DESIGN AND PERFORMANCE OF SINGLE LOOP PULSATING HEAT PIPE CAPABLE OF WORKING IN HORIZONTAL POSITION

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ABSTRACT

Pulsating Heat Pipe (PHP) is a promising device for heat transfer and became popular in last two decades. Heat transfer in PHP is a combination of sensible and latent energy exchange. Interfacial processes like bubble nucleation, pumping, agglomeration, and collapse under strong thermo-hydraulic coupling characterize the flow behavior inside the PHP. PHP’s have strong dependence on operating parameters, geometrical details and thermo-physical properties of the fluid. The complex physical phenomenon and involved dependence of constraints of PHP are still intriguing the researchers. The wickless structure of PHP provides a remarkable simplicity in its design. The circulation is aided by both gravity and the pressure difference between different parts of the loop which essentially needs a narrow cross-section. It has been a constant endeavor of the researchers to make the design operate independent of gravity. Reasonable success has been achieved by increasing the number of loops or turns. However, design of a PHP with limited number of turns yet independent of its orientation is still an open question. Present research proposes a unique design of a single loop PHP capable of working even in a horizontal position. Acknowledging the importance of gravity, operation of single loop PHP with “Source and Sink” at same elevation is attempted by providing gravitational assistance in the evaporator and the condensing sections. Gravity head is altered by varying the flow path of the PHP. Cooper tube is bent to form a closed loop of desired shape, in line with the aim of present study. Distilled water is used as a working fluid. PHP is experimented for varying fill ratios at different heat fluxes. Results shows that the proposed PHP shape works as a heat transfer device, transferring heat between “Source and Sink” at same elevation. High fill ratio and high threshold heat flux seems essentials for the PHP operation, gravity being a low head. Unidirectional flow, in line with the effect of gravity on the system, is achieved throughout the operation. Knowledge obtained from present thermal-hydraulic study can be used for commercial development of efficient PHP.

INTRODUCTION

On the way to miniaturisation, industries are continuously striving for efficient thermal management system which could remove high heat fluxes. Development of reliable and efficient device at low cost has always been the challenge for the scientific community to meet the raised demands. Breakthrough came to the heat transport enhancement with the development of Conventional heat pipes, which were first conceptualized by Gaugler [1] and later invented by Groover [2]. Heat pipes are two-phase sealed heat transfer device, where a closed tube is partially filled with liquid and evacuated thereafter by taking out air. When heat source is applied at one end of the tube and sink at the other end, heat pipe starts functioning. If heat source is at the bottom of the tube and sink at the top, system transfers heat in the principle of Thermosyphon. Evaporating liquid at the bottom section moves up due to density difference and condenses at top section giving up the latent heat. The condensate returns back to evaporator section along the circumferential surface due to gravity and the cycle continues. The process transfers considerable amount of heat at very small temperature difference, but such transfer of heat is not possible against gravity. This limitation is eliminated by introducing a capillary wick structure at circumferential surface area of the tube. Due to capillary pumping action, liquid flow without gravitational help became possible and heat pipes are conceptualized. Depending on the procedure of condensate return there are varieties of heat pipe developed during last fifty years [3].

In 1990, a new variety of heat transfer device is added to the family of heat pipe, termed as pulsating heat pipe (PHP). Though, the phenomenon and its application were in use; but to the scientific community it got appreciation in 1990, after its invention by Hisateru Akachi [4]. PHPs like conventional heat pipes are closed two-phase device. PHPs are made of capillary tube bent in serpentine manner to have number of turns. The two end of the tube are either closed individually or join together to have open loop or closed loop PHP structure [5]. The PHP structure is first evacuated to take of non-condensable gas or air and thereafter partially filled with the working fluid. Due to low saturation pressure corresponding to the ambient temperature, a part of the liquid flashes to vapour at equilibrium condition. Further, the capillary effect leads to the formation of distinct liquid slugs and vapour plugs. The liquid slugs and vapour plugs distributes randomly in size and position throughout the PHP loop. When one end of the tube is heated and other end is cooled, pressure difference is created. The randomly distributed vapour plugs at evaporator and condenser sections, expands and contracts respectively. Due to expansion-contraction, liquid slug and vapour plug movement is initiated. Moreover there are local temperature and pressure differences owing to the non-uniform heating and different slug-plug distribution at different channels. Due to this non-equilibrium condition, self-sustained thermally driven oscillating or circulating flow occurs inside the PHP.

Akachi in his patent [4] showed twenty four types of preferred embodiments and all the structures had check valve. Check valve incorporation has advantages to keep the flow unidirectional but it is difficult to fabricate and has long term reliability issues. Later Akachi [6, 7] developed PHP's without check valves. Large numbers of experiments were done to establish PHP as a heat transfer device. Effect of variation in inclination angle and number of turns was studied. With large number of turns (500) orientation independent operation of PHP has been reported [7]. Large number of turns and high heat input seems essentials for achieving orientation independent operation of the device. Large number of turns increases the degree of freedom, hence the level of perturbation; and further, high heat input to the system enhances the instability to overcome the gravitational effect on the system performance. If the numbers of turns are less, possibility of stopover of PHP functioning increases due to evaporator dry out [8]. Single loop PHP is observed to show complete stop over for horizontal heat transfer and gravity is reported to be essential force for the operation [8, 9]. This brings in the critical number of turns below which PHP cannot operate in horizontal and top heating mode. Design Equation for single loop PHP can be written as [8]:

$$\Delta \mathbf{P}_{\mathbf{Cap}} + \Delta \mathbf{P}_{\mathbf{Sat}} \pm \Delta \mathbf{P}_{\mathbf{G}} \geq \Delta \mathbf{P}_{\mathbf{Two\text{-}Phase}} \quad (1)$$

Sum of the driving forces like capillary head (ΔP_{Cap}), saturated pressure head (ΔP_{Sat}), gravity head (ΔP_G) should be positive and greater than dissipative two phase pressure drop head ($\Delta P_{Two\text{-}Phase}$).

Operation of single loop or few loops PHP for horizontal heat transfer is still a requirement to the scientific community. Acknowledging the play of forces inside the PHP, efforts are made to develop and experimentally investigate a single loop PHP which could transfer heat horizontally or between same elevations.

NOMENCLATURE

ΔP	[N/m^2]	Pressure head
Eö	[-]	Eotvos Number
Bo	[-]	Bond Number
D	[m]	Diameter
g	[m/s^2]	Acceleration due to gravity
T	[K]	Temperature
R	[K/W]	Resistance
Q	[W]	Heat Input
V	[V]	Voltage
I	[A]	Current
Special characters		
ρ	[kg/m^3]	Density
σ	[N/m]	Surface Tension
Subscripts		
Cap		Capillary
Sat		Saturation
G		Gravitational Force
Cr		Critical
liq		Liquid
vap		Vapour
E		Evaporator
C		Condenser
Th		Thermal

EXPERIMETAL INVESTIGATION

It is well accepted by the scientific community [4, 5, 8, 10] that formation of slug-plug distribution inside the PHP is essential for its proper functioning. Expansion and contraction of vapor plug at the evaporator section and condenser section act as pumping action for the movement of fluid, which in turn is a reason of the heat transfers between the two sections. The slug-plug distribution inside the tube requires domination of surface tension force to the gravitational force. White and Breadmore [10] showed that when Eötvös number (Eö) which is the ratio of gravitational force to surface tension force, is less than 4, the terminal velocity of the vapor bubble become zero in adiabatic static condition, due to dominance of the surface tension force and the bubbles are sticked to the wall of the tubes. This value of critical Eötvös number (or Bond number = 2) may vary due to varying experimental condition [5, 8, 9].

$$(\text{E}ö)_{cr} = (\text{Bo})^2_{cr} = \frac{D^2_{cr} . g.(\rho_{liq} - \rho_{vap})}{\sigma} = 4 \quad (2)$$

$$\text{D}_{cr} = 2 \sqrt{\frac{\sigma}{g.(\rho_{liq} - \rho_{vap})}} \quad (3)$$

Within the limits of Bond number criteria [8, 9], a cooper tube of inner diameter 3 mm and outer diameter 6 mm is chosen for experiments for distilled water (PHP fluid). Cooper tube is bent to form a closed loop.

Saturation pressure head acts as dominating head in the PHP, whereas capillary turns out to be a low one (constant, defined by diameter). Gravity head is altered by varying the flow path of the PHP. Design of single loop PHP with "Source and Sink" at same level is attempted by providing gravitational assistance in evaporator and condensing sections of the PHP, with minimum variation at the plane of adiabatic section. The Shape extends to 3-dimensions, with a minimal variation at plane of adiabatic section of the PHP. Variation at evaporator and condensing sections are of interest. Three dimensional design of single loop PHP and necessary dimensions are shown in Figure 1 and the corresponding planar views of the three dimensional loop are shown in X-Z, X-Y and Y-Z plane of Figure 2.

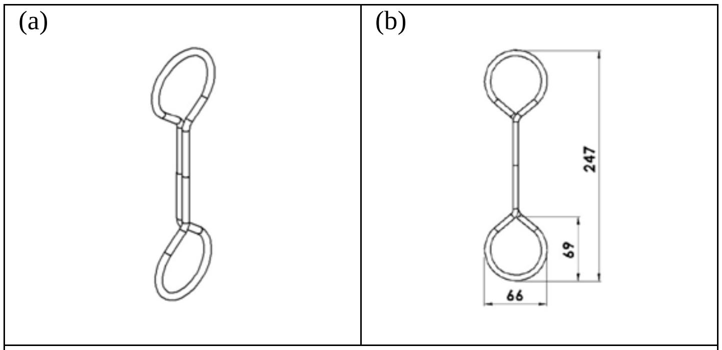

Figure 1 (a) Isometric view of the PHP loop and (b) Outer Dimension of the PHP loop in mm

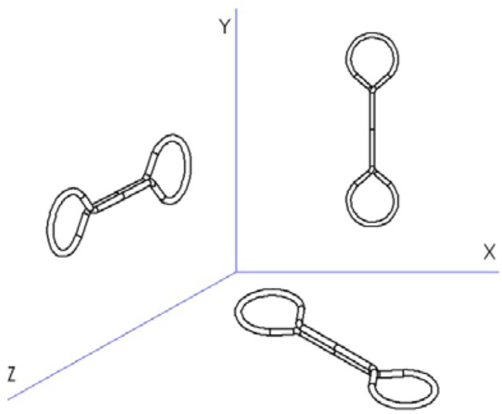

Figure 2 Figure shows three planes and the associated PHP orientation

The bent loop is provided with two valves for the charging and discharging of the fluid. The two ends of the loop constitute the evaporator and condenser section; central straight part of the loop constitutes the adiabatic section of the PHP (Figure 3).

Evaporation section consists of Nichrome heating wire (1500W and 4.2 ohm), wrapped around one end of the PHP. Evaporator section is well insulated by asbestos paste. Heat supply was controlled by DC power source (Agilent 6675A, 0-200V, 0-11A). Heat input is given in steps, varying the voltage as 9V, 12V, 15V, 18V and 21V. Corresponding heat input varies in limit 32.26 W (9V) to 165.21 W (21V). Condenser section consists of copper casing covering the other end of the PHP. Cooling water (Coolant) was supplied at normal atmospheric temperature (25°C) from a JULABO FL4003 cooling bath to the condenser inlet at a controlled flow rate. Condenser size and the flow rate are large when compared to the PHP dimension. Temperature difference between inlet and outlet of the cooling water in condenser can be neglected and it can be assumed that isothermal condition is maintained.

In this experiment, an Agilent-20 channel multiplexer programmable universal data logging system is used. The data logging system is connected with a computer via Rs-232 data cable. Temperature data has been recorded at a frequency of 1 Hz, with a resolution of 0.01°C. Four K-type (chromel–alumel) thermocouples are used in the experiment which works well in the range of -200°C to 1350°C. Since both conductors in this thermocouple are non-magnetic, there is no Curie point and thus no abrupt change in characteristics.

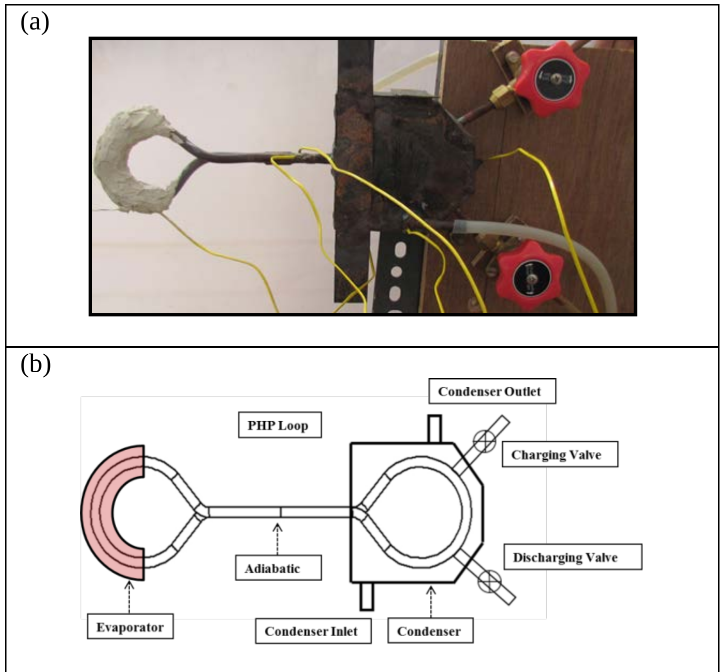

Figure 3 (a) Photograph of PHP set-up and (b) shows the Schematic of the PHP set-up in Y-Z plane

One thermocouple each at evaporator and condenser section, two thermocouples in two parallel channels of adiabatic section were used to analysis the behavior of the loop. The CLPHP is first evacuated with a high vacuum pump. When a stable pressure of 10^{-4} mbar is attained, desired amount of working fluid is filled through a syringe. In this experiment the working fluid is distilled water. Charged PHP is then provided heat at evaporator end and condensation at other end. Heat Input is provided in steps and temperature readings of thermocouples are analyzed to study the operational behavior. The PHP set-up is hinged onto a frame board, which can rotate and all the three planes can be attained.

RESULTS AND DISCUSSION

Considering the role of gravity on single loop PHP, study is not made in X-Z Plane. In X-Z plane gravity is absent and two phase pressure drop needs to be balanced by capillary and saturation pressure head. But $\Delta \mathbf{P}_{\mathbf{Cap}}$ is not a dominating head in PHP and $\Delta \mathbf{P}_{\mathbf{Sat}}$ alone is not sufficient to make the loop functional in the absence of gravity in X-Z plane.

Hence, PHP Shape is experimented in the rest two planes (Y-Z, X-Y), for different filling ratios (0.45, 0.54, 0.63, 0.72, 0.81, 0.90, and 1).

Y-Z Plane (horizontal adiabatic section):

PHP Shape tried in Y-Z plane, provides gravity assistance at evaporator and condenser sections; while Heat Source and Heat Sink maintained at same head. Of the tried filling ratios, PHP was found to work as heat transfer device in the range (FR 0.63 – 0.81). Temperature behaviors of the thermocouples during the experimental run are plotted in Figure 5. For FR 0.45 and 0.54, similar trends were observed. PHP tends to start, followed by initial dry out. Temperature of the evaporator section rises with initial input heat flux. After crossing the start-up threshold, sudden drop in the Evaporator section is observed owing to the movement of the fluid. With heat input, at evaporator section high pressure develops and the expansion of the vapor plug takes place. This effect tends to move the slug-plug train in upward direction due to buoyancy (from viewer's side the fluid movement will be seen in clockwise direction in figure 4). Similarly, the gravity assists the movement of the fluid at the condensing section in the downward direction (clockwise direction from viewer's side). Thus the thermocouple at the adiabatic section following the upper half evaporator section shows rise in temperature, as heated fluid from the evaporator crosses this limb of adiabatic channel; and the other thermocouple at the other limb of adiabatic section preceding the lower half of the Evaporator section shows fall in temperature as liquid supply comes in here from the condensing section. This behavior shows the direction of the initial movement of the fluid. The two forces at the two ends of the PHP loop – rise of vapour plugs at evaporator section and downfall of the condensing liquid at the condensing section – seems to be responsible for the depicted behavior of the PHP shape. After initial start-up movement, stop over is observed and evaporator section attains local dry-out condition.

For FR 0.63 and 0.72, similar trends were observed. PHP starts in unidirectional manner, confirming the assistance provided by the gravity at the evaporator and condensing section (figure 5). The attained direction of circulation is maintained and no flow reversal is observed. High start-up temperature is observed. The low amplitude and high frequency pulsations are observed.

At FR 0.81, PHP shows the similar starting and operational behavior i.e., unidirectional circulation. The behavior of flow is maintained. A high start-up threshold is observed. Low amplitude oscillations are marked by the PHP behavior.

PHP at FR 0.90 and 1 did not work leading to high values of evaporator temperature and hence undesirable high values of thermal resistance.

Thermal resistance for the PHP loop has been calculated for the PHP as a system. Temperature indication of thermocoule at the Evaporator Section of the PHP is taken as the Heat Source temperature and that of thermocouple at the Condenser Section constitutes the Heat Sink Temperature. Heat input at the Heat Source is taken as reference for Thermal Resistance estimation. Heat input is measured at the evaporator end, as the input heat to the PHP at pseudo-steady conditions.

$$R_{Th} = \left(\frac{T_E - T_C}{Q} \right)$$

$$with,\quad Q = VI$$

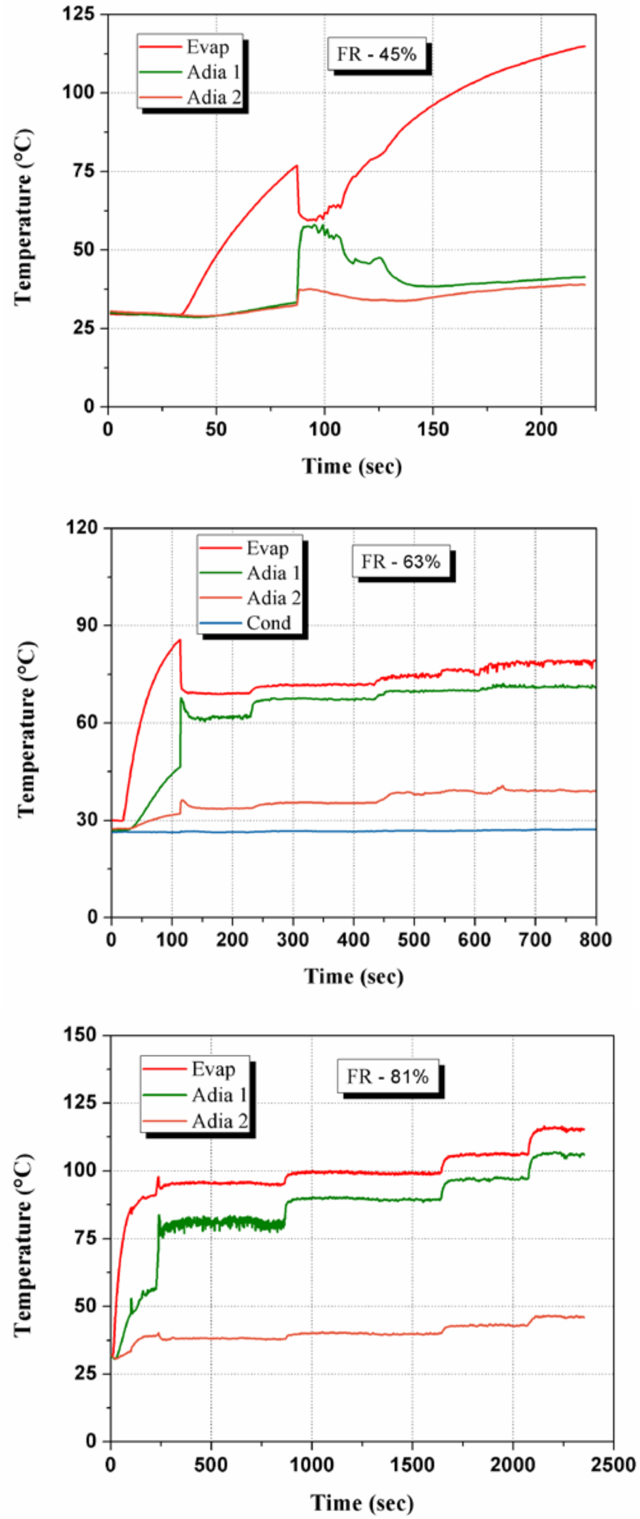

Figure 4 Temperature plot of the three filling ratios (0.45, 0.63, 0.81

Thermal resistance against heat input, for the three filling ratios (0.63, 0.72, and 0.81) is being plotted in figure 6. It can be observed that thermal resistance decreases with increase in heat input. FR 63% seems to offer low resistance among all.

But at high heat flux above (120W), dry-out at evaporator section is observed leading to undesirable high value of thermal resistance and is marked by dotted line in Figure 5.

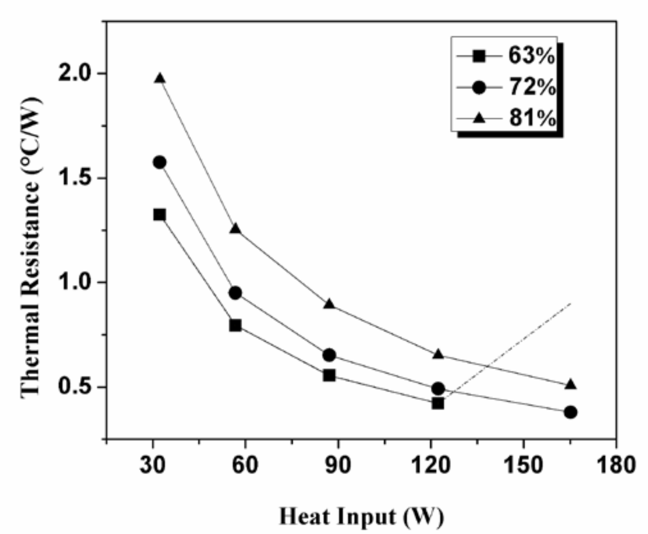

Figure 5 Variation of thermal resistance as heat input changes; three different filling ratios are tried

X-Y Plane (vertical adiabatic section):

PHP shape tried in X-Y plane provides gravitational assistance in all the three sections of the PHP i.e. evaporator, condenser and adiabatic section. It varies in evaporator and condenser section as a sine function and is constant in adiabatic section.

Among the tried FRs, temperature plot of the FR 0.45, 0.63 and 0.81 are shown in figure 6. Trends of the temperature plot for FR 0.54 were found to be similar to that for FR 0.45. At initial heat input, temperature of the evaporator rises and after start-up threshold is achieved fluid movements starts. Evaporator is observed with a drop in temperature and oscillates with high amplitude and low frequency signals. At the adiabatic section oscillatory behavior of the fluid is shown by the temperature indications. The two limbs of the adiabatic sections alternatively gets condensed fluid and heated fluid owing to the pulsations and Oscillatory flow behavior is observed. With increase in heat flux, oscillatory flow is observed to have low amplitude and high frequency pulsations. Further at high heat flux, increase in frequency is observed and the flow is pulsating with circulation intermittently. Temperature plot for FR 0.63 and FR 0.72 also show similar trends. Deviating from pulsating behavior at higher fill ratio, circulation is preferred by the PHP at low heat flux. Further increase in heat input brings in pulsating behavior, without much hindrance to the continuing circulating behavior. Though flow reversal is observed and tendency of the fluid to circulation is retained. With no constraint from gravity over the preferred direction for circulation, either of the limbs of the adiabatic section can serve the way to hot fluid from the evaporator section or cold fluid from the condenser section. FR 0.81 also shows result on similar lines figure 6. PHP starts with circulation. PHP seems to depict behavior similar to Thermosyphon at low heat flux. With increase in heat input pulsations are observed of low amplitude and high frequency.

At FR 0.91, PHP behaves similar to single phase thermosiphon (FR 1), with very small oscillations of low frequency and low amplitude. Figure 7 shows plot of thermal resistance against input heat flux for the variation of fill ratio. Decrease in thermal resistance is observed with increase in heat input.

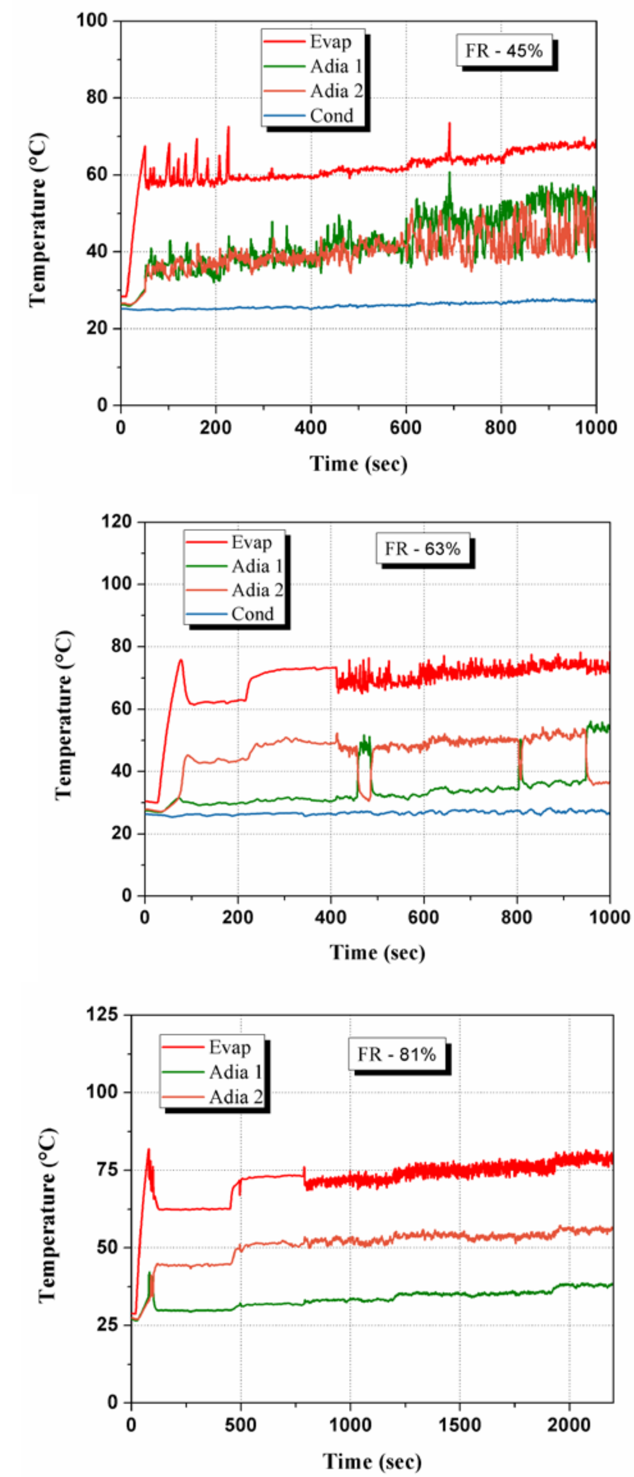

Figure 6 Temperature plot of the three filling ratios (0.45, 0.63, 0.81)

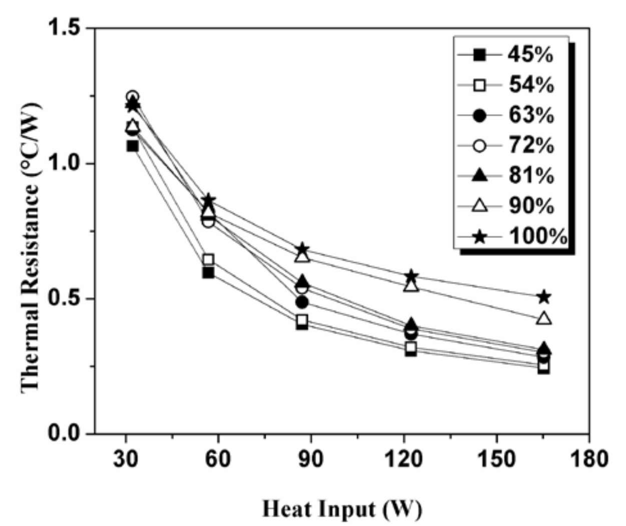

Figure 7 Plot of thermal resistance against heat input, for the different filling ratios.

CONCLUSIONS

Experimental observations are made for testing the efficiency of a three dimensional PHP. Both horizontal and vertical adiabatic sections are tried and followings are the major findings:

Horizontal adiabatic section:

- Efforts are made to check the working of PHP in situation where only the evaporator and condenser gets gravitational help but adiabatic section has almost same potential head. It has been observed that loop is working in such configurations.
- High filling ratio and high threshold heat flux for the PHP operation seems a perquisite requirement.
- Unidirectional flow in line with the effect of gravity on the system is achieved.
- Damped oscillations, as a result of PHP geometry and orientation, are observed.

Vertical adiabatic section:

- PHP Shape tried in vertical plane shows pulsating behavior at low filling ratios i.e. 0.45, 0.54.
- At high fill ratios (0.63, 0.72, and 0.81); PHP tends to take circulation first at low heat flux followed by addition of pulsating behavior to the continuing circulation at high heat fluxes.

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