E3S Web of Conferences **391**, 01031 (2023) https://doi.org/10.1051/e3sconf/202339101031
ICMED-ICMPC 2023

A Review Paper on Thermal Performance of Pulsating Heat Pipe

J.Venkata Suresh[1*],*P.* Bhramara[2],*B.*Manisha[1],*K.I*shitha[1],*R.*Nagalakshmi[1],*Ram* subbiah[1]

[1]Department of Mechanical Engineering, GRIET, Hyderabad, Telangana, India
[2]Department of Mechanical Engineering, JNTU College of Engineering, Hyderabad, Telangana, India

Abstract. In past few years, as indirect convection cooling equipment, heat pipes have grown in favour for a variety of uses, including heat recovery and electronics. A sensible heat is categorized as not having a filter arrangement as a "pulsating heat pipe". It transfers heat from its evaporator to condenser portions by moving the circulating flow back and forth a reaction of its ongoing phase shift that occurs inside of it. It is difficult to truly understand how it operates since the two-phase flow is the result of combining physical and thermodynamic factors. Despite this, the PHPs have caught the interest of researchers all over the world because of its simple design and large several scenarios necessitating an elevated heat transfer rate. Presented here begins and a preface outlining several researchers' trying to model experimental explain how PHPs work. A short tabular review of the most recent experimental investigations on PHPs is offered. Novel ideas have been explored, including the use of Nano-fluids to improve PHP performance.

1. INTRODUCTION

Electronic devices have established a permanent presence everywhere from our homes to our workplaces in an effort to improve our quality of life. We need our tiny devices to operate more quickly. What is left behind, though, is not something we ever think about. Heat rejection from the unit surface increases with miniaturization. Region has significantly grown. A two-phase phenomenon has proven to be a more effective method for handling such issues. One application that uses two-phase flow is PHP. Due to its small size, straightforward structure, quick thermal response, and low thermal resistance, Using PHP, widely used for electronics heating control since its creation by Akachi in 1990 [1] Applications for PHPs have expanded to include technologies that recover waste heat from the sun, air conditioning, air to air heat exchangers, fuel cell radiators, hybrid automobiles, and chip cooling, among many other things. PHP is a passive device that removes heat more quickly than other cooling methods because to the concept of liquid evaporation. In the evaporator, the operational fluid is heated, and heat is expelled in the condenser. It must

*Correspondingauthor:venkatasureshj@gmail.com

be assured that the effect of surface tension outweighs the gravity force, which causes liquid bubbles to span the whole loop [2 3] The terms "closed loop pulsating heat pipe" and "open loop pulsing heat pipe" (CLPHP) are the two main categories into which PHPs may normally be divided (OLPHP).As a result of PHP's great characteristics, including its small-scale, low manufacturing Cost, straightforward design, and excellent heat transfer performance have attracted scientists and engineers from around the world have extensively studied its performance. A number of variables, including how well a PHP performs depend on the working fluid, filling ratio, number of turns, inclination degree, and PHP settings [4] In recent years, other mathematical to forecast the PHPs' oscillating furthermore, models have been made motion and heat transfer capabilities. The model is able to forecast how under the constant conductance mode, the two-phase zone of the condenser will shorten as a result of the liquid in the compensation chamber expanding in volume. The test data in the mode of constant conductance and the simulation results for the operating temperatures are extremely similar. Despite substantial research, several fundamental PHP concepts remain poorly understood, and some analytical findings from various researchers even run counter to the experimental data [5-7] The findings of experimental studies on PHPs by a number of researchers revealed that the main factors affecting PHPs' capacity to transmit heat were the working fluids, evaporation/condensation lengths, inner diameters, turn counts, etc. Several clean working fluids have benefits in certain scenarios. Yet up to now, little research has been done on the mixtures utilized as working fluids in PHP. Heat source and working fluids can have good temperature matching thanks to the non-azeotropic mixes that exhibit phase transition with temperature floating. By monitoring the temperatures of the PHP for various combinations, experimental research has been done to identify the properties of thermal resistance [8-10]

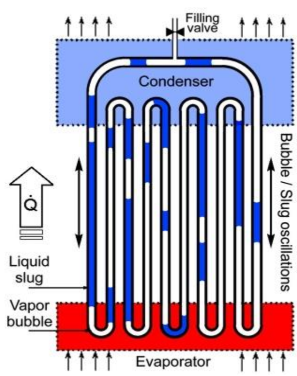

Fig. 1. Pulsating heat pipe [17]

1.1 Heat pipe

A heat pipe is a device for transferring heat between two solid contacts that uses phase transition. Heat pipes, a type of two-phase passive heat transfer system, are powered internally. It is adaptable, easy to build, and easy to control. A typical heat pipe consists of a working fluid, a wick structure, and a sealed container. Despite the fact that they can be any size and shape, heat pipes frequently employ cylindrical containers. The condenser, evaporator, and adiabatic portions are the heat pipe's three primary divisions. The working fluid travels from the condenser to the evaporator and back again through the wick structure, a porous structure on the inside of the container [11] By creating vapor pressure inside the container, the working fluid is moved from the evaporator to the condenser.

There, it condenses and loses heat, turning back into liquid. [12] To transfer heat from the evaporator to the condenser component, the cycle is completed and then repeated numerous times. This liquid is pumped once more into the evaporator zone by pressure that develops in the wick structure [13]

1.2 Pulsating heat pipe

Composed of wavering capillary tubes that are lined up parallel to one another. The three a new type of heat pipe oscillates in two phase form of heat transmission equipment. It is primary sections of PHP are the condenser, adiabatic system, and evaporator [14]. At least three distinct methods exist for producing PHP: (1) Pulsating closed loop heat pipe is a type of closed loop. Capillary tubes' two ends are typically sealed in this way either by uniting two ends at a common point or at two separate ends. (2) Open loop is a pulsating heat pipe. (3) This exposes two tube ends to the outer world.(4) Circular flow within a closed loop regulator. In this, the working fluid flow is controlled by a flow control valve [15]. According to research and prior PHP work, CLPHP is more effective type of pulsating heat pipe than other sorts. Although LPHP construction is very simple, comprehending the complicated thermodynamic, fluid dynamic, and heat transfer principles of CLPHP is necessary to comprehend how it functions [16].

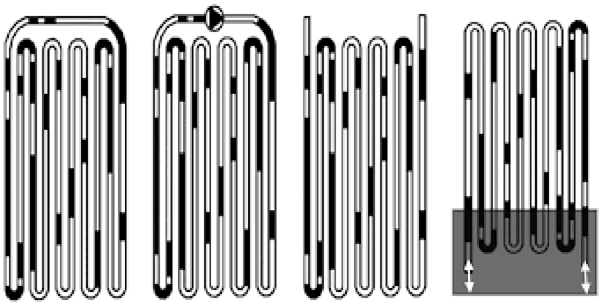

Fig. 2. Types of pulsating heat pipe [12]

(a) Closed loop PHP (b) Closed loop with check valve (c) Closed end PHP

1.3 General working principle

PHP operates on the basis of phase change phenomena and the oscillation of a capillary tube's working fluid. The closed loop pulsating heat pipe is the main topic of this review paper (CLPHP). The CLPHP is made up of a compact loop of curving tubes through which the working fluid for heat transfer passes. Meandering capillary tubes are typically arranged in a U-shape, parallel to one another. The center adiabatic portion, the condenser portion, and the evaporator portion are the three main divisions of these tubes [17] In a PHP tube, a vacuum is created before the working fluid is charged with the proper filling ratio. These results in a particular ratio of the working fluid's liquid and vapor phases, known as liquid slug and vapor bubbles, respectively, when charging is complete. Heat is applied during the evaporation phase, which causes the liquid droplet to change into vapor bubbles and the vapor's pressure to rise. The fluid vapor bubbles are then transported to the condenser portion by the adiabatic component [18]

1.4 PHP performance

A PHP's functionality is determined by its structure, form, composition, and length. The reduction in temperature (T) throughout the heat pipe for a given heat load Q is a crucial thermal performance measure.

1.5 PHP resistance

From the evaporator to the condenser, a number of parts make up the overall resistance. Thermal resistance along the length of the heat pipe, Two thermal resistances (Rcont = T/Q) that are related with the contact resistances caused by the surf, thermal resistance at the evaporator and condenser, as well as the conductive thermal resistance along the wall and the thermal resistance due to fluid head capabilities, are all present. Wick structures in wicked heat pipes need to have additional thermal resistance taken into account in addition to the wall resistance. The heat transmission capacity, Q, for an Item can be calculated. If T is the overall difference in temperature between the heating and cooling sections, Keff and Leff are the effective thermal conductivity and length, and Aacross is the PHP's cross sectional area ($k_{eff} = QL_{eff} / A\Delta T$) PHP's design objective is to provide maximal heat distribution for a given T by minimizing all resistances in the equation given by [19]. PHP research can be divided into experimental and theoretical categories. Experimental study focuses on either characterizing the heat transport properties of heat pipes or visualizing the flow. The main focus of the experimental investigation is the thermal analysis of PHP. The heat transfer capacity, Q, for an PHP if ΔT is the overall temperature difference between the heating and cooling section, k_{eff} and L_{eff} are the effective thermal conductivity and length and A_{across} is the cross sectional area of the PHP ($k_{eff} = QL_{eff} / A\Delta T$) PHP's design objective is to provide maximal heat distribution for a given T by minimizing all resistances in the equation given by [20]. PHP research can be divided into experimental and theoretical categories. Experimental study focuses on either characterizing the heat transport properties of heat pipes or visualizing the flow. The main focus of the experimental investigation is the thermal analysis of PHP.

2. Work on experimental analysis

Many researchers from all over the world have conducted experimental studies on the effects of these parameters. Some of the most recent experimental experiments are summarized in Table 1. The conclusions of experimental studies conducted by various researchers to look at the influence of the aforementioned parameters are covered in the following parts.

Table 1. An overview of recent Experimental analysis

Reference number	PHP Type	Turns	Working fluid	Special Features	Conclusion
[1]	CLPHP	8	Acetone, Water	Without fin and with fin structure	With greater heat inputs, CLPHP with fin structure experiences evaporator dry out and exhibits superior thermal performance than CLPHP without fin structure.
[2]	CLPHP	8	Acetone, Ethanol, Methanol	Removal of moving components from a cooling system	Thermophysical characteristics are significant for working fluids. Higher heat performance of CLPHP can be attained at lower filling ratios while running under stable conditions.
[3]	CLPHP	2	Zinc oxide, Water, Nano fluids	Dual diameter CLPHP	Dual diameter CLPHPs perform thermally substantially better than single diameter configurations. The performance of PHP increases with an increase in heat input for single diameter and dual diameter configurations.
[4]	CLPHP	2	Ethanol, Methanol, Acetone and Water	Vertical orientations for different heat loads	The thermal resistance of closed loop pulsing heat pipe reduces with the increase of heat input. The thermal resistance decreases gradually at lower heat inputs, although the difference is less noticeable at larger heat inputs.
[5]	CLPHP		Methanol and de-ionized water	Different orientations	A water-charged PHP was found to have a minimal thermal resistance of 0.55 C/W at a 45-degree inclination and 0.81 C/W at a horizontal orientation, whereas a methanol-charged PHP was found to have a minimal thermal resistance of 0.52 C/W and 0.63 C/W, respectively, at the ideal filling ratio. As a result, it is possible to consider PHP that has been charged with methanol to be orientation-free.
			water, acetone,		Acetone-water mixture has demonstrated the least thermal

[6]	CLPHP	______	benzene and binary mixture, viz., Acetone-water and Benzene-water	________	resistance of the water-based binary mixes examined. In contrast to pure fluids, the thermal resistance of the binary mixes showed a rather flat change with heat flux. Benzene water mixture has shown smaller fluctuation in thermal resistance with heat flux than acetone-water mixture among the two binary mixtures taken into consideration.
[7]	CLPHP	8	Methanol	CLPHP with condenser sections that are finned and unfinned and have inclinations of 0C (vertical), 300C, and 450C	Different performance levels result from the internal flow patterns being altered by the inclination angle. In this study, a 45° orientation produced the best results. In every case, the experiment's finned structure outperforms the conventional structure in terms of performance.
[8]	CLPHP	5-23	water, ethanol and R-123	semi-empirical correlations, critical visualization	Under certain working situations, different fluids are advantageous. According to the enforced thermo-mechanical boundary conditions, an optimal tradeoff of various thermo physical qualities must be accomplished. Performance increases with internal diameter for a given temperature difference.
[9]	CLPHP	5	________	local low-frequency vibrations	The thermal resistance of the php can be decreased by the vibrations at the evaporation section and at the adiabatic section. The vibrations at the evaporation section and at the adiabatic section will provide a decrease impact more effectively the lower the heating power level is. However, the thermal resistance of the php is not significantly affected by the vibrations at the condensation

					portion.
[10]	CLPHP	10	________	gravity inhibits circulation of the working fluid	The working fluid is circulated by gravity, and the inclination angle changes the mechanism of temperature oscillation but not how heat is dispersed. When the working fluid is circulated with gravity restrictions, the temperature is uniformly distributed and the oscillations in a single tube have a limited amplitude.
[11]	CLPHP	4	HFE-7100, Ethanol	pulsating heat pipe under different inclination angles	The characteristic that the installation angle affects the ethanol working medium can be improved by the non-uniform heat flux heating condition. The application situation for a php can then be expanded by decreasing the overall thermal resistance of the ethanol working liquid. This experiment also offers suggestions for how to arrange heat pipes in various heat dissipation components.
[12]	CLPHP	9	Water	In the condenser section, natural convection serves as the heat transfer mechanism.	For the same input heat flux, the system operates more effectively with a lower FR. For the same heat input values, an increase in FR is seen to cause the steady state evaporator temperature Te to rise. The difference between the steady state condenser temperature Tc and the steady state evaporator temperature Te grew as FR and input heat flux increased. Due to the chaotic fluid movement, Rth diminishes as the heat input increases.
[13]	CLPHP		Water, Ethanol	The correlation prediction's root-mean-square deviation	Using the experimental data sets for the CLPHPs that are currently accessible, To predict the input heat flux of the CLPHPs, a power-law correlation built on dimensionless groups was developed. Root-mean square deviation between the

					correlation prediction and the experimental data was 19.7%, and 88.6% of the changes were within 30%.
[14]	CLPHP	1	Acetone, Ethanol, Methanol	————	Acetone-filled PHP outperformed the other working fluids evaluated when subjected to various heat inputs and filling ratios. With a filling ratio of 50%, the acetone-filled PHP performed better.
[15]	CLPHP	8	Methanol	Different filling ratios and angles of inclinatio n.	When designing a heat pipe, the three crucial variables of bubble formation, phase transfer, and pressure are taken into account. The ideal thermo mechanical boundary conditions that lead to the convective flow boiling state in the evaporator design can be highlighted. Varying heat inputs to these devices result in various tube-internal flow patterns. In turn, this is in charge of numerous aspects of heat transfer. Methanol provides greater heat resistance in this test at 30° tilt for 40% filling ratio. Heat transfer coefficient performs better with a 40% filling ratio for various angles.
[16]	VCLPH P	5	Acetone –Ethanol and Ethanol - Methanol	Binary mixed fluids	With the lowest thermal resistance of 0.725°C/W and the maximum heat transfer coefficient of 193.6W/m2 °C, acetone-ethanol outperformed the other fluid combinations evaluated. The heat transfer coefficient for the ethanol-methanol mixture was 172.59 W/m2 °C, and the average thermal resistance was 0.82°C/W. Although ethanol-methanol mixture outperformed acetone-ethanol mixture thermally, the former can be viewed as a more suitable working fluid for PHP.

3. Design element influencing PHP

Inner Diameter (I.D.), Fill Ratio (FR), PHP Configuration, Inclination Angle (o), Number of Turns (n), Length of Evaporator (Le) and Condenser (Lc), and Working Fluid Characteristics are only a few of the factors that influence PHP behaviour.

3.1 Impact of Filling Ratio

The working fluid should only be partially inserted into the tube for the CLPHP to function. The volumetric filling ratio has an impact on PHP performance. The working fluid volume in the device divided by the device's overall volume is known as the filling ratio. The formation of relatively few bubbles is a result of a greater filling ratio percentage. There aren't enough disturbances, which results in insufficient pulsating motion. Very little liquid will be present at lower filling ratios, not enough to create separate slugs and there may be a dry out occurrence. Hence, 40% to 60% is the proper range for filling ratios [18]

3.2 Impact of Number of Turns

The minimum number of turns below which a PHP experiences the stop over phenomenon is known as the crucial value. A stop over phenomena occurs when the entire evaporator is filled with vapor bubbles and the remaining portion of the Tank is filled with liquid. In order to maximize the level of disturbances and the pulsating motion within the device, the optimal number of turns is therefore required. Additional turns provide more places for the application of heat, and as a result, more local pressure reductions occur, improving the production of liquid-vapor plugs and slugs. Typically, there are 5 to 23 turn options [19]

3.3 Impact of Geometry/ Construction

Changing the working fluid, changing the orientation, increasing the number of turns, altering the geometry, or changing the structure of PHPs can all improve heat flow. Numerous researchers have been looking into various methods that could encourage a one-way circulatory flow of the working fluid in a PHP because pauses and flow reversals that inexorably happen in it while it operates impair performance. Integrating a check valve into a PHP is a common method for causing the working fluid to achieve a one-way circulatory flow, which improved the thermal performance of PHPs [18]

3.4 Impact of Working Fluid

Working fluid characteristics must be taken into consideration as a crucial parameter since they have an impact on the development of two phase flow.

- High thermal conductivity – Fluids with this property can transfer heat from the evaporator to the condenser very quickly.
- Low latent heat: In an evaporator, bubbles form more quickly in fluids with lower latent heat.
- High specific heat—a higher specific heat will result in a greater transmission of sensible heat.
- Low surface tension: An unstable flow forms more slowly in a fluid with a high surface tension. Thus, a liquid with a low surface tension should be employed.
- Container compatibility: The working fluid shouldn't damage the tubes or walls of the evaporator or condenser.

• Low dynamic viscosity: This property makes it simple for liquid-vapor plugs and slugs to form. Moreover, the fluid around the walls will experience less shear stress. The recommended working fluids are typically water, methanol, ethanol, ethyl alcohol, etc. [18]

3.5 Impact of Orientation of tubes

Tubes that are oriented horizontally do not perform as well as tubes that are oriented vertically. The performance of horizontally oriented tubes in a CLPHP is often improved by a large number of turns supported by a high input heat flux. The tubes can be angled at 0, 30, 45, 60, 90, or 180 degrees [19]

3.6 Impact of Inclination Angle

According to experimental findings, PHP's heat transmission properties may change with inclination angle, particularly for those with fewer turns. Different performance levels occur from the direction PHP is inclined, which modifies how the working fluid moves. So, gravity plays a crucial part in how PHP functions. Several studies on PHP with 6 to 8 turns indicate a significant improvement in heat transfer at a 45-degree angle [19]

3.7 Impact of Length of Evaporator, Adiabatic and Condenser Section

Due of the numerous factors affecting how PHPs function, the complex physics dictating their properties is still highly challenging to comprehend and define. In a large PHP, the length of the flow path could result in a particular heat transfer characteristic that isn't necessarily present in a small PHP. As a result, it becomes important to determine how PHP's performance is affected by the length of the evaporator, adiabatic, and condenser sections. According to the authors, very little research has been done on the aforementioned subject so far [20]

3.8 Impact of Input Power

Heat input to the PHP has a substantial impact on its thermal performance because it changes the working fluid's resultant flow pattern. A popular method for analyzing how input power affects PHP is to measure its Thermal resistances (R_{th}) when heat input increases. The following equation is used to mathematically compute the Thermal Resistance (R_{th}):

$$R_{th} = (T_{e,\,avg} - T_{c,\,avg}) / Q \qquad (1)$$

Where Q is Heat Rejected to the heat reservoir at the condenser, and $T_{e,\,avg}$, and $T_{c,\,avg}$ are the Average Temperatures of the Evaporator and the Condenser, respectively. The majority of the investigations showed that the PHP's Rth decreased as heat input increased. If there was no dry-out, the thermal resistances of various working fluids and FRs exhibited a trend to converge with increased heat input. Studying how effective thermal conductivities change in response to heat input is another method. Equation gives the mathematical formula for a PHP's effective thermal conductivity as

$$k_{eff} = \{[(Q \times L_{eff}) / A] \times (T_{e,\,avg} - T_{c,\,avg})\} \qquad (2)$$

where L_{eff} is the Length, and A is the Heat Transfer Area [20]

4. Conclusion

This paper aimed to figure out the scenario of experimental analysis of pulsating heat pipe in different sectors. Using pure natural convection, heat generated in the heating portion was carried to the condensation section and then dissipated into the surrounding air. This entry makes it evident that CLPHP is the subject of a lot of research, whether it is to improve its functionality and understand how it works or to construct and use quantitative modeling to ascertain its heat transfer qualities. This study provides the CLPHP's simple functionality and design as well as the extensive research on numerous CLPHP design elements. Also suggested for usage in next development are a few freshly established concepts. As a result, it is concluded that there is still much research to be done on PHP in a number of areas, such as the development of extraneous phenomena like acoustic waves, the comprehension of Taylor's bubble flow, the development of accurate and consistent relationships for PHP to compute its heat transfer capacities.

References

1. Md. Lutfor rahman, Md. Faisal kader, Md. Zakaria rahman, M. Ali, American Journal of Mechanical Engineering **4**, (2016)
2. N. Santhi sree, N. V. V. S.Sudheer, P. Bhramara, Journal of mechanics of continua and mathematical science **15**, 6 (2020)
3. Shreyas R. Harne, Prof. R.S. Mohod International Journal for Research in Applied Science & Engineering Technology **10**, (2022)
4. Dharmapal A Baitule, Pramod R Pachghare, International Journal of Mechanical Engineering and Robotics Research **3**, (2013)
5. Bhawna Verma , Vijay Lakshmi Yadav, Kaushal Kumar Srivastava, Journal of Electronics Cooling and Thermal Control **27-34**, (2013)
6. Marco Marengo, Vadim S. Nikolayev, *Pulsating Heat Pipes: Experimental Analysis, Design and Applications* (2023)
7. M. Lutfor Rahman, Rasel A. Sultan, T. Islam, Noor M. Hasan, Mohammad Ali,*An Experimental Investigation on the Effect of Fin in the Performance of Closed Loop Pulsating Heat Pipe (CLPHP),* Procedia Engineering, Volume 105, (2015)
8. Piyanun Charoensawan, Sameer Khandekar, Manfred Groll, Pradit Terdtoon, Applied Thermal Engineering **23**,16 (2003)
9. Chen, Jing & Dong, Junbiao & Yao, Ye. Experimental Study on the Starting-Up and Heat Transfer Characteristics of a Pulsating Heat Pipe under Local Low-Frequency Vibrations. Energies. **14,** 19 (2021)
10. Shang, F., Fan, S., Yang, Q. et al. An experimental investigation on heat transfer performance of pulsating heat pipe. J Mech Sci Technol **34**, 425–433 (2020)
11. Dong Zhang, Haixia Li, Jianghao Wu, Qingliang Li, Baorui Xu, Zhoujian An, Energies **15**, 21(2022)
12. Harshal Gamit, Vinayak More, Bade Mukund, H. B. Mehta, *Experimental investigations on pulsating heat pipe.* International Conference on Applied Energy, 75 ,(2015)
13. M. B. Shafii, S. Arabnejad, Y. Saboohi, H. Jamshidi, Heat Transfer Engineering **37-41** (2015)
14. Jagadeesh S, Umesh C, International Journal of Science and Research **2319-7064** (2016)

15. Md. Lutfor Rahman, Farah Nazifa Nourin, Zaimaa Salsabil, Nusrat Yasmin, , and Mohammad Ali, *An experimental study on the performance of closed loop pulsating heat pipe (CLPHP) with methanol as a working fluid*. AIP Conference Proceedings 1754, (2016)
16. G. V. Pradeep, K. Rama Narasimha, International Journal of Engineering **31** (2018)
17. N SanthiSree, N V V S Sudheer, P.Bhramara, International Journal of Innovative Technology and Exploring Engineering **8** (2019)
18. Bhushan G. Patil, Pramod R. Pachghare, International Journal of Mechanical And Production Engineering **4** (2016)
19. Dadong Wang, Xiaoyu.Cui, International Symposium on Transport Phenomena **2-5** (2010)
20. Chirag Dave1, Prajwal Dandale, Kushagra Shrivastava, Dashrath Dhaygude, Kavi Rahangdale and Nilesh, Journal of Thermal Engineering **7** (2021)