Title
Experiment of Thermal Performance of Oscillating Heat Pipe Under Various Conditions

Author
Hai, Yanfeng

Publication Date
2020

UNIVERSITY OF CALIFORNIA,
IRVINE

Experiment of Thermal Performance of Oscillating Heat Pipe Under Various Conditions

THESIS

submitted in partial satisfaction of the requirements for the degree of

MASTER OF SCIENCE
in Mechanical and Aerospace Engineering
by
Yanfeng Hai

Thesis Committee:
Professor. Yun Wang, Chair
Assistant Professor. Penghui Cao
Assistant Professor. Yoonjin Won

2020

Dedication

I dedicate my dissertation work to my family and many friends. A deep feeling of gratitude to my loving parents, Binling Ma and Jianguo Hai whose words of encouragement and strong supports to my academic life.

I also dedicate this dissertation to my many friends and colleagues who have supported me throughout the process. I will always appreciate all they have done, especially Chuanning Zhao for helping me for many times of proofreading, Hince Qu for technical supports.

In addition, I want to give special thanks to my best friend Chen Cui for being there for me throughout the entire program.

Table of Contents

List of Figures

List of Tables

Nomenclature

A_{cross} – Cross-sectional area (m^2)

Bo- Bond Number (Ratio of Buoyancy force to surface tension force)

$C_P - Specific\ heat\ with\ constant\ pressure\ (\frac{J}{kgK})$

$D_i - inner\ diameter$

Fr- Froude Number (Ratio of dynamic viscosity to weight)

g- Gravitational acceleration ($\frac{m}{s^2}$)

$h_{fg} - latent\ heat\ of\ vaporization$

k- Thermal conductivity $\left(\frac{W}{K}\right)$

L – Length (m)

$L_{eff} - Effective\ length$ for evaporator or condenser

N – Number of turns of OHPs

Pr – Prandtl Number (Ratio of momentum diffusivity to thermal diffusivity of vapor)

Q - Heat (kJ)

q' – Heat transfer rate (W)

q'' – Heat Flux $\left(\frac{W}{m^2}\right)$

$q_c'' - Critical\ heat\ flux\ \left(\frac{W}{m^2}\right)$

R – Ideal gas constant $\frac{J}{kgK}$

r – radius (m)

Re – Reynolds Number

$R_{thermal} - Thermal\ Resistance$

$\Delta T - Change\ of\ temperature\ (°C\ or\ K)$

Wa – Wallis Number

We – Webber Number (ratio of dynamic force to surface tension)

Greek Symbols

$\rho - Density\ \left(\frac{kg}{m^3}\right)$

$\sigma - Surface\ Tension\ \left(\frac{N}{m}\right)$

π - Ratio of a circle's circumference

$\theta - Inclination\ angle\ from\ the\ horizontan\ axis\ (degree)$

$\phi -$ Filling Ratio

$\Delta -$ Change in a variable

Subscripts

A= adiabatic section

Evap – Evaporator section

Cond – Condenser section

l – liquid

v - vapor

eff – effective

Acronym List

CLOHP – Closed Loop Oscillating Heat pipes

CEOHP – Closed End Oscillating Heat pipes

CLOHP /CV– Closed Loop Oscillating Heat pipes with Checking Valve

HP – Heat Pipes

OHP – Oscillating Heat Pipe

Acknowledgements

I would like to express my appreciation to the Department of Mechanical and Aerospace Engineering faculties at University of California, Irvine for all the supports and helps throughout my academic career. I would like to express my great appreciation to Dr. Yun Wang who inspires me with his knowledge and direct me on the world of academic researches. Dr. Yun Wang is a great teacher, mentor, and friend; he offered me an opportunity of academic research while I was an undergraduate student at University of California, Irvine; he offered me many great suggestions to help me go further in both academic and life. I wouldn’t be who I am now without his guidance and persistent help.

I would like to appreciate the adviser from my thesis committee members, Professor Penghui Cao and Professor Yoonjin Won, who helped me in comprehending the underlying principles in the thermodynamic and material selections and heat transfer areas. I really want to express my highest appreciation to them for everything they did to make my thesis a better one.

Abstract of the Thesis

Experiment of Thermal Performance of Oscillating Heat Pipe Under Various Conditions

by

Yanfeng Hai

Master of Science in Mechanical and Aerospace Engineering

University of California, 2020

Professor Yun Wang, Chair

Thermal management is important for many engineering systems such as PEM fuel cells, batteries, electrochemical supercapacitors, solar energy, and heat engines. Heat transfer, such as dissipation and cooling, is a major subject in thermal management. Among all the modern technologies of heat dissipation and cooling, heat pipes (HP) have received a growing attention because of their great potential in high thermal and heat transfer performance. The Oscillating Heat Pipe (OHP), a passive HP device originally developed in 1990, is a promising technology involves complex and dynamic two-phase flow and heat transfer. It is regarded as one of the most efficient HPs with two outstanding features: 1.) no external power for operation and 2.) no wick structure build in the capillary tube. In this study, a testing OHP with 150mm x 100mm x 4mm is developed to investigate OHP performance under various conditions. 2 mm thick mini channels are used with 7 turns on the evaporator section. Water and 91% ethanol are used as the working fluid and the filling ratio are tested from 30% to the maximum approachable ratio to investigate the thermal performance. Horizontal and vertical orientations are also studied for its influence on the thermal performance. Various temperatures at the evaporator and condenser sides are applied, along with comparison against literature results. Basic theoretical analysis is performed to assist the experimental study. We find: 1) that water tends to have better heat transfer performance compare to ethanol when operate at low heat transfer rate; and 2) the orientation of the OHP shows little influence on the start-up of the heat transfer system but strongly affects the thermal performance of the system. The vertical orientation has a significant low thermal resistance compared to the horizontal orientation in the testing.

Chapter 1. Introduction

1.1 Importance of Thermal Management

With growing incentives such as tax exemptions, driving in the carpool lane, and free charging stations, electric vehicles and even fuel cell vehicles are becoming more and more popular. Both electric vehicles (EVs) and Fuel Cell vehicles (FCVs) use renewable power sources as an alternative fuel to either eliminate or greatly reduce the need for gasoline. However, a large barrier for the renewable energy technologies is the large amount of heat generation in limited space that cannot be released. Therefore, a good thermal management must be involved in order to lead the performance of these technologies to another stage. Thermal management play an important role in PEM fuel cells and lithium-ion batteries [24, 35,36,37,38,39,40,41, 42].

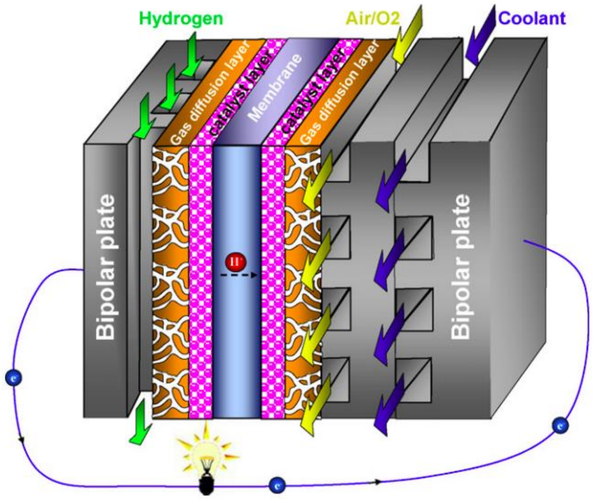


Figure 1. Cooling units in a PEM fuel cell [36]

PEM fuel cell converts electricity from hydrogen by the electrochemical reactions in the electrolyte. This technology is widely applied in multiple areas and one symbolic category is the automobile industry (Toyota Mirai, Honda Clarity). Figure 1 above is a schematic diagram of a proton exchange membrane fuel cell which we can see all the components from the outer bipolar plate to the electrolyte at the center. A stack of fuel cell usually includes 300 to 400 cells, and there are many components to interact together while operating a stack of fuel cell as a single system [37]. A major issue for a complete fuel cell stack is the overheat since fuel cell stack cooling is very challenging due to the small temperature differences. Traditional thermal management usually done by air and liquid cooling. However, air cooling only valid for stack range of 200W to 2kW and liquid cooling involves disadvantages such as water leakage. Therefore, oscillating heat pipes can be a great choice for the thermal management of a PEM fuel cell due to its flexibility, operation methods, and simplified system.

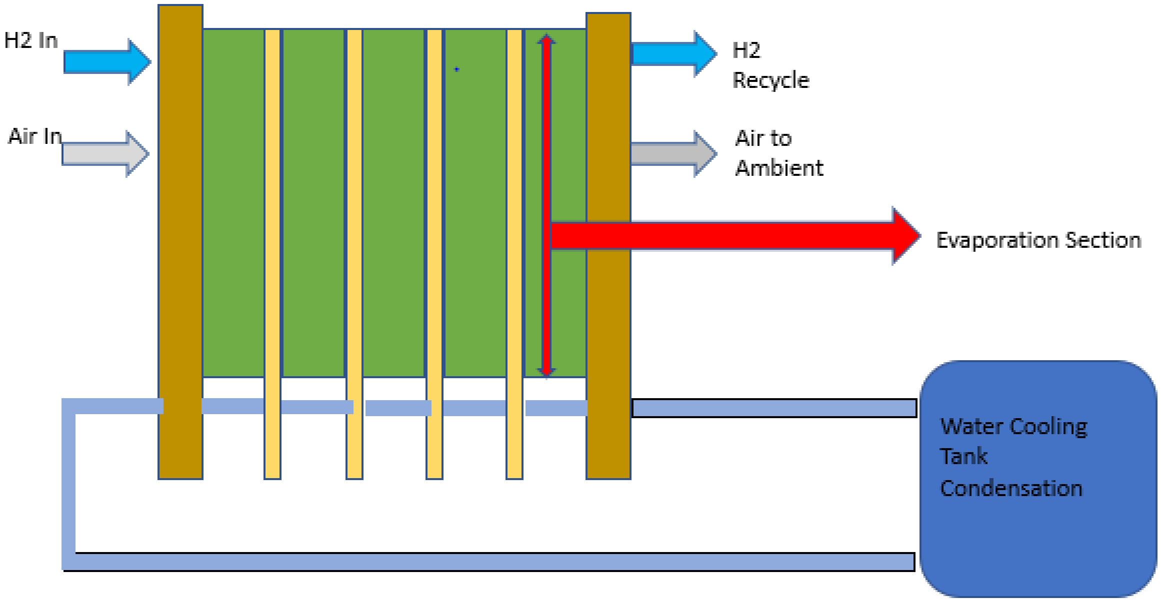


Figure 2. OHP as Cooling Units in PEM Fuel Cell

Figure 2 above shows the cooling strategy of the cooling unit for each single cell. The green plates are the fuel cells, and yellow plate are the OHP. When the fuel cell stack is operating, heat generated at the green parts which can be considered as the evaporator section of the oscillating heat pipes. Then the external water tank connects the bottom part of each OHP can be treated as the condensation section. By apply this method, each OHP can transfer the heats generated by the fuel cells; and without the limitation of heat transfer, the fuel cell stacks can achieve a better performance. In order to prove this method is achievable, later sections will include an analyzation of the relations between the evaporator and condenser for proper operation.

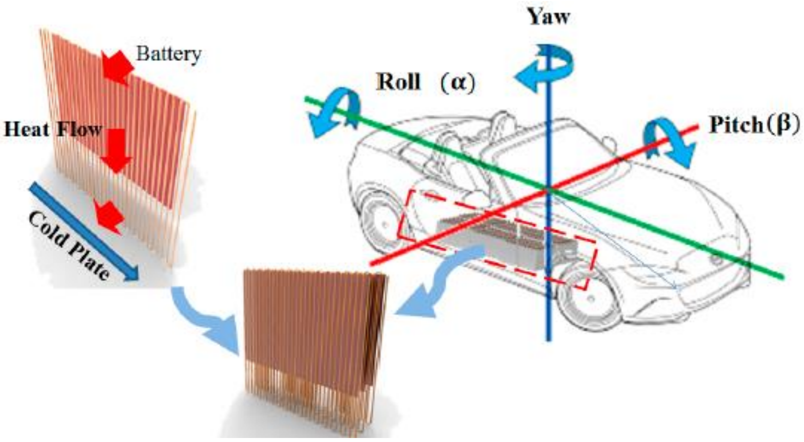


Figure 3. Electric Car Cooling Modeling by using OHPs [24]

The performance of Lithium-ion batteries was limited by the thermal resistance of the heat generation during the charging and discharging; the large amount of heat generated can reduce the capacity and lifetime of the battery [29]. Traditional ways for lithium-ion battery thermal management are either conventional air cooling or water cooling. However, the conventional air cooling cannot satisfy the high demand in heat transfer performance due to the limited thermal conductivity and specific heat of air. Water cooling satisfies most of the requirements for heat transfer of the battery, but side effects such as water leakage, friction loses stopped it from being commercialized. Therefore, advanced heat transfer device must be interpreted with the lithium-ion battery for better performance. Oscillating heat pipe is one of the promising technologies among all the heat transfer devices with its compact size, high heat transfer rate, and low construction cost. Figure above shows the combined system of Lithium-ion battery and two oscillating heat pipes by [24]. The OHP shows above is a Closed-End Oscillating Heat pipe has 150mm evaporating section connected with the lithium ion battery and 15mm for the condensation section. The result shows that the system works out great if the working fluid ratio is larger than 10%, and the overall heat transfer rate depends on the amount of working fluid charged.

1.2 Traditional Heat Pipes

Oscillating Heat Pipes were originally developed from the tradition heat pipe, it is a device of very high thermal conductance and operating with small temperature difference. The idea of the traditional heat pipe was first developed by Gaugler, then fully invented Grover [1]

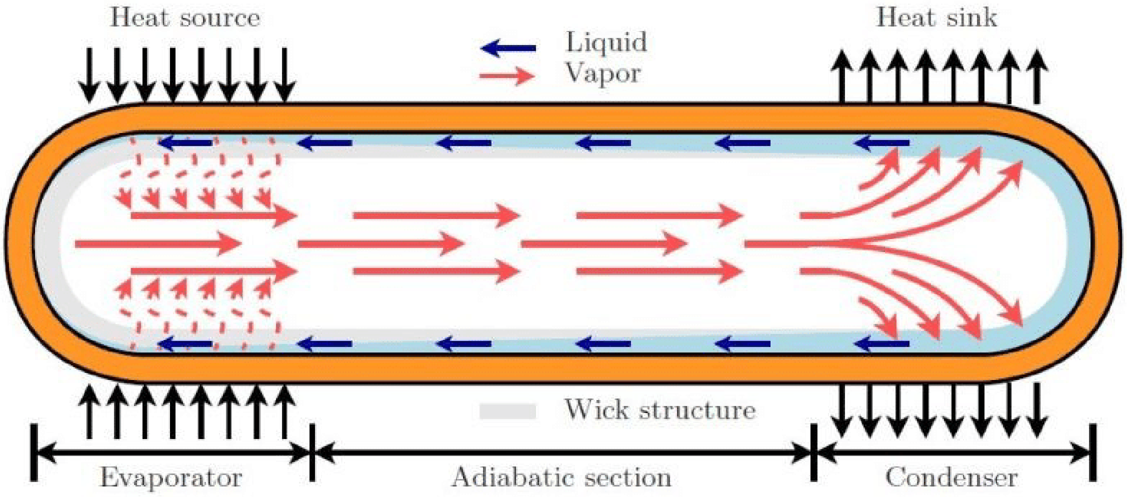


Figure 4. Schematic of a traditional heat pipe with tubular structure and closed ends [31]

The figure above is a simple schematic of a traditional heat pipe contains the evaporator as the heat source and the condenser as the heat sink; also, the working fluid to transporting heat. The traditional heat pipe usually is constructed by the hollow metal tubes with closed ends; before installation, the tubes will be vacuumed and filled with the working fluids. There is also a component called the “wick structure” to transport the working fluid from one end of the heat pipe to another end.

1.3 Oscillating Heat Pipes

Since the invention of the tradition heat pipe by Grover [1], there were more types of heat pipes with different focus developed. Oscillating heat pipe is one of these technologies that comes with better thermal performance, wide application, and lower temperature requirements. Oscillating heat pipe is an upgraded version of the traditional heat pipe; similar to the traditional heat pipe, it is also a two-phase heat transfer device and divided into three components, the evaporator section, adiabatic section and the condenser section. There are also some improvements made from the traditional heat pipe, such as higher heat transfer rate, and better thermal performance, and, the wick structure from the traditional heat pipe was removed from the oscillating heat pipe.

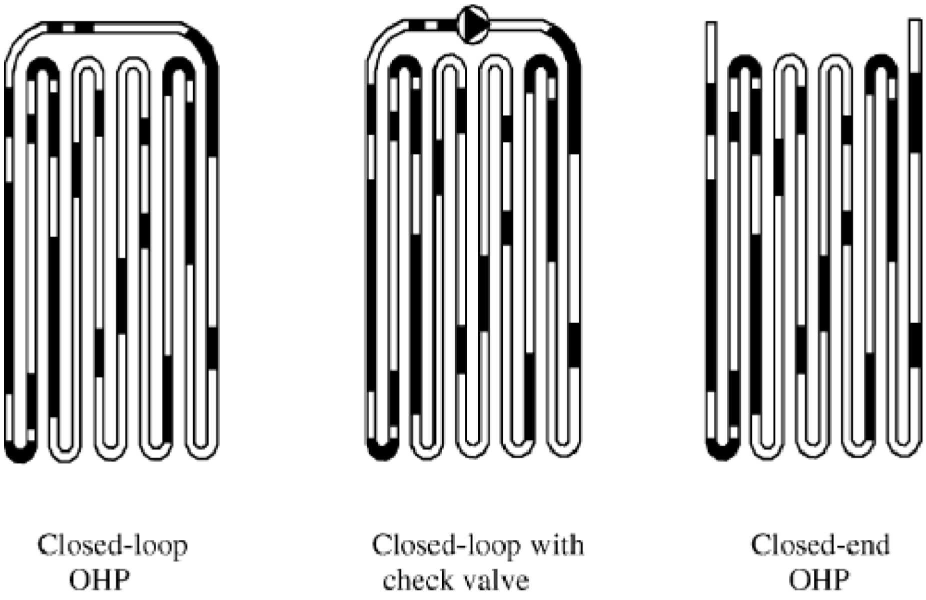


Figure 5. Types of Oscillating Heat Pipes [33]

The figure above shows the three types of the oscillating heat pipes. The first one on the left is the Closed Loop- Oscillating heat pipe, the two ends of the tubes are joined together to create a closed loop environment. The second one on the middle is the Closed Loop OHP with Check Valve; the check valve is a flow control valve, and in this type of OHP, the flow control valve is the outstanding point, it controls the flow/ flow rate of the working fluids. The last one on the right side is the Closed End- Oscillating Heat Pipe or known as the open loop oscillating heat pipe. The two ends of the tubes are open to the surroundings. All three models were designed to fit the corresponding conditions. The Closed Loop Oscillating heat pipe operates with a bulk circulation in either direction. The Closed Loop Oscillating heat pipe operates with a one direction circulate for the working fluid. The Closed End Oscillating heat pipe operates with no bulk circulation. From many past researches on OHPs shows that the Closed Loop Oscillating heat pipe is the most efficient type compared to others.

Design Ref.	Material	Turns	Tube Diameter	Method of Cooling	Reference
1.	Copper	23	2mm	wind fan	[14]
2.	Copper & Borosilicate Glass	7	1mm & 2mm	water cooling	[8]
3.	Aluminum	7	1.8mm	water cooling	[24]
4.	Stainless steel	6	2mm	water cooling	[15]
5.	Copper	5,11,16,26	1mm, 1.5mm, 2mm	wind fan	[21]

Table 1. Designs done by other researchers

The table above shows some typical designs by literature review. Each design above targets to different goal from thermal performance to the specific application. The first design was done by Liu [14], the purpose of this experiment is to test the thermal performance of coupled OHP Both OHP consists the same configuration as shown above but filled with water and ethanol as working fluid separately. The result shows that the heat transfer performance for a coupled OHP is better than a single OHP when operating at small temperature difference. This design can be used in the fuel cell stack cooling and the lithium ion battery cooling due to the outstanding performance when operates under small temperature difference. The second design done by

Babu [8] used copper and borosilicate glass to construct the OHP. Copper used in the U-turns and borosilicate glass used in the adiabatic section for observation of the working fluid motions. The purpose of this design is to test the influence done by the working fluid with different filling ratios to the thermal performance. The article shares the performance of five different working fluids (Acetone, Benzene, CCL_4, Methanol, Ethanol) under the configuration shown above. The result indicates that Acetone has the lowest value of thermal resistance among all five working fluids, and the thermal resistance is decreasing while the heat power input is increasing. The purpose of the third design done by Wang [24] was to exam the performance of OHP in the battery thermal management system. This paper focused on test the temperature of the condenser and evaporator under different conditions. Result of this paper suggested that the oscillating heat pipe-based battery thermal management system is better than the traditional ways. The next design was constructed by the stainless steels. The purpose of this design was to test the difference between use the base fluid- water, and the $Al_2O_3\ nanofluid.$ Qu [15] states in the conclusion that compare to pure water, the heat transfer performance improved by use the alumina nanofluid when 70% filling ratio, 0.9% mass fraction and 58.8W power input. The last design shows on table 1 was made by copper. Piyanun [21] used this design for exam the thermal performance of the horizontal orientation OHP. The experiment runs for multiple set ups; number of turns contains 5,11,16,26 turns in the design. Water and pure ethanol used for the working fluid with filling ratio from 30% to 80% tested. The results indicated that there is an operation limit for the horizontal oriented OHP. For 2mm tubes, the number of turns should be more than 11. For 1.5mm and 1mm tubes, the number of turns should be more than 16. In addition, the thermal performance of the horizontal orientated OHP can be improved by increase the evaporator temperature and shorten the effective length of the evaporator.

1.4- Objectives

The objective of this paper is to investigate the parameters that influences the thermal performance of the closed loop oscillating heat pipe and ways to develop the heat transfer performance to a better stage. Specifically,

1.) The filling ratio;
2.) The working fluids;
3.) The orientation of the oscillating heat pipe;
4.) The operation conditions of the evaporation and condensation section;
5.) The nanofluid boost with magnetic field.

Chapter 2. OHP Operation Principles

2.1 History & Backgrounds

Oscillating heat pipes (OHPs) or referred to the pulsating heat pipes (PHPs) were a relatively invention from the heat transfer area of the heat pipe technologies. The idea was first developed by a Japanese researcher Hisateru Akachi at 1990. The basic structure of OHPs included U-shape mini channels with working fluid filled; evaporation and condensation sections were also attached to help the working fluid "Pulsating" in the mini channels for heat distribution and better thermal performance. The operation methodology is making the working fluid transferring between the liquid and vapor phase to create the bubbles "jumping" across the tube for transferring the heat. The advantage of this new technology compares to the traditional heat pipes where it can be working at higher heat fluxes without a wicking structure to transport the working fluid. [3]

2.2-Operation theories of the Closed Loop Oscillating Heat Pipes

The basic operation principle of the oscillating heat pipe is to oscillate the working fluid by the phase change phenomena caused by the temperature difference to delivery heat inside the capillary tube. This paper mainly focused on the Closed Loop Oscillating Heat pipes; the CL-OHP is a type of OHP including the U shape tubes to form up a closed loop; heat transferred by the working fluids that flows inside the loop. There are three main sections of the CL-OHPs which are the condenser, evaporator, and the middle adiabatic section.

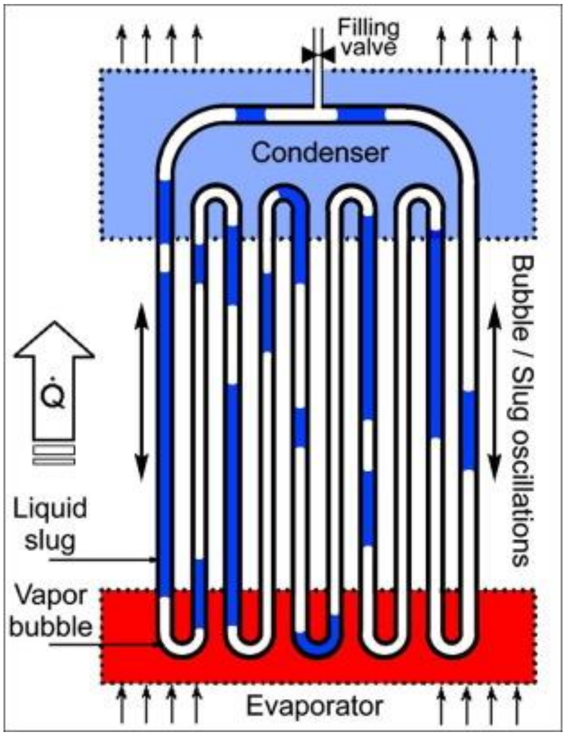


Figure 6. Schematic of a Closed Loop- Oscillating heat pipe [12]

The figure 6 shows a simple schematic diagram of a Closed Loop- Oscillating heat pipe; it is a very symbolic set-up of the CL-OHPs which it is vertically oriented with condenser on the top and evaporator on the bottom. This set up is to take the advantage of the gravitational force when the fluid is vaporized by the evaporator, it will move up to the condenser, also, when the fluid is condensed to liquid by the condenser, it will be dragging down by the gravitational force to the evaporator. By applying the processes and creating a small temperature difference, the working fluid can be a constantly changing in the vapor and liquid phase that causing the working fluid to oscillate in the meandering tube to increase the thermal performance. The filling ratio of the CL-OHP is usually within the rage from 20% to 80% respecting to the evaporator and condenser temperature [10,5]. The inner tube must be vacuumed before adding the working fluid for a better thermal performance. When adding the appropriate ratio of the working fluid, there will be proportion of liquid and vapor form of the working fluid that shows in figure 6 from last page; the blue part is the liquid slug and the white part is the vapor bubbles. As talked before, the whole cycle process starts from the vapor bubbles condensed to liquid slug at the condenser then transferred to the evaporator by the adiabatic section; the liquid slug burns into vapor bubbles in the evaporator then goes back to the condenser. By operating the completed cycle, working fluid in the CL-OHP oscillates inside the system, and heat will be transferred due to the temperature and pressure difference inside the whole system.

The whole system can be described by a pressure vs. enthalpy diagram which the OHP maintains isothermal throughout every process of the system and the equilibrium state exists for the liquid and vapor phase when the saturation pressure and the fixed isothermal temperature matches.

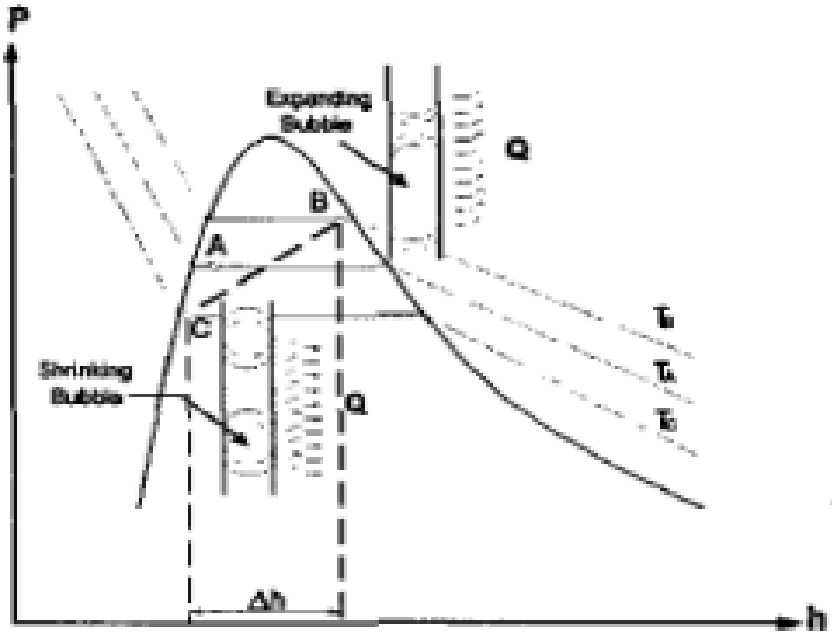


Figure 7. Pressure vs. Enthalpy diagram [32]

Figure 7 above is a thermodyanmic diagramic which describes every process of the system. The diagram shows that the heat transfer to the evaporator caused the vapor bubbles and these vapor bubble grow continuously then move from Point A to Point B at higher pressure and temperature. At the same time, the liquid slug occurs at the condenser due to lower temperature and pressure were forced to move from point A to point C. These processes results a non-equilibrium condition. Due to these reactions in to the system, the motions of liquid slug and vapor bubbles at the condenser leads the actions of the liquid slug and vapor bubbles near the evaporator as well; the interactions between all of the compnents leads the oscillation of vapor bubbles and liquid slug in the pipe; however, the CL-OHP will never able to reach to steady state pressure equilibrium as the traditional heat pipes does.

2.3 Experimental Investigation

The performance of the OHP relies on different factors such as the structure, working fluid, orientation, material etc. The purpose of this paper was focusing on analyzing the influence on the thermal performance of a CL-OHP by the working fluid, filling ratio, orientations, and evaporator & condenser sections. The fundamental equation to configure the thermo performance of the OHP is

$$Q = \frac{\Delta T}{R_{th}} \tag{1}$$

This equation describes the relation where the heat load equals to the change in temperature (evaporator & condenser), divided by the total thermal resistances. The thermal resistances can be broken to two parts the thermal resistance from the evaporator and condenser; by combing the thermal resistances, the equation was derived as

$$Q = \frac{\Delta T}{L_{eff}/(k_{eff} * A_{cross})} \tag{2}$$

The denominator means the effective length divide by the produce of effective thermal conductivity and cross-sectional area of the tube. The working fluid selection is important for an

OHP since oscillates and transfers heats. There is a board selection on the working fluid, and to choose the appropriate one is the most important. A simple way is to use the Clausius-Clapeyron relation to determine the corresponding working fluid to the system which the equation was written as:

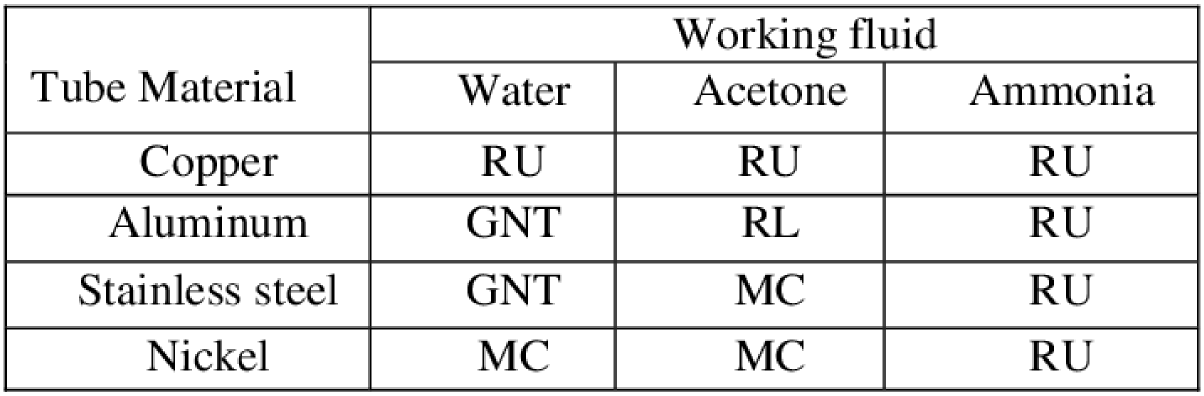
$$\left(\frac{dP}{dT}\right)_{sat} = \frac{l}{T_{sat}v} \tag{3}$$

The equation basically characterizes a discontinuous phase transition between two phases of matter of a single constituent. l is the latent heat, and v is the specific volume. The filling ratio of the working fluid is important, and the later sections tests the thermal performance corresponding to different filling ratios from the range 20%~80%. Different from the traditional heat pipes, oscillating heat pipe can operate at any orientation. However, different orientations of OHP can be resulted in the increase or decrease in the thermal performance; the experiment also tested the different orientations of the OHP from vertical to horizontal. Temperatures in the condenser and evaporator is also important in order to get best performance; therefore, different temperature of the condenser and evaporator were also examined and will be described in later sections.

2.3.1. Working Fluid & Filling Ratios

Working fluid is the most important factor along all the components of an Oscillating heat pipe; it is also the easiest way to increase the thermal performance of an existed oscillating heat pipe. Different working fluid requires different operating temperatures and filling ratios for the best performance. According to Himel Barua in his Journal Paper *Effect of filling ratio on heat transfer characteristics and performances of a closed loop pulsating heat pipe*, the filling ratio for water to the best thermal performance is around 30% at low heat input (lower than

70W); however, ethanol requires 50% of the filling ratio to achieve the optimum heat transfer. Working fluid selections must obey some rules, [10] summarized the rules that must be considered when selecting the appropriate working fluid. The first one is that in order to make the fluids oscillate in the tube quick, the latent heat must be small; the viscosity of the working fluid must be low since high viscosity fluids causing high shear stress. Also, if the surface tension drops to a low level, additional pressures drops at the same time. Working fluid selection involves considerations from many areas, the properties of the working fluid itself, and the properties of the material that used to develop the OHP.



Tube Material	Working fluid		
	Water	Acetone	Ammonia
Copper	RU	RU	RU
Aluminum	GNT	RL	RU
Stainless steel	GNT	MC	RU
Nickel	MC	MC	RU

Table 2. Matching of OHP material with Working Fluids [32]

The Table above shows the compatibly of three common working fluids width the tube material on the effects of the performance. RU means recommended by past successful usage; RL means recommended by literature; MC means may compatible; GNT means generation of gas all temperatures. From the table, copper is the best choice which it can properly works with all three working fluids; however, the cost of copper from manufacturing and material is high, therefore, Aluminum is a good alternative to replace copper. Stainless Steel and Nickel are also popular material for special cases. [10]

2.3.2 Testing Bed Orientation

The configuration and orientation of the Oscillating heat pipes may cause a different in the heat transfer. For instance, the thermal performance of Closed Loop- Oscillating heat pipe is better comparing to other types of OHPs since it created a closed loop which making the velocity of working fluid increasing and sensible heat. Oscillating heat pipes can be orientated in any direction, and this is one of the main advantages comparing to the traditional heat pipe. However, the orientation of OHPs may influence the filling ratio and number of turns for the system; as mentioned by [10], vertical orientation requires a smaller number of turns in OHPs to work properly compares to the horizontal orientation. Xue Zhihu and Qu Wei proposed a study of the influence on the orientation to a Closed Loop- Oscillating Heat pipe with ammonia as the working fluid and 50% as the filling ratio. The tube that used for the testing bed were 6mm outer diameter and 2mm inner diameter. The experiment runs from 90° (vertically) to 0° (horizontally) with power input from 40W to 280W. The results show that the startup performance is good regardless of the inclination of the testing bed; however, the closer to the horizontal orientation requires higher filling ratio to avoid the “vaporization” of the working fluid.

2.3.3 Operating Temperature and Location of Condenser & Evaporator

The location and operating temperature are important for the whole system to be operated; for example, the effective length of the condenser and evaporator will influence the thermal performance. Operating temperature of the condenser and evaporator were also considered as a fundamental factor of Oscillating Heat Pipes. Similar to a simple Rankin Cycle, the change of temperature in the evaporator or condenser will resulting either increase or decrease to the thermal efficiency. [2] introduced the influence from the condenser temperature to the overall system. The working fluid used for this experiment is distilled water with 50%

filling ratio; copper tube with 5 turns and 3.18 inner diameter and 4.76 mm outer diameter were applied. The condenser zone was used by a cold plate which the temperature can be adjusted from the range of 10 C° to 60 C°. The experiment set up is a basically combine the heat pipe with the cold plate (silicon cold plate, not water cooling); and the tube was vacuumed before the working fluid injection to increase the performance of the system. The experimental heat input was from 20W to 140W, and each power input comes with 6 runs for the temperature of the condenser from 10C° to 60C°. The results show that in order to make the system working, the lower of the power input requires a higher condenser temperature. For example, if the power input was only 40W, then the condenser temperature must be at least 40C° to start working, and 50C° to fully operate.

Chapter 3. Methodology

This section focused on the experimental details. The initial and latest design of the Closed Loop- Oscillating heat pipe is introduced and explained for the purpose of the design modification. Experimental tests for multiple components to increase the thermal performance are also included.

3.1 Closed Loop-Oscillating Heat Pipe Design

Designs were made into a flat plate with groove build in instead of using U-shape pipes due to the purpose of observe the motion of the working fluids. This section explains the transition from the initial design to the latest one.

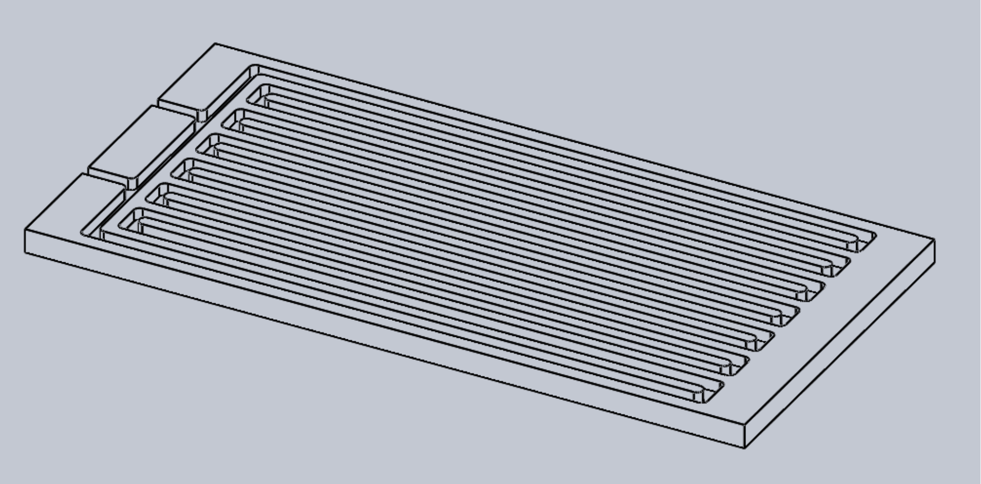


Figure 8. Initial Design of the Closed Loop-Oscillating Heat Pipe

Figure 8 is the initial design that was developed for the CL-OHP by referencing others' work that had been done; The dimension of the plate is 120mm x 60mm x 4mm. There are 7 turns at the evaporator section and this number was designed because the CL-OHP requires to be tested at different orientations, horizontal orientation requires more turns in order to operate properly []. Each tube that build in the plate has a 2 mm diameter; the effective length of evaporator and condenser are flexible since it will be tested in later section. The material of the plate was selected by a trade of study by comparing some common materials used to construct a Closed Loop- Oscillating Heat Pipe.

Material	Cost	Thermal Conductivity	Manufacturing Difficulty
Copper	$310	$385\frac{W}{mK}$	High
Aluminum	$275	$205\frac{W}{mK}$	Low
Stainless Steel	$450	$50.2\frac{W}{mK}$	Medium

Table 3. Trade of Study on CL-OHP Materials

The table above is the trade of study on the CL-OHP initially designed, it compared Copper, Aluminum, and Stainless Steel from different areas. The first one is cost, it included both material and manufacturing cost. As we can see that Aluminum cost the lowest. The second category is the thermal conductivity of the material; thermal conductivity is basically the amount or speed that heat transmitted through a material, therefore heat will be transferred across the material faster with higher thermal conductivity. Among all the materials, copper has the highest thermal conductivity. Manufacturing difficulty refers to the deformation possibility, and hardness level of grooving these pipes on the plate. All the manufacturing evaluation were based on the standard of industrial CNC machine, and specialist from the machine shop. Copper is the highest because it is easy to be plastic deformation after the material processed. Stainless steel is medium because that material is very “hard” so better knife must be used for processing which increased the cost. Aluminum is low since it is easy to be manufactured and the possibility of deformation is lower than copper. By combining all three categories; aluminum became the best choice.

Before manufacturing the initial design, there were few problems and concerns of the design; after the fully consideration, the latest design is known to improve the Oscillating Heat Pipe significantly from the initial one.

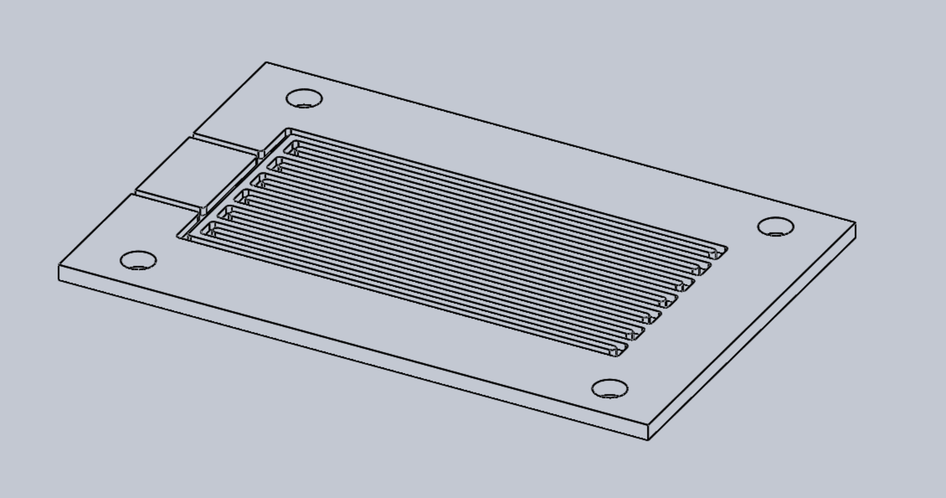


Figure 9. Latest Design of Closed Loop Oscillating Heat Pipe

Components	Configuration
OHP Material	Aluminum
OHP Plate Dimension	150mm x 100mm x 4mm
Condenser Length	35mm
Evaporator Length	35mm
Adiabatic Length	42.5mm
Channel Thickness	2mm

Table 4. Statics of the CL-OHP

Figure 9 is the latest design of the CL-OHP. This design keeps the 7 turns at evaporator section from the initial one, but the dimension of the plate changed to 150mm x 100mm x 4mm. The diameter of the tube is still 2mm and each tube is 104.5mm long. As showed on the figure, four holes trepanned on the plate for mechanical connections; the diameter is 8.73mm which fits the #8 nuts.

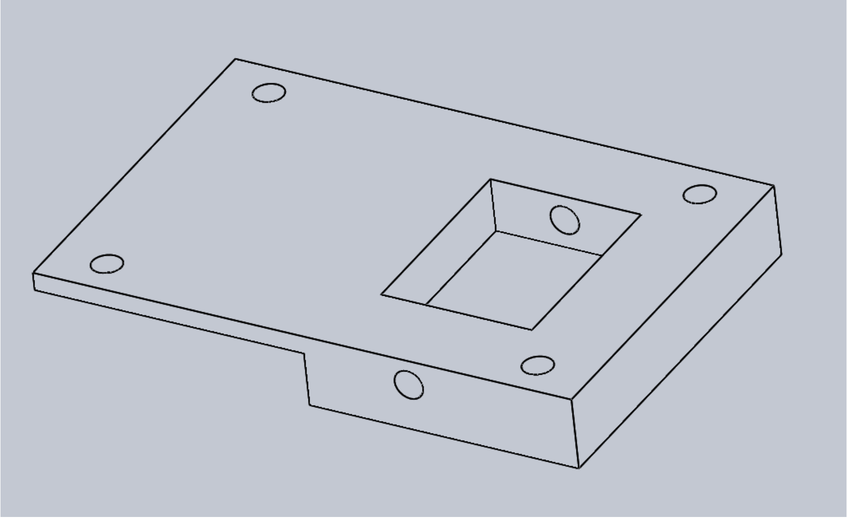


Figure 10. Lower Plate with Water Sink

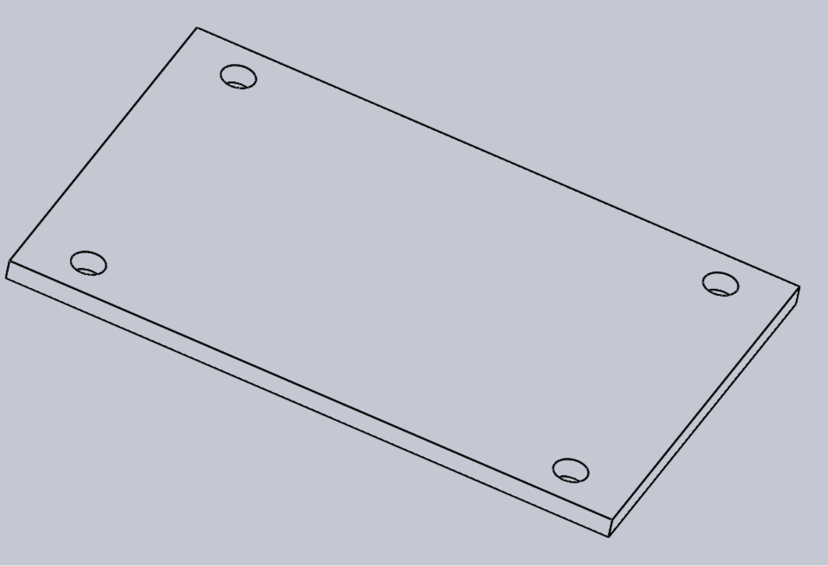


Figure 11. Upper Plate

Figure 10 and figure 11 are 150mm x 100mm (length and width) which fit with the OHP plate. The lower plate contains a specially designed water sink as the condenser; the dimension of the water sink was 54mm x 42mm x 15mm and the volume is around 34ml; the material for lower plate is plastic which processed by 3D printer. The upper plate is made by clear acrylic board which used to observe motion of working fluids, also seal the OHP plate to avoid gas leakage.

3.1.1 Experiment Set-up

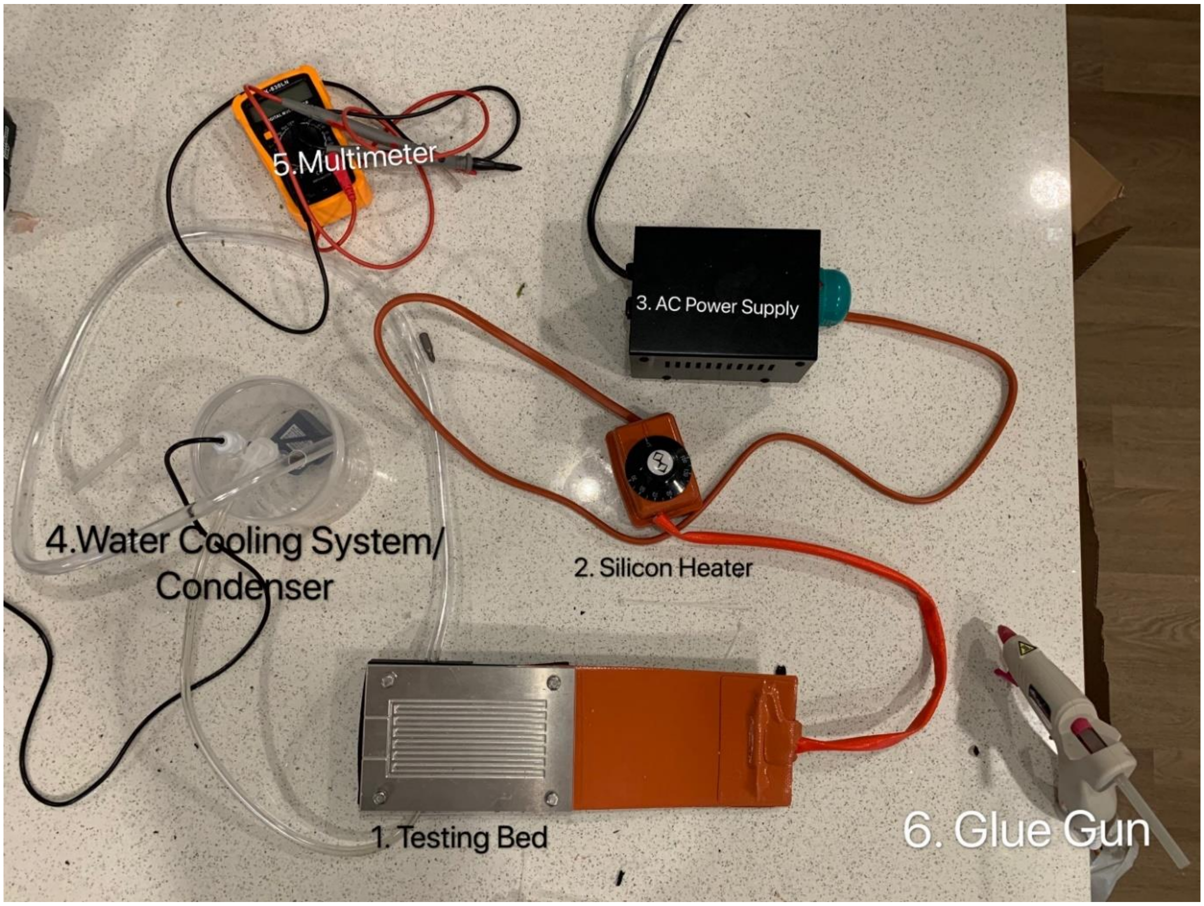


Figure 12. Experimental Set-Up

Figure above is an experiment set-up for the whole system; 1 indicates the testing bed of the OHP. 2 indicates the silicon heater which is the evaporator. 3 is the AC Power Supply which can adjust the power input. 4 is the water-cooling system which connects to the condenser, water flows to the water sink at the lower plate then goes back to the water tank. 5 indicates the multimeter and it is for testing purpose on the wires. 6 is the glue gun used to seal the gaps to avoid vapor or liquid leakage. Temperature of the condenser can be changed by control the temperature of the water, and temperature of the evaporator can be changed by the switch of the silicon heat from 0° to 150 °; in addition, effective length of the evaporator can also be modified by increase the heating area.

Figure 13. Vacuum Pump connects with the OHP

Figure 13 is the vacuum pump which used to vacuum the OHP testing bed before starting the experiment. The connecting was made by a needle injector and sealed by hot glues to avoid gas leak.

3.1.2 Thermal Performance of the Closed Loop-Oscillating Heat Pipe

The thermal performance of the CL-OHP can be influenced by multiple components such as the structure, material, working fluid, or temperature. An easy way to determine the thermal performance of the CL-OHP is to compare the thermal resistance of the CL-OHP, which the fundamental equation is

$$\mathrm{R}_{\mathrm{thermal}} = \frac{\Delta \mathrm{T}}{\mathrm{Q}} \tag{4}$$

However, the total thermal resistance of the CL-OHP relies on different factors since it is a two-phase heat transfer device which involves multiple factors that causes the thermal resistance to the overall system.

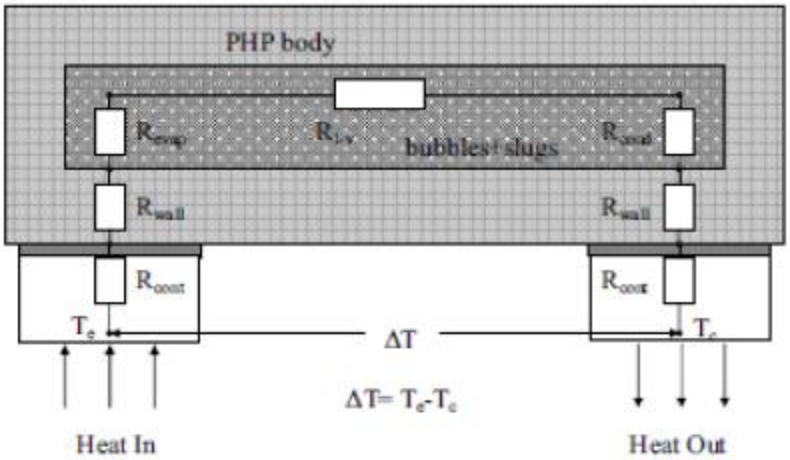


Figure 14. Thermal Circuit for Oscillating Heat Pipes [35]

Figure above is a thermal circuit for the OHP, as we can tell that there all multiple places that has a thermal resistance must be considered. The evaporator & condenser section is causing thermal resistance while operating due to the thermal process (R_{evp}, R_{cond}). Also, through the heat pipe tube there is a conductive thermal resistance (R_{eff}) appear due to the working fluid head capabilities. There are also two contact thermal resistances R_{cont} due to the surface roughness. After analyzing all the factors, an equation for the heat transfer capacity of the system can be written as:

$$Q = \frac{\Delta T}{2R_{wall} + R_{evp} + R_{cond} + R_{eff} + 2R_{cont}} = \Delta T / \left(\frac{L_{eff}}{k_{eff}} - A_{cross}\right) \qquad (5)$$

where the temperature means the change of temperature between the evaporator and condenser, and the L_{eff}, k_{eff} means the effective length and thermal conductivity. A_{cross} is the cross sectional area of the capillary tube.

3.2 Experimental Procedure

There are multiple components within an OHP that influences its thermal performance; this section focuses on the effects of the working fluid, filling ratio, orientations and operating temperatures on a closed loop- oscillating heat pipe.

3.2.1 Filling Ratio on OHPs with Different Working Fluids

Working fluid is a very important factor which influences the thermal performance of Oscillating heat pipe. The stronger motion of the working fluid results in higher heat transfer rates. The working fluid should be chosed from the boiling point, the latent heat of vaporization, dynamic viscosity, and fluid thermal conductivity. After evaluating the best available working fluids, water and ethanol were selected. The experiment tested for both pure water an 91% concentrated ethanol for the filling ratio from 30% to 80%; analyzations of the best performaning filling ratio was also included, and a mathmatical model was developed for the filling ratio. A easy way to determine is to compare the thermal resistance between each filling ratios. The oscillation of the working fluid was mostly depended on the pressure & temperature difference from both sections; if the vaporization of the fluid increases, the vapor pressure increases. By interpreting the Lapace-Young's equation, the pressure equation should be[4]

$$\Delta P = P_{vapor} - P_i = \sigma \left(\frac{1}{r_1} + \frac{1}{r_2}\right) \tag{6}$$

From the dimension of the system we can tell that the radius of the tube is veryh small, and can be assumed as constant at the liquid vapor interface. Since there are pressure difference all over the liquid vapor interface we can develop a relation for the radius which $r_1 = r_2 = \frac{r}{\cos\theta}$. By referencing Butt's work [4,17] we can get the equation which:

$$P_{vapor1} - P_{vapor2} = \frac{2\sigma(\cos\theta_1 - \cos\theta_2)}{r} + (P_i - P_v)g(h_2 - h_1)\cos\theta \tag{7}$$

The equation above basically defined a relationship between the pressure difference with the liquid interferance, to the hydraulic pressure difference with the gravitional force. Now by differentiate the ideal gas equation which $P = \rho RT$ we got that:

$$\frac{dP}{dt} = RT\frac{(D\rho)}{dt} + R\rho\frac{dT}{dt} \tag{8}$$

Now assuming the density and temperature from the initial to the trasient to be $\rho_{vapor} = \rho_{vapor,i} + \Delta\rho;\ T = T_i + \Delta T$, then interpreting to the differenated ideal gas equation.

$$\frac{dP_{vapor}}{dt} = R(T_i + \Delta T)\frac{d\rho_{vapor}}{dt} + R\left(\rho_{vapor,i} + \Delta\rho\right)\frac{dT}{dt} \tag{9}$$

The equation can be similified as: $\frac{dP_{vapor}}{dt} = RT_i\frac{d\rho_{vapor}}{dt} + R\rho_{vapor,i}\frac{dT}{dt}$;

Previous work indicates that the expression of the heat addition can be modified as [4,17]

$$q_{vapor} = \frac{d\rho_{vapor}}{dt}V_{vapor}h \tag{10}$$

We can tell that both equations can be interpreted to one equation and by taking the integral from both side of the equation, we can get the heat addition for the system which:

$$q_{vapor} = \frac{\left(2\sigma(\cos\theta_2 - \cos\theta_1) + r_b\left((\rho_{liquid} - \rho_{vapor})g(h_2 - h_1)\cos\beta - R\rho_{v,i}\Delta T\right)\right)(1-\phi)\pi r h u_{liquid} u_{vapor}}{RT_i(u_{liquid} - \phi(u_{liquid} + u_{vapor}))} \tag{11}$$

Since the heat addition can be control for the testing bet; we can easily isolate ϕ from the equation to get the maximum filling ratio of the specific working fluid, and the performance of each conditions.

The testing bed was operated vertically; 7 turns at evaporator and 2mm as the inner diameter. Water cooling was used for the condesenation and silicon heating pad used for the evaporatorization. Everyting in the system remains constant as a given value except the working fluid and filling ratios.

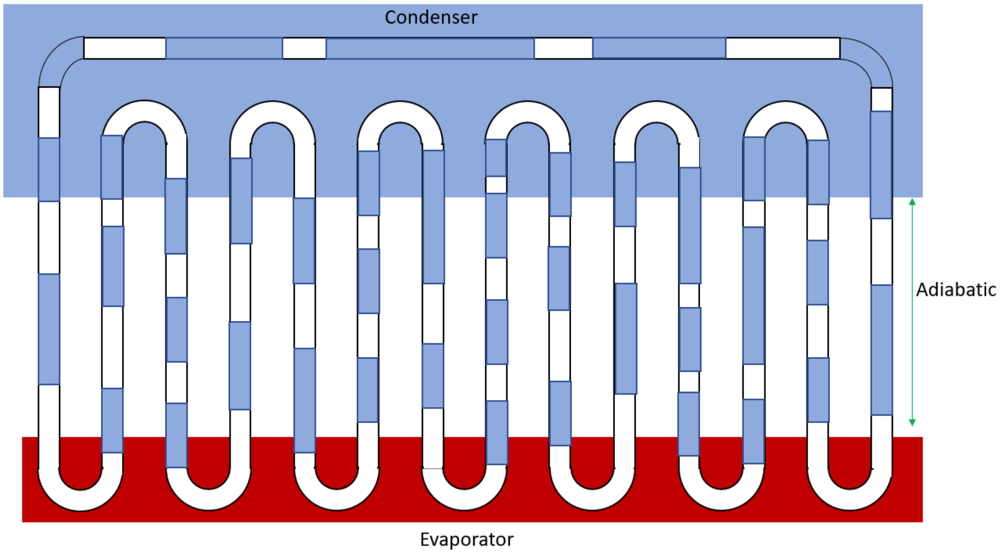


Figure 15. Demonstration of working fluid oscillating in the pipe

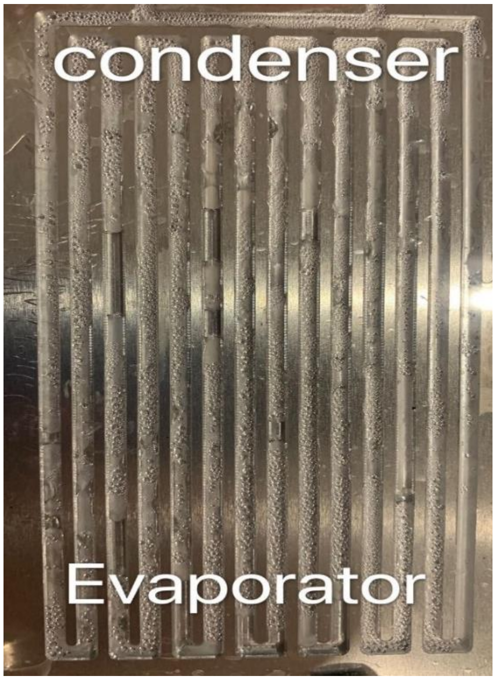


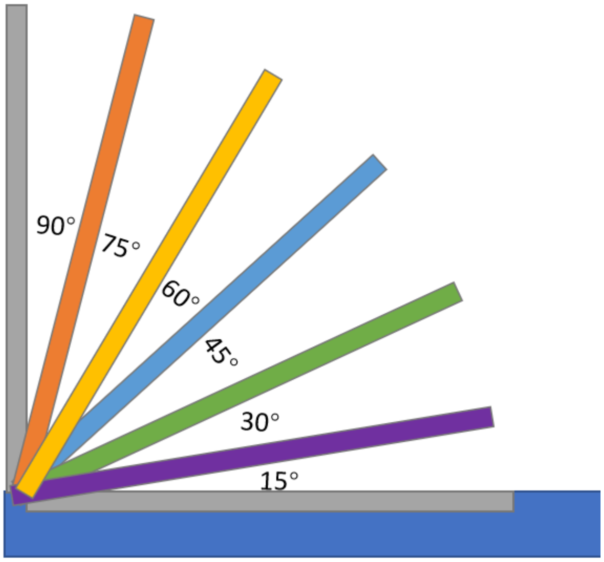
Figure 16. Working fluid inside the channels

These two figures show the motion of the oscillating heat pipes working; the plate was sealed by both plastic wrap and hot glues to keep the environment sealed. The first figure offers a clear view of a Closed Loop Oscillating Heat pipe with approximately 70% of the filling ratio; which we can see the vapor plug and liquid slug were oscillating. However, in the real experiment, the vapor plug and liquid slug are not totally separately. The second figure shows an OHP operating at

30% working fluid. We can see that most of the water became vapor and small pieces around the tube, and there were a few liquid slugs near the condenser section.

3.2.2 Influences of Testing Bed Set-up on the Thermal Performance of OHPs

Oscillating heat pipe is a recent technology; one of the most important reason that it is better than the traditional heat pipe is OHP can be placed in any orientation and still operates. This section of the experiment continued using the same testing bed as the other sections. All the dimensions, tubes diameters, are the same. Water used as the working fluid 50% as the filling ratio are tested for accurate conclusions. Procedure of the experiment were all the same which the silicon heater was used for the evaporator; water cooling for the condenser; every time before running the experiment, the whole plate must be sealed by plastic wrap & hot glue, also, vacuumed by the pump. The experiment runs for orientations from vertical to horizontal as showed in figure 17.



.

Figure 17. Orientation Demonstration of the Testing Bed

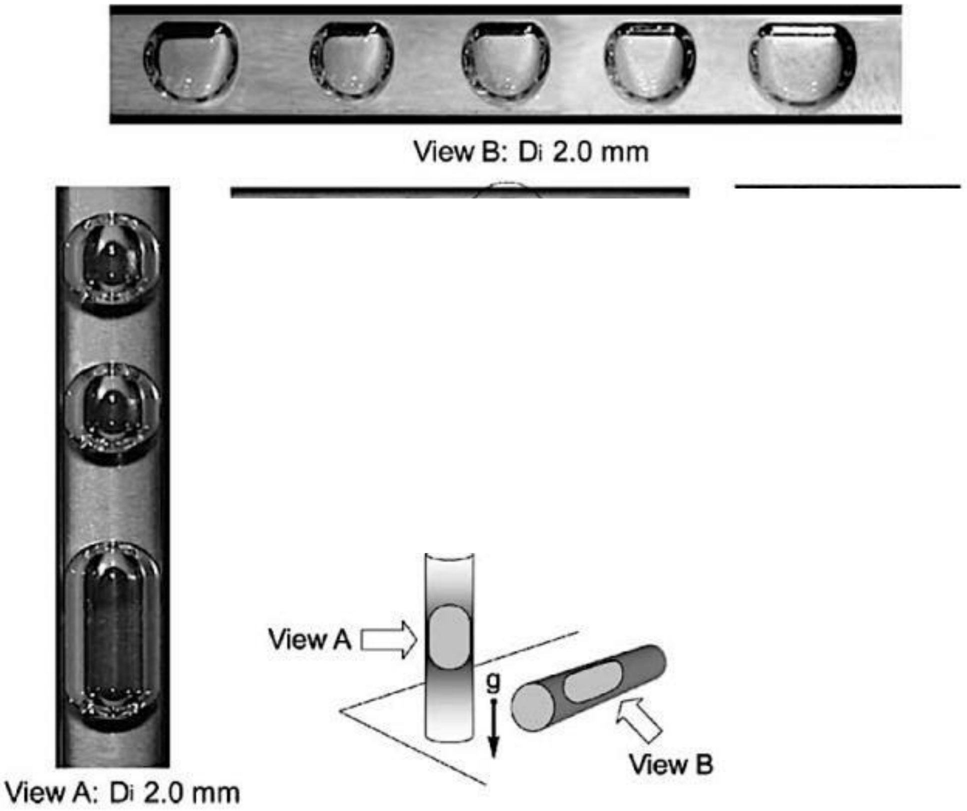


Figure 18. Ethanol Slugs and Bubbles in the simulated condition of OHP [34]

Figure 18 demonstrates the motion of ethanol inside a simulated environment of OHP; consider the 2mm pipe with view A and view B. Focusing on view B first which is the horizontal orientation; the liquid seems to the downward direction. Refer to the view A, larger droplet at the bottom part and seems be dragged by something. Both orientations show that the gravitational force influences the fluids inside the pipe; so, the gravity must impact with the performance with the OHP performance. In addition, the working fluid inside the pipe perform different since the testing bed is a flat plate instead of actual tube. Sealing is the hardest part of the vertical orientated experiment and takes extra steps compares to the horizontal orientation. Plastic wraps need to be fully covered the testing bed and then use hot wind blower to make it stick with the testing bed and avoid the working fluid leave the mini channels. The mathematical analyzation was based on the thermal resistance and the heat flux. The thermal resistance is basically the unit area of the overall inner surface of the channel on the evaporator section and can be written as: $R'' = \frac{T_{evaporator} - T_{conderser}}{q''}$; and the heat flux can be calculated by the equation: $q'' = \frac{q}{2n\pi D L_e}$; the character n means the number of turns for the OHP, and L_e means the effective length.

3.2.3 Evaporator and Condenser impacts with the Thermal Performance

Condenser and the evaporator are the two major parts of an oscillating heat pipe, all the temperature & pressure differences produced by these two components. The influence made by the evaporator and condenser to the overall thermal performance were not clear. [2] mentioned in his work that the higher of the condenser temperature with the same heat input results lower thermal resistance. However, the suggestion done by [2] may not be full fill all the conditions, and probably there will be different if working fluid's dynamic viscosity, density and others may be different as mentioned in the previous section. The purpose of this section is to exam the influence on CL-OHP's thermal performance done by the changing temperature of the evaporator and the condenser. The experiment continued used the same testing bed from the previous section which is the aluminum plate with 2mm channels built inside to simulate a closed loop oscillating heat pipe. Small change for the experiment made to this experiment was this experiment used the 3D-Printed upper plate which covers the middle testing bed with the cooling plate for better experimental environment.

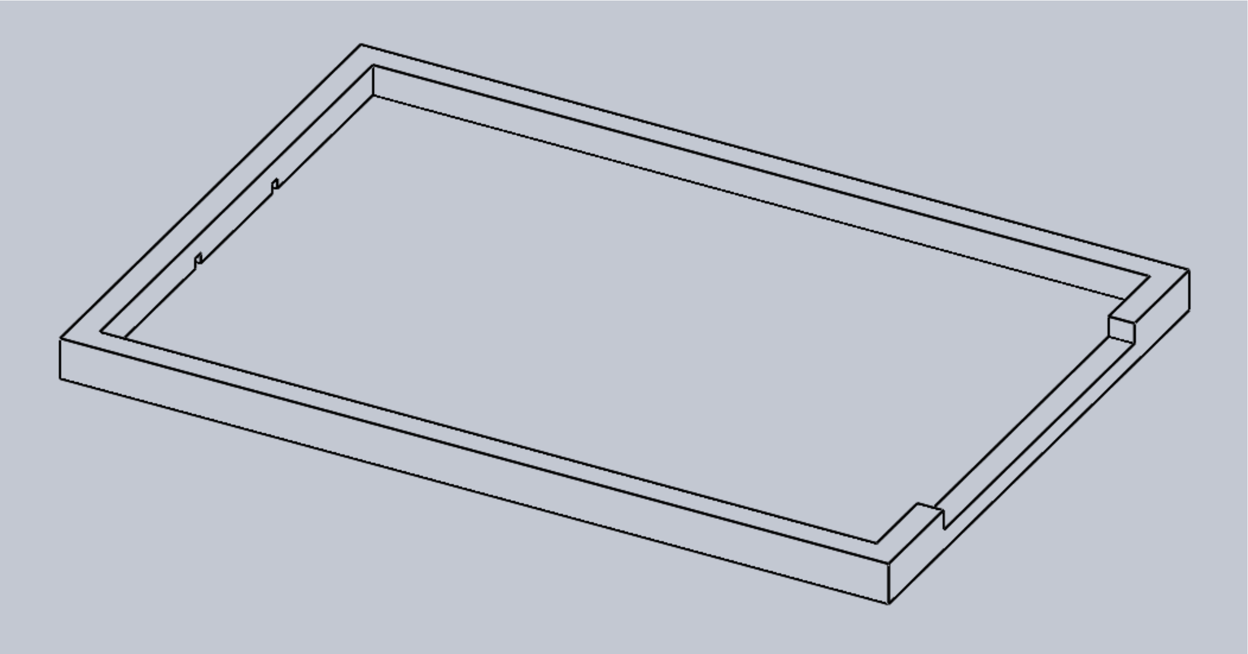


Figure 19. Upper plate for CL-OHP

The figure above is the upper plate which build to cover the whole system inside. The dimension of the plate was 160mm x 110mm x 8mm with a 150mm x 100mm x 4mm inner section cut to fit the testing bed. Space for working fluid injection and vacuum process made on the left side, and the evaporator installation area shows on the right side. Experiment procedure is basically to start up the whole system first, then by using the power supply to control the heat input. Condenser temperature was controlled by the water tank by adding hot or cold working fluids to reach the temperature level.

3.2.4 Special Working Fluid & Magnetic fields.

Special working fluid can be useful under some special circumstance. This section used water as the base fluid combined with 325 mesh iron powder to simulate the features of nanofluid and observing the performance of the nanofluid. The 325-mesh iron power means each particle is 44nm. The heat transfer performance was determined by the thermal resistance which can be calculated by

$$R = \frac{T_{evap} - T_{cond}}{Q_{in}} \qquad (12)$$

Where T_{evap} and T_{cond} represents the average temperature at the section and Q_{in} means the heating power input which is the product of electric current and voltage of the input at the power source.

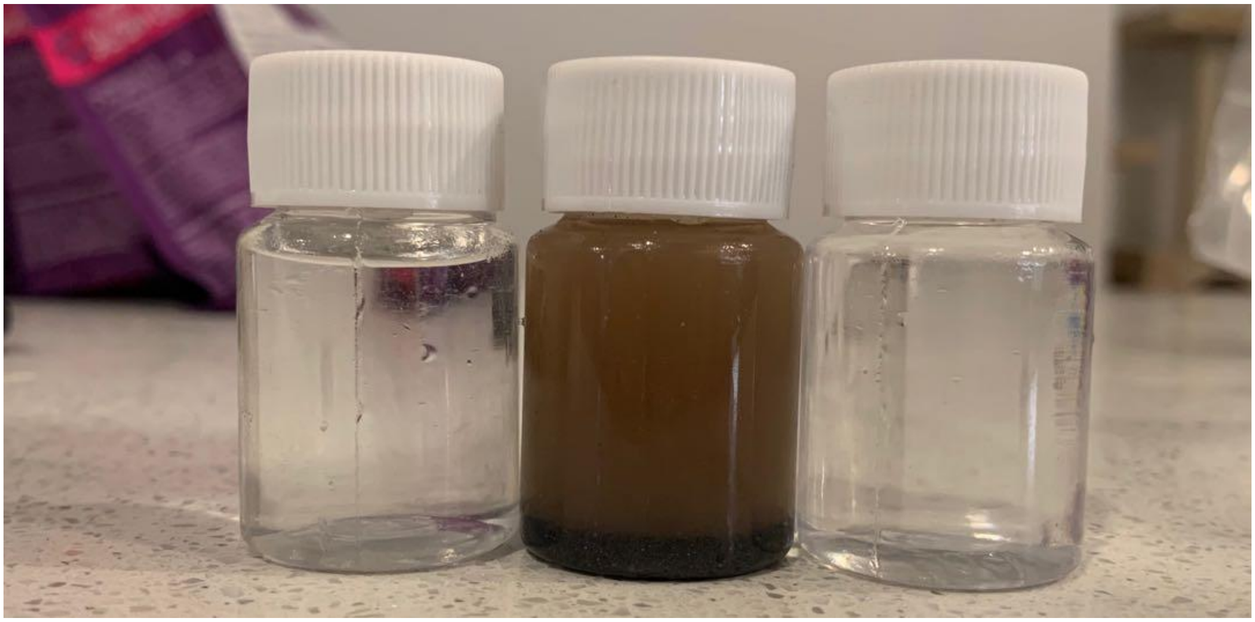


Figure 20. Comparison between Water, Nanofluid, and Ethanol

Figure above shows the three different working fluids, the left one is the water, center one is nanofluid with 325mesh iron and water base, the right one is the ethanol. The experiment procedure for the nanofluid is similar to other working fluids. Different filling ratios of the working fluid charged to 7 turn (at evaporator) testing bed with 2mm channels build in. Only different is this experiment runs for a trial with nanofluid only, another trial with boost by magnets locate at the condenser.

Chapter 4. Results & Discussion

This chapter shows results get from the previous experiments then explains the influence that the change in the specific part caused to the overall thermal performance such as the working fluid with filling ratios, orientation of the testing bed, and the temperature change in evaporator & condenser section.

4.1. Influence of Filling Ratio on OHPs with Different Working Fluids

The thermal performance of the CL-OHP that was tested was determined by its thermal resistance. The higher of the thermal resistance results the lower in the heat transfer rate for the whole system. The experiment tested two working fluids, water and ethanol with different filling ratios and heat input from low to high. The result shows that the highest thermal resistance always appear at the low heat input that we can tell from figure 16, and 17; dark blue line representants 10W always locate at the top part and it even goes to 7 $\frac{\mathrm{K}}{\mathrm{W}}$ for ethanol when operating at 30% filling ratio and 10W heat input.

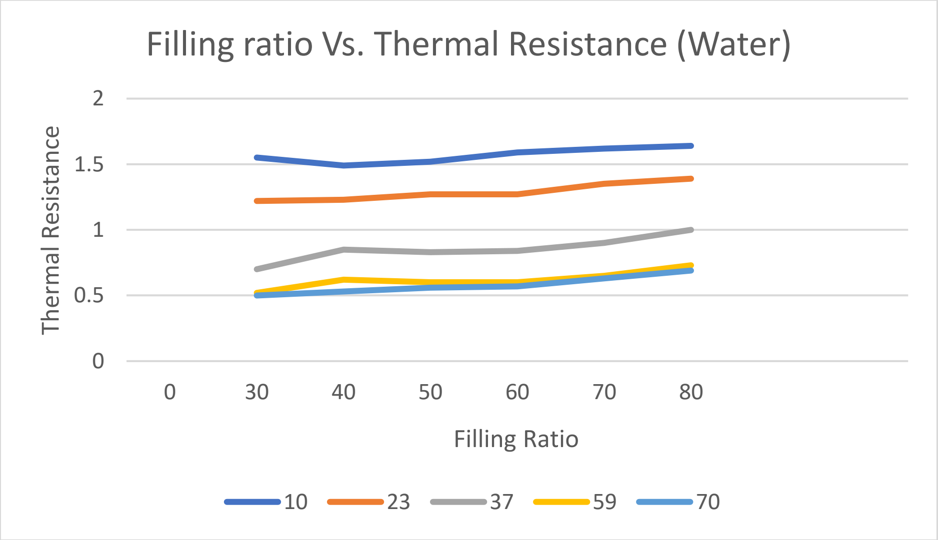


Figure 21. Thermal Resistance of CLOHP with Different Filling Ratios (Water)

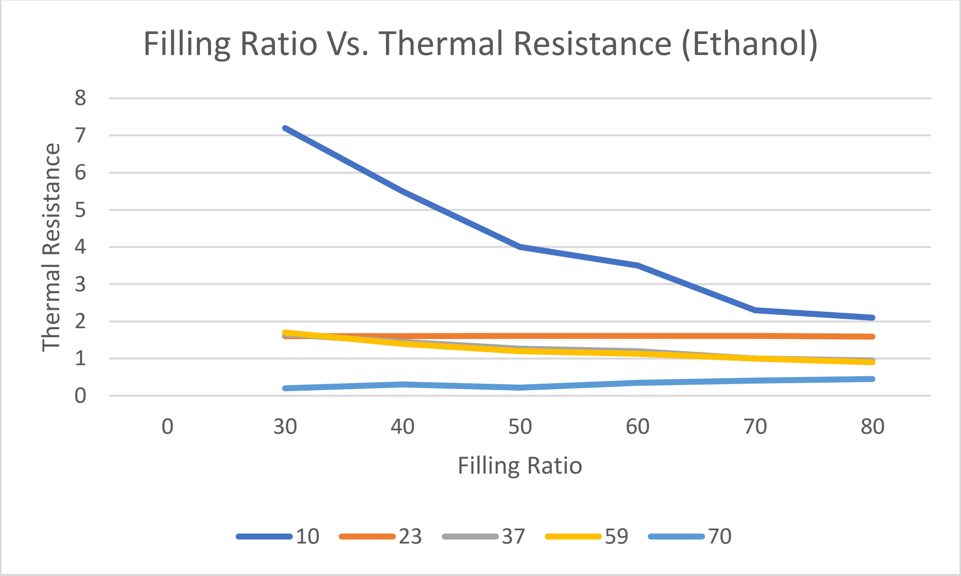


Figure 22. Thermal Resistance of CLOHP with Different Filling Ratios (Ethanol)

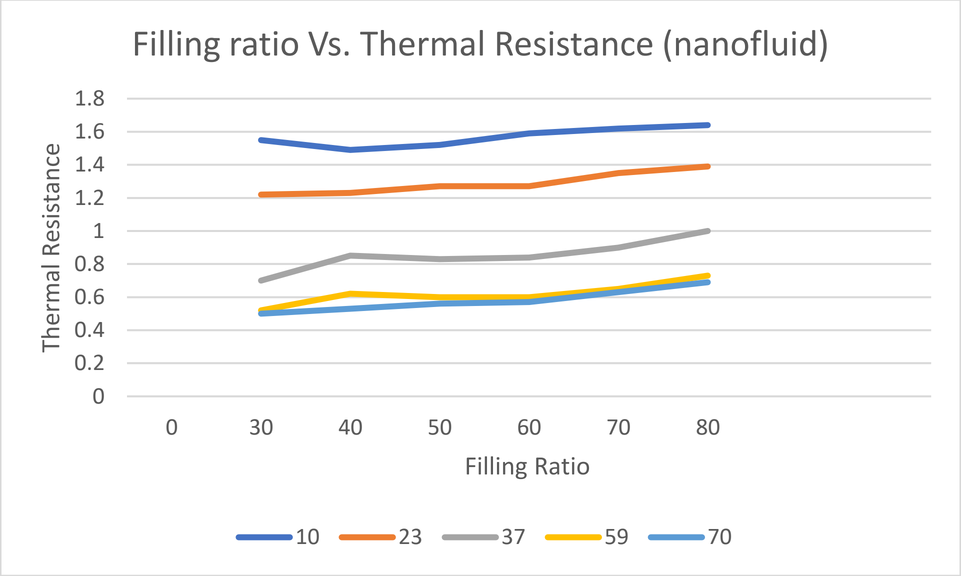


Figure 23. Thermal Resistance of CLOHP with Different Filling Ratios (nanofluid, without magnet)

Figures above shows the thermal resistance with different conditions. The filling ratio are tested at an increasing pattern with 10% each time; as calculated from section 3.2.2, the maximum filling ratio of both water and ethanol operates at 100°C were 80% approximately, so the range of filling ratio is from 30% to 80%. The light blue line represents 70W heat input and yellow line represent 59W tends to have the smallest thermal resistance which concludes at high heat input, both working fluids performance better. Another feature shows in the graph is that the increase of the filling ratio, the thermal resistance changes. By comparing both graph, we can clearly see that water shows better performance since in most conditions, water has a lower thermal resistance; for example, at heat input 37W, 59W, and 70W, all the thermal resistance with different filling ratios were under 1 $\frac{\mathrm{K}}{\mathrm{W}}$, but for ethanol, only operate at 70W results all thermal resistance under 1$\frac{\mathrm{K}}{\mathrm{w}}$. The thermal resistance for ethanol drops significantly with high heat input as 23W, 37W,59W, and 70W at lower filling ratio then performance nearly constant at higher filling ratios; this can be explained by that at lower filling ratios the flow transition was from slugs to bubbles; and the thermal resistance increases at higher filling ratios was because that the heat transfer rate almost being constant at the vapor layer in the internal tube surface region.

In addition, the result of the nanofluid composited by the 10% concentrated 325 mesh iron powder showing no significant different performance compare to its base fluid- pure water. I believe a major reason was all the working fluid in the system are bulk flow dominated, so, the 10% concentrated nano particles hardly influence the whole system. Minor reasons caused this probably be the accuracy in measuring, and the uncertainty.

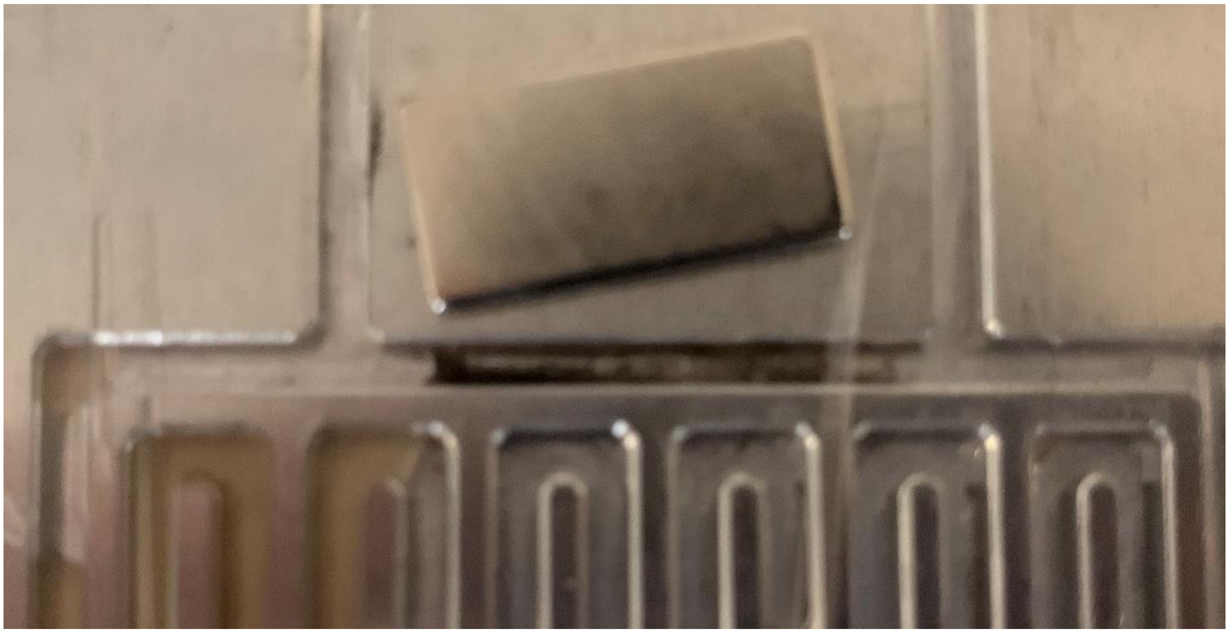


Figure 24. Nanoparticles attracted by the Magnets

Figure above shows the OHP operating with nanofluid and magnet booster. Obviously, the trial was failed since all the iron powders stack at the condenser after the whole system run for a while. The reason causes this failure probably due to the extra strength of the magnet.

4.2 Influences of Testing Bed set-up on the Thermal Performance of OHPs

This section tested the thermal performance influenced by the orientation of the OHPs. The testing bed were oriented from 0° (horizontal) to 90° (vertical) with 50% filling ratios and water as the working fluid.

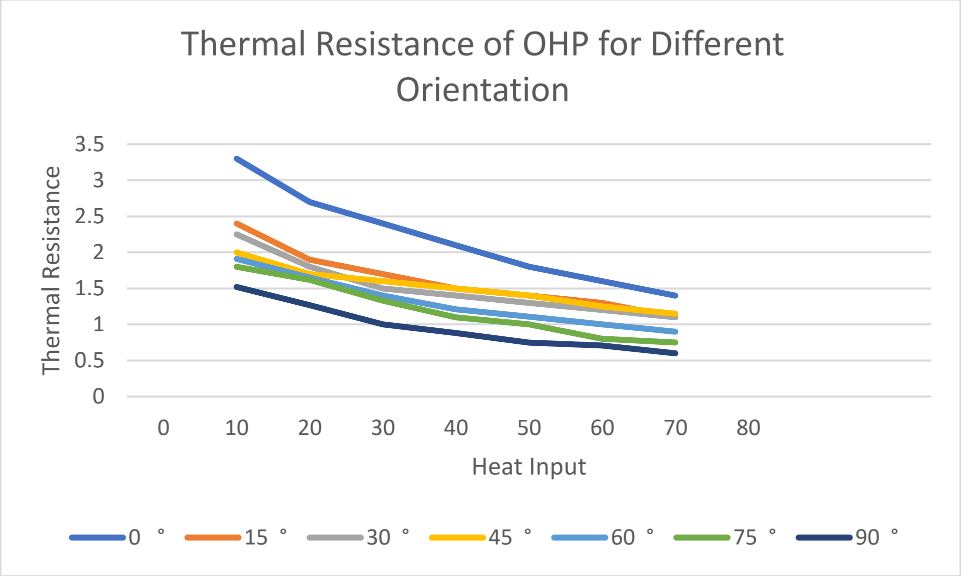


Figure 25. Thermal Resistance of OHP with Different Orientations

As the figure shows, the overall thermal resistance of the CL-OHP with water as the working fluid is decreasing with higher heat input which agrees with the results from last section; water performances better at higher heat input. There are multiple lines showing in the figure representing different orientations of the CL-OHP; the figure shows for orientations from 15° to 75° tends to have similar thermal performance. However, the horizontal and vertical orientation of the CL-OHP shows totally different performances. The horizontal orientation line shows the highest thermal resistance and the vertical orientation was the lowest. The work done by [7] suggested the similar result with testing a copper-based CL-OHP from 75° to 15° orientation the thermal performance is decrease constantly, and it became lowest when operating horizontally. Compare to the traditional oscillating heat pipe which cannot operate in multiple orientations, OHPs having advantages for allowing operate in multiple orientations; however, actual installation orientation of OHP still need to be analyzed to the specific case since it has a large difference in vertical and horizontal orientations.

4.3 Evaporator and Condenser Impacts with the Thermal Performance of OHPs

Evaporator and condenser are also very important components while operating an OHP. This section analyzes the thermal performance of a CL-OHP with water as the working fluid and 50% filling ratio by changing the condenser temperature and heating power input. As showed from the previous sections, the installation of condenser was a water tank, with a water pump to deliver the water to the lower plate of the testing bed. The temperature of the condenser were controlled by the water temperature, and recorded by a temperature scanning gun. The temperature of the condenser may not be prefect since the water temperature changed by adding ice or hot water. The figure 19 shows the thermal performance of the testing bed with different evaporator and condenser conditions. As we can tell from the figure, thermal resistance is decreasing while the heating power input is increasing. Similar to results from section 4.1, thermal resistance changes significantly at lower heating power input and nearly constant at higher ones. The heat transfer performance also became better while the condenser temperature is increasing. Once the condenser temperature reaches 40℃, the OHP shows almost be the same performance for any higher temperatures. This situation basically proves [1] Akachi's idea which OHP can operate with great thermal performance with small temperature and pressure difference.

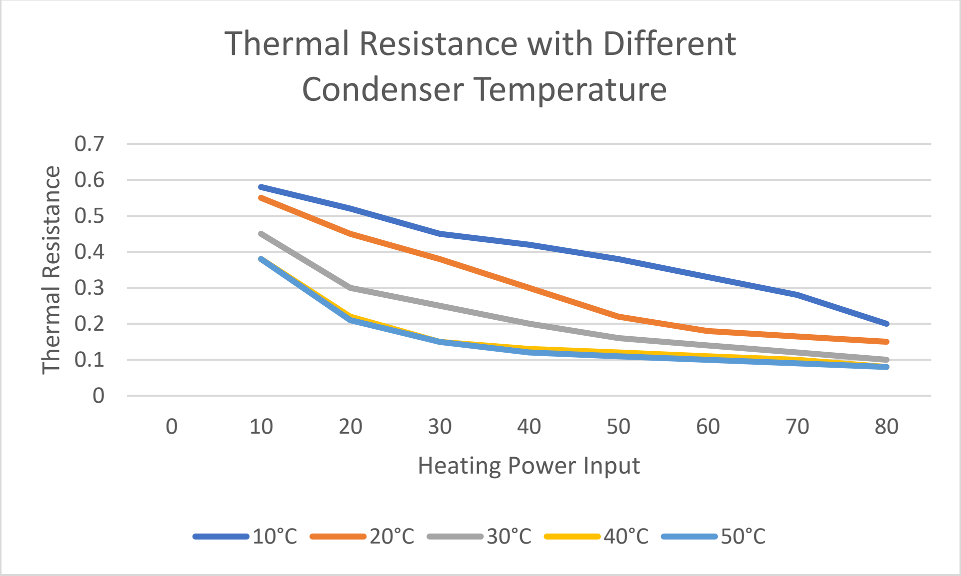


Figure 26. Thermal resistance with different condenser Temperatures

4.4 Comparison with Others

This section focused on compare the results obtained from the experiments with other researchers' work. Figure $$$ below shows the comparison of water as working fluid and 40% as filling ratio with different OHP designs. From the figure we can tell that both results consist similar slope of the performance. The thermal resistance decreases sharply from 10W to higher power input then become stable at a value. The next figure shows the comparison of ethanol as working fluid and 40% filling ratio with different OHP designs shows the similar result. At 10W, the experiment data shows the thermal resistance is around $5.5\frac{\mathrm{K}}{\mathrm{W}}$ and data from [8] was only $2.9\frac{\mathrm{K}}{\mathrm{W}}$.; I believe the reason caused the huge difference in the thermal resistance was due to the design of the CL-OHP. [8] used copper tube to construct the OHP, but mine was Aluminum Channels. Even the structure of the OHP were similar, but the performance of the material was not the same, and that must be the reason caused this large difference. However, both set of data obtained the same thermal resistance when operating at 20W.

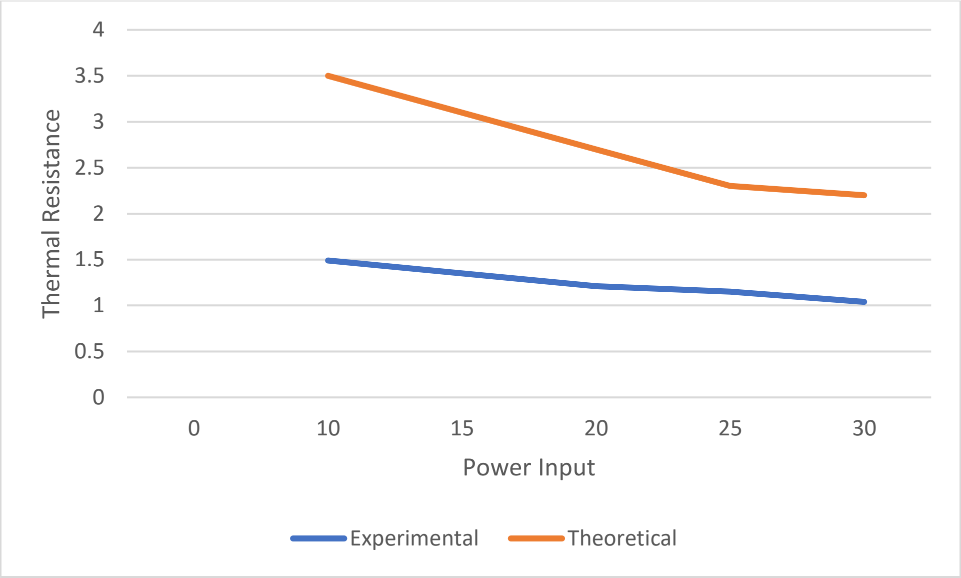


Figure 27. Thermal Performance Comparison of water between experimental result and other literature [30]

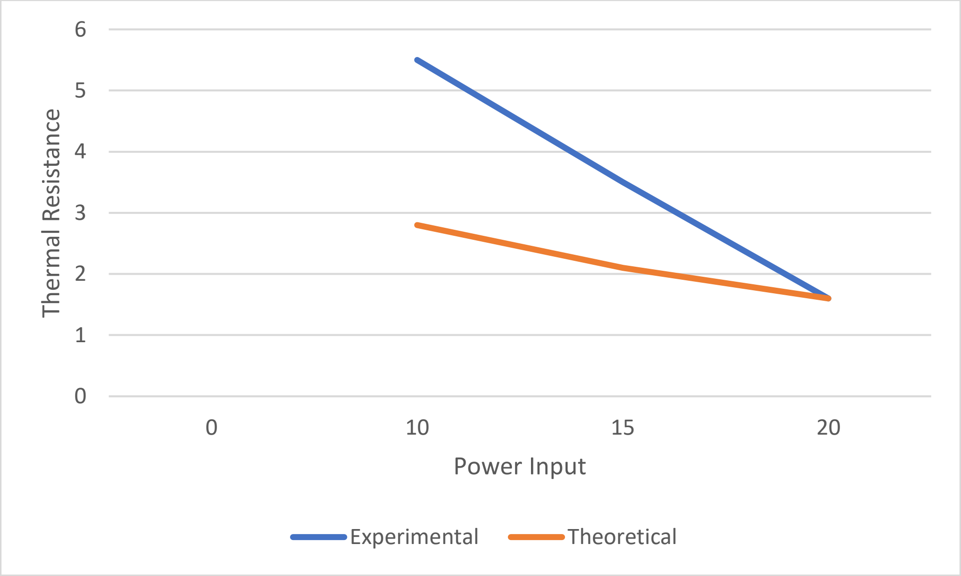


Figure 28. Thermal Performance Comparison of ethanol between experimental result and other literature [8]

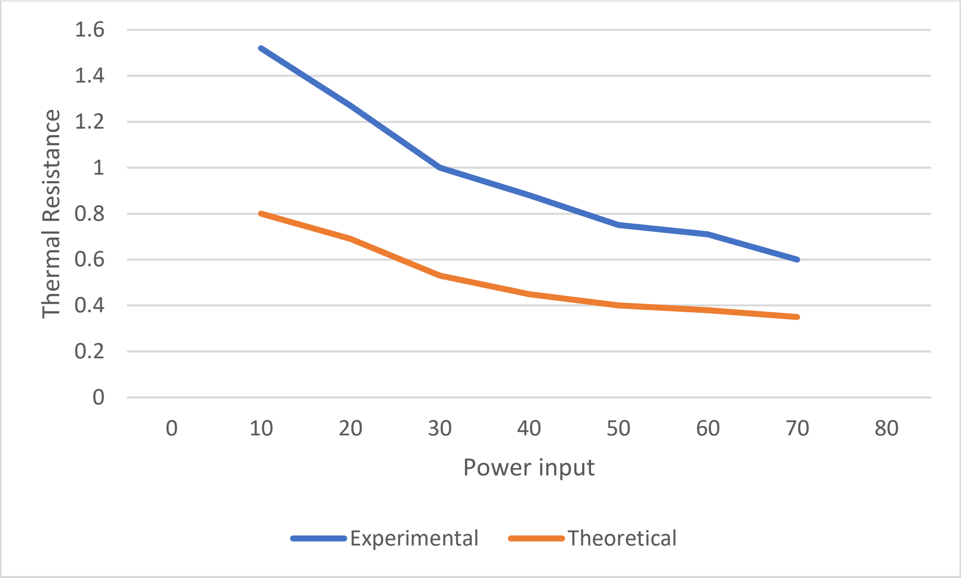


Figure 29. Thermal Performance Comparison of 90-degree orientation between experimental result and other literature [16]

The figure above shows two OHP operates at 90° with water as working fluid and 40% filling ratio charged. The performance of both set of data were similar, they all have a turning point around 30W then the slope become close to constant. The thermal resistance obtained from [16] is much lower than the data obtained from experiment. I believe the reason was the material of the capillary tube and the structure difference. Copper has better thermal conductivity and performance compare to aluminum, and that is the main reason caused the OHP from [16] has better thermal performance. However, the trajectory of both set of data are similar.

Chapter 5. Conclusion

In this study, experiment was carried out to investigate the performance of an OHP with different filling ratios, heat transfer rates, working fluid, and OHP orientations. The OHP system was designed with a dimension of 150mm x 100mm x 4mm, and channel as the capillary tube of dimension 2mm and constructed based on aluminum and acrylic material. The experimental data were also compared with the literature data, showing a good match for high heat transfer rate and a major deviation under low rate. Specifically, we found:

1.) Filling ratios 60% has the thermal resistance of $0.6\frac{K}{W}$. the operation power input is 70W. In most conditions, if the filling ratio is between 40% to 60%, the thermal resistance tends to be nearly constant.

2.) Water tends to be the one has the higher heat transfer performance when operating at lower power input, and ethanol tends to be the one with better heat transfer performance when operates at higher power input.

3.) The orientation of the CL-OHP is important which can influence the heat transfer performance a lot. Vertical orientation contains better thermal performance then horizontal orientation significantly; the orientation between 75° to 15° the heat transfer performance is dropping constantly. Lastly, the investigation for the change in evaporator and condenser section shows that the testing bed performance the best at the condenser temperature larger than 40°, and heating power input larger than 45W.

Future work includes studies of the two-phase flow dynamics and channel dimension, and incorporation with a fuel cell or lithium-ion battery system.

References

[1]. Akachi, H., 1990, Structure of a Heat Pipe, U.S. Patent #4,921,041

[2]. Akachi, H., 1993, Structure of a Heat Pipe, U.S. Patent #5,219,020

[3]. Betancur, Luis & Mangini, Daniele & Mameli, Mauro & Filippeschi, Sauro & Kessler Slongo, Leonardo & Paiva, Kleber & Mantelli, Marcia & Marengo, Marco. (2016). Condenser Temperature Effect on the Transient Behavior of a Pulsating Heat Pipe.

[4]. Chi, R.-G & Chung, W.-S & Rhi, S.-H. (2018). Thermal Characteristics of an Oscillating Heat Pipe Cooling System for Electric Vehicle Li-Ion Batteries. Energies. 11. 10.3390/en11030655.

[5]. Closed-loop oscillating heat-pipe with check valves (CLOHP/CVs) air-preheater for reducing relative humidity in drying systems, Applied Energy, Volume 84, Issue 4, 2007, Pages 363-373, ISSN 0306-2619, http://www.sciencedirect.com/science/article/pii/S0306261906001206

[6]. D. Yin, H. Rajab, H.B. Ma, Theoretical analysis of maximum filling ratio in an oscillating heat pipe, International Journal of Heat and Mass Transfer, Volume 74, 2014, Pages 353-357, ISSN 0017-9310, http://www.sciencedirect.com/science/article/pii/S0017931014002245

[7]. Dao Danh Tung, Shuichi Torii, “heat transfer performance of a self oscillating heat pipe using pure water and effect of inclination to this performance”, December 30, 2011

[8]. e R, Babu & REDDY, G.. (2016). Effect of working fluid and filling ratio on performance of a closed loop pulsating heat pipe. Journal of Engineering Science and Technology. 11. 872-880.

[9]. G. Burban, V. Ayel, A. Alexandre, P. Lagonotte, Y. Bertin, C. Romestant, Experimental investigation of a pulsating heat pipe for hybrid vehicle applications, Applied Thermal Engineering, Volume 50, Issue 1, 2013, Pages 94-103, ISSN 1359-4311, (http://www.sciencedirect.com/science/article/pii/S1359431112004152)

[10]. Hamid Reza Goshayeshi, Marjan Goodarzi, Mohammad Reza Safaei, Mahidzal Dahari, Experimental study on the effect of inclination angle on heat transfer enhancement of a ferrofluid in a closed loop oscillating heat pipe under magnetic field, Experimental Thermal and Fluid Science, Volume 74, 2016, Pages 265-270, ISSN 0894-1777, http://www.sciencedirect.com/science/article/pii/S0894177716000042

[11]. Himel Barua, Mohammad Ali, Md. Nuruzzaman, M. Quamrul Islam, Chowdhury M. Feroz, Effect of Filling Ratio on Heat Transfer Characteristics and Performance of a Closed Loop Pulsating Heat Pipe, Procedia Engineering, Volume 56, 2013, Pages 88-95, ISSN 1877-7058, (http://www.sciencedirect.com/science/article/pii/S1877705813004475)

[12]. Honghai Yang, S. Khandekar, M. Groll, Operational limit of closed loop pulsating heat pipes, Applied Thermal Engineering, Volume 28, Issue 1, 2008, Pages 49-59, ISSN 1359-4311, http://www.sciencedirect.com/science/article/pii/S1359431107000683

[13]. Yuwen zhang, Amir Faghri, "Advances and Unsolved Issues in Pulsating Heat Pipes", Heat Transfer Engineering, 29(1):20–44, 2008, Taylor and Francis Group, ISSN: 0145-7632

[14]. Jianhong Liu, Fumin Shang, Dengying Liu, Experimental Study on Enhanced Heat Transfer Characteristis of Synergistic Coupling between the Pulsating Heat Pipes, Energy Procedia, Volume 16, Part C, 2012, Pages 1510-1516, ISSN 1876-6102, https://doi.org/10.1016/j.egypro.2012.01.237.

[15]. Jian Qu, Huiying Wu, Thermal performance comparison of oscillating heat pipes with SiO2/water and Al2O3/water nanofluids, International Journal of Thermal Sciences, Volume 50, Issue 10, 2011, Pages 1954-1962, ISSN 1290-0729, http://www.sciencedirect.com/science/article/pii/S1290072911001207

[16]. Jian Qu, Qian Wang, Experimental study on the thermal performance of vertical closed-loop oscillating heat pipes and correlation modeling, Applied Energy, Volume 112, 2013, Pages 1154-1160, ISSN 0306-2619, http://www.sciencedirect.com/science/article/pii/S0306261913001384

[17]. Manfred Groll and Sameer Khandekar, "Pulsating heat pipe: progress and prospects", proceeding on international conference on energy and the environment, May 22-24,2003, Shanghai, China

[18]. Meena, P., Rittidech, S. and Poomsa-ad, N., (2007), Closed-loop oscillating heat-pipe with check valves (CLOHP/CVs) air-preheater for reducing relative humidity in drying systems, Applied Energy, 84, issue 4, p. 363-373, https://EconPapers.repec.org/RePEc:eee:appene:v:84:y:2007:i:4:p:363-373.

[19]. Pachghare, Pramod & Mahalle, Ashish. (2012). THERMAL PERFORMANCE OF CLOSED LOOP PULSATING HEAT PIPE USING PURE AND BINARY WORKING FLUIDS. Journal of Heat Transfer. 3. 1-6. 10.5098/fhp.v3.3.3002.

[20]. Patel, V. M., & Gaurav, H. B. (2016, September 6). Influence of working fluids on startup mechanism and thermal performance of a closed loop pulsating heat pipe. Retrieved May 16, 2020, from https://www.sciencedirect.com/science/article/pii/S1359431116316179

[21]. Piyanun Charoensawan, Pradit Terdtoon, Thermal performance of horizontal closed-loop oscillating heat pipes, Applied Thermal Engineering, Volume 28, Issues 5–6, 2008, Pages 460-466, ISSN 1359-4311, (http://www.sciencedirect.com/science/article/pii/S1359431107001883)

[22]. P. Charoensawan and P. Terdtoon, "Thermal Performance Correlation of Horizontal Closed-Loop Oscillating Heat Pipes," 2007 9th Electronics Packaging Technology Conference, Singapore, 2007, pp. 906-909, doi: 10.1109/EPTC.2007.4469768.

[23]. Prajwal D. Chawane, Sujay A. Basunathe, Shweta D. Borekar, “Thermal Performance of Closed Loop Pulsating H"eat Pipe Using Different Working Fluid: A Review”, International Journal of Engineering Science, ISSN 2319 – 6726 , September 2013

[24]. Qingchao Wang, Zhonghao Rao, Yutao Huo, Shuangfeng Wang, Thermal performance of phase change material/oscillating heat pipe-based battery thermal management system, International Journal of Thermal Sciences, Volume 102, 2016, Pages 9-16, ISSN 1290-0729, http://www.sciencedirect.com/science/article/pii/S1290072915003464

[25]. Smoot, C. D., Ma, H. B., Wilson, & Greenberg. (2011, June 1). Heat Conduction Effect on Oscillating Heat Pipe Operation. Retrieved May 16, 2020, from https://asmedigitalcollection.asme.org/thermalscienceapplication/article-abstract/3/2/024501/469361/Heat-Conduction-Effect-on-Oscillating-Heat-Pipe?redirectedFrom=fulltext

[26]. Takurou Daimaru, Shuhei Yoshida, Hiroki Nagai, Study on thermal cycle in oscillating heat pipes by numerical analysis, Applied Thermal Engineering, Volume 113, 2017, Pages 1219-1227, ISSN 1359-4311, http://www.sciencedirect.com/science/article/pii/S1359431116333762

[27]. Winarta, Adi & Putra, Nandy & Bakhtiar, Fadli. (2017). Thermal Performance of Oscillating Heat Pipe with Ethanol/Methanol for Heat Recovery Application Design. International Journal on Advanced Science, Engineering and Information Technology. 7. 1268. 10.18517/ijaseit.7.4.2692.

[28]. Zhihu Xue, Wei Qu, Experimental study on effect of inclination angles to ammonia pulsating heat pipe, Chinese Journal of Aeronautics, Volume 27, Issue 5, 2014, Pages 1122-1127, ISSN 1000-9361, (http://www.sciencedirect.com/science/article/pii/S1000936114001241)

[29]. Jin, L.; Lee, P.; Kong, X.; Fan, Y.; Chou, S. Ultra-thin minichannel LCP for EV battery thermal management.
Appl. Energy Eng. **2014**, 113, 1786–1794.

[30]. Salem, M., Meakhail, T. A., Bassily, M. A., & Torii, S. (2016, June). Experimental Study of Filling Ratio Effect on the Thermal Performance in a Multi-Heat Pipe with Graphene Oxide/Water Nanofluids. Retrieved May 20, 2020, from https://pdfs.semanticscholar.org/900b/794caf2fd38ea69cf78ac2dc6f5d2852bd2d.pdf

[31]. Wits, W. (2010, March 25). Heat Pipe .nl. Retrieved from http://www.heatpipe.nl/index.php?page=heatpipe&lang=EN

[32]. Sathe, T. M. (2014). Review on Closed Loop Oscillating Heat Pipe. International Journal of Engineering Research & Technology, 3(3).

[33]. Fasula, C. (2009). OSCILLATING HEAT PIPES (OHP).

[34]. Vassilev M., Avenas Y., Schaeffer C., Schanen J.-L. Experimental Study of a Pulsating Heat Pipe with Combined Circular and Square Section Channels, 42nd IAS Annual Meeting Conference Record of the 2007 Industry Applications Conference, IEEE, pp 1419-1425, 2007.

[35]. Charoensawan P., Khandekar S., Groll M., Terdtoon P. Closed Loop Pulsating Heat Pipes Part A: Parametric Experimental Investigations, Applied Thermal Engineering, vol. 23, pp 2009-2020, 2003.

[36] Wang, Y. (2008). Modeling of two-phase transport in the diffusion media of polymer electrolyte fuel cells. Journal of Power Sources, 185(1), 261-271.

[37]. Zhang, G., Yuan, H., Wang, Y., & Jiao, K. (2019). Three-dimensional simulation of a new cooling strategy for proton exchange membrane fuel cell stack using a non-isothermal multiphase model. Applied Energy, 255, 113865.

[38]. Wang, Y., & Gundevia, M. (2013). Measurement of thermal conductivity and heat pipe effect in hydrophilic and hydrophobic carbon papers. International Journal of Heat and Mass Transfer, 60, 134-142.

[39]. Wang, Y., Diaz, D. F. R., Chen, K. S., Wang, Z., & Adroher, X. C. (2020). Materials, technological status, and fundamentals of PEM fuel cells–a review. Materials Today, 32, 178-203.

[40]. Ge, N., Chevalier, S., Lee, J., Yip, R., Banerjee, R., George, M. G., ... & Kotaka, T. (2017). Non-isothermal two-phase transport in a polymer electrolyte membrane fuel cell with crack-free microporous layers. International Journal of Heat and Mass Transfer, 107, 418-431.

[41]. Afshari, E. (2020). Computational analysis of heat transfer in a PEM fuel cell with metal foam as a flow field. Journal of Thermal Analysis and Calorimetry, 139(4), 2423-2434.

[42]. Wang, Y., & Chen, K. S. (2013). PEM fuel cells: thermal and water management fundamentals. Momentum Press.