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Experimental analysis of close loop pulsating heat pipe at different filling ratio

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***Abstract*— Pulsating Heat Pipes (PHPs) have high heat spreading performance and are capable of removing higher heat fluxes. OHPs have superior performance compared to traditional heat pipes and can be used to solve the future electronic cooling problems. Among the novel methods for thermal management of the high heat transfer rate found in microelectronic devices, Pulsating Heat Pipes are the most effective heat removal device. Experimental tests are one of the more popular ways to determine the thermal performance of pulsating heat pipe.**
Experimental method was conducted to study the heat transfer and other parameter like temperature distribution, thermal resistance in pulsating heat pipe. In experimental method, heat is applied at constant temperature and heat transfer rate is obtained. This procedure is repeated for different temperature for a particular feeling ratio. Then procedure is repeated for four different feeling ratios like 60%, 70%, 75% and 80%. Experimental set up is consists of 5 turn and acetone is used as a working fluid. The best results are obtained at 75% F.R.

***Key Words*—Pulsating Heat Pipe, Closed Loop, oscillation, filling ratio**

I. INTRODUCTION

Pulsating Heat Pipes (PHPs) are a passive heat transfer device and do not require a pump or additional power to operate. They also do not need a wicking structure to transport the liquid and can work at higher heat fluxes. Heat transfer is through natural oscillations of the working fluid between the evaporator and condenser sections.

PHPs consist of a long meandering tube which is heated and cooled at various points along its length. Their operation is based on the principle of oscillation for the working fluid and a phase change phenomena in a capillary tube. The diameter of the tube must be small enough such that liquid and vapour plugs exist.

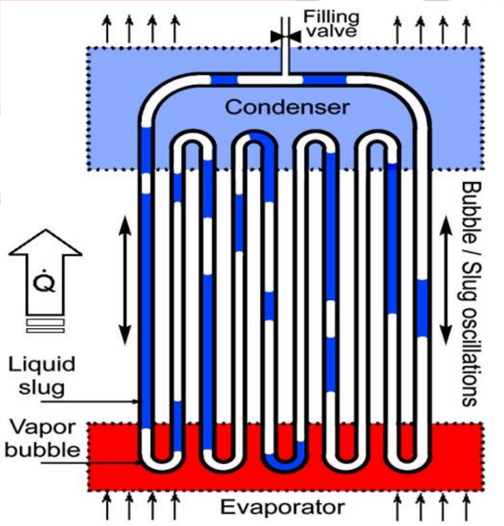

Fig. 1 Pulsating Heat pipe [22]

Initially, the PHP is evacuated and then partially filled with the working fluid. Effects from surface tension cause the formation of liquid slugs interspersed with vapour bubbles. As heat is applied to the evaporate section, the working fluid begins to evaporate. These results in an increase of vapour pressure inside the tube which causes the bubbles in the evaporator zone to grow and pushes the liquid towards the condenser. As the condenser cools, the vapour pressure reduces and condensation of bubbles occurs. This process between the evaporator and condenser section is continuous and results in an oscillating motion within the tube. Heat is transferred through latent heat of the vapour and through sensible heat transported by the liquid slugs.

When one end of the bundle of turns of the undulating capillary tube is subjected to high temperature, the working fluid inside evaporates and increases the vapour pressure, which causes the bubbles in the evaporator zone to grow. This pushes the liquid column toward the low temperature end (condenser). The condensation at the low temperature end will further increase the pressure difference between the two ends. Because of the interconnection of the tubes, motion of liquid slugs and vapour 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. The inter-play between the driving force and the restoring force leads to oscillation of the vapour bubble and liquid slugs in the axial direction. The frequency and the amplitude of the oscillation are expected to be dependent on the shear flow and mass fraction of the liquid in the tube.

II. LITERATURE REVIEW

Xiangdong Liu, et al, [1] analyzed the start-up performance of the closed-loop pulsating heat pipes (CLPHPs) based on an experimental investigation with various working fluids under different working conditions. The transfer functions for the typical under damped second-order system and first-order LTI system, and the corresponding six dynamic performance evaluation criteria are proposed to quantitatively characterize the dynamic performance of two most common types of start-ups for the CLPHPs, respectively. The present study offers a tool for theoretically simulating the dynamic thermal response of CLPHPs during the start-up, which is useful for judging whether the CLPHPs start-up normally in the practical application. The effects of filling ratio, inclination angle, heat load, and especially the thermo physical properties of working fluid on the start-up performance of the CLPHP are also quantitatively investigated. Based on such analysis, it is indicated that the optimal liquid filling ratio for start-up is about 41% for water, 52% for ethanol, and falls within the range from 35% to 41% for methanol. The start-up performance is improved with increasing inclination angle from 0^0 to 90^0. With the increasing heat load, a faster start-up speed and a better relative stability are observed while the start-up temperature is increased. Moreover, the working fluid with small dynamic viscosity, small specific heat, and especially large saturation pressure gradient versus temperature is beneficial to the start-up performance of the CLPHPs.

Brian Holley, et al, [2] presented Variation in channel diameter is investigated as a means of enhancing heat transfer in a pulsating heat pipe with capillary wick using the model presented here. The model is one-dimensional with slug flow where the momentum equation is solved for each liquid slug. The number and mass of liquid slugs are allowed to vary throughout a simulation. The energy equation is solved both in the wall and wick and in the working fluid. The effects of diameter profile, gravity, fill ratio, and heating and cooling schemes can be studied with the model. Results also indicate that heat transfer can be enhanced when the diameter of the channel is varied along the channel length, thereby providing increased range of heat load capability, less sensitivity to gravity, and in some cases smaller temperature differentials. For configurations with more parallel tubes, varying the tube diameter profile resulted in less sensitivity to inclination angle and a larger range of heat load capability.

Sejung Kim, et al, [3] presented to study of the effects of fluctuations of heating and cooling section temperatures on the oscillatory flow, temperature and pressure of the vapour plugs, as well as latent and sensible heat transfer of a pulsating heat pipe. The fluctuations of wall temperatures include a periodic component and a random component. The periodic component is characterized by the amplitude and frequency, while the random component is described by the standard deviations. The results showed that both amplitude and frequency of the periodic component of the temperature fluctuation have effects on the liquid slug displacements, temperatures and pressures of the two vapour plugs, as well as the latent and sensible heat transfer. It is concluded that the frequency of the liquid slug oscillation decreases with increasing amplitude and frequency of the periodic fluctuation of the wall temperature. However, the change of different standard deviations did not have any effect on the performance of the PHP.

B.Y Tong, et al, [4] conducted flow visualisation for the closed loop PHP using a charge coupled device (CCD). It was observed that during the start-up period, the working fluid oscillates with large amplitude, however, at steady operating state, the working fluid circulates. The direction of circulation for the working fluid is consistent once circulation is attained, but the direction of circulation can be different for the same experimental run. It was also concluded that large amplitude oscillations from the evaporator to the condenser occur in the closed loop PHP during the start up period. After this period, continuous circulation in the working fluid occurs. When the working fluid is circulating, the slugs also experience local oscillations.

W. Qu, et al, [5] conducted analysis to determine the primary factors affecting the start-up characteristics of a pulsating heat pipe. It is found that the wall surface condition, evaporation in the heating section, superheat, bubble growth, and vapour bubbles trapped in cavities at the capillary inner wall affect the start-up of oscillating motion in the pulsating heat pipe. When the capillary inner surface is coated or fabricated with cavities or roughness, the pulsating heat pipe can be readily started up. And it is found that the working fluid significantly affects the start up characteristics of a pulsating heat pipe. The cavity size on the capillary inner surface strongly affects the PHP start-up. When a PHP is charged with water, the cavity radius on the capillary inner surface should be larger than 2 μm, which can result in a smaller superheat starting up a PHP. The vapour bubble shape affects the superheat and vapour bubble growth. The globe-type vapour bubble needs smaller superheat than the one with the Taylor-type vapour bubble. The start-up performance can be improved by using a rougher surface, controlling vapour bubble type, and selecting a right working fluid.

Franco Andrey Silvério de Souza, et al, [6] presented preliminary experimental results of pulsating heat pipes operating with an evaporator average temperature ranging from -20°C to 5°C and having carbon dioxide (CO2) as the working fluid. Since their invention in the mid-nineties, pulsating heat pipes (PHPs) have been typically suited for micro electronics cooling. The results show the effects of input heat flux, inclination angle and volumetric filling ratio on the PHP thermal performance. The present results enable one to conclude that CO2 can be used as a working fluid to efficiently transfer heat at low temperature. It was verified that the CLPHP had adequate performance for all tests, up to the power level of 25W. The number of turns should be increased in order to fulfil the requirements necessary for operation in anti-gravity mode (with negative inclination), in consequence also raising the overall heat transport capacity.

M. Aboutalebi, et al, [7] presented Rotating closed loop PHP (RCLPHP) in which the thermodynamic principles of PHP are combined with rotation. Effect of rotational speed on thermal performance of a RCLPHP is investigated experimentally. The research was carried out by changing input power (from 25 W to 100 W, with 15 W steps) and filling ratio (25%, 50%, and 75%)

for different rotational speeds (from 50 rpm to 800 rpm with an increment of 125 rpm). The results presented that at a fixed filling ratio, thermal resistance of RCLPHP decreased with increasing heat input applied to evaporator. The rotational speed of the RCLPHP generated a centrifugal force, which slowed down the dry out and led into higher thermal efficiency of the system. The optimum filling ratio was found to be 50% for all rotational speeds. At this filling ratio, the existence and circulation of the working fluid is guaranteed through the pipe. Thus, favourable performance of the system is resulted.

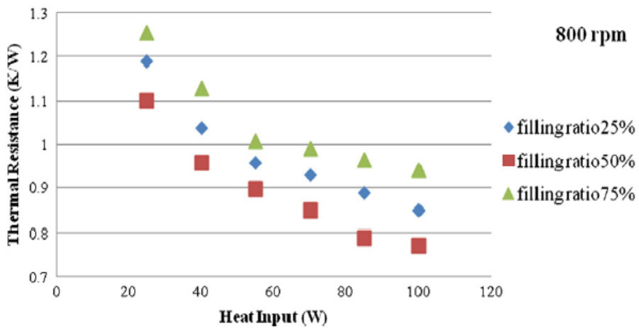

Fig. 2 Overall thermal resistance v/s heat input [7]

Stéphane Lips, et al, [8] conducted experiments on two full-size pulsating heat pipes (PHP) which differed from their diameter, number of turns, and working fluid. Experiments were conducted at the scale of a single branch of a PHP. An oscillating motion was imposed to a single liquid plug surrounded by two vapour slugs in a capillary tube and high speed visualizations were performed. The analysis of the experimental results showed two kind of operating curves (overall thermal resistance vs. heat rate): for low heat fluxes, the curve is irregular and the PHP performance is sensitive to the orientation. For high heat fluxes, the operating curve is smooth and independent from the orientation.

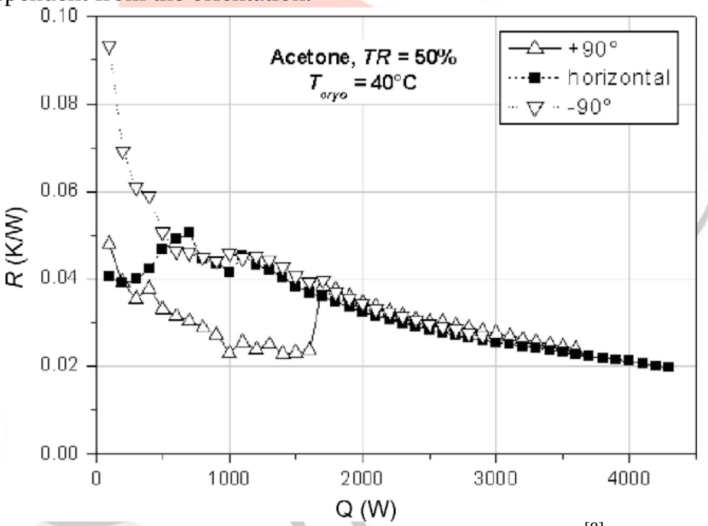

Fig. 3 Overall thermal resistance v/s heat rate [8]

Pramod R. Pachghare, et al, [9] presents preliminary experimental results on thermal performance of closed loop pulsating heat pipe (CLPHP). The copper capillary tube was used having internal and external diameter 2.0 mm and 3.6 mm respectively. For all experimentation, filling ratio (FR) was 50 %, number of turns was 10 and different heat inputs of 10 to 100W were supplied to PHP. The equal lengths of evaporator, adiabatic and condenser sections were 50 mm each. Working fluids are selected as Methanol, ethanol, acetone, water and different binary mixtures. The graphs are plotted, in order to study, characteristics of the thermal resistance and average evaporator Temperatures at different heat input for various working fluids. The result shows that, the thermal resistance decreases more rapidly with the increase of the heating power from 20 to 60 W, whereas slowly decreases at input power above 60 W. 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.

Dharmapal A Baitule, et al, [10] conducted a transient and steady state experiments are conducted on a two turn closed loop PHP. Copper is used as the capillary tube material in the evaporator and condenser sections with inner diameter of 2 mm and outer diameter of 3 mm. The total length of the closed loop pulsating heat pipe is 1080 mm. The evaporator and condenser sections are 360 mm and 280 mm respectively. The experiments are conducted on vertical orientations for different heat loads varying from 10 W to 100 W in steps of 10 W. The PHP is tested on Ethanol, Methanol, Acetone and Water as working fluids for different fill ratios from 0% to 100% in steps of 20%. The performance parameters such as temperature difference between evaporator and condenser, thermal resistance and the overall heat transfer coefficient are evaluated. The experimental results demonstrate the heat transfer characteristics, lower thermal resistance and higher heat transfer coefficient of PHP are found to be better at a fill ratio of 60% for various heat input. The thermal resistance of closed loop pulsating heat pipe decrease with the increase of heat input. At the lower heat input (Q ≤ 60 W) the thermal resistance is decreased slowly and at higher heat input ($Q \leq 60$ W) the difference is smaller. The thermal resistances have the results of $R_{acetone} < R_{methanol} < R_{ethanol} < R_{water}$. This condition is occurs up to 48 W and above the 48 W the thermal Resistance of Acetone is increased slightly. The filling ratio is a critical parameter, which needs to be optimized to achieve maximum thermal performance and minimum thermal resistance for a given operating condition. From this experimental setup we are conclude that at 60% filling of PHP give the optimum result.

Subhash Y.Nagwase, et al, [11] presents the CFD simulation with Di-water as a working fluid. The VOF model was selected to analyse phase change process. The surface force model was selected to consider the surface tension effects. It was concluded that simulation with unsteady model was successful to reproduce the same behaviour of vapour generation in evaporator and oscillation due to the pressure difference. It was proved that the heat transfer takes place due to oscillation of liquid and vapour. It can also possible to predict the performance of CLPHP for the different diameter with the same model without the experimental model.

Zirong Lin, et al, [12] presents the two phase flow behaviour in vertical bottom heating mode. Water was used as the working fluid. The volume of fluid (VOF) and mixture model in FLUENT were used in the simulations. The continuum surface force (CSF) model was used to consider the effect of surface tension. The result showed that the mixture model was more suitable for the two-phase flow simulation in a PHP. It was concluded that the inner diameter had a greater impact on the thermal performance of PHPs than the heat transfer length. Increasing the inner diameter was beneficial to improve the thermal performance of PHPs.

III. EXPERIMENTAL SET UP

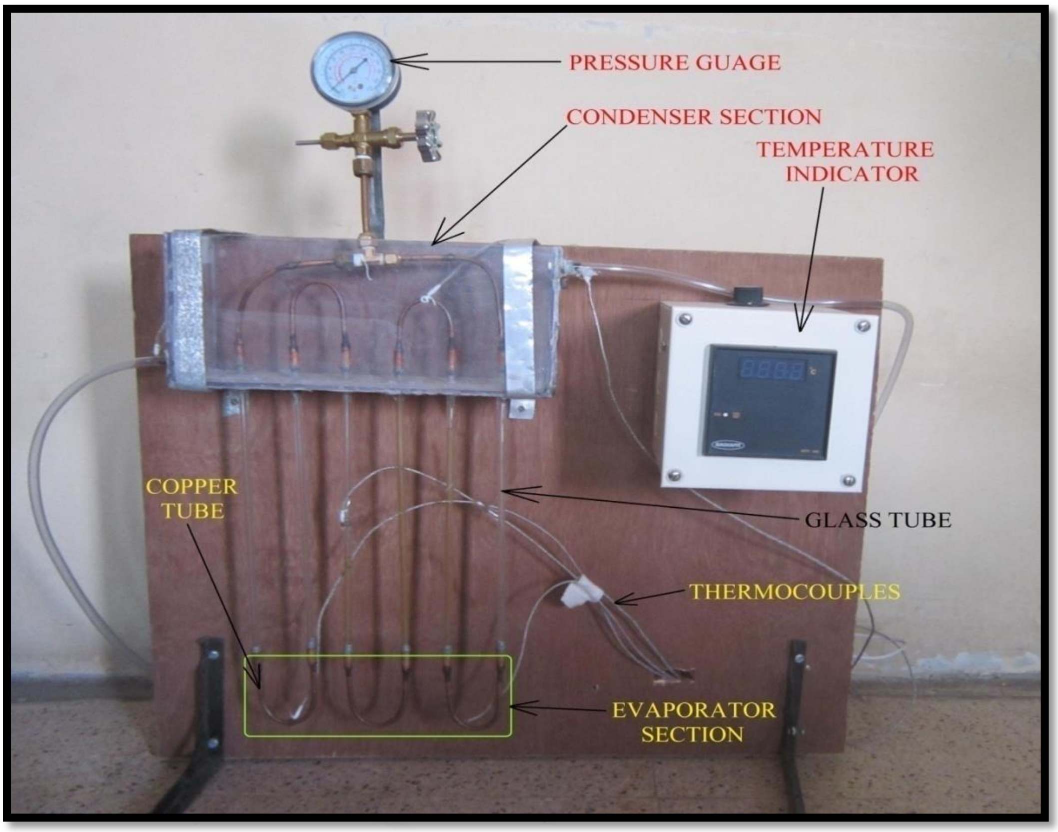

Fig. 4 Experimental Set Up

In this setup, copper is used as the capillary tube material in the evaporator and condenser sections with inner diameter of 4 mm and outer diameter of 5 mm. The length of evaporator and condenser is 25 mm and 35 mm respectively. In order to visualize the flow in the PHP, a glass tube is connected between evaporator and condenser sections. This section of glass tube is considered as adiabatic section having length of 205 mm. In the present investigation, borosilicate glass of inner diameter 4 mm and outer diameter 7 mm is employed.

The evaporator section consists of electrical immersion heater is employed during the experiments for heating the working fluid. K type thermocouples are used for the temperature measurement. Three thermocouples are fixed in the evaporator section and condenser section, similarly one on the glass tube and two are fixed at the inlet and outlet of water at condenser section. The thermocouples are fixed on the walls of the copper tube. The measured temperatures are indicated in digital temperature indicator which is mounted on control panel. Acetone is used as working fluid in this experiment. Experiment is carried out for four different filling ratios (60%, 70%, 75% and 80%).

Table 1 Properties of Acetone

Melting point	- 94 °C
Boiling point	56 °C
Density	0.791 kg/m^3
Critical temperature	235 °C
Critical pressure	48 bar

IV. ASSUMPTIONS AND EQUATIONS FOR THERMAL ANALYSIS

Following are the assumptions for thermal analysis.

- Radiation effects are neglected.
- There is no heat loss at adiabatic section.
- No fouling is considered.
- Potential and Kinematic energy changes are negligible.
- Specific heat of a fluid remains constant throughout the heat exchanger.
- Overall heat transfer coefficient is uniform throughout the heat exchanger.
- The mass flow rate of each liquid slug is constant along its length at a given time.
- The menisci of the liquid slugs are assumed to maintain a spherical meniscus shape with zero contact angles at the wall.
- The effect of the turns is neglected.
- Vapour exists at saturated conditions

Heat transfer rate is calculated by following equations.

$$Q = h \times A_{ext} \times \Delta T_{w\text{-}f} \qquad (1)$$

Thermal resistance is calculated by following equations.

$$R_{th} = \frac{T_w - T_o}{Q} \qquad (2)$$

V. RESULT AND DISCUSSION

Figure 5 shows heat transfer rate diagram for different filling ratio. For a particular filling ratio, heat transfer rate is increasing as inlet temperature increases. If we compare heat transfer rate at different filling ratio then for same inlet temperature, heat transfer rate increases as filling ratio increases from 60% to 70% and from 70% to 75%. But if we increase filling ratio from 75% to 80% then we can see that heat transfer rate is decreasing for a same inlet temperature. So it was concluded that optimum filling ratio for CLPHP with acetone as working fluid is 75%.

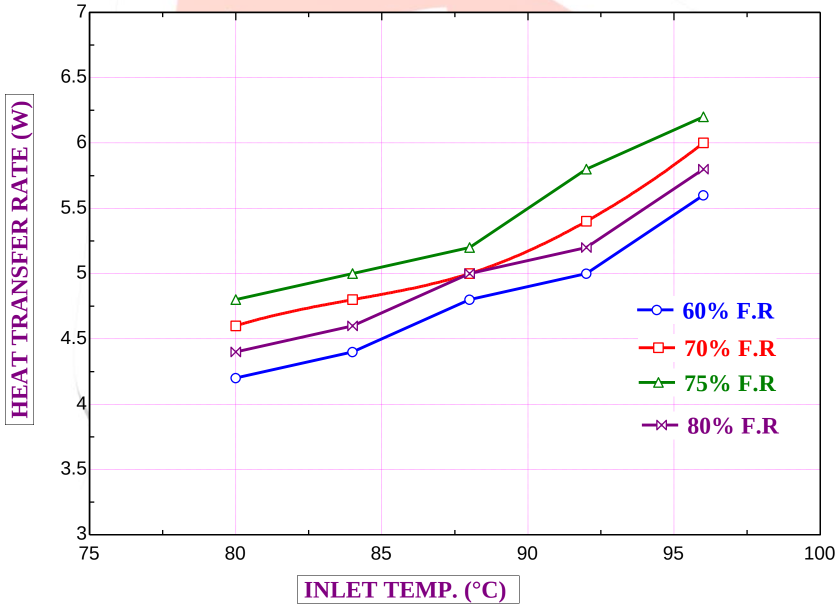

Fig. 5 Heat transfer rate at different filling ratio

Figure 6 shows thermal resistance diagram for different filling ratio. For a particular filling ratio, thermal resistance is decreasing as inlet temperature increases. If we compare thermal resistance at different filling ratio then for same inlet temperature, thermal resistance decreases as filling ratio increases from 60% to 70% and from 70% to 75%. But if we increase filling ratio from 75% to 80% then we can see that thermal resistance is increasing for a same inlet temperature. So it was concluded that optimum filling ratio for CLPHP with acetone as working fluid is 75%.

Figure 7 shows pressure vs inlet temperature diagram. Pressure inside the tube is increasing continuously as inlet temp increases.

Figure 8 shows wall temperature at different height of close loop at constant heat flux for different filling ratios. For a particular filling ratio, wall temperature is decreases with increasing height. Maximum temperature is recorded at 75% F.R for a particular constant heat flux.

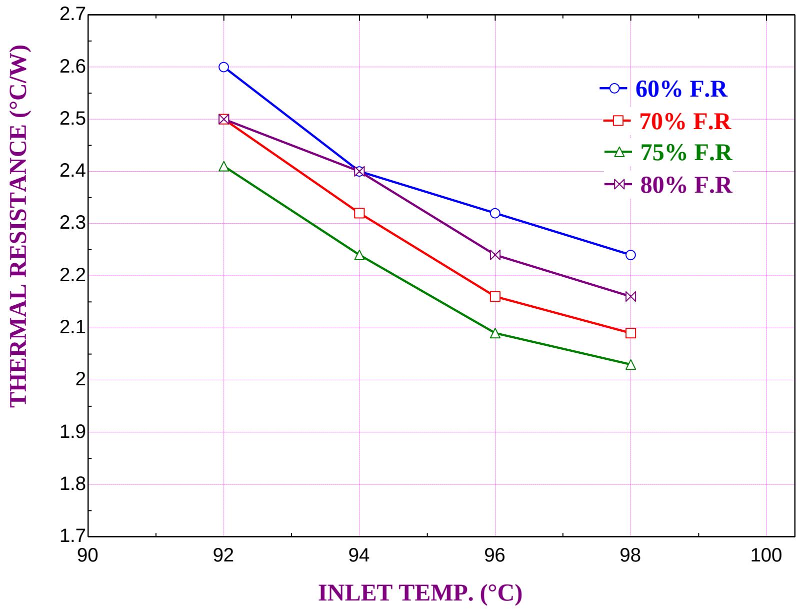

Fig. 6 Thermal resistance at different filling ratio

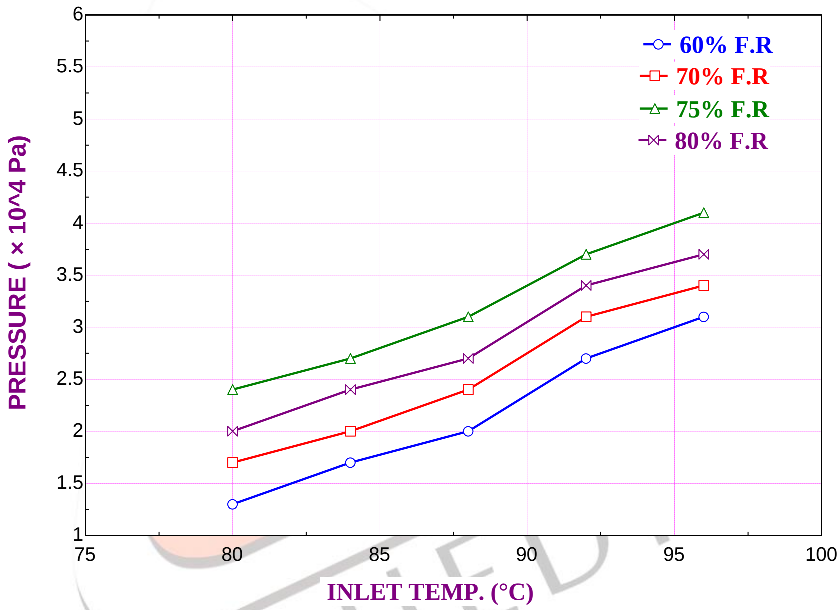

Fig. 7 Pressure at different filling ratio

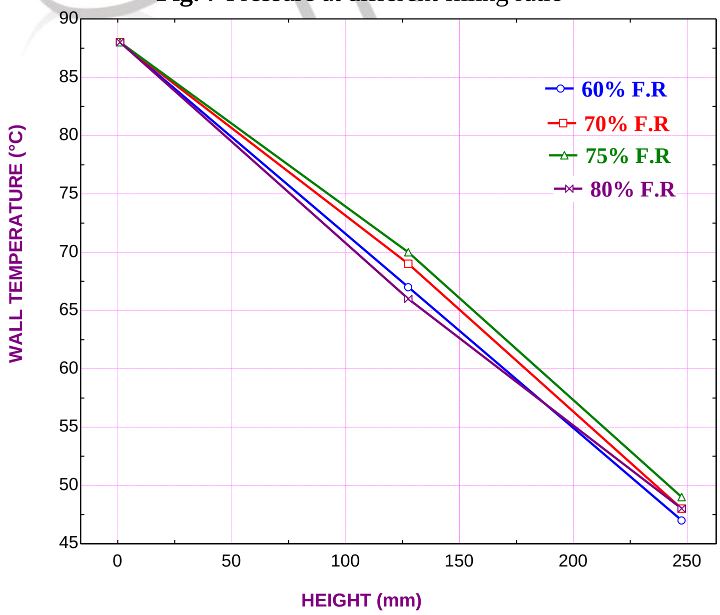

Fig. 8 Temperature distribution at different height

VI. CONCLUSIONS

Experimental model was made to analyse the performance of PHP in electronic cooling. The heat transfer rate is increases with increase in inlet temperature where as thermal resistance is decreases with increase in inlet temperature for all filling ratio. The best results are obtained at 75% filling ratio. The maximum value of heat transfer rate at 75% F. R is 6.2 W. And thermal resistance is decreases up to 2^0C/W.

Among the novel methods for thermal management of the high heat fluxes found in electronic devices, PHPs are most effective for heat removal. The two important objectives in electronics cooling, minimization of the maximum substrate temperature and reduction of substrate temperature gradients can be achieved by the use of PHPs. This study will benefit the design engineers involved in electronic cooling. Using the approach presented in this work, the design engineers can carry out optimization of parametric CAD models, for the selection or design of PHPs for effective thermal management in their electronic assemblies.

NOMENCLATURE

PHP - Pulsating Heat Pipe
CLPHP - Closed Loop Pulsating Heat Pipe
F.R - Filling Ratio
T_w – condenser wall temperature
T_o - outlet temperature of cold water
Q - Heat transfer rate
R_{th} - Thermal resistance
ΔT_{w-f} - temperature difference between condenser solid wall and cooling medium
P_r - Pressure
A_{ext} – Area
h – Convective heat transfer co efficient

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