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On the Design Fundamentals of Pulsating Heat Pipes: An Overview

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***Abstract*— Pulsating heat pipes (PHPs) are the new addition to the wickless heat pipe family introduced by Akachi in 1990's, in last few decades this device acts as a promising source for cooling electronic devices where temperature difference between source and sink is very small. Pulsating heat pipes are highly acceptable devices due to its simple design, light weight feature and small size. Initially the review is focused on mechanism of fluid transport inside the PHPs and number of parameters which effect the working of PHPs is listed. The next half outlines the fundamentals of design and effect of design parameters on Thermal Performance of PHPs. The progresses in design of Critical Diameter, Numbers of Meandering Turns, Working Fluids and Filling Ratio are reviewed in this literature.**

Keywords— ***Pulsating heat pipes, closed loop pulsating heat pipes, critical diameter, critical number of turns, filling ratio, working fluids, Thermal resistance, start-up power.***

I. INTRODUCTION

In last few decades' rapid development in electronic industry forced researchers to do work on small size effective heat transfer devices for cooling of electronic components. Use of Phase change materials, jet cooling, two phase flow of fluid are the few methods used for cooling purpose. Heat pipes are widely used as one of the effective heat transfer device, researcher are working on different geometries and principle of fluid transport in heat pipes. The Components of heat pipe are Evaporator, Condenser & Wick structure. Adiabatic section is used to connect evaporator and condenser section. Heat pipe can be differentiate on the basis of wick structure as wick heat pipe and wickless heat pipes ,in wickless category there are Thermosyphon and Pulsating heat pipes .In this literature focus is on pulsating heat pipes (PHPs). [1]

In Conventional Heat Pipe, Capillary force is responsible for liquid transport from condenser to evaporator, in Thermosyphon the position of evaporator is always below the condenser and liquid transport is due to gravity as driving force. PHPs are also providing the pump less system but the force which ensure the fluid transport is pulsating action of working fluid.

Pulsating heat pipe is new addition in wickless heat pipe family with promising heat transfer capacity introduced by Akachi in 90's. He further patent on PHP which is long meandering tube heated and cooled at two separate ends, the operation of PHP is depends on oscillation / pulsating action of working fluid inside the tube. [2]

According to Akachi PHP is " When one end of the bundle of turns of the undulating capillary tube is subjected to high temperature, the working fluid inside temperature increases vapour pressure which causes the bubble in the evaporator zone to grow, this pushes the liquid column towards the low temperature end, the condensation at the low temperature end will further increases the pressure deference between the two ends, because of the interconnection of the tubes, motion of the fluid slug and vapour bubbles at one end section of the tube towards the condenser also leads to the motion of slugs and bubbles in the next section towards the high temperature end. This works as restoring force. The Inter-play between the driving force and restoring force leads to oscillation of the vapour bubbles and liquid slugs in the axial direction. The frequency and amplitude of the oscillation are expected to be depend on the shear flow and mass fraction of the liquid in tube".[3]

Pulsating heat pipes are preferable for thermal control in different space applications due to its high thermal performance. V.Ayel [4] et al. did an experiment on closed loop flat plate pulsating heat pipes (FPPHP) under varying gravity force by using FC-72 as working fluid, horizontal and vertical orientation according to floor of the aircraft, they concluded as FPPHP tested in horizontal inclination is not influenced by changes of gravity levels.

II. FLUID DYNAMIC PRINCIPLE OF PHPS

Working of PHPs can be explained with the help of Pressure - Enthalpy Diagram as shown in Fig.1

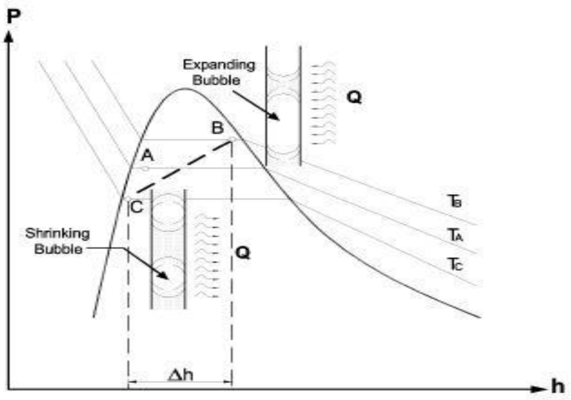

Fig. 1. Pressure Enthalpy Diagram [5]

While drawing above graph isenthalpic pressure drop during fluid transport sections is assumed. Initially the whole process is subdivided into two thermodynamic processes, constant pressure heat addition and isentropic pumping. During operation heat is supplied to evaporator end ,bubbles grow in evaporator section and because of temperature gradient they start travelling from point A to point B at high pressure and temperature ,this pushes the liquid slugs towards condenser ,simultaneously condenser located at opposite end further increases the pressure gradient and forces the point A to shift to point C at lower temperature and pressure ,this situation leads to the non-equilibrium inside the working fluid. Due to inner connection of tube the motion from liquid slugs and vapour plug at condenser also leads to the motion of liquid slugs and vapour plus in another section near the evaporator [3]. H.B.Ma [6] et al. worked on heat transport capability in an oscillating heat pipe, they prepaid one mathematical model for predicting the oscillating motion of oscillating heat pipe and in order to verify the mathematical model an experiment is did with eight numbers of copper turns. Experimental results indicated that there exists an onset temperature difference for the excitation of oscillating motions in an OHP, i.e. when the input power or the temperature difference from the evaporating section to the condenser was higher than this onset value the oscillating motion started.

We can say that PHP are non-equilibrium two phase heat transfer device which is from family of wickless heat pipe. PHP's are simple in design, without wick structure, small in size and providing promising excellence in thermal performance. The operation of PHP is based on instability in two phase flow and formation of liquid slugs and vapour plug. The PHPs (OHPs) can be Categorised as Closed loop PHP's, closed loop with check valve PHP's and Open loop PHP's (Closed end OHP). Fig. 2 shows the types of PHPs [7].

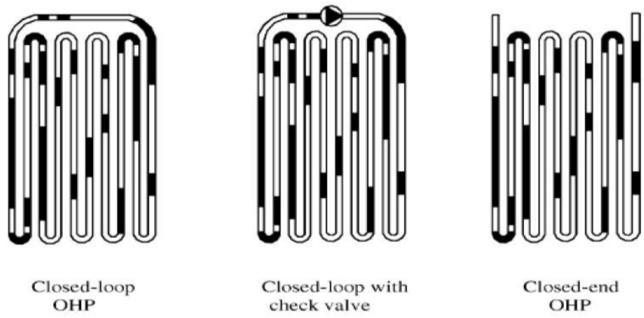

Fig. 2. Types of PHPs. [7]

closed loop pulsating heat pipes (CLPHPs) perform better than open loop PHPs, we can increase the performance of PHPs by introduction of check valves within the loop structure but installation of such valves are costly and difficult because of small size of PHPs [8].

Thermal Performance of CLPHPs is depend on Diameter of PHPs, Number of meandering turns, Working fluid, filling ratio, Orientation of PHPs, Capacity of Evaporator and condenser, Length of Evaporator, Condenser and adiabatic section .This literature discussed the fundamental of Critical diameter, Critical Number of turns, Working fluids and volumetric filling ratio of PHPs.

III. CRITICAL DIAMETER OF PHPS

The rise of bubbles inside the duct in stagnate fluid is depends on the buoyancy force, surface tension, inertia force and viscous force. When the surface tension and viscous forces are neglected than velocity with which bubble is rise is calculated with help of Froude Number, When viscous force is predominant over others forces than Poiseuille Number is used and if surface tension dominate over other forces than Eötvös Number is used to calculate the diameter of tube and which is our present interest [9].

Eötvös number is

$$(E\ddot{o})_{crit} \approx \frac{D_{crit}^2 g(\rho_{liq}-\rho_{vap})}{\sigma} \approx 4 \qquad (1)$$

Where

Dcrit Critical Diameter, m

g gravitational acceleration, m/s2

σ Surface tension, N/m

ρ Mass density kg/m3

And the bound number is frequently used as

$$Bo = \sqrt{E\ddot{o}} \qquad (2)$$

Bound Number (Bo): The Bond number (Bo) is defined as the ratio of gravitational (buoyancy) and capillary force scales.

About Eötvös number.

1. If Eötvös number increases beyond the certain value (≈ 70) for water & ethanol than viscous forces & surface tension are neglected.
2. If Eötvös number is Below 70, the terminal velocity continuously decreases.
3. Around Eö ≈ 4 terminal velocity continuously decreases, surface tension dominates the other force which is our present interest [9].

Hence in PHPs critical diameter is calculated with the help of following formula

$$D_{crit} \approx 2\sqrt{\frac{\sigma}{g(\rho_{liq} - \rho_{vap})}} \quad (3)$$

This value is not always constant and varies according to surface roughness and contact angle between liquid and metal surface, the approximate value of ID of PHPs tube at 20°C saturation temperature for water, ethanol, methanol is must be less than 5.4 mm, 3.6 mm, and 3.4 mm. If Small value of diameter is used than it is too difficult to develop annular flow, diameter above critical value helps to lose the fundamentals of pulsating action of PHPs and it start act as two phase Thermosyphon [10]. In loop Thermosyphon if outer diameter of tube keep constant and inner diameter is reduced than the thermodynamic performance and liquid behavior get changed, which loop Thermosyphon start working like PHPs, since there is presence of finite boundary in the form of diameter which differentiate the working of PHPs and loop Thermosyphon [9].

IV. NUMBER OF MEANDERING TURNS

N.Panyoyai [7] et al. performed experiment ON CLPHPs, R123 as working fluid and 0.66 mm, 1.06 mm and 2.03 mm ID of copper tube ,length of evaporator, condenser and adiabatic section keep same for each set and vary as 50,100 and 150 mm in each set . Number of meandering turns also vary as 5, 10 and 15 turns, they concluded as number of turn's increases from 5-15 turns it's not affected the maximum heat flux.

S.Khandekar [11] et al. used 20 number of turns in each evaporator and condenser section, 2 mm ID, 3 mm OD of CLPHPs and they are concluded as large combination of number of turns with high input heat flux ensures the continuous operation of CLPHPs in any orientations.

S.Khandekar [12] et al. used 2 mm ID CLPHPs, Water, Ethanol, Methanol as working fluid, The PHPs is tested at vertical bottom heating mode and horizontal mode but tested PHPs is not operate in horizontal mode for all the working fluids, for this failure of operation they concluded as small number of turns and small pressure difference existing at testing condition.

Piyanun Charoensawan [13] et al. worked on design of total no of turns on CLPHPs. Experimental results indicates that there is existence of critical number of turns (Ncrit) ,which effects on thermal performance of CLPHPs .For 2mm ID, Ethanol as working fluid and Le=15 cm, Ncrit is 16 turns. If N< Ncrit, the CLPHP is not satisfactory operate in the horizontal orientation and higher thermal performance occurs at vertical bottom heating mode. If N> Ncrit ,thermal performance of is increases with increase in inclination angle from horizontal and almost remains comparably up to 60° from horizontal as shown in Fig.[3] and Fig.[4]

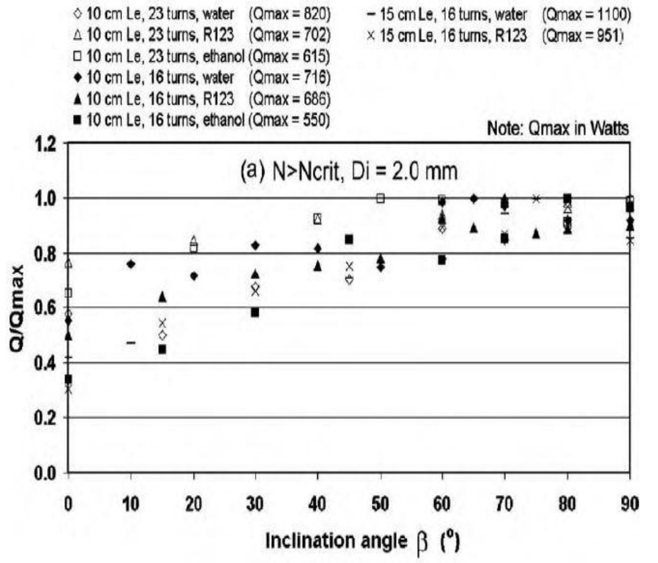

Fig. 3.Thermal performance of CLPHP for ID 2mm and N > Ncrit. [13]

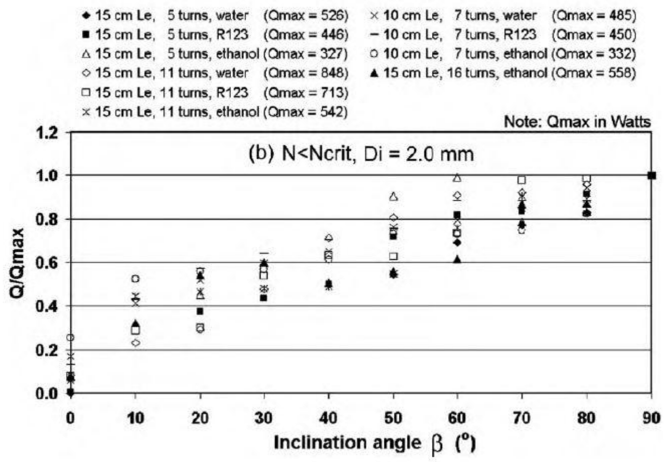

Fig. 4. Thermal performance of CLPHP for ID 2mm and N < Ncrit [13]

K.H.Chien [14] et al. worked on new design of CLPHPs with fewer turns application to all orientations by introducing the non-uniform channel CLPHP, they made two copper CLPHPs One is having 16 parallel square channels with 2mm×2mm cross section (c/s) as uniform c/s and other is 8 parallel square channels with 1mm × 2 mm c/s as non-uniform c/s. An Experimental results showed that Uniform channel PHP is more sensitive to inclination especially when inclination angle is small and not functional at horizontal configuration but non uniform channel CLPHP is functional to all directions if filling ratio is above 50 % .

Hence from above literature we can conclude that the working of PHPs is depends on the un stability of working fluid inside the tube, if pressure difference inside the tube is large than maximum numbers of perturbations will occur, this instability inside the working fluid can be created by increasing the numbers of meandering turns, if numbers of turns will increase than more turns will available for heating and cooling purpose since mote pressure difference will occur hence thermal performance of CLPHPs will increase. The critical value of numbers of turns is depend on the working fluids, internal diameter of tube and input heat flux. It has been observed that certain numbers of turns are required to perform the horizontal operation of CLPHPs.

V. WORKING FLUID

Bhawna verma [15] et al. performed experiment to study the effect of working fluid on the start-up performance, thermal performance and heat transfer coefficient of PHPs, Methanol/DI Water as working fluid with varying filling ratio. They tested the PHPs in vertical, horizontal and inclined at 45° orientation, experimental results indicates that in all orientations of PHPs the start-up temperature and start-up time is considerably reduces if Methanol is used as working fluid. Thermal resistance of PHPs in inclined and horizontal orientation for water are 0.55 $^{\circ}C/W$ and 0.81 $^{\circ}C/W$ respectively same values for Methanol are 0.52 $^{\circ}C/W$ and 0.63 $^{\circ}C/W$ respectively. Hence they conclude that PHPs with Methanol as working fluid is perform better than water and can be used as orientation free PHPs.

Kambiz Jahani [16] et al. did experiment with micro pulsating heat pipe (MPHP) with hydraulic diameter of 508 μm. They used water, silver nanofluid and Ferrofluid as working fluids inside MPHP with different filling ratio. The experiment is performed at different inclination angles with respect to horizontal, with the help of Experimental results they conclude that in most of the cases, MPHP with nanofluid gives better thermal performance than water filled MPHP.

Xiangdong Liu [17] et al. performed experiment on CLPHP for analyzing the start-up performance with Water, Ethanol and Methanol as working fluids ,they conclude as under the same working condition the start-up of CLPHP with methanol possesses the superiority of lowest start-up temperature and shortest start-up time while the CLPHP with water has the highest start-up temperature and required longest start-up time since Methanol has low dynamic viscosity, High value of saturation pressure gradient ($\frac{dP}{dT}_{sat}$), lower saturation temperature which helps it to perform better than other two fluids .

Piyanun Charoensawan [13] et al. did experiment on CLPHPs with three different working fluids as Water, Ethanol, and R123.Experimental results indicates that thermo-physical properties of fluids with geometry of the device has effect on performance of CLPHP, 2 mm ID CLPHP with water as working fluid perform better than Ethanol and R123 filled CLPHP in vertical orientation but for 1 mm ID tube R123 and Ethanol perform better than Water as working fluid as shown in Fig 5.

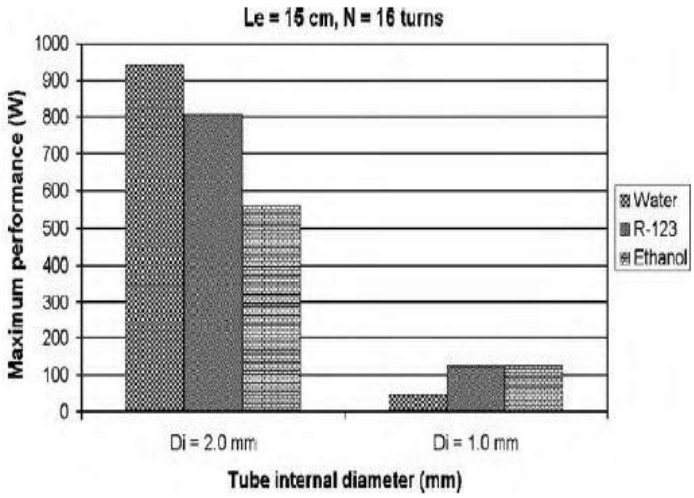

Fig. 5. Effect of working fluid on the thermal performance CLPHPs. [13]

Yulong Ji [18] et al. used different size Al_2O_3 particle with water as base fluid to analysis the effect of particle size on heat transfer performance of Oscillating heat pipe (OHP), They used 50nm, 80nm, 2.2μm and 20μm diameter particles and observed that OHP charged with water and 80nm Al_2O_3 achieves the best heat transfer performance rather than other particles they also concluded that all particles significantly improves the start-up performance of OHP.

Roger R. Riehl [19] et al. did experiment using Water-Copper nanofluid and investigate on potential of using nanofluid in an open loop PHP for passive thermal control. They conclude as the presence of solid nanoparticles in the working fluid contributes to increase the nucleation sites necessary for bubble formation. Since, more intense pulsations were observed during the PHP operation, which resulted in more presence of vapor in the channels. Thus higher thermal conductance were observed when compared to the PHP operation with pure water.

The most essential consideration for selecting the working fluid is operating temperature range within which CLPHPs is operating ,within certain temperature range more than one fluids are available than selection of working fluid is based on following criteria

High Thermal stability
High thermal conductivity
Low latent heat
High specific heat
Low surface tension
Compatibility with container
Low dynamic viscosity
High value of ($\frac{dP}{dT}_{sat}$)

The rate of growth of bubbles in evaporator section is inversely proportional to the latent heat ,the fluids having very small latent heat enhances the growth of bubbles in evaporator section but this situation promotes the dry out condition at evaporator but this situation can be avoid by increasing the filling ratio. If high latent heat fluids used inside the CLPHPs than its reduces the pressure pulses and leads to minimize the oscillations inside the CLPHPs hence low latent heat fluids are preferable [20].

High surface tension fluids are always preferable in wick heat pipes because of high capillary action is required in heat pipes .In pulsating heat pipes we required large amount of instability in form of liquids slugs and vapour plugs, if high surface tension fluid is used as working fluid than it retards the formation of unstable flow hence retardation in oscillations of PHPs results into low thermal performance. PHPs need working fluids which are having low surface tension property. Methanol and ethanol having low surface tension since they gives better results in PHPs. High value of $\frac{dP}{dT}_{sat}$ insures the small change in evaporator or condenser temperature gives the large change in pressure difference inside the working fluid hence maximum numbers of bubbles generation will occur which will aid thermal performance of CLPHPs.

VI. FILLING RATIO (FR)

The filling ratio is defined as the ratio of available working fluid (by volume) inside the PHPs to the total volume of PHPs (by volume).

Kambiz Jahani [16] et al. did experiment with micro pulsating heat pipe (MPHP) with hydraulic diameter of 508 μm. They used water, silver nanofluid and Ferrofluid as working fluids inside MPHP with 20, 40, 60 and 80 % volumetric filling ratio and analysis the effect of charging ratio on thermal resistance of MPHP as shown in fig, they are observed that for Water and nanofluids the optimum charge ratio are 40 and 60% respectively in vertical mode of operation as shown in following table.

Table I Lowest Thermal Resistance for different working fluids.

Sr. No	Working Fluid	Thermal Resistance ($°C/W$)	Charging Ratio (%)
1	Water	1.40	40
2	Silver nano fluid	1.02	60
3	Ferrofluid(without Magnetic field)	1.22	60

Xiangdong Liu [17] et al. performed experiment on CLPHP for analysing the start-up performance with Water, Ethanol and Methanol as working fluids with different filling ratios and analysis the effect of filling ratio on start-up performance of CLPHP. It has been observed that with increase in filling ratio all the values of evaluation criteria decreases and then increases, since there is existence of optimum filling ratio for all different fluids and with the help of experiment this has been conclude that optimum FR for Water and Ethanol are 41% & 52 % respectively.

Bhawna verma [15] et al. performed experiment to study the effect of working fluid on the start-up performance, thermal performance and heat transfer coefficient of PHPs, Methanol/DI Water as working fluid with varying filling ratio, they are studied the effect of filling ratio on thermal resistance as shown in Fig 6 and Fig.7. they concluded that Optimum filling ratio for ID Water /Methanol are 50% and 40% respectively.

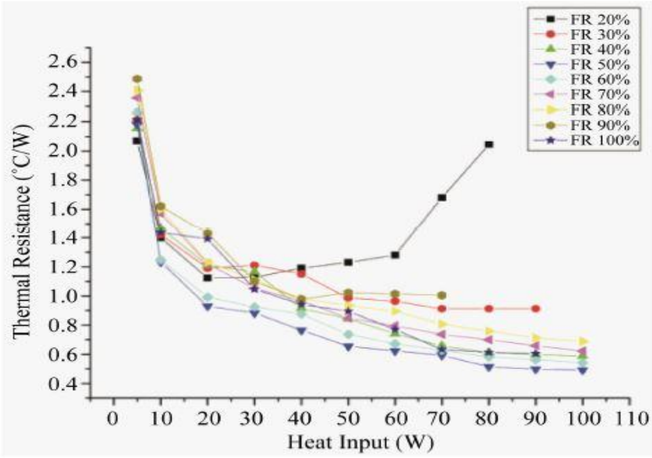

Fig.6.Effect of filling ratio on thermal resistance for DI Water [15]

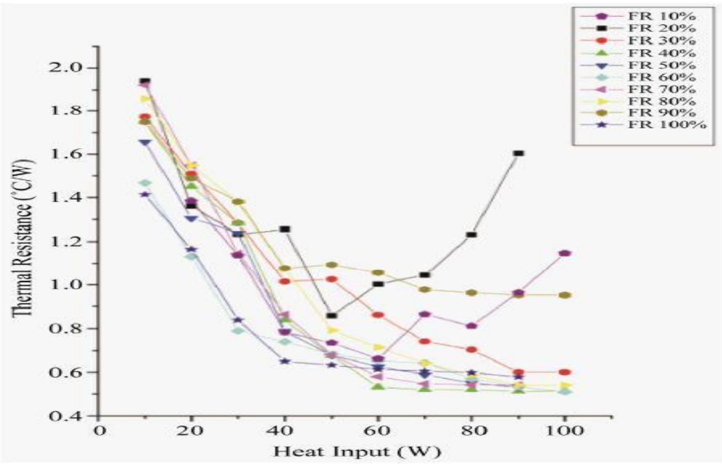

Fig.7. Effect of filling ratio on thermal resistance for Methanol [15]

On the basis of FR definition we can say that CLPHPs are working under two extreme limits such as 0 FR and 1 FR.

1. Filling ratio 1: The CLPHPs is said to have 100 % filling ratio when whole tube is fill with working fluid. If CLPHPs is fully filled with working fluid than there is only single phase flow inside the tube and also known as single phase closed loop Thermosyphon. The working of such Thermosyphon is not depends on oscillations of working fluid, the fluid transport is based on the gravity field and hence it limits the orientation of PHP such type of device cannot operate horizontally.

2. Filling ratio 0: CLPHPs with 0 % filling ratio is simple tube without fluid, the heat transfer through such tube is by conduction mode only through material of tube such as extended surface known as fin.
3. Working range of CLPHPs: The PHP works in between (10-90) % filling ratio hence this filling ratio enhance the bubbles growth, mixture of liquid slugs and vapour plugs, two phase flow.
4. Optimum filling ratio :The filing ratio at which maximum heat flux is take place that filling ratio is known as optimum filling ratio, the value of optimum filling ratio of CLPHPs is depends on construction and operating parameters of CLPHPs. this is observed that CLPHPs do not work satisfactory at less than 20 % FR and more than 80 % FR. In between (20-80) % FR it works better again it's depends another factors as explain above.

SUMMARY

Pulsating heat pipes are most complex system with high potential as heat transfer device which can be used in varies applications. The Mechanism is yet too difficult to understand because of presence of two phase phenomenon inside the working fluid, Design of PHPs is easy but dependency of one parameter on other makes it critical to define in single line. The thermal performance of PHPs is simultaneously function of more than two variables at single time which makes analysis difficult. Above literature focused on design issue and concluded some statements with the help of available literature.

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