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Experimental Analysis of Pulasating Heat Pipe

N Santhi Sree, Dr.N V S S Sudheer, Dr.P Bhramara, S Jeevani

Abstract— thermal management has become an important criterion and many devices have come up for this purpose. One among them is a heat pipe. A simple pipe consists of a tube with a suitable working fluid, an evaporator and a con-denser side. The transfer of heat takes place by absorption of heat from the evaporator side by the working fluid and dissipating it at the condenser side through latent heat. An improvement in the heat pipes is pulsating heat pipe which is also called as php. Pulsating heat pipe (php) is a heat transfer device which uses the oscillating motion of the working fluid as the source for heat transfer .tthe working phenomenon of pulsating heat pipe differs from that of a regular heat pipe.the php has a lot of thermo-hydrodynamic characteristics which define its performance. The evaporation and condensation of the working fluid results in a two phase flow which transfers heat. The vari-ous factors that affect the performance of the php's are the diameter of the pipe, working fluid, filling ratio, heat flux, orientation etc. Study of the performance of php's will help in better understanding of the heat transfer mechanism by which the application of heat transfer devices can be improved..the present paper describes the detailed experimental analysis and working principle of php with water as working fluid and the results are carried out to calculate the efficiency of php with mathematical calculations.

Index terms: condenser, efficiency, evaporator, heat pipe, heat transfer, pulsating heat pipe (php), working fluid.

1 INTRODUCTION

Heat pipes are heat transfer devices which have a very good efficiency. These pipes absorb heat from a hot source and release it at a colder sink with the help of a working fluid. The phase change from liquid to vapor occurs in the evaporator and the vapor changes to liquid in the condenser. These heat transfer devices were developed in the 1960's and since then have been constantly studied. Today there are many classifications in heat pipes. One such simple and intriguing device is the pulsating heat pipe (PHP).The pulsating heat pipe belongs to the family of two phase heat transfer devices [2]. Pulsating heat pipe consists of a tube wound in a serpentine manner.Before partially filling with working fluid the PHP's are initially evacuated.

COMPARISON BETWEEN CONVENTIONAL AND PULSATING HEAT PIPE

A heat pipe consists of a small tube with evaporator and con-condenser at both its ends. The working fluid is heated in the evaporator end so that it turns into a gas. The gas travels along the length of the heat pipe to the condenser where it releases the heat in the condenser and becomes a liquid. This liquid is then sent back to the evaporator by capillary wick action.A PHP consists of a tube which is structured in a serpentine manner with a number of turns. The heating of the working fluid in the evaporator leads to the creation of vapor bubbles and ultimately slugs and plugs which give rise to heat transfer [3]. It can transfer heat without any wick structure [4].

Conventional heat pipe	Pulsating heat pipe
1. Wick structure for fluid transfer.	1. Slug-plug formation of fluid for fluid transfer.
2. Conduction and phase transition are employed for heat transfer.	2. Conduction and pulsating motion of fluid are responsible for heat transfer.
3. Gravitational force mainly acts as the driving force for fluid flow.	3. Vapour pressure bubbles formed acts as the driving force for fluid flow.
4. Heat pipe can be singular pipe with evaporator and condenser ends.	4. Pulsating heat pipe needs to have a few numbers of turns for the pulsating action to occur.
5. Counter flow of liquid and vapour occurs.	5. Counter flow does not occur as there is no wick structure.

Table 1 Comparision Of Heat Pipes

~~About the author~~
N SANTHI SREE, Asst Professor, Institute Of Aeronautical Engineeing, Hyderabad.
Dr NVVS SUDHEER, Associate Professor, RVRJC College of Engineering, Guntur.
Dr P Bhramara, Professor, JNTUH, Kukatpalli, Hyderabad
S Jeevani student, IARE, Hyderabad

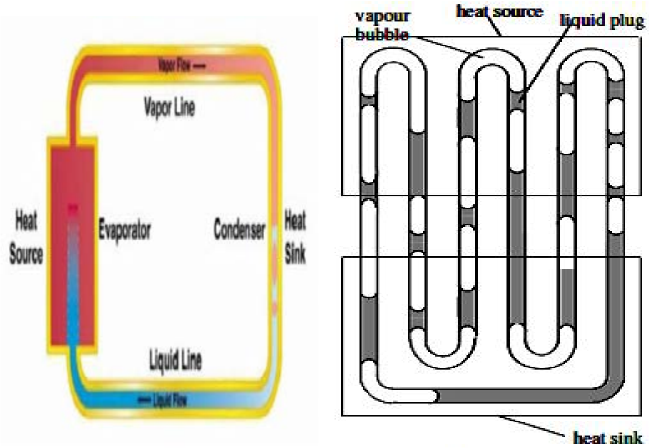

Fig 1heat Transfer In Conventional And Pulsating Heat Pipe

2 LITERATURE REVIEW

In the 1990's, Akachi *proposed* the pulsating heat pipe. 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 the vapor 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 increase the pressure difference between the two ends. Because of interconnection of tubes, motion of the fluid slug and the vapor bubbles at one end section of tube towards the condenser also leads to the motion of slugs and bubbles in the next section to the high temperature end. This works as a restoring force. The interplay between the driving force and restoring force leads to oscillation of the vapor bubbles and liquid slugs in the axial direction. The frequency and amplitude of oscillation are expected to be dependent on the shear flow and mass fraction of the liquid in the tube."

Khandekar and Groll studied effect of number of turns on the performance of the device. Their study states that gravity effects in systems with low number of turns. Khandekar and Groll also observed the stop over phenomenon and came to the conclusion that a minimum number of turns are mandatory for the PHP device to work.

Akachi. studied the closed loop PHP and proposed that a closed loop PHP with check valves is the most effective heat transfer device. It has a simple structure and fast thermal response.

3 CLASSIFICATION

Pulsating heat pipes can be classified into two types-

- open loop pulsating heat pipe (OLPHP)
- closed loop pulsating heat pipe (CLPHP)

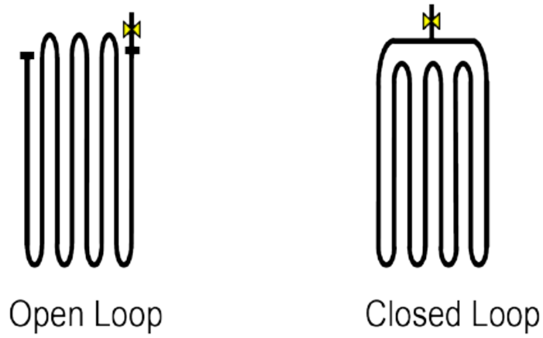

Fig 3 Classification Of Pulsating Heat Pipes

An open loop pulsating heat pipe, one end of the PHP is welded while the other end has valve for vacuum and charge. In open loop PHP, the condenser region is open so the water and water vapor that rises from the evaporator due to heat input leaves the PHP from one of the end. Here the continuous supply of the working fluid is needed. The closed loop PHP is an endless tube as both ends are welded together. In the closed loop PHP there is a continuous circulation of the working fluid within the pipe, the whole time. Each PHP configuration has different operation modes, which are mainly guided by the chaotic slug/plug motion.

In OLPHPs, there is no possibility of an overall flow circulation. Because of this, annular flow cannot be achieved in the OLPHP. The flow will be as a pulsating capillary slug flow regime with long vapor bubbles forming at higher heat fluxes. Local internal heat transfer is usually more in the convective annular flow regime. Therefore, CLPHP'ss show better performance than OLPHPs.

4 STRUCTURE OF THE CLPHP

PHP's do not have a wick structure as in the other heat pipes. It consists of one evaporator zone, one condenser zone and an optional adiabatic zone. Sealed pipe or tube of a small internal diameter is taken. The material of the CLPHP should have high thermal conductivity such as copper, aluminium etc. This sealed tube is evacuated and then partially filled with the working fluid. The working fluid distributes itself into liquid plugs and vapor slugs inside the tube due to the het flux provided at the evaporator.

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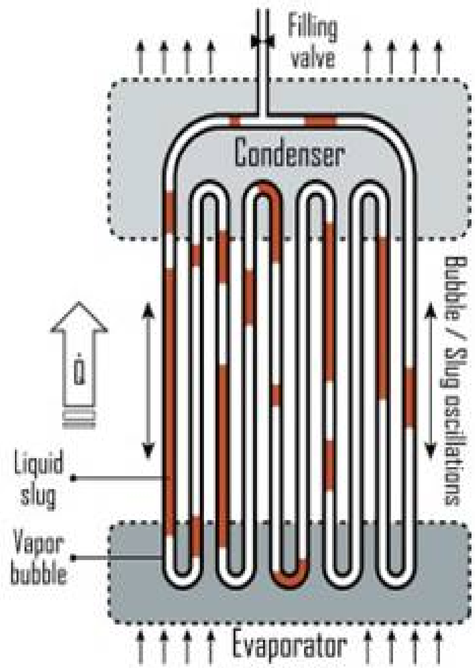

FIG 4 STRUCTURE OF CLPHP

5 PRINCIPLE OF HEAT TRANSFER

Performance of a PHP depends on the continuous maintenance of non-equilibrium conditions within the system. Due to the heat absorbed at the evaporator end, a temperature gradient is formed between both the evaporator and condenser zone. Small temperature differences exist between individual U bends of evaporator and condenser due to local non-uniform heat transfer rates. There exists an asymmetric and different volumetric distribution of working fluid in each tube. Theboiling and condensation heat transfer takes place towards the bubbles and plugs motion of the flow.As the liquid plugs move back and forth in the pipe sensible heat transfer takeplace between the wall and the fluid along with latent heat transfer. [5 & 6]. There exists an asymmetric and different volumetric distri-bution of working fluid in each tube. Also, the volume fraction of the liquid plugs and vapor slugs varies continuously. This leads to imbalances in pressure resulting in a two phase flow of liquid-vapor plugs and slugs. The generating and collapsing bubbles act as the pumping elements for transporting the liquid plugs. This flow ultimately helps in the thermofluidic transport and the heat transfer becomes a combination of sensible and latent heat portions.

Continual generation of vapor bubbles from the evaporator and the condensation at the other end help in the formation of a sustained non-equilibrium oscillating state.

Flow Regimes

As the vapour pressure builds up in the evaporator zone due to the formation of tiny bubbles, the liquid above the bubbles gets pushed above. More amount of vapour is formed due to the continuously increasing heat input given to the evaporator. These small vapour bubbles start coming together to form larger bubbles and these bubbles, in turn, acquiesce and form into vapour slugs. Thus the flow regime changes from bubble to slug flow. In this flow, both the liquid and the vapour phase co-exist with a definite interface between them. These liquid plugs and vapour slugs keep moving towards the condenser due to increasing pressure. This acts as the primary and driving force. The same mechanism takes place in the adjacent turns of the loop. This acts as the restoring force for the first tube. The simultaneous occurrence of the driving and restoring force leads to the pulsating or oscillating motion of the liquid-vapor plugs and slugs. This slug flow slowly transitions into a semi-annular/annular flow where the vapour slugs reduce in size and the velocity of the liquid plugs increases. The pressure drop in a slug flow is divifed into

- Drop in liquid slug
- Drop around the ends of the bubble
- Drop along the body of the bubble

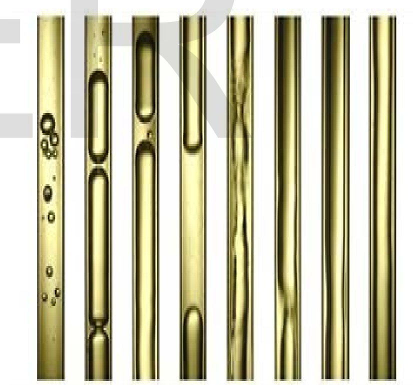

FIG 5 FLOW REGIMES THAT OCCUR IN PHP

6 FACTORS AFFECTING THE PERFORMANCE OF CLPHP

- Internal diameter of PHP
- Input heat flux
- Working fluid
- Filling ratio
- Orientation of tubes
- Number of turns

The above mentioned thermo physical parameters plays an important contribution for the better

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working of PHP system dynamics[7]and they are considered as basic design parmeters

Internal Diameter

The pulsating action in the CLPHP is possible only to a certain range of internal diameter values. The design rule is given by the critical bond number criterion.

$$D_{cri} = 2\left(\sigma / g\left(\rho_l - \rho_v\right)\right)^{0.5}$$

$$Bo = D_{cri} * \left(g\left(\rho_l - \rho_v\right) / \sigma\right)^{0.5}$$

$$Eö = [Bo]^2$$

Eö : Eötvös Number
Bo : Bond Number
D : Internal diameter of tube
g : Acceleration due to gravity
ρ : Density
σ : Surface Tension

By following this criterion, there is no possibility of agglomeration of vapor bubbles. So the liquid plugs and vapor slugs are continually maintained. If diameter is increased beyond the critical diameter, the device will start acting like an interconnected array of two phase thermosyphon. If diameter is reduced below the critical diameter, dissipative losses increase and lead to poor performance.

Input heat flux:

PHP's require high heat flux for good operation. This is because the heat flux only determines the pumping action and therefore the thermofluidic transport of the working fluid. The Heat flux applied effects the dynamics of the bubbe gowth and its sizes, flow perturbations and instabilities and also flow pattern in slug, annualr nd semiannular flows.

Working fluid:

The properties of working fluid affect the formation of two phase flow and thus have to be considered as an important parameter.

- High thermal conductivity- fluids having high thermal conductivity can carry heat very easily from the evaporator to the condenser.
- Low latent heat- fluids having less latent heat enhance the growth of bubbles in evaporator.
- High specific heat- higher specific heat will increase the amount of sensible heat transferred.
- Low surface tension- a high surface tension fluid retards the formation of unstable flow. Hence, low surface tension liquid should be used.
- Compatibility with the container- the working fluid should not corrode the tubes or evaporator and condenser walls.
- Low dynamic viscosity- low dynamic viscosity results in an easy formation of liquid-vapor plugs and slugs. The shear stresses in the fluid along the walls will also be reduced.

The working fluids that are generally preferred are water, methanol, ethanol, Ethyl Alcohol etc.

Working fluid	**Thermal conductivity(W/m K)**	**Latent heat(KJ /Kg)**	**Specific heat(J/g K)**	**Surface tension(dyne/cm)**	**Dynamic viscosity(mPa.s)**
WATER	0.6	2264	4.181	71.97	0.894
ETHANOL	0.171	855	2.44	22.27	1.074
METHANOL	0.202	1155	2.14	22.6	0.544
R134 A	0.0824	215.9	0.851	8.08	0.01198
AMMONIA	0.507	1369	4.7	24.8	0.01095

TABLE 2 Properties of different working fluids

Filling ratio:

For the CLPHP to work, the tube should be only partially filled with the working fluid. The volumetric filling ratio affects the performance of the PHP. Filling ratio can be defined as the ratio of working fluid volume in the device to the total volume of the device. A higher percentage of filling ratio leads to a situation where very few bubbles are formed. Not enough amounts of perturbations exist leading to insufficient pulsating motion. For a smaller percentage of filling ratio, very little liquid will be present which won't be enough to form distinct slugs and dryout phenomenon may occur. Therefore, the proper range of filling ratio is within 40% to 60%.

Orientation of tubes:

Horizontal orientation of tubes does not give as good a performance as vertical orientation. Large number of turns supported by a high input heat flux tends to improve the performance of horizontal orientation of tubes in a CLPHP.The tubes may be inclined to 0 degrees,30,45,60,90 and 180 degrees.

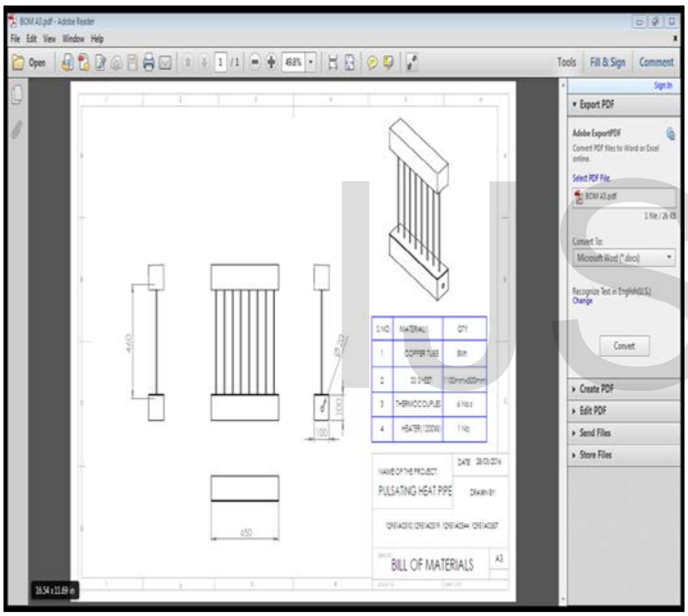
Number of turns:

There is a certain critical value for the number of turns below which stop over phenomenon occurs in a PHP. A stop over phenomenon is a situation where the whole of evaporator is filled with vapor bubble only and the rest of the PHP with liquid. Therefore an optimum number of turns is necessary so that the level of perturbations and the pulsating motion inside the device increases. More turns offer more locations for heat application and thus more local pressure drops take place giving rise to a better liquid-vapor plug and slug formation. In general 5 to 23 turns can be used.

7 Experimental Setup

MODELLING OF PHP

The modelling is done by using solidworks



In this experiment we are first winding a tube of 4.7m length in a serpentine manner of four turns. The tube has an inner diameter of 4mm and an outer diameter of 6mm.This tube is then attached to the evaporator and condenser through suitable manufacturing process. The evaporator and condenser both are made up of stainless steel and have a dimension of 100x140x450. Heat input is given at the evaporator side through a heater which has a capacity of 2KW. This heater is fixed to the evaporator via a hole. A valve is fixed at the condenser side through a 'T' joint to fill the working fluid. A total of six temperature sensors, which are J type thermocouples are placed-two at the evaporator, two at the condenser and two at the adiabatic walls. The total volume of the pipe is 57933.1m^3.

The filling ratio employed is 41% which amounts to 0.235liters.

8 Manufacturing Procedure

In the process of manufacturing pulsating heat pipe the following methods were used

1. Pipe bending
2. Drilling
3. Brazing
4. Evacuation

To make the serpentine tube, a copper tube of 5 meters tubes are inserted into the holes and is joined to the evaporator and condenser by brazing.The tubes are joined to each other using brazing joints.Then water is filled in both the evaporator and condenser.Vacuum is created in the tubes was taken and cut into smaller pipes.The U bends necessary for the evaporator and condenser sections were made by pipe bending operation using a die having a diameter of 40mm.The evaporator and condenser blocks were made by sheet metal operations on a stainless steel plate.The upper plate of evaporator and lower plate of condenser were drilled with holes to insert the copper tubes.The copper by vacuum pump and water is filled. Then the inet is closed using a valve.

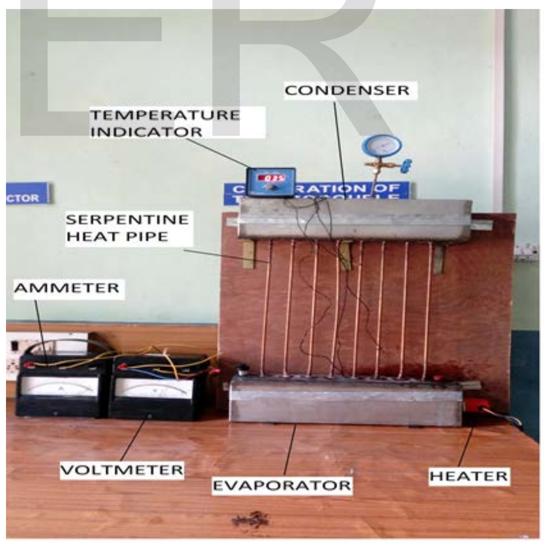


fig 7 experimental setup of PHP

Experiment is conducted for number of iterations. The main objectives of this experimental study are:

(a) To study the heat transfer performance of a Closed Loop Pulsating Heat pipe [CLPHP].

(b) To study the temperature profile and the heat transfer rate at different sections of PHP.

(c)To evaluate the heat transfer coefficient at different sections [8-10]

Thermo Physical properties of selected PHP material

Name of material	copper
heat cpacity	383J/kgK
Thermal conductivity	386 W/mK
Density	8954 kg/m3

Thermo Physical properties of selected Working fluid

Name of material	Water
Density of water liquid	$1000 kg/m^3$
Density of water vapour	$0.598 kg/m^3$
dynamic viscocity liquid	$3.54x10^{-4}$
dynamic viscocity vapour	$11.96x10^{-6}$

8 Tabular Form

Iteration 1

SNO	VOLTAGE	CURRENT	T_1	T_2	T_3	T_4	T_5	T_6
1	230	9.2	41	42	37	37	39	34
2	230	9.2	50	51	43	46	45	40
3	230	9.2	56	57	48	49	49	43
4	230	9.2	60	61	54	54	53	43
5	230	9.2	64	65	56	55	54	43
6	230	9.2	65	65	57	55	55	42

Iteration 2

S.No	VOLTAGE	CURRENT	T_1	T_2	T_3	T_4	T_5	T_6
1	230	9.5	68	68	58	56	57	57
2	230	9.5	69	68	59	57	56	57
3	230	9.5	70	70	61	58	58	59
4	230	9.5	72	73	63	60	60	60
5	230	9.5	75	76	65	62	61	61
6	230	9.5	81	80	71	66	65	66
7	230	9.5	82	81	72	65	66	66

9 Mathematical Calculations

1. The surface area of the pipe is given by the formula
   $A = \Pi \times D \times L = 3.14 \times 0.004 \times 4.7$
   $= 0.059032 m^2$
2. Ambient temperature is given by $(T_a) = 34^oC$
3. Surface temperature = 66^oC
4. Temperature difference $\Delta T = T_s - T_a$
   $= 66-34$
   $= 32^oC$
5. Heat input $Q_{ele} = V \times I$
   $= 230 \times 9.5$
   $= 2185W$
6. Heat transfer co efficient = $Q_{ele} / A \times \Delta T$

   $=1156.68 W/m^2 K$

To calculate theoretical h:

The convective heat transfer coefficient for evaporator and in the condenser are considered.

$\mathbf{h}_{\mathbf{evaporation}} = 0.62\{[k_v^3 \times \rho_v (\rho_l - \rho_v) \times g (h_{fg}+0.68 \times C_{pv} \times \Delta T)] / [\mu_v \times D \times \Delta T]\}^{0.25}$

Here, k_v = thermal conductivity of vapor
ρ_v = density of vapor
ρ_l = density of liquid , water in this case
h_{fg} = enthalpy of evaporation
C_{pv} = specific heat of vapor at constant pressure
μ_v = dynamic viscosity of vapor
D = diameter of the pipe
ΔT = Temperature differenc

$h_{evaporation} = 0.62\{[(0.02473)^3 \times 0.598 (1000-0.598) \times 9.81(2257 \times 10^3+0.4 \times 2.1 \times 10^3 \times 32)] / [1.0578 \times 10^{-6} \times 0.0064 \times 32]\}^{0.25}$
$=378.347 W/m^2K$

$h_{condensation} = 1.13\{g \times h_{fg} \times \rho_l(\rho_l - \rho_v)k_l^3\}/(\mu_l \times L \times (T_{sat}-T_s))\}\}^{1/4}$

$=2766.11 W/m^2K$

h (freeconvection) in adiabatic zone
This is calculated be natural convection phenomena for considereing a vertical tube as a croeesecion.
$h_{(freeconvection)} = 4.42 W/m^2K$

The total heat transfer rate
$= Q_{(eva} + Q_{(freeconv)} + Q_{(conden)} + Q_{(wall)}$
$=718.85+31.29+1380.855+27.735=2160 W$

RESULTS

1.The total amount of heat transfer n aPHP setup is obtained as2160 W

Th experimental value of heat transfer shows that PHP are more effective and the efficiencies are high.

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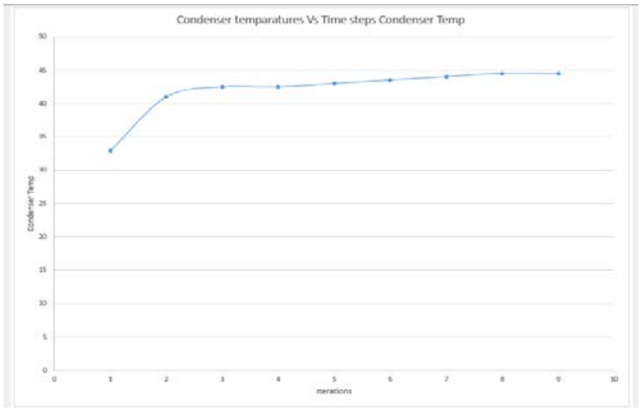

FIG:8 Representation of condenser temperatures

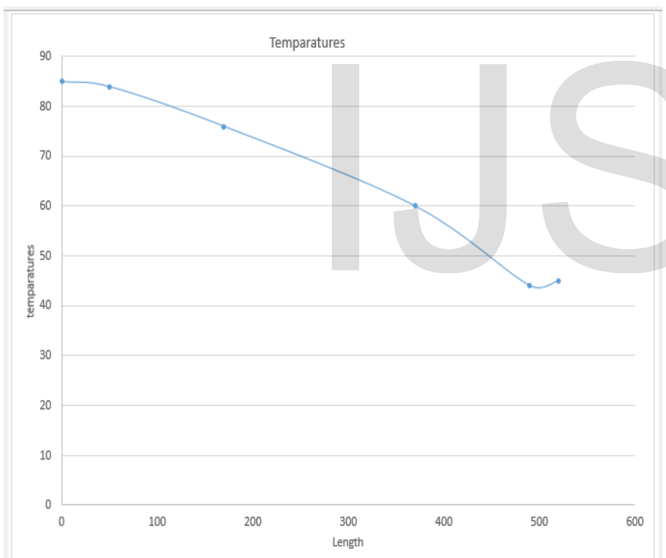

FiG9 Representation of temperature distribution from Evaportor to Condenser

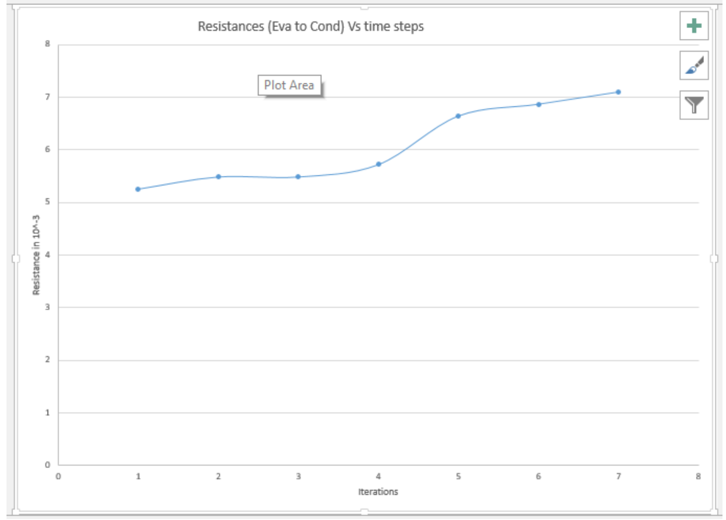

FIG 10 Representation of resistance from evaporator to condenser

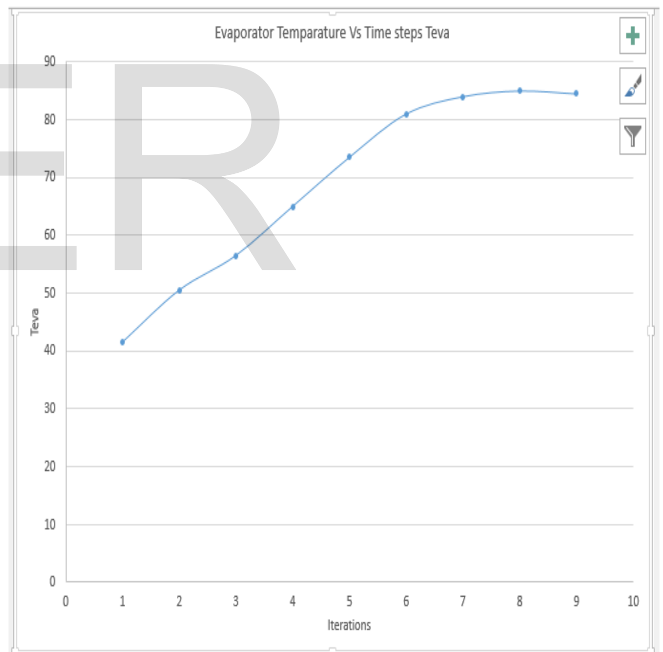

FIG 11 Representation of Evaporator temperatures

10 Advantages Of CLPHP

- Simple design and no complexities in construction.
- Smaller cross section with high heat transfer rates.
- As compared to an equivalent metallic finned array, it has less weight.
- Higher reliability.
- Miniaturization possibility.
- No external mechanical pumping equipment or sources required.

11 Conclusion

- PHP is a device which is comparatively a simpler and efficient heat transfer device.
- By controlling the various factors affecting its performance, their performance can be improved.
- The mathematical representation of the working of a PHP is not easily understandable due to its complex thermo hydrodynamic behavior.
- CLPHP's are devices having wide ranging cooling applications.
- PHP are useful in control of electronic and electrical devices and they are one of the best option in the thermal management.
- PHP are having more efficiency than conventionl heat pipes they are hightly used in space applications.

12 Future Scope

- **The experiments can be** carried out with different working fluids such as ethanol, methanol, ethyl alcohol etc.
- By changing amount of heat supplied value effective performance of php can be obtained.
- The heat source can also be obtained from sun's radiaton by using solar collector.
- The number of tubes can be increased for better flow and efficiency.
- The change in the tubes orientation is also used to improve efficiency of thermal systems.

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Nomenclature

A	Surface Area	m2
g	Acceleration due to gravity	m/s²
Q	Heat Load	Watt
Tcon	Average Condenser Temperature	ºC
Teva	Average Evaporator Temperature	ºC
m	Mass	kg
P	Inside pressure of PHP	
Tsat	Saturation Temperature	ºC
ρ_l	Liquid Density	kg/m³
ρ_v	Vapor density	kg/m³
σ	Surface Tension	N/m
L	Length	m
V	Voltage	V
I	Current	Amp
Cp	*Specific heat*	*J*/kgK
ΔT	Temperature Difference	°C
U	Overall heat transfer coefficient	W/m² °C
k	Thermal conductivity	W/m °C
R	Thermal resistance	°C/W
D	Diameter of Pipe	m
Bo	Bond number	

Abbreviations

CLPHP	Closed Loop Pulsating Heat Pipe
OLPHP	Open Loop Pulsating Heat Pipe
ID	Inner Diameter
OD	Outer Diameter
PHP	Pulsating Heat Pipe