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Review Paper

Parameters Affecting the Functioning of Close Loop Pulsating Heat Pipe: A Review

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Abstract

Advancement is taking place in every field of engineering and increasing the demand of smaller and effective heat transfer devices. This leads to the development of Pulsating Heat Pipe (PHP). PHP is a passive two-phase heat transfer device for handling moderate to high heat fluxes typically suited for power electronics and similar applications. It usually consists of a small diameter tube, closed end-to-end in a loop, evacuated and then partially filled with a working fluid. The internal flow patterns in a PHP are a function of the applied heat flux. This paper highlights the thermo-hydrodynamic characteristics of these devices. State of art indicates that at least three thermo-mechanical boundary conditions have to be met for the device to function properly as pulsating heat pipe. This includes internal tube diameter, applied heat flux and filling ratio. Additionally the numbers of turns and thermo-physical properties of working fluid also play a vital role in determining the thermal behaviour. Apart from this, paper is a literature review on pulsating heat pipe technology; work performed by researchers. Finally, unresolved issues on the mechanism of PHP operation with different type of working fluids, validation techniques and applications are discussed.

Keywords: Pulsating heat pipe, two phase heat transfer.

Introduction

As the advancement is taking place in all fields of engineering, especially in making components compact and efficient. These features are in vogue today and this elation has especially gripped the electronics and allied industries. Researchers are endeavor towards higher functionality at reduced package size led to denser electronics and increased power. Total dissipated power is not the only problem; heat flux is Complimentary to it. The solution for this is to develop a new material, novel cooling strategy in the cooling technology concepts and modes of implementation. This lead to development of Pulsating Heat Pipes (PHPs) a concept proposed by Akachi[1]. PHPs seem to meet all the present day cooling requirements. PHPs are highly attractive heat transfer elements, which due to their simple design, cost effectiveness and excellent thermal performance may find wide applications. Since their invention in the early nineties, so far they have found market place in power/micro electronics equipment cooling. These heat pipes are able to overcome some limitations of conventional heat pipe like capillary and entrainment limits. Although it is grouped as a subtype of the overall family of heat pipes. The complexity of thermo-hydraulic coupling is distinctly unique.

Basically a pulsating heat pipe consists of meandering tube of capillary dimensions with many U-turns partially filled with the working fluid[1,2]. In contrast to a conventional heat pipe, there is no additional capillary weak structure inside the tube. One end of this tube (called evaporator section) is brought in thermal contact with a hot point to be cooled. The other end (called condenser section) is connected to the cold point where the heat can be dissipated. A portion of the tube between evaporator and condenser is called adiabatic section. The working fluid and its pressure are chosen in such a way that the saturation temperature is between the evaporator temperature Te and condenser temperature Tc. The fluid is thus vaporized due heat absorption in the evaporator and its release in the condenser. The created vapour is transported to the condenser section and condenses there. The liquid is transported back to the evaporator section. Since the latent heat is large, the heat pipes are quite efficient. It has 100-200 W/cm^2 heat flux evacuating capability[3]. The heat is transferred mainly due to the latent heat between the tube wall and a vapour plug and in the meniscus region between the plug and slug, which requires complex analysis.

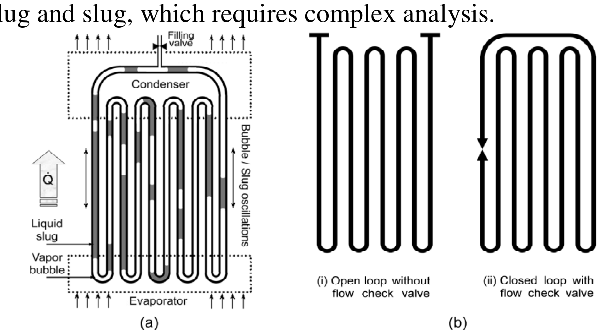

Figure-1
(a) Basic constructional details of a closed loop pulsating heat pipe, (b) Type of physical configurations a pulsating heat pipe

There are different kinds of pulsating heat pipes. They differ by their geometry and a mechanism of fluid transport inside the heat pipe as shown in figure-1.

Working Principle

Working of PHP depends on three principles, thermodynamic, fluid dynamics and heat transfer principles

Thermodynamic Principle: As heat is given to cooper tube in evaporator section, after some time vapor bubble formation starts and these bubble get condensed in the condenser section and heat rejection takes place. Due to heat addition, rejection and the growth and extinction of vapor bubbles drive the flow in a PHP. Even though the exact features of the thermodynamic cycle are still unknown[4].

Fluid Dynamic Principle: Fluid flow in a capillary tube consists of liquid slugs and vapor plugs moving in unison. The slugs and plugs initially distribute themselves in the partially filled tube. The liquid slugs are able to completely bridge the tube because surface tension forces overcome gravitational forces. There is a meniscus region on either end of each slug caused by surface tension at the solid/liquid/vapor interface. The slugs are separated by plugs of the working fluid in the vapour phase. The vapor plug is surrounded by a thin liquid film trailing from the slug.

Heat Transfer Principle: As the liquid slugs oscillate, they enter the evaporator section of the PHP. Sensible heat is transferred to the slug as its temperature increases, and when the slug moves back to the condenser end of the PHP, it gives up its heat. Latent heat transfer generates the pressure differential that drives the oscillating flow. The phase change heat transfer takes place in the thin liquid film

Parameters Affecting the Performance of Closed Loop PHP

There are the various parameters which affect the performance of closed loop pulsating heat pipe directly or indirectly, which are given bellow[5].

Design/Geometrical Parameters: i. Tube diameter and material, ii. Orientation of PHP, iii. Number of turns, iv. Design of evaporator and condenser section, v. Bend effect.

Operating Parameters: i. Filling ratio, ii. Heat Flux/Temperature, iii. Dry out condition,

Properties of working fluids: i. Operating temperature range, ii. Sensible heat and latent heat.

Design/Geometric Parameters: Diameter and material of tube: The diameter of heat pipe plays vital role in the selection of the heat pipe. Because it affects the performance of pulsating heat pipe. The internal diameter directly affects the PHP. A large hydraulic diameter results in a lower wall thermal resistance and increases the effective thermal conductivity. The capillary tube inside diameter must be small enough such that:

$$D_{max} = 2\sqrt{\frac{\sigma}{g(\rho_{liquid} - \rho_{vapor})}} \quad (1)$$

Where: σ = working fluid surface tension (N/m); g = gravitational acceleration (m/s^2); ρ_{liquid} = liquid density (Kg/m^3) ρ_{vapor} = vapor density (Kg/m^3)

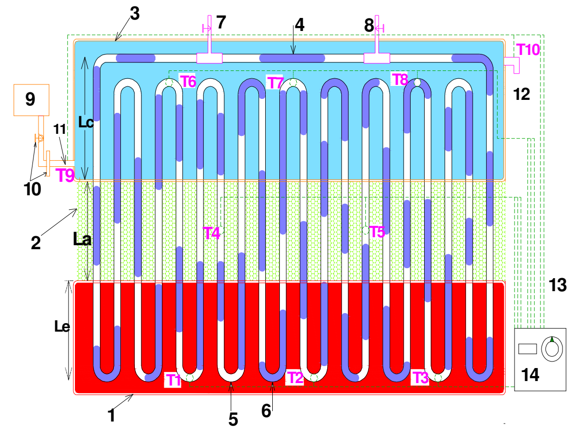

Figure-2
Schematic Diagram of Heat pipe

Table-1
Part Description of Figure-2

Part No.	Description
1	Evaporator
2	Adiabatic Section
3	Condenser
4	Cooper tube
5	Vapor plug
6	Liquid slug
7	Filling valve (T-joint)
8	To Vacuum pump (T-joint)
9	Cooling water tank
10	Control valve and Flow meter
11	Cooling water Inlet
12	Cooling Water Outlet
13	Thermocouple connections
14	Temperature Recorder

If $D < D_{max}$, surface tension forces dominate and stable liquid plugs are formed. However, if $D > D_{max}$, the surface tension is reduced and the working fluid will stratify by gravity and oscillations will cease[6]. Also the selection of tube material is important; the different type materials have their own coefficient of heat transfer.

Also their compatibility with the working fluid is important, because Problem of non compatibility is decreased performance, failure or corrosion. Decomposition of the working fluid can lead to corrosion and formation of non condensable gases through chemical reactions between the working fluid and material, can cause problem with the operation of the heat pipe. Compatibility test result is showed in table-1. Table-1 shows the compatibility of different material with working fluids. From the previous literature it is clear that copper is best heat pipe material. Table-1 shows Compatibility of working fluid with different material[7].

Table-1
Compatibility of working fluid with tube material

Tube Material	**Working Fluid**		
	Water	Acetone	Ammonia
Copper	RU	RU	RU
Aluminium	GCN	RL	RU
Stainless Steel	GNT	MC	RU
Nickel	MC	MC	RU

RU- recommended by past successful usage; RL- recommended by literature; MC- may compatible GNC- generation of gas all temperatures;

Orientation of PHP: Orientation of PHP has significant effect on the performance of heat pipe. Researcher has shown that the different inclination angle with respect to horizontal with evaporator at bottom gives the different results. The optimum angle of inclination is between 50-65 where the PHP gives its optimum performance[8].

Number of turns: As the number of turn of PHP increases it provides flexibility to the PHP to operating at any orientation (i.e. at various angle of inclination with horizontal). Researchers have shown that if the number of turns is less then it operates in vertical position only, not in horizontal position[8,9]. Mamelli also concluded that nine turns CLPHP has many advantages with respect to the one with three turns: i. It is able to work also in the horizontal heat mode. ii. Its thermal resistance is lower, iii. There are less evident differences between different fluids in terms of overall efficiency.

Design of evaporator and condenser section: Design of evaporator and condenser plays important role, which affects the performance of heat pipe. It is thumb rule that the condenser should have the larger area than the evaporator in order to avoid the dry out condition. Figure-3 shows that the evaporator section lengths affected on critical heat flux in this range. When the evaporator section lengths increased the critical heat transfer flux decreased.

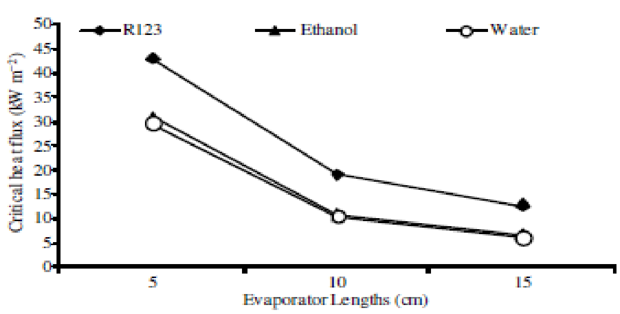

Figure-3
Evaporator length and critical heat flux

A typical performance characteristic of a conventional heat pipe is shown in figure 4. The heat pipe is assumed to be operating at an adiabatic temperature of T1 with heat input of Q1, very close to the dryout power Qdry-1 corresponding to the operating temperature. If, under such operating conditions the condenser capacity is increased, by either lowering the coolant temperature or increasing the coolant mass flow, there is a risk of a dryout to occur. This will happen since the operating temperature drops to T2 for which the heat input Q1 is too high. Thus, increasing the condenser capacity need not necessarily improve the heat transfer for conventional heat pipes. Although there is no well defined adiabatic operating temperature for pulsating heat pipes, a similar trend regarding the effect of condenser capacity may be observed. Increasing the condenser capacity affects not only the thermophysical properties of the working fluid but as a side effect alters the slug-annular flow pattern transitions, thereby altering the final performance. This aspect has to be addressed while practical designing[10].

Bend Effect: In PHP geometry there numbers of U-terns are present. Mamelli explained the effect of bend on the performance of PHP. Due to the 180^0 and 90^0 bent pressure loss occurs in heat pipe. Mamelli also have developed the numerical model to account for the local pressure loss taking place in the PHP. He concluded that Local pressure losses due to bends and turns affect the device operation especially in the horizontal mode and for high heat input levels[8].

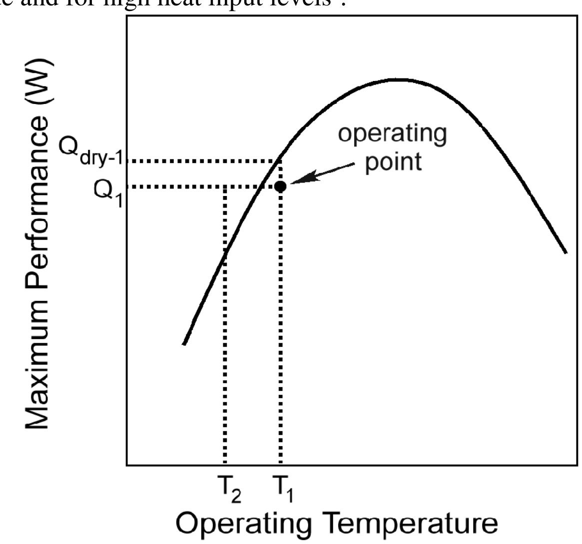

Figure-4
The effect of condenser capacity on a conventional heat pipe; dryout occurs when the operating temperature shifts from T1 to T2 10

Operating Parameters: Filling ratio: The filling ratio is defined as the fraction by volume of the heat pipe, which is initially filled with the liquid. The optimal filling ratio is determined experimentally when the maximum heat transfer rate is achieved at a given temperature. There are two optimum fill ratios limits 0% and 100%. In between these two extremities there exist three distinct sub-regions as shown in figure-5.

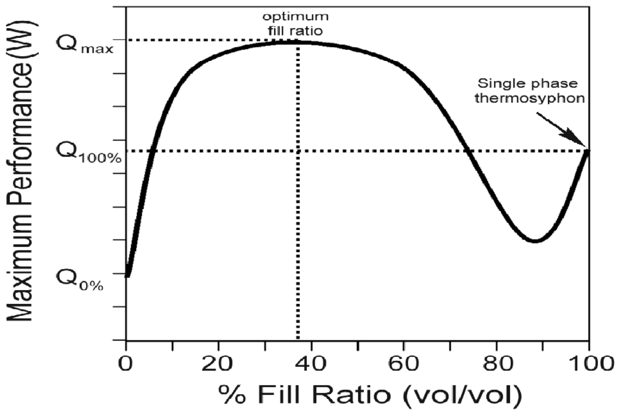

Figure-5
Effect of fill ratio for a closed loop pulsating heat pipe in vertical orientation, heater down position (maximum performance for a specified maximum average evaporator temperature) 10

100% filling ratio: In this mode there are only very few bubbles present rest being liquid phase. These bubbles are not sufficient to generate the required pumping action/perturbations resulting in a small overall degree of freedom. The buoyancy induced liquid circulation, which was present in 100% filled case, gets hindered due to additional surface tension generated bubble friction. The few bubbles present tend to agglomerate in the upper condenser section and it becomes difficult for the bulk liquid to push them down due to buoyancy. Thus, the performance of the device is seriously hampered compared to a 100% filled PHP.

0% filling ratio: In this mode, there is very little liquid to form enough distinct slugs and there is a tendency towards evaporator dry-out. The operational characteristics are unstable. The device may, under some operating conditions, work as a two-phase thermosyphon but capillary bridging and intermittent flow characteristics render the operation unstable and ineffective.

PHP true working range: In between about 20% to 80% filling ratio the PHP operates as a true pulsating device. The exact range will differ for different working fluids, operating parameters and construction. The more bubbles (lower fill charges), the higher is the degree of freedom but simultaneously there is less liquid mass for sensible heat transfer. Less bubble (higher fill charges) cause less perturbations and the bubble pumping action is reduced thereby lowering the performance. Thus, an optimum fill charge exists[11,12].

Heat Flux/Temperature: PHPs are thermally driven non-equilibrium devices, and although they may be very effective heat spreaders, a temperature difference must exist between the evaporator and condenser to maintain their operation. In many cases, there was observed to be some minimum heat flux or differential temperature necessary to initiate oscillating flow. Like the optimum charge ratio, the onset heat flux was different for each experiment. Therefore, parametric investigation is required to fully understand this phenomenon. When the number of turns is small a critical heat flux between 5.2 and 6.5 W/cm2 is needed to ignite a stable fluid motion and reach an acceptable pseudo steady state.

Dry out condition: This factor limits the operation of heat pipe. When the complete working fluid vaporized and there is no any liquid in the evaporator section then we can say dry out condition is occurred. This condition occurs when there is very low filling ratio and high heat input is given to the pipe. When dry out condition reaches the heat transfer take place completely due to conduction.

Properties of Working Fluid: The selection of working fluid is also important parameter which affects the performance of PHP. Selection of working fluid is directly linked to the properties of the fluid. The properties are going to affect both the ability to transfer heat and the comparability with the tube material. The working fluid should be selected such that it supports the PHP operating temperature range. The temperature range of different fluids is shown in table 2. When selecting a working fluid, the following working fluid characteristics should be examined: i. Compatibility with the OHP material(s), ii. Thermal stability, iii. Wettability, iv. Reasonable vapor pressure, v. High latent heat and thermal conductivity, vi. Low liquid and vapor viscosities, vii. Acceptable freezing point.

Table-2
Temperature Range of Working Fluid

Working Fluid	Melting point (^oC)	Boiling point (^oC)	Useful range (^oC)
Helium	-271	-261	-271 to -269
Nitrogen	-210	-196	-203 to -160
Ammonia	-78	-33	-60 to 100
Acetone	-95	57	0 to120
Methanol	-98	64	10 to130
Ethanol	-112	78	0 to130
Heptane	-90	98	0 to150
Water	0	100	30 to200

For most applications, the thermodynamic characteristics of water make it a good choice for PHP applications, as it has high latent heat, which spreads more heat with less fluid flow, and high thermal conductivity which minimizes ΔT. However, water does have high surface tension and may have adverse effects on the PHP as it may cause additional friction and limit the two-phase flow oscillations of the PHP. Methanol is a good substitution for water, especially for sub zero applications, as it has approximately one third the surface tension[13].

Unsolved Issues

From previous research it is clear that many working fluids with distinctly varying properties have been tried. Since the domain of experimental activity is quit widespread, all the fluids have not been tested in the entire experimental parameter matrix and amount of data is still growing. At this stage it is certainly difficult to prescribe or proscribe a certain fluid unless all the boundary conditions are exactly known and individual effects have been explicitly quantified. Different working fluids seem to be beneficial at different operating conditions. An optimum trade off of various thermo-physical properties has to be achieved depending on the imposed thermo-mechanical boundary conditions, also the performance of PHP using nono fluids[14]. This certainly requires further research. At different situations, different pure working fluids have their advantages. But till now, mixtures used as working fluids in PHP have not been thoroughly investigated. The non-azeotropic mixtures, which have the characteristics of phase transition with temperature floating, can make heat source and working fluids match well in temperature[9].

The optimum quantity of working fluid needed depends on various parameters and is still an area of research[12]. Also the different types of PHP design yet to be tested.

Conclusion

Pulsating heat pipe is gaining more and more popularity, which due to their simple design, cost effectiveness and excellent thermal performance may find wide applications. Since their invention in the early nineties, so far they have found market niches in electronics equipment cooling. The work compiled here significantly increases the understanding of the phenomena and effect of working fluids that govern the thermal performance of pulsating heat pipes. Many unsolved issues related to working fluids and design still exist, but continued exploration should be able to overcome these challenges.

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