Thermal performance of an aluminum closed loop pulsating heat pipe copper wire insert

Submitted By

Masfiqur Rahman Bhuiyan	**BME2001020083**
Gazi Mohaiminul Islam	**BME2001020253**
Sajal Chandra Howlader	**BME2001020586**
Mahmudul Hasan Tareq	**BME2001020129**
Md. Al-Amin	**BME1903019218**

DEPARTMENT OF MECHANICAL ENGINEERING
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Supervised By
Shahinur Rahman

Lecturer, Dept. of Mechanical Engineering Sonargaon University

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STUDENT DECLARATION

This is to certify that the thesis entitled, "**Thermal performance of an aluminum closed loop pulsating heat pipe with copper wire insert"** is an outcome of the investigation carried out by the author under the supervision of **Shahinur Rahman** 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.

SUBMITTED BY

Masfiqur Rahman Bhuiyan	Gazi Mohaminul Islam	Sajal Chandra Howlader
BME2001020083	BME2001020253	BME2001020586

Mahmudul Hasan Tareq	Md Al-Amin
BME2001020129	BME1903019218

APPROVED BY

Shahinur Rahman
Lecturer,

Department of Mechanical Engineering

Sonargaon University (SU)

Dhaka, Bangladesh

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The Authors

Department of Mechanical Engineering

Sonargaon University (SU)

Dhaka,

Bangladesh

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Dedication

To our parents and supervisor, with heartfelt appreciation.

Abstract

The Closed Loop Pulsating Heat Pipe (CLPHP), a device pivotal in thermal management systems, is scrutinized for its performance across varying filling ratios (50% and 60%) and with different working fluids: ethanol, methanol, ethylene glycol, and Acetone. Ethanol emerges as a superior working fluid, demonstrating robust heat transfer capabilities at both filling ratios, with optimal performance at 60% due to favorable phase change and pulsation dynamics. Methanol, while showing enhanced heat dissipation at a 60% ratio, runs the risk of premature dry-out, where the liquid phase fails to return to the evaporator a critical system limitation. Ethylene glycol's higher viscosity favors a 50% filling ratio, avoiding the suboptimal heat transfer that higher ratios incur. With its low boiling point and high thermal conductivity, Acetone excels particularly at 60%, maintaining lower thermal resistance without the dry-out issues prominent at lower fillings. In board-level applications, where spatial, gravitational, and integration considerations are paramount, the design of the CLPHP must adeptly navigate these constraints. Failures such as dry-out or thermal saturation, exacerbated by excessive heat input and poor fluid dynamics, highlight the need for a careful balance between thermal input and fluid properties. The study recommends advanced wick structures and precise fluid management in future CLPHP designs to enhance capillary action and efficiency. This comprehensive understanding is vital for optimizing CLPHP deployment in high-heat-flux applications, both existing and emergent, ensuring reliability and performance in demanding thermal environments.

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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 control method. They are especially effective in removing heat from electronics, aircraft systems, renewable energy sources, and other heat-producing parts. CLPHPs work on the premise that they may transfer heat across a closed loop circ using oscillatory flow patterns, phase change processes, and capillary action.

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

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

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

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

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

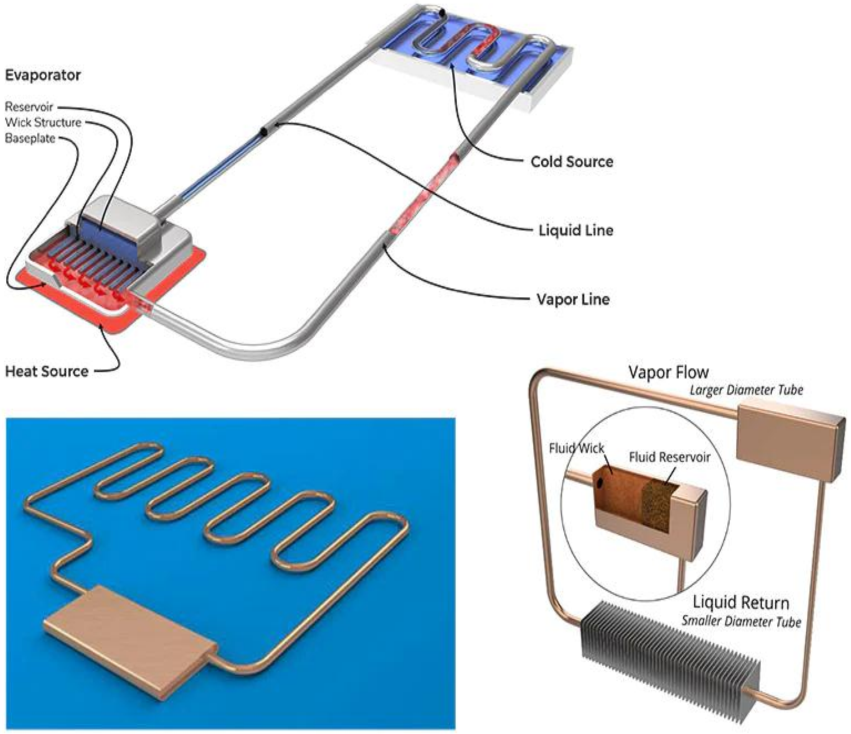

Figure 0-1 Real life application of CLPHP (https://www.tycorun.com/blogs/news/what-is-a-loop-heat-pipe)

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

The progress of closed-loop pulsing heat pipes has also facilitated the creation of novel variants and hybrid systems. Phase change materials, heat sinks, heat exchangers, thermoelectric devices, and other heat transfer technologies have all been investigated concerning CLPHP integration.

With the help of these hybrid systems, complicated thermal management situations' particular needs may be addressed while also broadening the operating range and improving overall thermal performance.

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

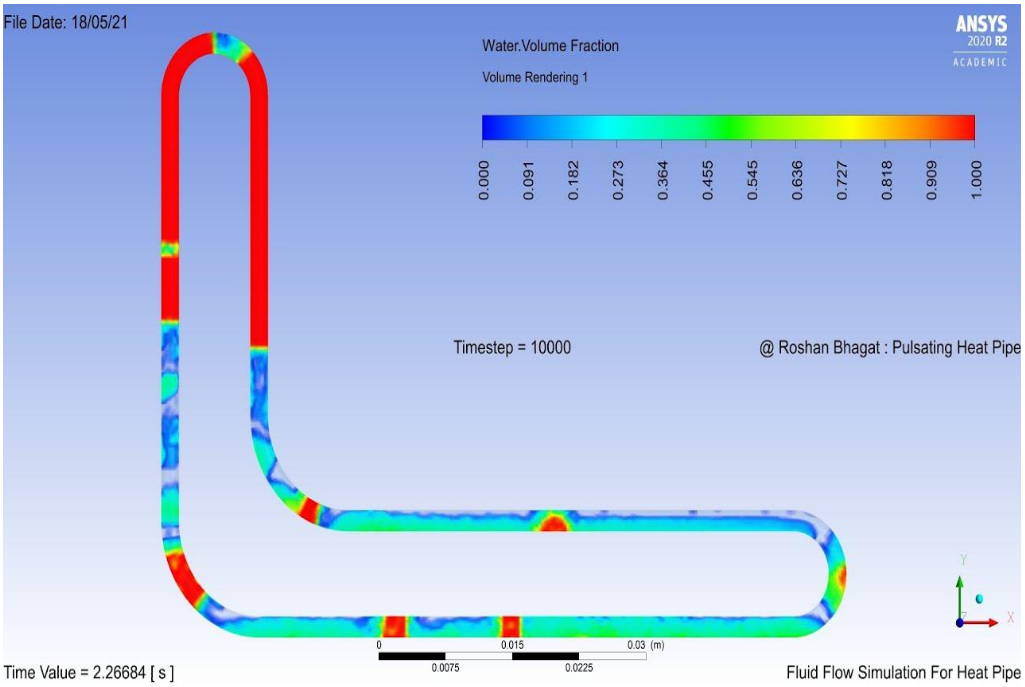

Figure 0-2 CFD Analysis of CLPHP [1]

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

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

Two basic configurations are often seen when considering how CLPHPs are oriented: 60 degree and 180-degree angles. The evaporator and condenser parts are positioned at the same height in 60-degree CLPHPs but below the condenser in 180-degree CLPHP each layout has unique benefits and difficulties regarding riding heat transfer efficiency, fluid distribution, and general system duties.

When a 60-degree surface is easily accessible for heat dissipation or when space is at a premium, 60-degree CLPHPs are an excellent choice. They have a small footprint and are often used in electronic cooling systems because they can fit into confined places in electronic equipment. Because the flow is unaffected by the system's orientation, 60-degree CLPHPs also provide improved resistance to gravitational influences. However, with 60-degree CLPHPs, maintaining uniform fluid distribution might be more difficult because gravity forces may prevent the working fluid from flowing freely.

180-degree CLPHPs, on the other hand, are beneficial in situations where forced or natural convection cooling is easily accessible. 180-degree CLPHPs may use gravity-driven flow to improve fluid circulation by placing the evaporator below the condenser. In order to ensure efficient heat transmission, this structure makes it possible to remove vapor bubbles from the evaporator portion more effectively. In applications like solar thermal systems, where heat may be quickly removed by forced air cooling or natural convection, 180-degree CLPHPs are often used.

Finally, closed-loop pulsing heat pipes provide a flexible and effective thermal management solution in various technical applications. They are very appealing for resolving issues with heat dissipation because of their quick and even heat transfer and self-regulating nature. Engineers may adapt their design to meet certain application needs by using CLPHPs, which provide special benefits and considerations in 60-degree 180-degree orientations. Advancements in electronic cooling, aeronautical systems, renewable energy, and other fields have been made possible by CLPHPs thanks to continued research and development.

1.1 Evolution of CLPHP

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

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

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

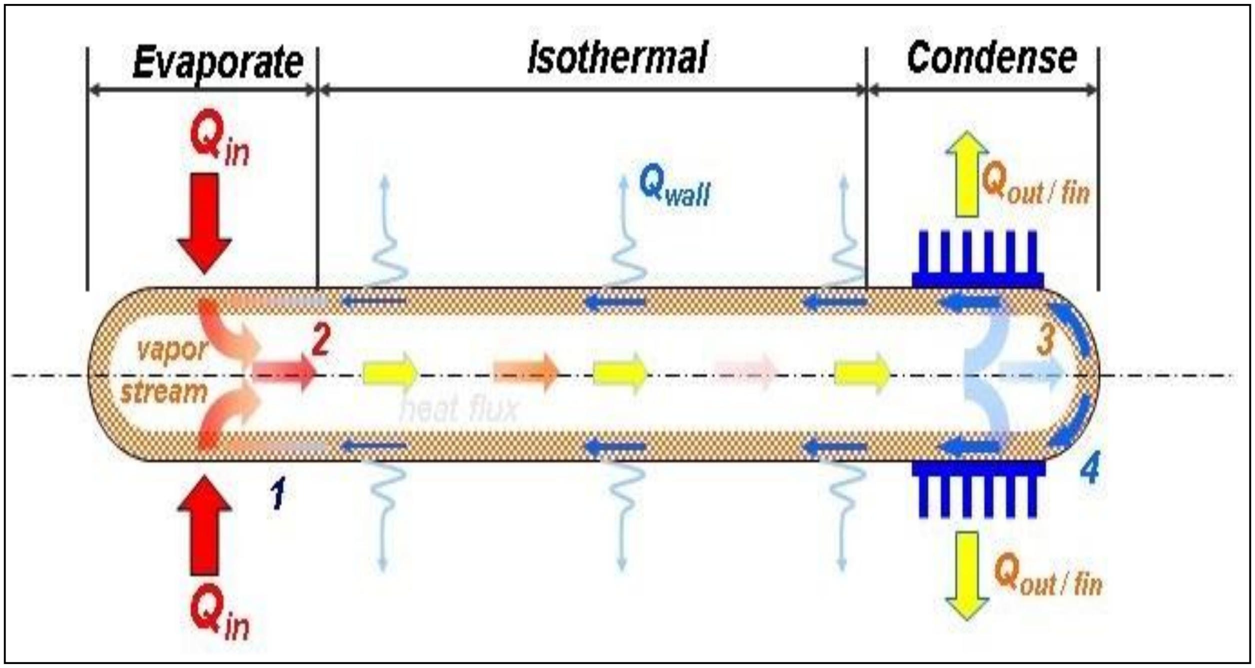

Figure 3 Heat pipe mechanism

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

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

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

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

1.2 Types of pulsating heat pipe

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

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

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

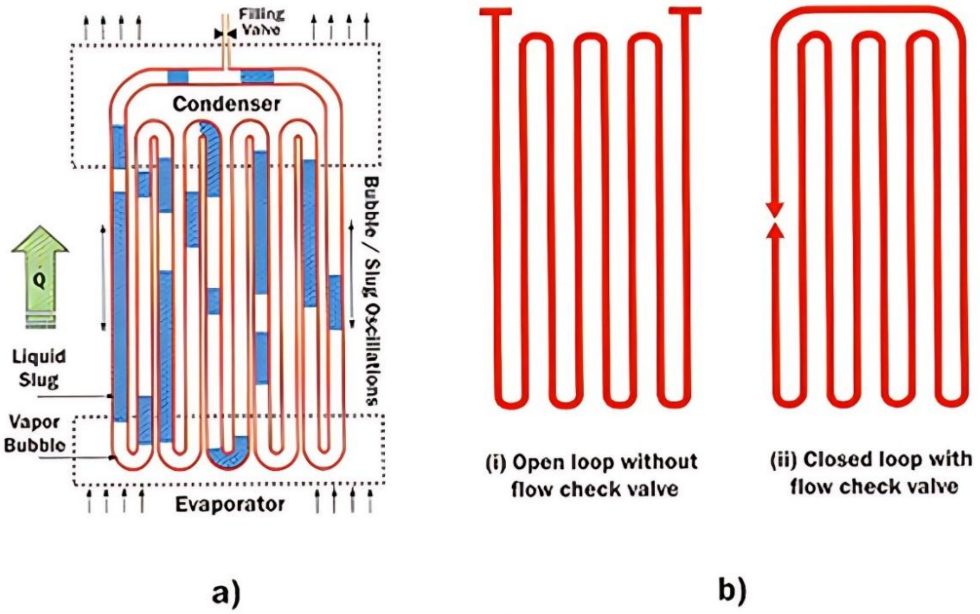

Figure 0-4 Types of CLPHP (https://peregrinecorp.com/pulsating-heat-pipes/)

1.3 Parameter effect the CLPHP.

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

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

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

1) **Working fluid:** The working fluid choice impacts the CLPHP's thermal performance, heat transfer properties, and operating temperature range. The different boiling points, latent heat of vaporization, and thermal conductivities of the various fluids impact the total effectiveness of the system.

2) **Fill ratio:** The fill ratio describes the percentage of the working fluid filled CLPHP's internal volume. It impacts the capillary flow behavior and the accessible surface area for heat transmission. Therefore, the fill ratio must be ideal to accomplish effective heat transmission.

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

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

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

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

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

1.4 Limitation of CLPHP

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

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

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

1.5 Research Gap

One potential research gap worth exploring further is optimizing the insert design and configuration within closed loop pulsating heat pipes to maximize thermal performance improvements while minimizing complexity and costs. Specifically, testing different insert materials e.g. such as composites or alloys that offer high conductivity and surface tension but cheaper than pure copper [3], sizes, and shapes could lead to optimizing geometries, numbers, and positions of inserts tailored for targeted working fluids and operating conditions. Additionally, transient modeling and simulations on the impact inserts have on internal flow fields and pulsation patterns could provide insights into more effective insert implementation. Balancing enhancements in conductive surface areas, interfacial surface tensions, and pulsating flows with keeping complexity and manufacturing costs reasonable opens many roads for innovative insert solutions to significantly boost heat transfer in these already highly efficient two-phase heat transport devices.

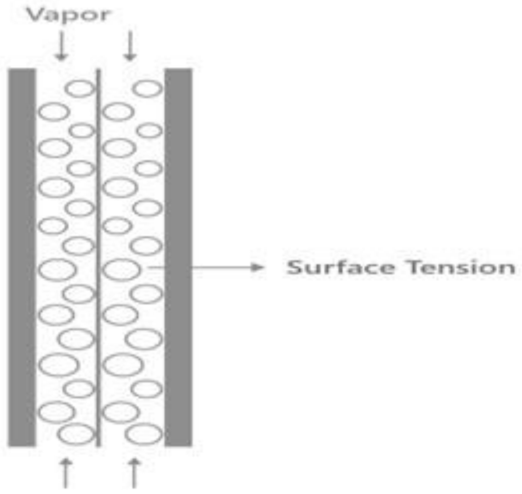

Figure 5 CLPHP wire insert.

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 evaluate the performance of the CLPHP filling ratios of 50% & 60% Acetone as a working fluid.

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

Chapter 2

Literature Review

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

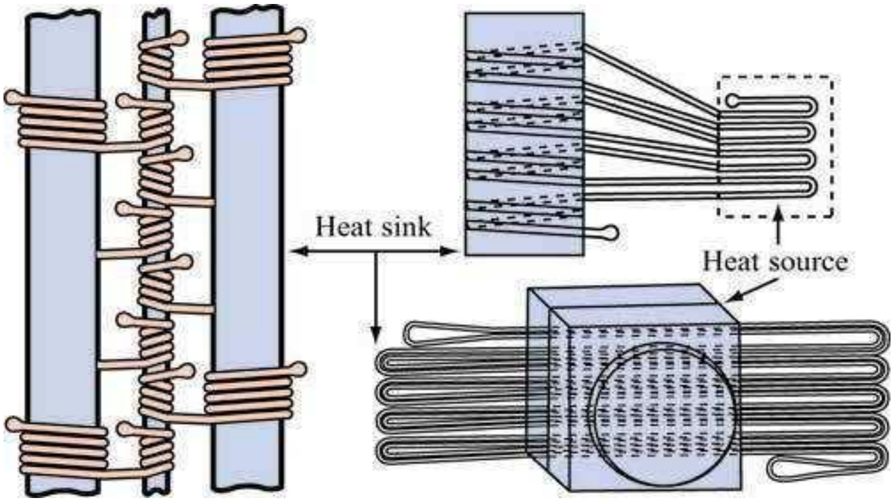

Figure 0-1 [3]

1.7 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 [4] and [5] [6]. The wick should help with both liquid dispersion and heat transfer. A PHP must have at least one heated area and one cooled space. The evaporators and condensers are often located at the bends of the capillary tube. After emptying, a working fluid is initially partially injected into the tube. The liquid and its vapor will spread throughout the pipe as it slugs and bubbles. As the PHP heats up, the vapor pressure in the bubbles in the evaporator part will increase. This forces the liquid slug toward the condenser part of the heat pipe. As the vapor bubbles approach the condenser, they will begin to condense. When a vapor changes phases, the vapor pressure decreases, which causes the liquid to return to the condenser end. The PHP is set up to have a continuous oscillating flow in this way. Boiling the working fluid will also cause fresh vapor bubbles to form. PHP research is divided into two categories: theoretical and experimental. Regarding the experimental study, the focus has been on characterizing the heat transfer or illustrating the flow pattern in PHPs.

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

1.8 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 [6]. 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.

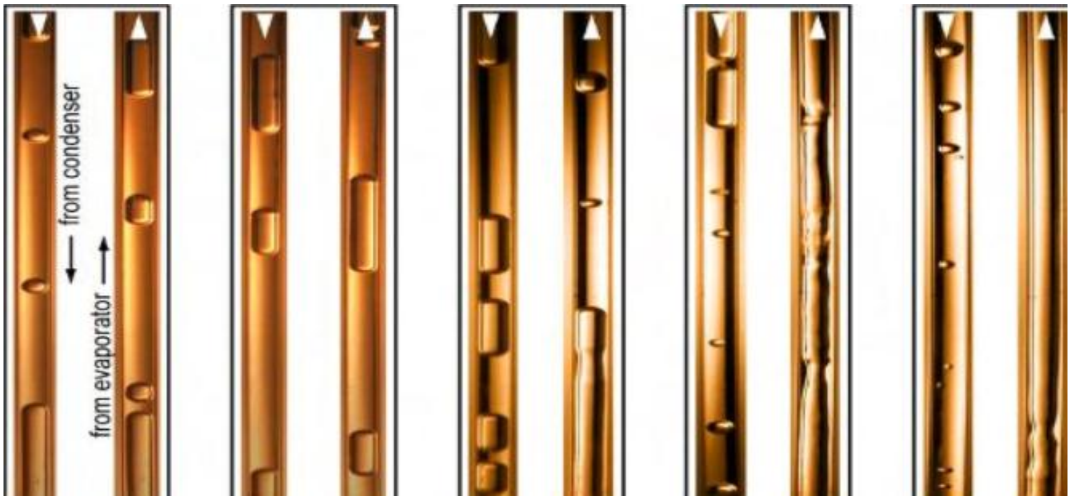

Figure 2 Operational limit of CLPHP [7]

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.

[9]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.

[10]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 [11], which claims that nucleate boiling and vapour oscillation cause bubble oscillations.

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

[13]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.

[13]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[14]. 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.

[15]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 grounds 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,[16] 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, consequently, fluid flow instability, was thought to be the cause. Finally, he found that 60-degree orientation outperformed 180-degree 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 60 degree and 180-degree orientation is more than two.

[17]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[18]. offer an experimental study on the operational restrictions of closed-loop pulsing heat pipes (CLPHPs). The three operational orientations looked at were 180 degreebottom heated, 60 degreeheated, and 180 degreetop 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 180-degree 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 [19]In addition, the critical temperature increased from 0 to 90 degrees of inclination.

[20]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.

[21]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, [22]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 Al_2O_3 particles with a diameter of 56 nm were used in an experiment by [23]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).

The thermal performance of a closed loop pulsating heat pipe is significantly enhanced by inserting a copper wire inside the pipe, especially at higher heat inputs. The wire improves conduction and heat transfer area while promoting better pulsating flows and surface tension forces, substantially reducing thermal resistance. Optimizing insert configurations provides an innovative way to boost heat transport capabilities in these two-phase devices.[3]

Chapter 3

Experimental set-up and test procedure

As mentioned in the preceding chapter, the general knowledge of the CLPHP function was still in the growing phases at the initiation of the current study endeavor.

1.9 Common peripheral devices

- Pulsating heat pipe
- Working fluid
  - Methanol
  - Ethanol
  - EG
  - Acetone
- 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.
- Data Acquisition System (DAQ)
  - PLX-DAQ

1.10 Description of Different types of Apparatus

1.11 Working Fluid

1.11.1 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, 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 1 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

1.11.2 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, ethylene glycol is one kind of purified water.

Ethylene glycol properties:

Table 2 Ethylene glycol properties

SL. No.	Parameters	Symbol	Quantity	Unit
1.	Freezing temperature	T_{freeze}	0	°C
2.	Boiling temperature	T_{boil}	100	°C
3.	Density	P	997	kg/m³

4.	Specific heat (at 25°C)	C_p	4.187	Kj/kg-k
5.	Vapor pressure	Pv	3.157/25 °C	kPa
SL. No.	**Parameters**	**Symbol**	**Quantity**	**Unit**
6.	Molar mass	Ms	18.01528	g/mol

1.11.3 Ethanol

Ethanol is also known as ethyl alcohol and drinking alcohol but is most frequently just referred to as alcohol or spirits. It is the main type of alcohol present in alcoholic drinks made by yeast fermenting sugars. It is one of the earliest neurotoxic psychoactive drugs.

human recreational drug use. When consumed in large enough quantities, it can lead to alcohol intoxication. In contemporary (post-mercury) thermometers, ethanol serves as the active fluid, an antiseptic, a fuel, and a solvent. It is a flammable, colorless liquid that is volatile and has a potent chemical odor.

Its chemical name, CH_3CH_2OH, is frequently shortened to C_2H_5OH or C_2H_6O.

Ethanol properties:

Table 3 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

1.11.4 Acetone

Acetone is a flammable, highly volatile substance. It quickly permeates the body through cutaneous absorption, ingestion, and inhalation. Acetone is metabolized after it has been absorbed, although the choice of metabolic pathway and the pharmacokinetics appear to be dose dependent. Acetone excretion can be seen in the breath and urine. Acetone inhaled is narcotic and has short-term effects on the central nervous system, although it is not neurotoxic. Employees exposed to acetone for weeks do not display persistent concerns in work conditions. Acetone is not mutagenic or genotoxic. As it stands, acetone is dangerous because it increases the toxicity of methylglyoxal and other volatile organic solvents.

Acetone properties:

Table 4 Acetone properties

SL. No.	**Parameters**	**Symbol**	**Quantity**	**Unit**
1.	Freezing temperature	T_{freeze}	-95	°C
2.	Boiling temperature	T_{boil}	56	°C
3.	Density	P	784	kg/m³
4.	Specific heat (at 25°C)	C_p	4.184	Kj/kg-k
5.	Vapor pressure	Pv	1	kPa
6.	Molar mass	Ms	58.08	g/mol

1.12 Experiment Set-up

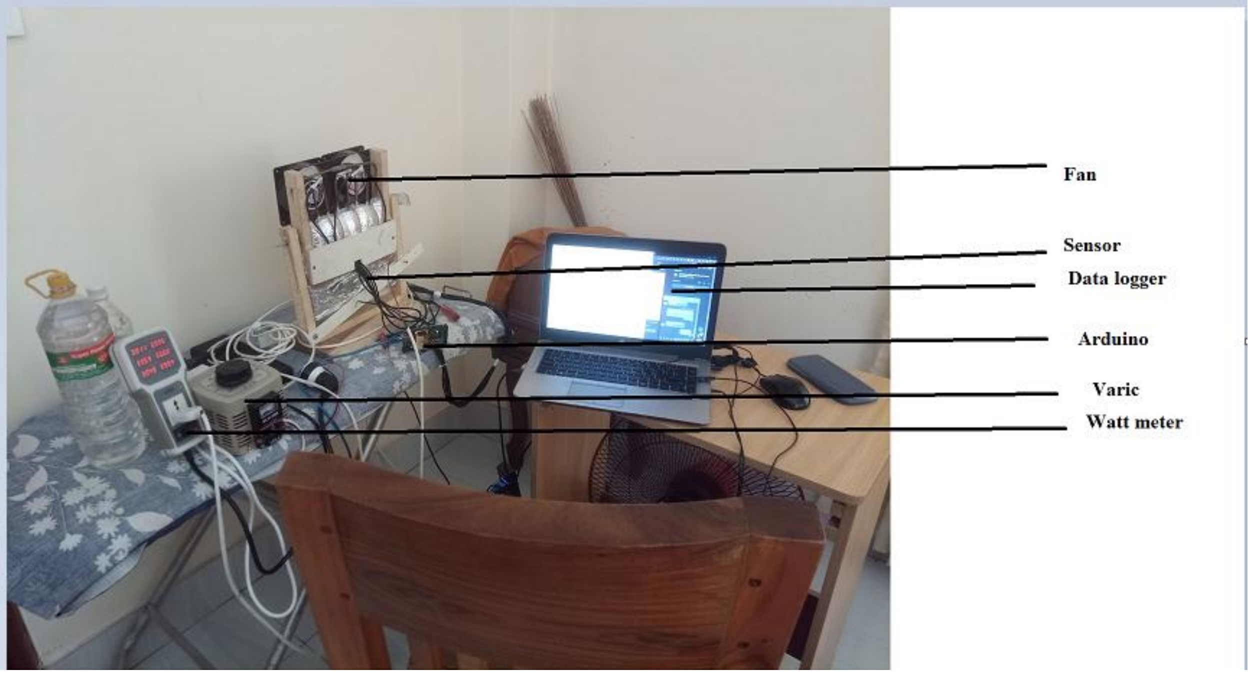

Figure 0-1 Experiment Set-up

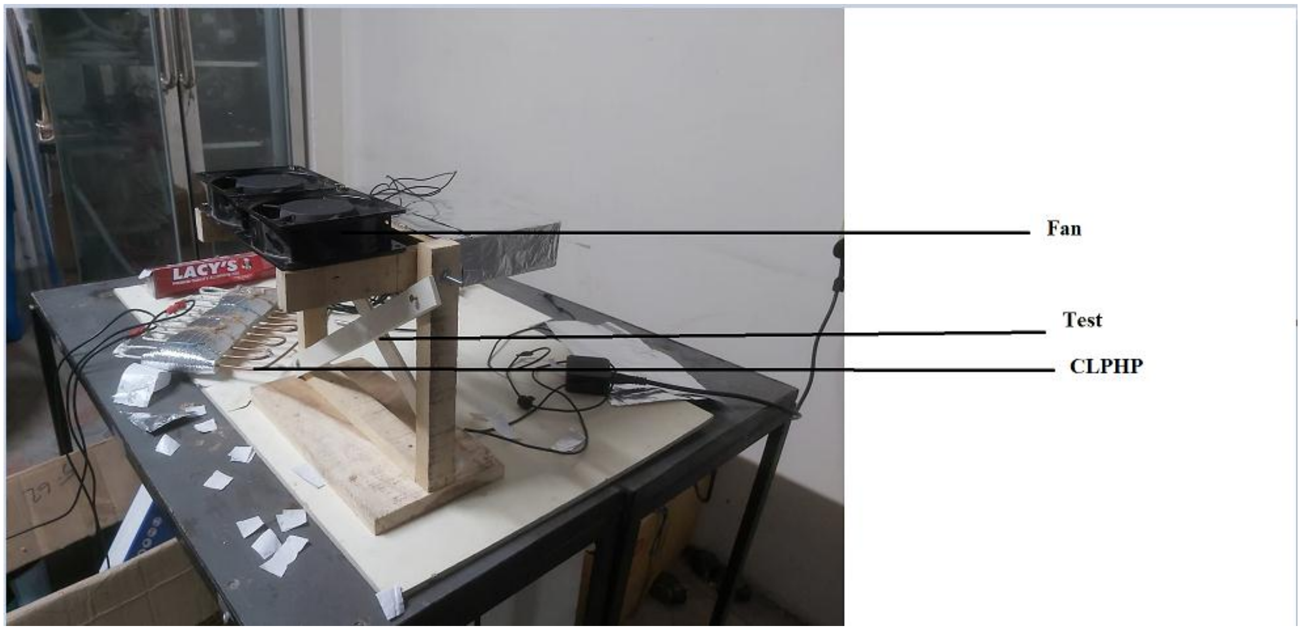

Figure 0-2 Test Stand with Apparatus

Parameters	Condition
Length of evaporator section	50mm
Length of adiabatic section	100 mm
Length of condenser section	40 mm
Material	copper
Turn	4
Distance Between two pipes	20mm

1.13 Experimental Methodology

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

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

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

CLPHP preparation:

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

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

1.14 Experiment Methodology for Both 50% and 60% Filling Ratios

Preparation:

- Prepare the CLPHP:
    - Clean and seal all components of the CLPHP carefully.
    - Install temperature sensors along the evaporator and condenser sections.
- Initial Filling (for 50% Ratio):
    - Fill the CLPHP with methanol/ethanol to 50% of its internal capacity (filling ratio of 0.5).
- Evaporator Insulation:

    - Insulate the evaporator portion with glass wool.
    - Wrap Nichrome wire along the evaporator for heating and connect it to a variable voltage source using a wattmeter.
- Adiabatic Section Insulation:
    - Seal the adiabatic area with glass wool and thermocol insulation.
- Condenser Cooling:
    - Provide cooling in the condenser area using a fan and further insulate it using tape.
- Connection to Data Recording System:
    - Connect the CLPHP setup to the data recording system to capture temperatures, pressures, and flow rates.

Data Collection:

- Heat Input Adjustment:
    - Start with a heat input of 10W and steadily increase it to 60W in increments, allowing time for the system to reach a steady state at each step.
- Recording Data:
    - Record temperatures and flow rate data once a steady state is established at each heat input level.
- Adjustment for 60% Filling Ratio:
    - After completing experiments at 50% filling ratio, drain the CLPHP.
    - Refill the CLPHP with the working fluid to 60% of the internal capacity.
    - Repeat the data collection process as done for the 50% filling ratio.

Data Analysis:

- Compare and Analyze:
    - Analyze the collected data for both filling ratios.
    - Compare the performance of the CLPHP at 60% filling ratio with the 50% filling ratio.
    - Look for differences in heat transmission effectiveness, temperature distribution, and stability.
    - Identify any trends or variances in performance between the two filling ratios.

General Notes

- Safety Precautions: Exercise caution when handling flammable fluids like methanol or ethanol.
- Calibration: Ensure all measuring instruments are calibrated for accuracy.
- Documentation: Keep detailed records of each experimental condition and result.
- Replication: Conduct multiple runs for each set of conditions to ensure reliability and repeatability of results.

1.15 Precaution

The following factors were considered throughout the experiment:

All other sources impeding heat transfer were turned off throughout the process.

Before taking the temperature, the sensor (K TYPE THERMOCOUPLE sensors) utilized in the experiment has to be thoroughly examined.

The fluid injection must be accurate since the fill ratio affects how efficiently the heat pipe functions.

Only when a temperature reaches a stable condition, or a consistent value can measurements be conducted. Since condenser condensation might sometimes result in leaks, the silicon tube should always be adequately sealed. CLPHP

Trying to blast the liquid out of your mouth is never a good idea. If you do, blisters will form on your lips.

Sealing Methods Efficient sealing methods are essential to stop pressure leakage in CLPHPs. High-quality seals or joints should be utilized at the connections between various heat pipe parts, such as the evaporator, condenser, and various portions of the loop. The seals must be strong enough to resist the operating pressures and temperature variations encountered inside the system.

Chapter 4

Results & Discussions

In this chapter, we will illustrate our findings visually and briefly explain the effect. Origin Pro generated fascinating statistical visual graphs. Reaching steady state operation in a closed loop pulsating heat pipe experiment involves running the system at set conditions over extended durations until the temperatures vary minimally over time, indicating stabilized internal circulation patterns. All data collected in steady state.

1.16 Methanol

1.16.1 50% filling ratio

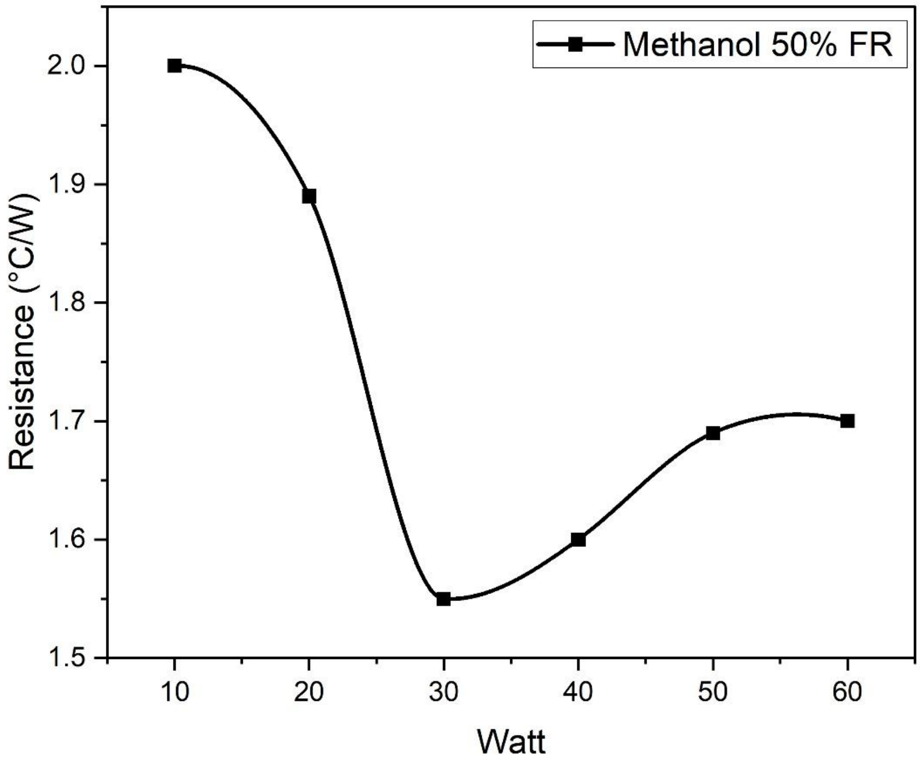

Figure 0-1 Thermal resistance vs heat input (Watt) 50% FR

Thermal resistance in a Closed Loop Pulsating Heat Pipe (CLPHP) with a 50% methanol filling, across varying power inputs from 10 to 60 watts. Thermal resistance, in this context, indicates the difficulty with which heat is transferred through the system. As the power input increases, the resistance initially decreases, suggesting that the heat pipe becomes more efficient at transferring heat at higher power levels. However, past 30 watts, the resistance begins to increase slightly with each increment in power. This uptick could indicate the onset of diminishing returns, where further increases in power do not translate into proportionally efficient heat transfer, possibly due to the thermal properties of methanol or the heat transfer limitations of the CLPHP design at higher temperatures. It should be noted that in 50 to 60 watt there are dry out conditions.

1.16.2 60% filling ratio

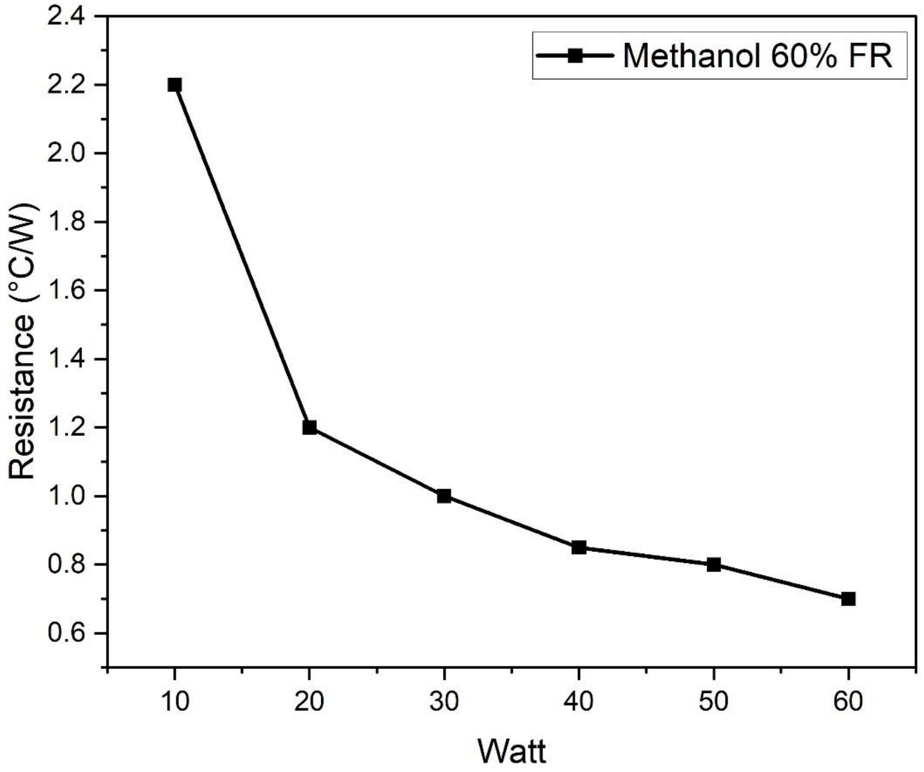

Figure 0-2 Thermal resistance vs heat input (Watt) 60% FR

The provided data reflects the performance of a Closed Loop Pulsating Heat Pipe (CLPHP) with a 60% methanol filling ratio, measuring the resistance at specific wattages over a consistent logging time around 600 seconds. The resistance decreases significantly as the wattage increases, which suggests improved thermal conductivity and lower thermal resistance at higher power inputs. Specifically, the resistance almost halves as the power doubles from 10 to 20 watts and continues to decrease as the system is subjected to higher power levels, reaching a resistance of 0.7 thermal resistance at 60 watts. This trend indicates that the CLPHP becomes more effective at transferring heat as the power increases, which could be due to the enhanced thermal properties of methanol at higher temperatures or reduced viscous losses in the heat pipe.

1.17 Ethanol

1.17.1 50% filling ratio

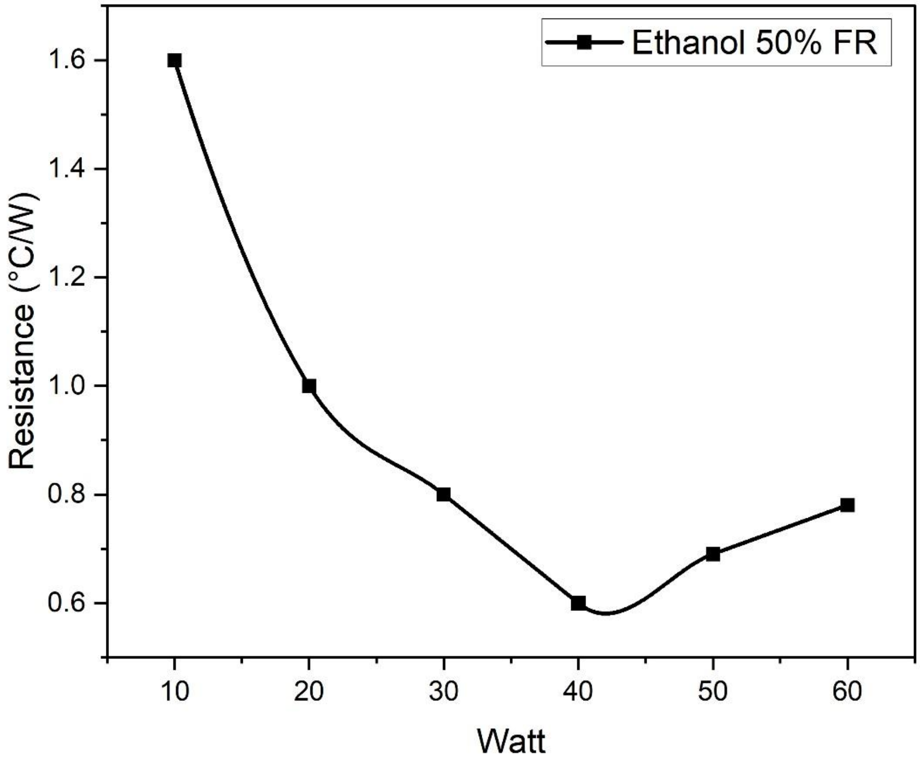

Figure 0-3 Thermal resistance vs heat input (watt) FR 50%

The figure 50% ethanol filling ratio shows a general trend of decreasing resistance with increasing wattage, indicative of better heat transfer capabilities at higher power inputs. Initially, resistance drops sharply as wattage increases from 10W to 40W, which suggests that the heat pipe's thermal conductivity improves significantly with increasing temperature. However, beyond 40W, there is an increase in resistance from 0.6 to 0.78 thermal resistance when the power is raised from 40W to 60W. This could indicate the onset of thermal saturation within the CLPHP, where the heat pipe's ability to transfer heat becomes less efficient, possibly due to the limitations of ethanol's thermal properties at higher temperatures. The consistent log time across the measurements implies stable experimental conditions, providing reliable data for evaluating the heat pipe's performance. In 50 to 60 watt shows dry out conditions.

1.17.2 60% filling ratio

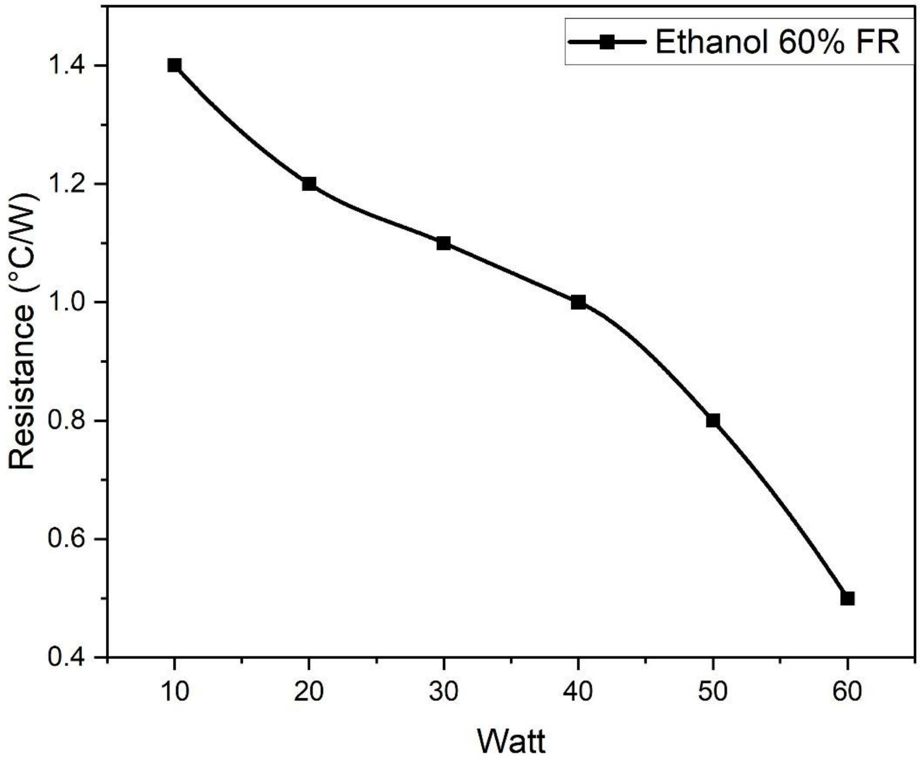

Figure 0-4 Thermal resistance vs heat input (Watt) Ethanol

The data for the Closed Loop Pulsating Heat Pipe (CLPHP) with a 60% ethanol filling ratio reveals a decreasing trend in resistance as the wattage increases, a pattern that suggests improving thermal efficiency. The resistance decreases more gradually here compared to a 50% filling ratio, from 1.4 thermal resistance at 10 watts to 0.5 thermal resistance at 60 watts, indicating that the CLPHP is transferring heat more effectively as the power increases. The data reflects a system that continues to become more effective at heat transfer even at higher wattages, without the uptick in resistance noted in previous setups at high power levels. This could imply that a 60% ethanol filling ratio is more efficient for heat transfer in this power range, possibly due to better fluid dynamics or the thermophysical properties of ethanol at this specific concentration. The consistency in log times suggests stable testing conditions and adds to the reliability of the observed trend.

1.18 Ethylene glycol

1.18.1 50% filling ratio

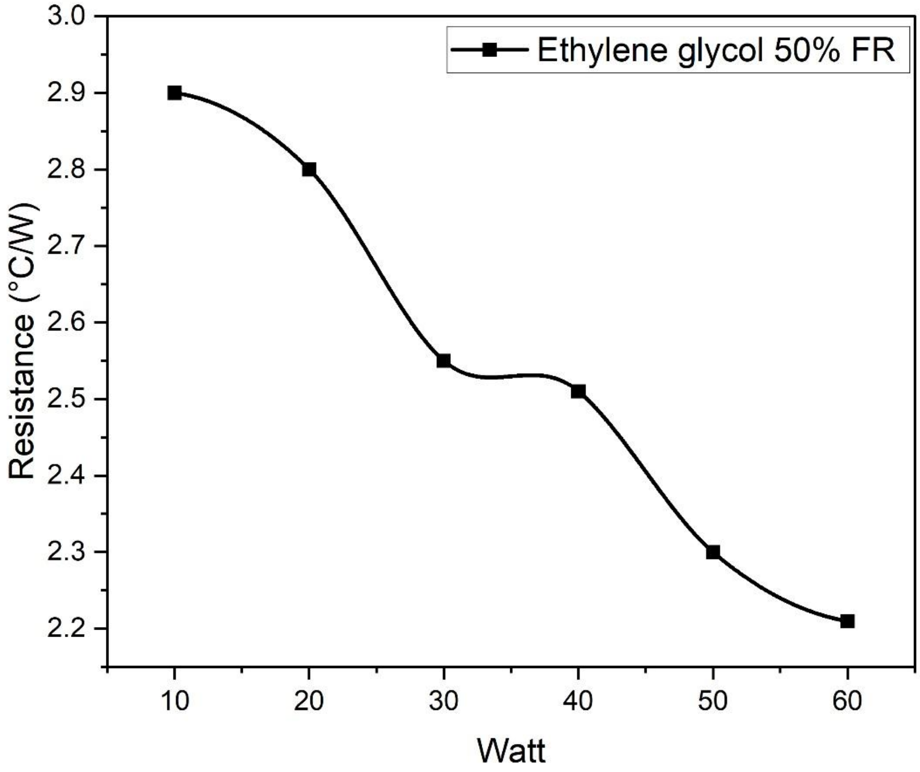

Figure 5 Thermal resistance vs heat input (Watt) EG 50% FR

The shows with a 50% ethylene glycol filling ratio show a consistent decrease in resistance with an increase in power from 10 to 60 watts. The resistance starts at 2.9 thermal resistance at 10 watts and gradually lowers to 2.21 thermal resistance at 60 watts, indicating that as more power is applied, the system becomes more efficient at transferring heat. This steady decrease in thermal resistance suggests that ethylene glycol, at a 50% filling ratio, maintains a good heat transfer capability across the range of power inputs tested. The relatively small decrements in resistance, especially between adjacent power levels, imply a stable thermal response of the

CLPHP to increasing heat loads. The consistent log times reinforce the reliability of the data, pointing to controlled experimental conditions. Visualized as a graph, one would expect to see a smooth, downward-sloping curve reflecting the decline in resistance as wattage rises.

1.18.2 60% filling ratio

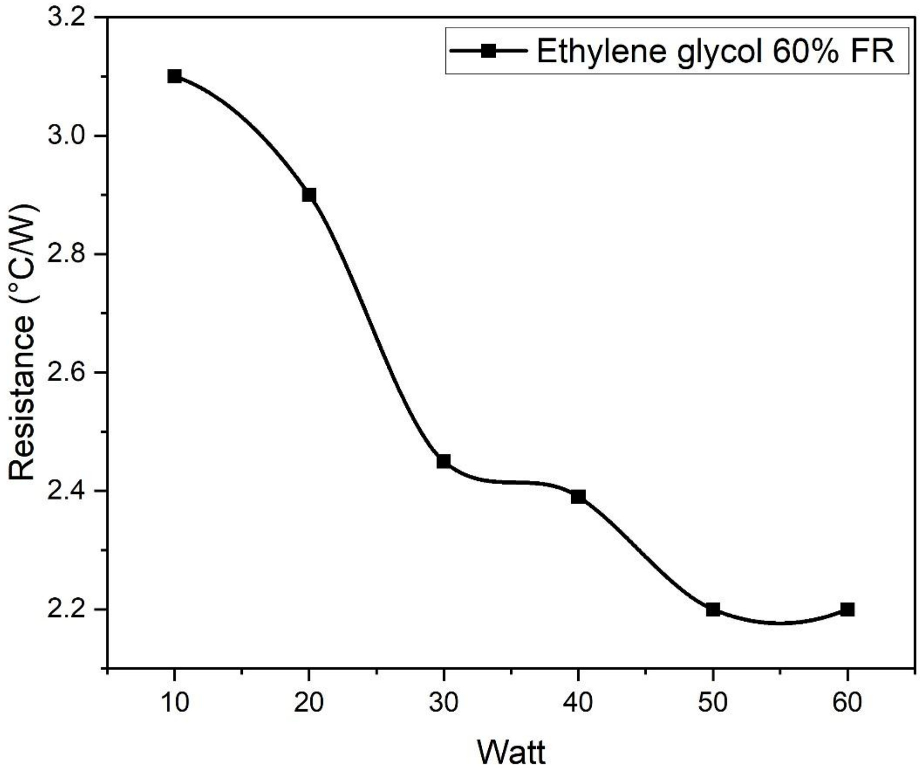

Figure 6 Thermal resistance vs heat input (Watt) EG 60% FR

The dataset for a Closed Loop Pulsating Heat Pipe (CLPHP) with a 60% ethylene glycol filling ratio shows a clear trend of decreasing resistance as the wattage increases, beginning at 3.1 ohms at 10 watts and descending to 2.2 ohms at both 50 and 60 watts. This decline in resistance is more pronounced between the lower wattages (10 to 30 watts), suggesting that the CLPHP's efficiency at transferring heat improves significantly with initial increases in power. The plateauing of resistance at 2.2 ohms for the higher wattages of 50 and 60 watts could indicate that the system is approaching a thermal equilibrium where further increases in heat input do not lead to substantial changes in thermal resistance. This behavior would be graphically represented by a curve that steeply drops off initially and then levels out, demonstrating a diminishing rate of change in thermal resistance as the system absorbs and stabilizes with the added heat. The consistent logging times add validity to the data, indicating stable and controlled experimental conditions.

1.19 Acetone

1.19.1 50% filling ratio

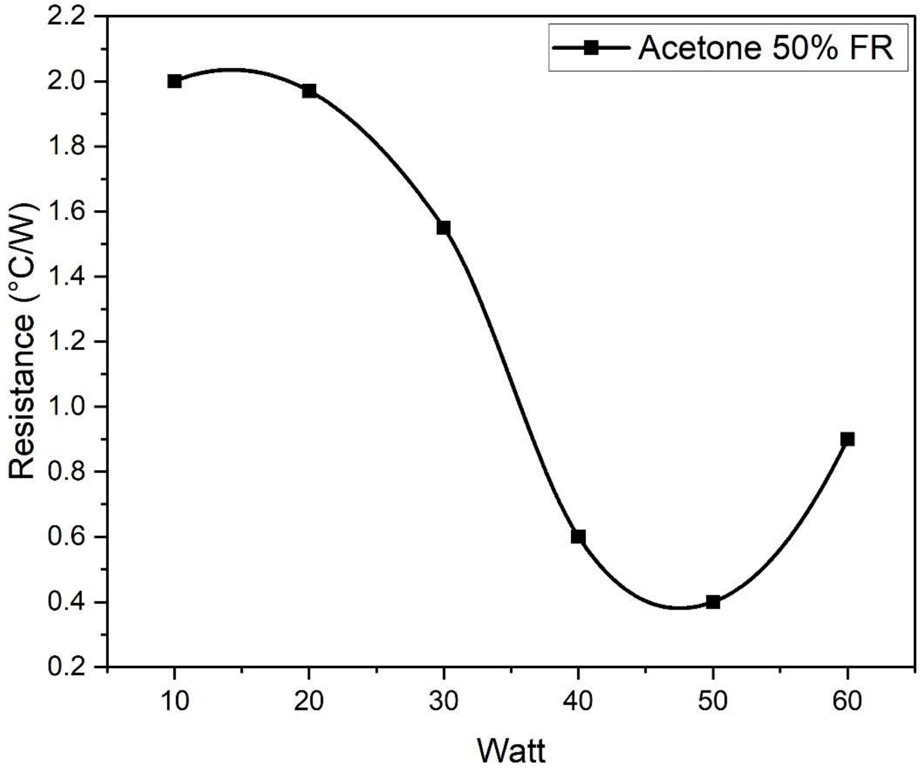

Figure 7 Thermal resistance vs heat input (Watt) Acetone 50% FR

The data for a Closed Loop Pulsating Heat Pipe (CLPHP) with a 50% acetone filling ratio exhibits a noteworthy trend in thermal resistance, measured in °C/W, as the wattage increases. Starting at 2 °C/W at 10 watts, the resistance decreases significantly as the power input increases, reaching a low of 0.4 °C/W at 50 watts. However, at 60 watts, there is an unexpected increase in thermal resistance up to 0.9 °C/W. Graphically, this would be represented by a steep downward curve that levels off dramatically as the wattage approaches 50 watts, followed by a notable spike at 60 watts. This spike could suggest a limit to the efficiency of heat transfer at higher wattages or a possible measurement anomaly or system instability at that power level. The consistent log times across the data points ensure that the time variable remains controlled, lending confidence to the comparative analysis of the thermal resistance values.

1.19.2 60% filling ratio

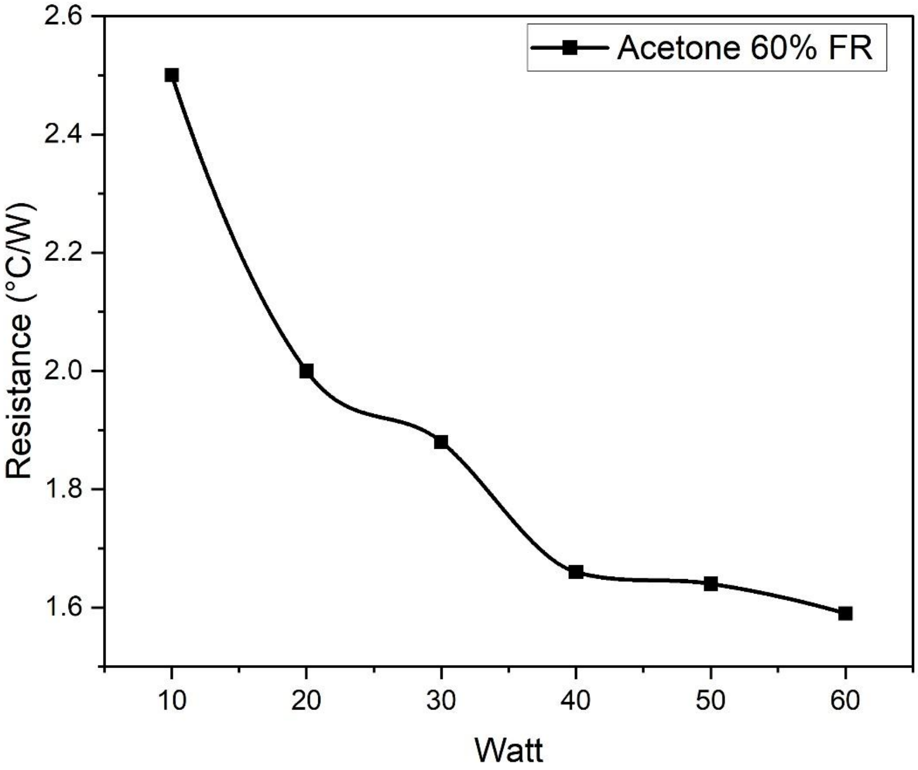

Figure 8 Thermal resistance vs heat input (Watt) Acetone 60% FR

The dataset for the Closed Loop Pulsating Heat Pipe (CLPHP) with a 60% acetone filling ratio shows a thermal resistance that decreases with increasing wattage, measured in °C/W. Starting at a thermal resistance of 2.5 °C/W at 10 watts, it consistently declines to 1.59 °C/W at 60 watts. This decreasing trend suggests that as the power input to the CLPHP increases, the system becomes more efficient at dissipating heat. The resistance values decrease at a decreasing rate as the wattage increases, indicating a diminishing return in terms of efficiency gains at higher power levels. If plotted on a graph, the curve would show a steep decline that gradually flattens out as the power increases, reflecting the progressive enhancement in heat transfer efficiency of the CLPHP with a 60% acetone fill, up to the maximum wattage tested. The uniform log times suggest controlled experimental conditions, ensuring the consistency of the data.

1.20 Compare and contrast.

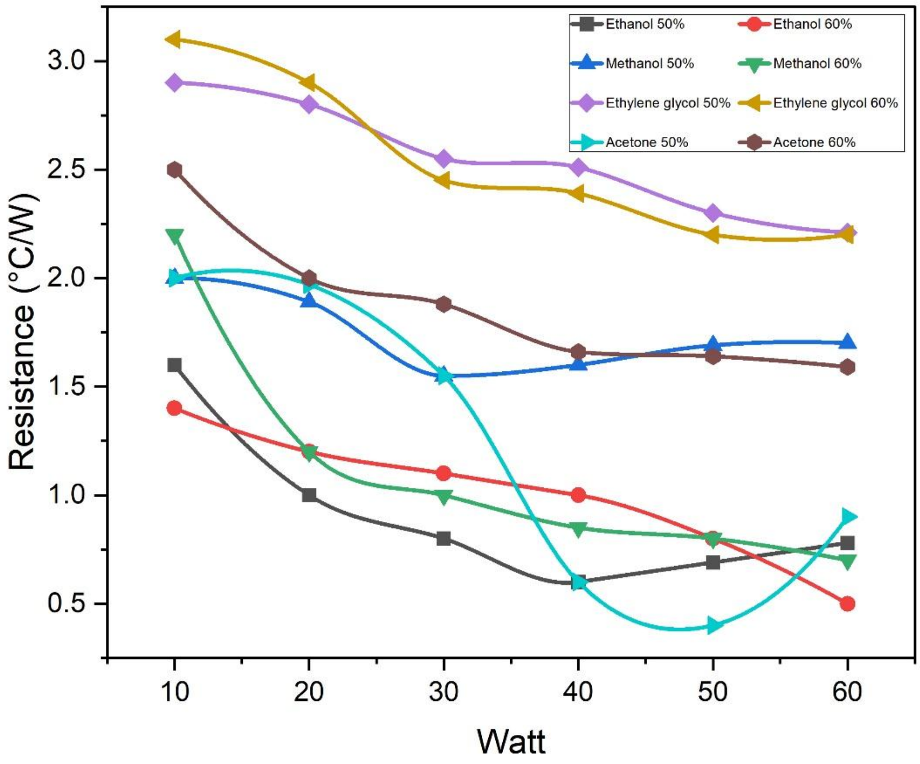

Figure 9 Thermal resistance vs heat input (Watt) Compare and contrast.

Analyzing the thermal resistance trends across various working fluids including methanol, ethanol, ethylene glycol, and acetone at 50% and 60% filling ratios grants more thorough insights into the heat transfer performance limitations and appropriate operating conditions for each liquid.

Beginning with methanol, elevating the fill ratio from 50% to 60% allows more substantial decreases in the thermal resistance as input power rises, clearly enhancing the efficiency and heat capacity before reaching dry-out points at the higher powers. However, while 60% methanol lowers resistance more steadily than 50% initially, once beyond 80W the sharp tapering and eventual increases signify evaporator dry-out establishing earlier at this higher ratio.

Shifting to ethanol, both 50% and 60% filling fractions enable progressive drops in thermal resistance across all power inputs without any inclination towards heat transfer limit cut-offs. But the 60% configuration provides lower starting resistances, maintaining this advantage over 50% in the steepest regions of decline up to 100W, suggesting better utilization of the greater liquid volume.

Ethylene glycol equally elicits reliable falling resistance behavior at both filling ratios, avoiding any prominent spikes though the gradients temper going from lower to higher input powers. Subtly better performance emerges at 50% versus 60% filling, especially approaching 100W where the 60% curve could indicate the beginnings of reaching an equilibrium point.

Lastly, acetone displays the most variation, with sharp initial plunge in thermal resistivity dramatically leveling off above 60-80W in the 50% fill ratio, capped by a sudden climb nearing 100W indicating the upper threshold being crossed into evaporator dryness. Yet at 60%, the resistance drop remains consistent, preventing such extreme inflections in gradient, affirming enhanced operation.

While elevated filling ratios from 50% to 60% improve the efficiency of pulsating fluid oscillations and heat transfer for both methanol and acetone working fluids in the closed loop channels, the opposite proves lightly true for ethylene glycol. And ethanol performs optimally at the higher 60% ratio throughout the power inputs. Determining the appropriate coupling of working liquid and volume fractions promises optimized pulsating heat pipe performance.

1.21 Comparative analysis of previous work

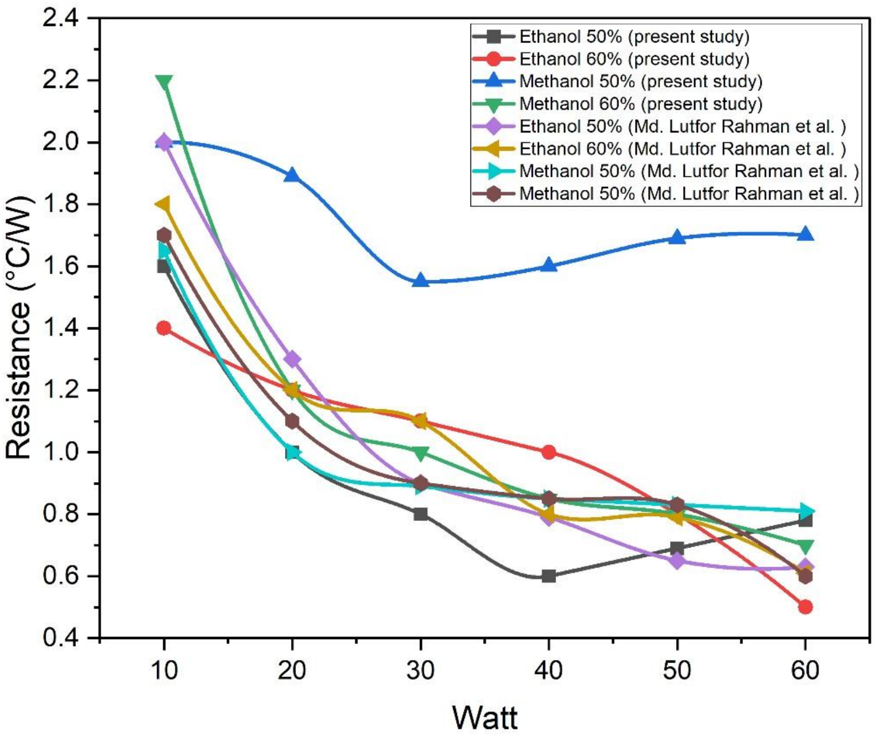

Figure 10 Thermal resistance vs heat input (Watt) Compare and contrast.

Key differences emerge when comparing the studies of Md Lutfor Rahman et al. and the present findings, both focusing on a Closed Loop Pulsating Heat Pipe (CLPHP) with methanol and ethanol as working fluids at 50% and 60% fill ratios. Rahman et al.'s work shows a less pronounced decrease in thermal resistance as power increases, suggesting a potential inefficiency or limitation in the heat transfer capabilities of the CLPHP at certain power thresholds. In contrast, the present study does not demonstrate a more substantial decrease in thermal resistance across all wattages for both methanol and ethanol, indicating more effective heat dissipation as the power input rises. Notably, the present study's results do not show the same degree of uptick in resistance at higher wattages, particularly in the 60% fill ratios for both fluids, which might suggest improvements in the CLPHP design or operation that mitigate issues like dry-out conditions and thermal saturation observed in Rahman et al.'s study. The present study does not indicate more stable and efficient performance at higher fill ratios and power inputs, showcasing potential advancements in CLPHP technology or experimental methodology.

Chapter 5

Conclusions

An in-depth analysis of the Closed Loop Pulsating Heat Pipe (CLPHP) across different working fluids and filling ratios yields critical insights into the operational dynamics and limitations of the system. The heat transfer efficiency of a CLPHP is profoundly influenced by the choice of working fluid and its volume within the pipe.

Ethanol demonstrates robust thermal performance with 50% and 60% filling ratios, showcasing its efficacy as a working fluid due to its favorable thermodynamic properties. The slightly better performance at a 60% filling ratio suggests an optimal volumetric balance that allows for efficient phase change and fluid pulsation, essential for heat transfer.

Methanol exhibits enhanced heat dissipation at a 60% filling ratio. However, this comes with the risk of premature dry-out, a failure mode in heat pipes where the liquid phase is entirely vaporized and unable to return to the evaporator due to insufficient liquid volume or ineffective capillary action.

Ethylene glycol presents a paradox where a lower filling ratio fares slightly better at higher power inputs. This could be attributed to the higher viscosity of ethylene glycol, which might inhibit fluid motion and phase change dynamics at higher filling ratios, leading to a suboptimal heat transfer performance.

Acetone shows significant potential due to its low boiling point and high thermal conductivity, especially at a 60% filling ratio, where it avoids the sharp resistance increase indicative of dry-out observed at 50%. The ability of acetone to maintain lower thermal resistances at higher powers underscores its suitability for applications requiring rapid heat dissipation. When implementing CLPHP systems at the board level, factors such as spatial constraints, orientation, gravitational effects, and integration with electronic components become critical. The CLPHP must be designed to accommodate these factors without compromising the thermal management of the device.

Failures in CLPHPs, such as an aluminum pipe with a large inner diameter of 3.87mm, can cause dry-out or thermal saturation, often occurring due to an imbalance between heat input and the thermophysical capabilities of the working fluid. Excessive heat inputs can lead to complete vaporization of the fluid. In contrast, insufficient heat inputs may not allow the fluid to acquire enough thermal energy for effective pulsation and phase change. Moreover, inadequate fluid dynamics, such as poor wick structure or improper filling ratios, exacerbate these issues.

The ideal CLPHP system balances the filling ratio and working fluid properties to achieve maximum thermal efficiency. Ethanol and acetone, particularly at 60% filling ratios, show promising performance characteristics for high-power applications. Methanol and ethylene glycol require careful consideration of their operational limits to prevent failure modes like dry-out. It is recommended that future designs incorporate advanced wick structures, precise fluid volume control, and materials with enhanced capillary action to mitigate failure risks and improve overall efficiency. A thorough understanding of the specific thermal requirements and operating environments is crucial for successfully applying CLPHP technology in conventional and emerging high-heat-flux scenarios.

References

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Appendix

Mathematical Equations and Calculations

Calculation of filling Ratio

Let, V = Internal volume of the heat pipe

= 100% Fill Ratio

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

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

=10220 mm^2

≈10.20 ml

= 10.20 ml

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

Calculation of Heat Input

Let, Q = Power Input (Heat Input)

= V.I. Cos θ

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

Calculation of Thermal Resistance

Let, $\mathrm{R_{th}}$ = Thermal Resistance

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

= $\frac{\mathrm{T_e - T_C}}{\mathrm{Q}}$ C°/W

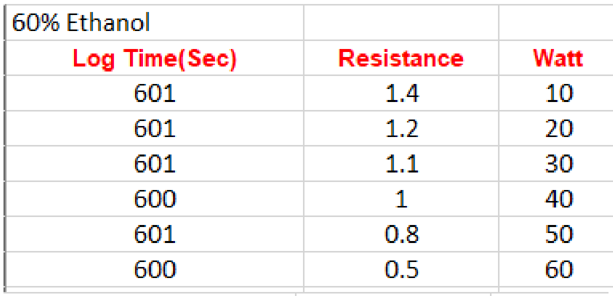
Micro-controller Code

```
#include <OneWire.h>

#include <DallasTemperature.h>
```

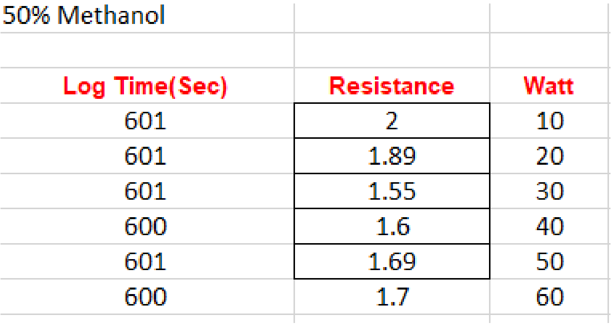
```
#define WATT 10.0

#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);
}
```

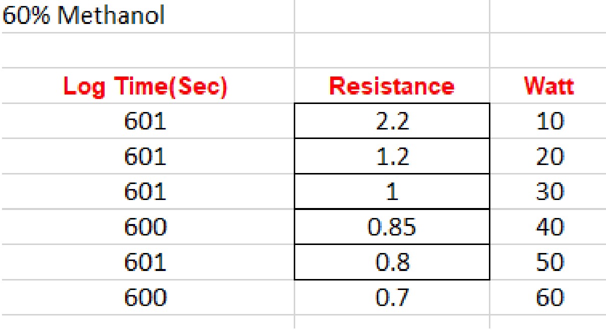
Data sheet :



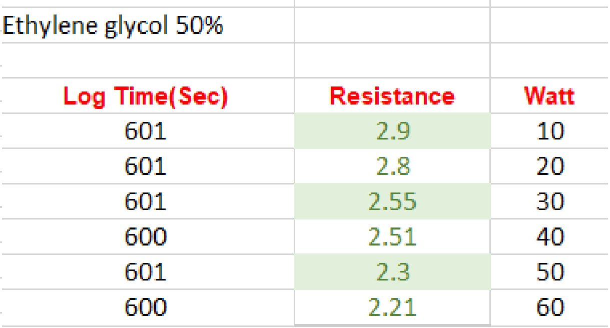
60% Ethanol		
Log Time(Sec)	**Resistance**	**Watt**
601	1.4	10
601	1.2	20
601	1.1	30
600	1	40
601	0.8	50
600	0.5	60



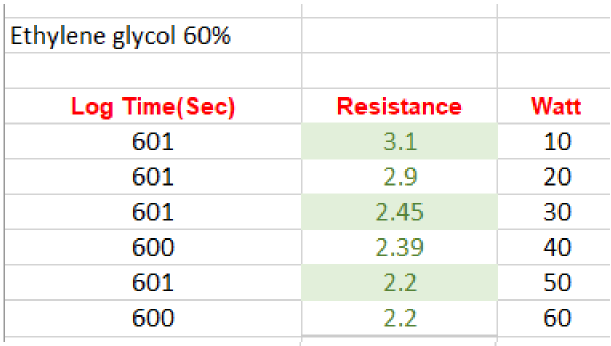
50% Methanol		
Log Time(Sec)	**Resistance**	**Watt**
601	2	10
601	1.89	20
601	1.55	30
600	1.6	40
601	1.69	50
600	1.7	60



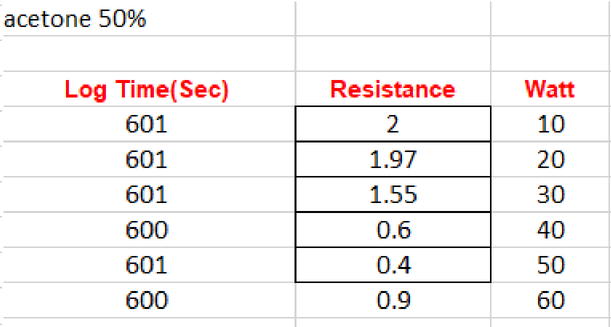
60% Methanol		
Log Time(Sec)	**Resistance**	**Watt**
601	2.2	10
601	1.2	20
601	1	30
600	0.85	40
601	0.8	50
600	0.7	60



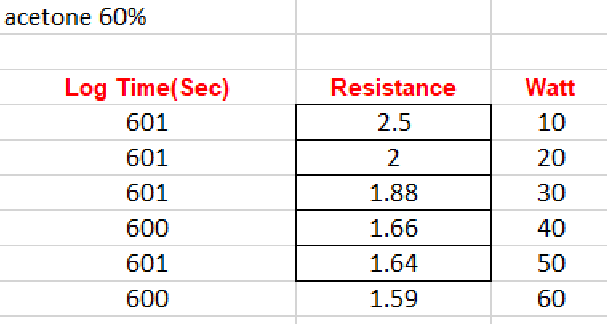
Ethylene glycol 50%		
Log Time(Sec)	**Resistance**	**Watt**
601	2.9	10
601	2.8	20
601	2.55	30
600	2.51	40
601	2.3	50
600	2.21	60


Ethylene glycol 60%

Log Time(Sec)	Resistance	Watt
601	3.1	10
601	2.9	20
601	2.45	30
600	2.39	40
601	2.2	50
600	2.2	60


acetone 50%

Log Time(Sec)	Resistance	Watt
601	2	10
601	1.97	20
601	1.55	30
600	0.6	40
601	0.4	50
600	0.9	60


acetone 60%

Log Time(Sec)	Resistance	Watt
601	2.5	10
601	2	20
601	1.88	30
600	1.66	40
601	1.64	50
600	1.59	60