Effect of Working Fluids and Fill Ratio on Design Parameters of Closed Loop Pulsating Heat Pipe: A Review

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Abstract— A closed loop pulsating heat pipe (CLPHP) is small passive heat transfer device with an extremely high effective thermal conductivity. The unique feature of this device compared with conventional heat pipe is that, there is no wick structure to return the condensate fluid to the evaporator section; it means that there is no counter flow between the liquid and the vapor. This paper reviews an influence of different working fluids for different heat input and variable filling ratio of many U turn on CLPHP. The main objective of this paper is to attempt theoretical and experimental investigation of different working fluids such as distilled water, ethanol, acetone and heptane etc., for different heat input and variable filling ratio using a single turn CLPHP to find suitable working fluid for a device. A filling ratio of 50% of its total volume is optimum.

Key words: CLPHPs, single turn, Working Fluid

I. INTRODUCTION

All electronic components, from microprocessors to high power generators, generate heat and rejection of this heat is necessary for their optimum and reliable operation. Thermal management is the challenge of the day in electronic product development. Presently the chip flux ranges between 40 to 120W/cm^{2}and in next few coming decades it is expected to increase up to 200 W/cm^2 [2] To reduce such type of load on these device there are novel technologies available which is in small size and shape electronic devices, because they are compact in nature and more efficient, due to this it has less area for cooling system, to manage these type of problem i.e. thermal management of microelectronic devices there is a requirement of miniaturization of two phase passive heat transfer device.

A Pulsating heat pipe (PHP) is phase change device typically suited for microelectronics cooling consists of a plain capillary tube of small dimensions with number of U turns. The pipe is first evacuated and then filled partially with a working fluid. If the diameter of the pulsating heat pipe is very small, the fluid distributes itself into an arrangement of liquid slugs separated by vapor bubbles and moves into the capillary tube due to pressure gradient. The pulsating heat pipe proposed and presented by Akachi. H. in 1990 [1], due to its excellent features the pulsating heat pipe is used in space system, cold region, automobile industry, electrical, nuclear Industries and other electronic cooling application.

II. WORKING PRINCIPLE

A Pulsating Heat pipe is a very efficient instrument for transfer of heat from one location to another. Heat pipe consist of mainly three parts namely evaporator, condenser and adiabatic region. The evaporator is the heating section and condenser is the cooling region, which is separated by adiabatic region. A pulsating heat pipe is working on three principles, thermodynamic, fluid dynamics and heat transfer principles.

A. *Thermodynamic Principle:*

The device is first evacuated and then charged with the working fluid (required fill ratio) prior to being airtight; the internal pressure is set by the vapor pressure of the fluid. The working fluid inside the capillary tube, distributes itself naturally in the form of liquid vapor plugs and slugs. The liquid Plugs are able to completely stalemate the tube, because the surface tension forces overcome gravitational forces. There is condenser region on either end of each slug caused by surface tension at the liquid /solid/ /vapor interface. In vapor phase the slugs are separated by plugs of the working fluid. The vapor plug is surrounded by a thin liquid film trailing from the slug**.**

B. *Fluid Dynamic Principle:*

When one end of the bundle of tube received the heat at evaporator region and subjected to high temperature, the working fluid inside evaporator evaporates and increases the vapor pressure, which causes the bubbles in the evaporator zone to grow, and extinction of vapor bubbles drive the flow in a device towards the condenser section.

C. *Heat Transfer Principle:*

This vapor bubbles pushes the liquid column toward the low temperature end (condenser) and reject the heat to the condenser region. The temperature and pressure decrease in the condenser due to condensation. Therefore a constant, unsteady internal pressure difference exists in the system which is the driving force. Because of the interconnection of the tubes; motion of liquid slugs and vapor bubbles at one section of the tube toward the condenser also leads to the motion of slugs and bubbles in the next section toward the high temperature end (evaporator), this works as the restoring force.

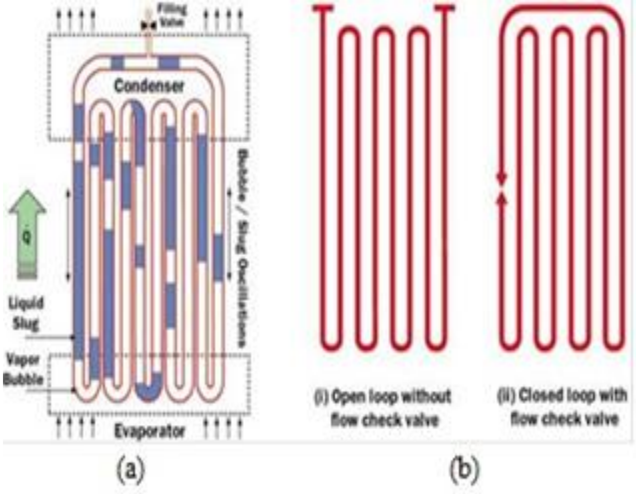

Fig. 1: (a) Basic constructional details of a closed loop pulsating heat pipe, (b) Type of physical configurations a pulsating heat pipe [3]

The inter-play between the driving force and the restoring force leads to oscillation of the vapor bubble and liquid slugs in the axial direction. The shear force and mass fraction of the liquid in the tube cause the frequency and the amplitude of the oscillation. In PHPs, heat is transferred from the evaporator to the condenser through sensible and latent heat transfer, which is a result of the working fluid oscillations and phase changes.

III. EFFECT OF DESIGN PARAMETERS

There are various design parameters which affect the thermal performance of closed loop pulsating heat pipe

A. *Design Parameters:*

(1) Tube diameter and material
(2) Orientation of PHP
(3) Number of turns
(4) Design of evaporator and condenser section
(5) Tilt angle [3, 4]

1) *Tube Diameter and Material:*

The internal diameter of the tube play vital role in the heat pipe design. It directly affect the performance of PHP. A large hydraulic diameter results in lower the thermal resistance and iincrease the effective thermal conductivity. The inside capillary diameter is small enough so that liquid slug and vapor plug exit. The critical diameter of tube is given by [3]

$$D_{cri} = 2 * \sqrt{\frac{\sigma}{(g * (\rho_l - \rho_v)}} \qquad (1)$$

Where: σ = surface tension of working fluid (N/m); g = acceleration due to gravity (m/s^2); ρ_l = liquid density (kg/m^3); ρ_v = vapor density (kg/m^3)

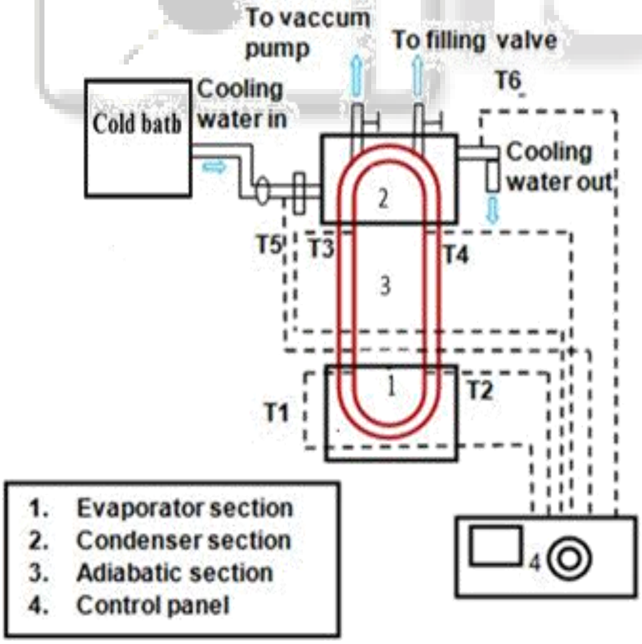

Fig. 2: Schematic of Closed Loop Pulsating Heat Pipe

If D < D_{cri}, the surface tension forces dominate and the steady liquid plug are formed. However, if D > D_{cri}, the surface tension is reduced and the working fluid will stratify by gravity and oscillations will cease [5]. Also the selection of tube material is important; the different type materials have their own coefficient of heat transfer.

2) *Orientation of PHP:*

The PHP are operated with three orientation; horizontal heated, vertical bottom heated and vertical top heated orientations. The best performance of PHP existed in the vertical heated orientation with heating at the bottom and the orientation played almost no role.

3) *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[4,6]. Mamelli also discused that nine turns CLPHP has many advantages with respect to the one with three turns: i. It is capable to work also in the horizontal heating mode. ii. Thermal resistance is lower, iii. There are less manifest differences between different fluids in terms of overall efficiency.

4) *Design of Evaporator and Condenser Section:*

Meena studied the effect of evaporator section lengths and working fluids on operational limit of closed loop oscillating heat pipes with check valves (CLOHP/CV). The result shows that, when the evaporator lengths increases the critical heat transfer flux decreases. There was working fluids change from R123 to Ethanol and water the critical heat flux decreased. The latent heat of vaporization affects the critical heat flux. For lower latent heat of vaporization with working fluid shows a higher critical heat flux [7].

5) *Tilt Angle:*

Thermal performance of pulsating heat pipe also depends upon how the pulsating heat pipe is located. Heat pipe can be used in various positions. It can be vertical, horizontal or in any other angle. In horizontal position, no gravity effect on the performance of heat pipe. But, when the angle changes, the gravity start playing its role in tube. With the change in angle, the effect of gravity changes causes the performance of pulsating heat pipe [8]. Also the orientation of heat pipe is important. With change in angle, gravity can aid or compete with the working of heat pipe. Dependent on this, there are two types of tilt angle- adverse and favourable [9].

When the evaporator is below and condenser is above the tilt angle is favourable and vice versa for adverse tilt angle. When we use favourable tilt angle i.e. evaporator is below and condenser is above, the performance of pulsating heat pipe increases with rise in tilt angle. This is because, in this type of orientation, gravity helps the movement of fluid from condenser to evaporator. Hence, with the rise in rate of transfer of fluid from condenser to evaporator, the rate of heat transfer increases and hence increases efficiency. While, in adverse tilt angle, condenser is below and evaporator is above and in this gravity opposes the flow of fluid from condenser to evaporator and hence the efficiency of heat pipe drops. Hereafter, the heat pipe must be kept in favourable Tilt angle for maximum efficiency. An rise in heat transfer rate of 39% is obtained for 2% iron oxide nano-particles, when the angle of inclination of heat pipe is 90 degrees. Efficiency of heat pipe usually increases with increase of angle in favorable tilt. However, when the heat pipe tilt angle exceeds a value of 60° for de-ionic water and 45° for alcohol, the heat pipe thermal efficiency tends to decrease [10].

IV. EFFECT OF WORKING FLUIDS AND FILLING RATIO

Working fluid selection is directly related to the properties of the fluid. The properties of working fluid is affect on both the ability to transfer heat and the compatibility with the case when no wick structure. A no. of characteristics must be evaluated in order to determine the most favourable fluid for the application considering the primary requirements which are compatible with the heat pipe materials such as thermal stability, wettability, sensible vapour pressure, high latent heat and thermal conductivity, low liquid and vapour viscosities and acceptable freezing point.

Working fluid	**Melting point (^{0}C)**	**Boiling point (^{0}C)**	**Useful range (^{0}C)**
Helium	-271	-261	-271 to -269
Nitrogen	-210	-196	-203 to -160
Amonia	-78	-33	-60 to 100
Acetone	-95	57	0 to 120
Methanol	-98	64	10 to 130
Ethanol	-112	78	0 to 130
Heptane	-90	98	0 to 150
Water	0	100	30 to 200

Table 1: Temperature Range Of Workin Fluids

For most of the applications , the water is used as base fluid in hydrodynamic characteristic of PHP, as it has high latent heat high effective thermal conductivity because of it it spreads more heat with less fluid flow.

Pachghare conducted experiments on thermal performance of closed loop pulsating heat pipe (CLPHP). The copper capillary tube was used having ID = 2 mm and OD = 3.6 mm respectively. For all experimentation, filling ratio (FR) was 50 %, number of turns = 10 and heat inputs = 10 to 100W were supplied to PHP. The lengths of evaporator, adiabatic and condenser sections were 50 mm each respectively. Working fluids were selected as water, methanol, ethanol, acetone, and different binary mixtures.

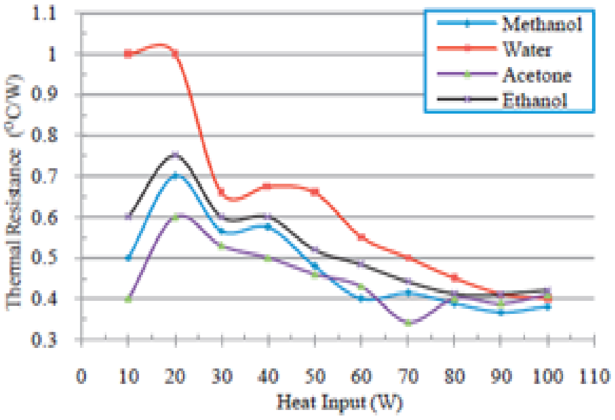

Fig. 3: Thermal resistance of pure working fluid PHP.

The experimentation result shows that, the thermal resistance decreases rapidly with the increase of the heating power from 20 to 60 W, whereas for a power above 60 Watt, thermal resistance decreases slowly. Pure acetone gives best thermal performance in comparison with the other working fluids. No measurable difference has been recorded between the PHPs running with pure and binary mixture working fluids [11].

Piyanun Charoensawan conducted experimental investigations on a range of PHPs. The closed loop pulsating heat pipe were made of copper tubes of inner diameters 2 mm and 1 mm. Water, ethanol and R – 123 were used as the working fluids.

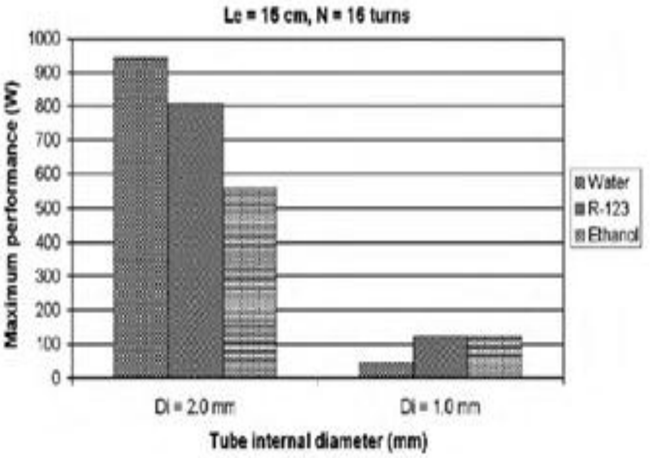

Fig. 4: Effect of working fluid on the thermal performance.

The result shows that relative share of sensible and latent heat in PHP is influenced by the working fluid. They also showed that the type of flow (i.e. slug/annular flow), the average flow velocity and overall pressure drop in PHP depends on the working fluid. They found that the collapse, shapes, bubble nucleation and bubble pumping action were influenced by the working fluid. In this experiments, authored observed that the better performance of PHP with water at vertical orientation with 2 mm inner diameter. For 1 mm diameter tubes, they obtained better results with R – 123 and ethanol [12].

A. *Filling Ratio:*

Filled ratio is 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.

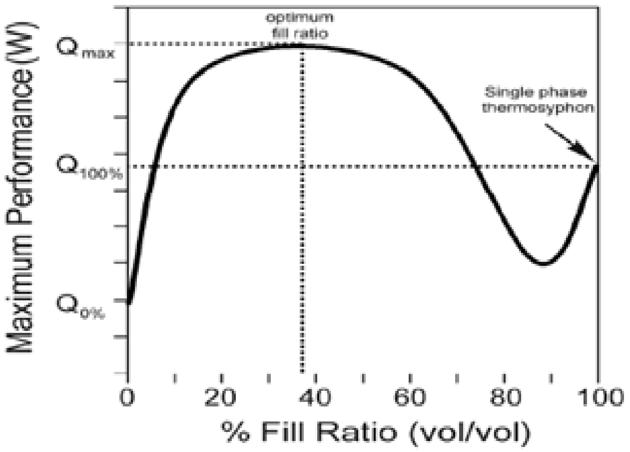

Fig. 5: Effect of fill ratio for a closed loop pulsating heat pipe in vertical orientation

Filled ratio is constricted by two operational limits. At 0% filled ratio, a heat pipe empty (no working fluid) and plain tubes only, is a heat transfer device in pure conduction mode with a very high undesirable thermal resistance. At 100% filled ratio, heat pipe operates like a single phase thermo- syphon with action maximum for a vertical heat pipe and stops for a horizontal heat pipe. The heat transfer takes place virtuously by axial direction through conduction in a horizontal heat pipe [13].

A number of experiments have been performed using varying heat inputs and filled ratios. Experiments were carried out in dry mode (without working fluid) and wet mode (with working fluid in it). The dry mode experiment represents the heat transfer characteristics in an ordinary conductor, and the wet mode experiment depicts the live heat pipe characteristics.

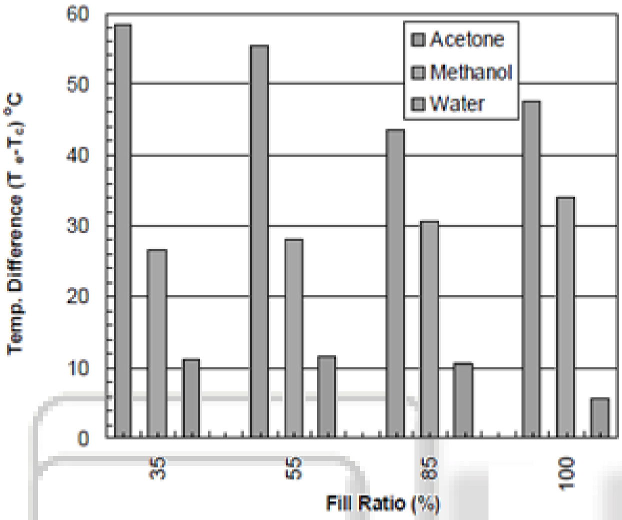

Fig. 6: Temperature vs fill ratio for different working fluids for input heat of 10 W

Three different working fluids namely distilled water; methanol and acetone are used in this study. The pulsating heat pipe was filled with 35%, 55%, 85% and 100% of the evaporator volume and tested for different heat input and working fluids. Results shows that , wet run shows the reduced thermal resistances for all levels of heat input and all types of working fluids. The dry run shows the largest values of thermal resistances and it is almost constant for varying heat loads. The experiments done over the years indicate that the filling ratio and the heat input are important considering the heat transfer performance and the heat pipe performs optimally when the filling ratio ranges between 50–75%, at 50o inclination angle. The minimum performance was found for filling ratio at 25% and inclination angle at 25^0 [14].

V. UNSOLVED ISSUES

From previous research it is clear that many working fluids tried for different filling ratio, heat flux range and numbers of turns. But increasing the demand for cooling application in various sectors and the novel technologies are available to solve this problem. Since the domain of experimental activity is widespread. Many of the fluid have been not tested experimentally and there is scope for the different working fluids. At present the working fluid prescribe the domain of experimental activity in hydraulic of PHP. 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 Nano Fluids. 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 heptane, nano fluids. 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 [4].

VI. CONCLUSIONS

Pulsating heat pipe is gaining more and more popularity, which due to their simple design, low weight, cost effectiveness, high thermal conductivity and excellent thermal performance may find wide applications in various fields. Since their invention in the early nineties, so far they have found market positions in electronics equipment cooling. The work assembled here significantly increases the understanding of the phenomena and effect of working fluids that govern the thermal performance of pulsating heat pipes. Voluminous unsolved disputes related to working fluids and design parameter still exist, but the technologies available should be able to overcome these challenges.

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