| 178 | 48.84 | 48.45 | 39.84 | 33.85 |
| 180 | 48.88 | 48.45 | 39.88 | 33.85 |
| 182 | 48.93 | 48.47 | 39.9 | 33.87 |
| 184 | 48.95 | 48.5 | 39.92 | 33.83 |
| 186 | 48.97 | 48.5 | 39.99 | 33.83 |
| 188 | 48.99 | 48.54 | 40.01 | 33.85 |
| 189 | 49.01 | 48.56 | 40.03 | 33.87 |
| 191 | 49.03 | 48.61 | 40.09 | 33.85 |
| 193 | 49.05 | 48.65 | 40.11 | 33.83 |
| 195 | 49.06 | 48.65 | 43.08 | 33.85 |
| 197 | 49.07 | 48.67 | 43.1 | 33.85 |
| 199 | 49.11 | 48.69 | 43.12 | 33.87 |
| 201 | 49.13 | 48.71 | 43.14 | 33.85 |
| 203 | 49.15 | 48.75 | 43.21 | 33.85 |
| 204 | 49.19 | 48.75 | 43.21 | 33.85 |
| 206 | 49.17 | 48.79 | 43.23 | 33.85 |
| 208 | 49.21 | 48.84 | 43.29 | 33.87 |
| 210 | 49.21 | 48.86 | 43.33 | 33.87 |
| 212 | 49.27 | 48.88 | 43.33 | 33.85 |
| 214 | 49.27 | 48.9 | 43.37 | 33.87 |
| 216 | 49.27 | 48.92 | 43.41 | 33.85 |
| 217 | 49.29 | 48.94 | 43.44 | 33.85 |
| 219 | 48.44 | 48.96 | 43.48 | 33.85 |
| 221 | 48.48 | 48.97 | 43.48 | 33.89 |

| Sec | Evaporator | Evaporator | Evaporator | Condenser |
|---|---|---|---|---|
| 223 | 48.48 | 48.98 | 43.5 | 33.87 |
| 225 | 48.5 | 49.02 | 43.54 | 33.85 |
| 227 | 48,54 | 49.04 | 43.54 | 33.89 |
| 229 | 48.54 | 49.06 | 43.58 | 33.89 |
| 231 | 48.58 | 49.1 | 43.6 | 33.85 |
| 232 | 48.6 | 49.08 | 43.65 | 33.89 |
| 234 | 48.65 | 49.12 | 43.69 | 33.91 |
| 236 | 48.69 | 49.12 | 43.69 | 33.89 |
| 238 | 48.69 | 49.16 | 43.71 | 33.87 |
| 240 | 48.71 | 49.16 | 43.73 | 33.89 |
| 242 | 48.73 | 49.2 | 43.75 | 33.87 |
| 244 | 48.75 | 49.23 | 43.79 | 33.89 |
| 245 | 48.79 | 49.25 | 43.79 | 33.89 |
| 247 | 48.79 | 49.29 | 43.83 | 33.89 |
| 249 | 48.83 | 49.27 | 43.88 | 33.87 |
| 251 | 48.88 | 49.31 | 43.9 | 33.9 |
| 253 | 48.9 | 49.31 | 43.92 | 33.9 |
| 255 | 48.92 | 49.37 | 43.94 | 33.91 |
| 257 | 48.94 | 49.37 | 43.96 | 33.89 |
| 258 | 48.96 | 49.37 | 43.98 | 33.89 |
| 260 | 48.98 | 49.39 | 44 | 33.91 |
| 262 | 49 | 54 | 44.01 | 33.89 |
| 264 | 49.01 | 54.01 | 44.02 | 33.89 |
| 266 | 49.02 | 54.02 | 44.06 | 33.91 |
| 268 | 49.06 | 54.06 | 44.08 | 33.91 |
| 270 | 49.08 | 54.08 | 44.1 | 33.91 |
| 272 | 49.1 | 54.1 | 44.14 | 33.91 |
| 273 | 49.14 | 54.14 | 44.14 | 33.91 |
| 275 | 49.14 | 54.14 | 44.17 | 33.91 |
| 277 | 49.17 | 54.17 | 44.17 | 33.91 |
| 279 | 49.17 | 54.17 | 44.19 | 33.98 |
| 281 | 49.19 | 54.19 | 44.23 | 33.93 |
| 283 | 49.23 | 54.23 | 44.25 | 33.93 |
| 285 | 49.25 | 54.25 | 44.29 | 33.91 |
| 286 | 49.29 | 54.29 | 44.27 | 33.95 |
| 288 | 49.27 | 54.27 | 44.31 | 33.91 |
| 290 | 49.31 | 54.31 | 44.31 | 33.93 |
| 292 | 49.31 | 54.31 | 44.37 | 33.95 |
| 294 | 49.37 | 54.37 | 44.37 | 33 |
| 296 | 49.37 | 54.37 | 44.37 | 31.93 |

| Sec | Evaporator | Evaporator | Evaporator | Condenser |
|---|---|---|---|---|
| 298 | 49.37 | 54.37 | 44.39 | 31.93 |
| 300 | 49.39 | 54.39 | | 31.89 |