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Thermal Design and CFD Analysis of Closed Loop Pulsating Heat pipe for High Density Heat Flux Electronic Components of Space Application

Manjunath H. S.*, Dr. M. Shivashankar
Department of Mechanical Engineering, Siddaganga Institute of Technology, Tumakuru, Karnataka, India

ABSTRACT

Space environment is found to be vacuum and heat transfer takes place only through Conduction and Radiation, The heat generated in the high heat flux electronic components of space borne Radar should distributed to the spacecraft or satellite box and then it is radiated to the space, for high heat flux electronics in space application Heat pipe is used as an heat transfer device, The CLPHP is the wickless heat pipe with diameter bigger then the capillary limit, the device is made of Aluminium material with inner diameter and outer diameter of 3mm and 4mm respectively, bent into 4 turns at evaporator,FC-72 as Working fluid and the heat load at the evaporator of 160 W and constant heat flux of 3w/cm2, the analysis is carried out in Ansys Fluent in microgravity condition, in microgravity condition due to the absence of gravitational force and buoyance force will activates the liquid slugs and vapour bubbles due to pressure variation, the effect of gravity on the performance of CLPHP is negligible, the thermal resistance is 0.15K/W, the analysis is carried out at 40%, 50%, and 60% filling ratio, the performance is maximum at 50% filling ratio, the CLPHP has extraordinary space adaptability.

Keywords : Heat Pipe, Loop Heat Pipe, Closed Loop Pulsating Heat Pipe, Microgravity, Space Environment, Aluminum 6061 T6 Alloy, Volume of Fluid.

I. INTRODUCTION

Heat pipe is a superconductor with extraordinary heat transfer capacity, two phase passive heat transfer devices used in spacecraft thermal control and Electronics cooling, nowadays electronic size is reducing but heat generating surface decreases, it results in generating large heat in a small area, to operate the electronics component in optimum temperature require proper cooling, in space electronics cooling CLPHP is lightweight ,reliability ,high performance and extraordinary space adaptability heat pipes are preferred to honeycomb structures in radiators panels and they have been widely used to reduce temperature gradients too, the CLPHP is developed by Akachi to reduce the effectiveness to cost ratio, the flow pattern is as shown in fig1

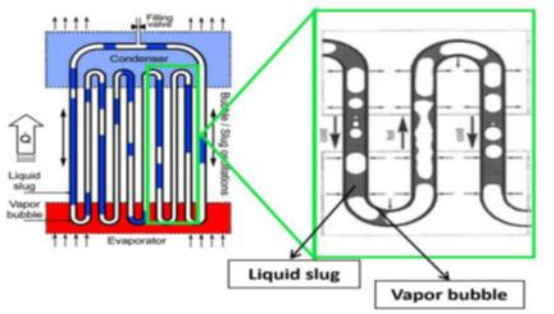


Figure 1. Basic scheme of a closed loop PHP, on the right, zoom of the internal flow patterns.

The CLPHP is developed by Akachi to reduce the effectiveness to cost ratio, the capillary forces and surface tension are strong enough to create an initial slug-plug configuration, gravitational and inertial forces still play a crucial role, When the device is gravity assisted vertical or bottom heated mode, the flow motion is more vigorous, and the thermal performance is higher with respect to the case when the PHP is perfectly horizontal and gravity ,The Bond number could give an indication of the confinement diameter and it is the ratio of body force to surface tension given in Eq 1.

$$\boldsymbol{Bo} = \frac{(\boldsymbol{\rho_L} - \rho_v)\boldsymbol{g}(\boldsymbol{ID})^2}{\boldsymbol{\sigma}}.............1$$

Bo =bond number
ρ_L =density pf liquid
ρ_v = density of vapour
g = accelaration due to gravity
ID = inner diameter of the tube
$\boldsymbol{\sigma}$ = Surface tension of the working fluid

When the tube diameter decreases, the surface tension forces become predominant, and it is possible to define, at least in static conditions, the minimum tube diameter below which capillary flow is achieved is given in the Eq 2

$$\boldsymbol{d}_{(\boldsymbol{crit,min})} = \sqrt{\frac{\boldsymbol{\sigma}}{\boldsymbol{g}(\boldsymbol{\rho_L} - \boldsymbol{\rho_v})}} ....2$$

Case 1: If the Bo < 4, in static conditions, surface tension force will overcome the body force: the two-phase appears as an alternation of liquid slugs and vapor bubbles, typical of a PHP.
Case 2: If the Bo > 4, the liquid and the vapor phase will appear separated within the tube, and the liquid batches can be lifted by the combined action of the vapor bubble formation and the restricted dimension of the ID This "pumping action" is possible until a maximum value of the tube diameter $d_{crit,max}$

The Critical diameter of the heat pipe is caluculated (Eq 3)

$$d_{Crit} = \sqrt{\frac{\sigma}{g(\rho_L - \rho_v)}}........3$$

ρ_L=density pf liquid
ρ_v= density of vapour
g = Accelaration due to gravity
$\boldsymbol{\sigma}$ = Surface tension of the working fluid

It is relatively complex to build a pulsating heat pipe, which is gravity-independent on ground, if some successful efforts of performance independent on orientation have been proposed with three dimensional layouts , in this regard, micrograviy experiments are mandatory if one is interested to decouple completely the buoyancy from the inertia effects, several experiments in microgravity conditions have been performed, the first testing a transparent tube PHP and a Flat Plate PHP in zero gravity conditions[2], concluding that under reduced gravity the PHP showed better heat transport performance than that under normal, to verify the effect of the gravity field on a perfectly planar PHP both in bottom heated mode and in horizontal position, Mameli et al. [5] tested the dynamic response to the gravity field of a planar copper tube PHP (sixteen turns,1.1 mm I.D.) filled with FC-72 during the 58th ESA Parabolic Flight Campaign and showing that the horizontal PHP performance was not affected by the gravity field variation occurring during the parabolic trajectories Both Gu et al. and Mameli et al. [7] illustrated the possibility to build a PHP for space application with an internal reduced gravity, body forces are negligible and the threshold diameter to obtain a slug-plug configuration increase. Since the mass of the thermal fluid per unit length is proportional to the square of the I.D, increasing the inner diameter is also beneficial in terms of total heat exchanged, dynamic threshold diameters over fluid temperature.

The present work involves design, selection of working fluid and analysis, flow visualization, that a two-phase wickless closed PHP with a diameter bigger than the static critical one on ground can work as a PHP (i.e. slug oscillating flow) under the occurrence of microgravity conditions, opening the frontiers to a new family of Pulsating Heat Pipes only for space applications.

II. DIAMETER SELECTION AND DESIGN

It is theoretically possible to build a PHP for space application (SPHP) with an ID bigger than the static critical diameter on ground. Since under reduced gravity the body forces are negligible, the threshold diameter to obtain a slug-plug configuration increase. This has an important consequence on the heat exchange, since the mass of the thermal fluid per unit length is proportional to the square of the ID, increasing the inner diameter is also beneficial in terms of global heat exchanged. the capillary limit threshold is also due to inertial and viscous effects, the dynamic threshold levels, evaluated by means of Weber and Garimella criteria proposed by Mameli et al. may be more suitable to define the limit for space applications.

The possibility to create a slug/plug flow in micro-gravity with an ID value higher than the critical one on ground, had also stressed that the inertial effects play a significant role in micro-gravity. When the fluid velocity is high, the liquid/vapor interface is unstable, and the slug-plug condition is only possible for smaller diameters with respect to the capillary limit. For these reasons, it should be more appropriate considers a Dynamic threshold to define the limit for space applications, evaluated by means of Weber(Eq 3) and Garimella criteria (Eq 4)proposed by Mameli et al. even if further experimental validations are necessary.

Weber Equation

$$dwe = \frac{4\sigma}{\rho_L U_L^2} \quad \ldots\ldots\ldots\ldots\ldots\ldots 4$$

$\boldsymbol{\sigma}$= surface tension
ρ_L=density of liquid
U_L= drift velocity ($0.1 m/s^2$)

Garimella criteria equation

$$d_{Ga} = \sqrt{\frac{160\mu_l}{\rho_L U_L \sqrt{\sigma/(\rho_L - \rho_L)g}}} \ldots\ldots\ldots\ldots 5$$

ρ_L=density of liquid
ρ_v= density of vapour
g = accelaration due to gravity
$\boldsymbol{\sigma}$ = Surface tension of the working fluid
μ_l= dynamic viscosity of the liquid
U_L= drift velocity ($0.1 m/s^2$)

Therefore, it is theoretically possible to design a PHP that is merely a PHP only in micro-gravity choosing properly the inner diameter dimensions. An additional table that points out the confinement diameters for FC-72 at 20 °C is reported, since this fluid will be used in this thesis to explore the effect of micro-gravity on the capillary limit

Table Confinement diameters for FC-72 at 20 °C accordingly to static and dynamic criteria for FC-72

Table II Critical diameter of the tube at different gravitational level

FC-72	**D_{cr}(mm) (Static)**	**D_{cr}(mm) (Dynamic)**
Earth $g=9.81 m/s^2$	1.68	0.75
Microgravity $g=0.01 m/s^2$	52.88	4.23

On ground, the device designed with an ID slightly higher than the $D_{cr, Ga}$ will act as a thermosyphon, since with a gravity acceleration of 9.81 m/s2 the fluid flow will be stratified. Additionally, if the ID is between **$d_{crit, min}$ <d<$d_{crit, max}$** pointed out respectively in Weber Eq and Garimella Eq, the thermosyphon will operate with the Bubble Lift Principle, as amply discussed.

Capillary limit in static and dynamic conditions on ground and reduced gravity conditions for FC-72.

Table III weber and Garimela criteria diameter of FC-72 at 20°C

FC-72 at 20°C	**D_{cr}(mm) Static**	**D_{Ga}(mm)U_l=0.1m/s**
Equations	$dwe = \frac{4\sigma}{\rho_L U_L^2}$	$d_{Ga} = \sqrt{\frac{160\mu_l}{\rho_L U_L \sqrt{\sigma/(\rho_L - \rho_L)g}}}$
Earth gravity level; g = 9.81 m/s^2	1.68mm	0.8mm
Microgravity g = $0.01 m/s^2$	52.88	4.2mm

taking also into account viscous and dynamic effects, it is still possible to design a device with an ID higher the capillary limit on ground but able to guarantee theoretically a slug/plug flow motion in micro-gravity. For example, designing a device with an ID of *3 mm*, filled up with FC-72, the fluid will appear stratified, on ground it should be expected a stratified flow, in micro-gravity a slug/plug flow.

III. CFD ANALYSIS

Physical Model

A 2D physical model was developed using the commercial software package ANSYS FLUENT, to simulate the internal liquid and vapour flow and heat transfer in a CLPHP. FC-72 was used as working fluid. The Aluminum was chosen as tube material. According to the experimental conditions four turn PHP is divided into 3 parts, evaporator, adiabatic and condenser section. The corresponding sections are shown in Fig 1. The geometric dimension of CLPHP are mentioned in fig

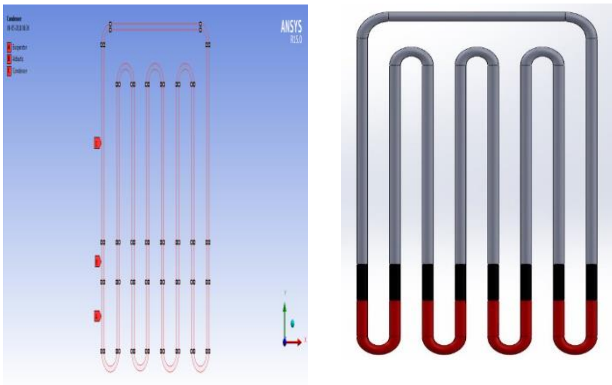


Figure 2. Physical model of Closed loop pulsating Heat pipe

Meshing

The meshing is done in Ansys mesh tool according to Lin with count cell of4,60,000, the element size is taken as min and max of 0.01mm and 0.1 mm respectively ,tetrahedral mesh, time step of 10^{-5}.

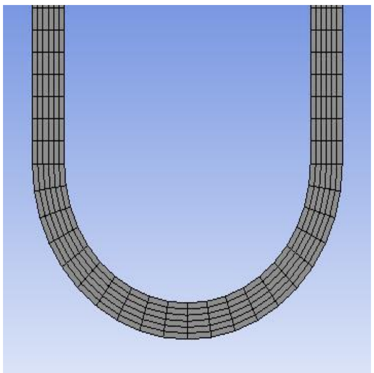


Figure 3 Shows the Meshing configuration of 2D CLPHP used in simulation.

Computational Model Set-up

Continuity equations, momentum equation and energy equations in VOF model were used to describe the motion of working fluid in a CLPHP. Volume of fluid (VOF) model with two Eulerian phases, FC-72 and FC-72-vapour with implicit body force formulation and 10^{-8} volume fraction cut off was activated. Energy equation was turned on to account for heat transfer. Viscous model was selected laminar. Water vapor and water were taken as primary fluid and secondary fluid respectively. The density (ρ) of FC-72 was taken to be temperature dependent, the temperature is calculated from data handbook.

Density (kg/m^3)= $\rho = 1740 - 2.61$ (T, °C)

Gravitational acceleration was turned on and operating pressure of 30900Pa was considered. the CLPHP is a negative pressure system and the boiling temperature of FC-72 was 303 K, affording to experimental observations. The phase change between liquid and vapor is carried out using evaporation-condensation model governed by Lee model. The continuum surface force (CSF) model was consider the effect of surface tension. The value of surface tension was taken to 0.01040 N/m along with wall adhesion.

The heat flux at evaporator region depend on the heat generation of electronic component, the heating powers are not over 160 W. Hence maximum heat flux of 3W/cm^2 is assigned at the evaporator. The adiabatic region was set as insulation boundary condition, the condenser region is given with boundary condition of temperature 40^{0}C, and radiation of external space temperature of 40^{0}C, the space boundary condition of Emissivity of 0.8 and Absorptivity of 0.01, because condenser region is placed over optical solar reflector (OSR), it has a property of high emissivity and very low absorptivity and maintain the condenser region 40^{0}C.

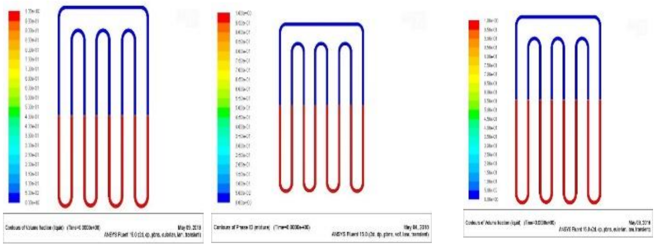
Solution Methods

The operating temperature was 301 K and the initialized filling ratio was taken as 50%. The pressure velocity coupling was selected as model solution, taken as PISO with skewness- neighbor coupling. in discretization scheme, pressure interpolation is taken as body force weighted, volume fraction momentum and energy were taken as first order upwind. The relaxation factors for momentum is 0.01, density is 1 and pressure 0.3, These control factors however were varied during the simulation to maintain the residuals in desired range.

The flow characteristics and thermal resistance for CLPHP were obtained for time-step of 10^{-5} s.

Filling Ratio

In pulsating heat pipe the liquid distributes inside the tube, the 100% filing of working fluid inside the tube it will act as a thermosyphon, the 0% filling of working fluid will act as a tube , the heat pipe is partially filled with the working fluid , the heat pipe tube is evacuated and filled working fluid using vacuum pump



40%VF **50%VF** **60%VF**

Figure 4 Different filling ratio of FC-72 in CLPHP

The performance of closed loop Heat Pipe depends on the percentage of liquid filling ratio, the analysis is carried out at different filling ratio 40%,50% and 60%.the too little filling leads to dry out and large filling of working fluid leads to delay of start-up of operation ,which leads to overheat in the heater or electronic component.

Liquid, Volume fraction

The liquid volume fraction of FC-72 at various filling ratio 40%,50% and 60% at different instant of time is shown in figure, when Electronic components starts generating heat, the working fluid in the Evaporator region of closed loop pulsating heat pipe start converting into vapour phase by absorbing sensible and latent heat ,it results in the phase change , the CLPHP start-up within a fraction of seconds.

Flow visualization in the heat pipe

In Closed Loop pulsating heat pipe is filled initially with the working fluid with certain percentage of volume , the 100% filling of working fluid the tube will act as a Thermosyphon , 0% filling of working fluid the tube works like higher thermal conductivity rod, the filling of working fluid to the heat pipe is less the 100%, certain volume is empty, the working fluid filling ratio depends on the Working fluid properties , operating flux. The evaporator region the heat pipe absorbs heat from the electronic component or sink then the liquid absorbs it latent heat of vaporization, then the liquid bubbles formation takes place after the start-up period, the flow of liquid-slugs and Vapour -bubbles is as shown in fig 5

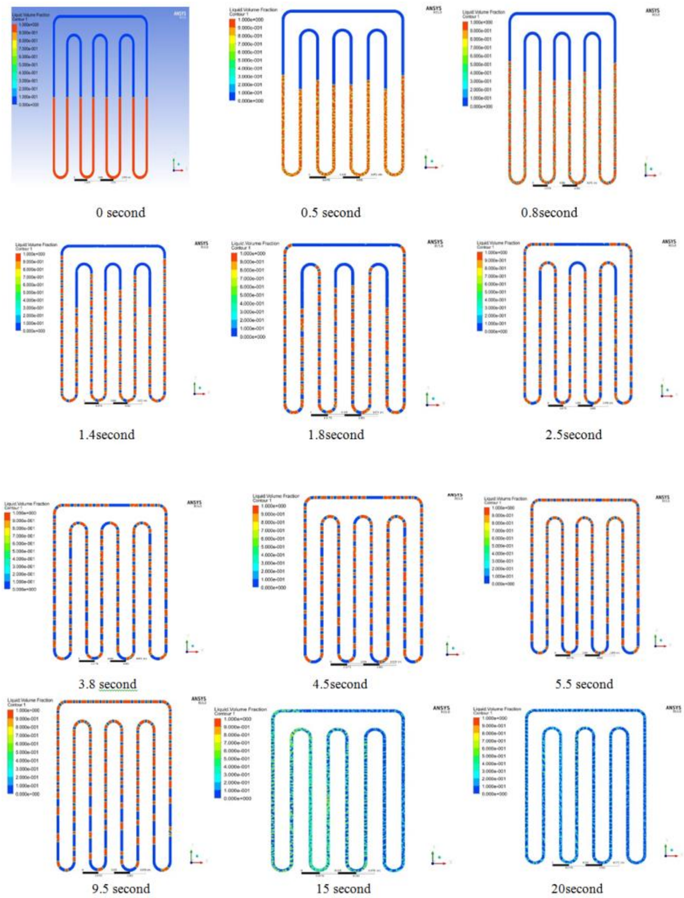


Figure 5. Flow visualization of the PHP and Liquid slugs ,vapour bubbles in the tube

Temperature distribution

Heat pipe is a Heat transfer device it transfers heat from source (Electronic components) to the sink, it will distribute the high heat flux density ($3w/cm^2$) to the base of condenser, it will transfer high heat flux into low heat flux ($0.25w/cm^2$), it will help us to maintain optimum temperature of Electronic components, the temperature distribution inside the Heat pipe of FC-72 liquid-vapour fraction is as shown in figure 6

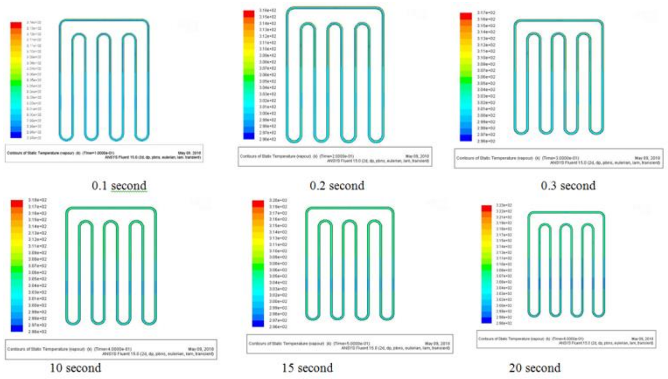
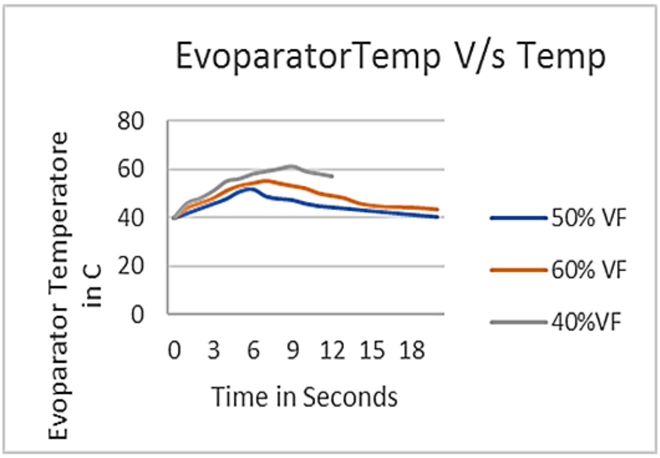


Figure 6. Temperature distribution in the Heat pipe

IV. RESULTS AND DISCUSSIONS

Graph is plotted with Evaporator temperature and Condenser at different time intervals at different filling ratio of 40%,50% and 60%, the temperature increases till startup of heat pipe, during this period the working fluid of heat pipe absorbs sensible and latent heat later the temperature decreases , the thermal performance of the heat pipe is maximum at 50%, at 40% filling ratio the working fluid is not sufficient to generation of liquid and vapour slugs, it results in dry-out of tube after few seconds , at 60% filling the excess working fluid will retard the startup period ,it results in the large heat accumulation in the evaporator region , which results in the increase in the optimum temperature , hence intermediate filling ratio has maximum thermal efficiency.



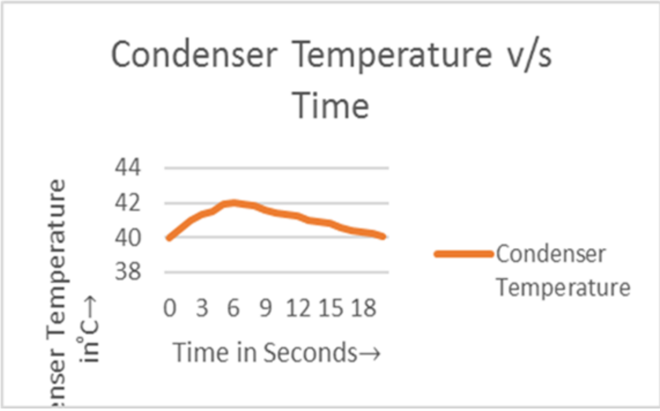


Figure 7. Evaporator and Condenser temperature plotted at different time interval

The graph is plotted for FC-72 as working fluid, the temperature plot at different regions like Evaporator, condenser at different time intervals, due to pressure variation between the Condenser and Evaporator the pulsation of liquid plugs and two-phase flow of liquid occur.

The thermal resistance (R) of CLPHP is the ratio of temperature change between the condenser and evaporator to corresponding heating power.

$$R = \frac{Te - Tc}{Q}$$

where T_e = Evaporator Temperature (Average),
T_c =Condenser Temperature (Average)
Q= Heating power.

Thermal resistance CLPHP with FC-72 as working fluid in vertical bottom heated mode was plotted against simulation time as shown in Fig.8

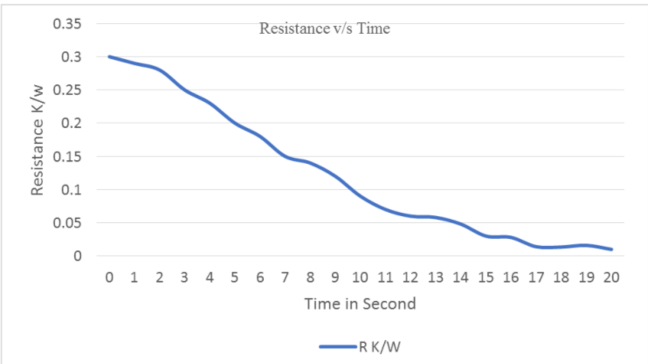


Figure 8. Graph plotted thermal resistance v/s Time

V. CONCLUSION

1. The Closed loop pulsating heat pipe has extraordinary heat transfer capacity and space adaptability compared to other heat pipe Low cost and design because of absence of wick.
2. The working fluid FC-72 is compatible with the aluminium, dielectric fluid and space adaptability.
3. The CLPHP designed for space is tested in ground acts as a thermosyphon due to gravity assistance and critical diameter should be greater than the capillary limit of CLPHP diameter, in microgravity condition due to absence of gravitation and buoyance force will develop liquid slugs and vapour bubbles due to pressure variation it acts as a pulsating heat pipe.
4. The thermal resistance of the heat pipe decreases with increasing the operating temperature.
5. Increasing the no of turns or loops of CLPH will increase the temperature distribution and performance.
6. The efficiency of the Heat pipe is maximum at 50% filling ratio.

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