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EXPERIMENTAL INVESTIGATION ON HEAT TRANSFER IN A CLOSED LOOP PULSATING HEAT PIPE

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ABSTRACT
Thermal management of electronic components is now an important sector in packaging technology. In many engineering applications higher heat flux is important. Two phase passive devices are proven solutions for modern microelectronics thermal management. This paper attempts to describe the heat transfer characteristics of closed loop heat pipe (CLPHP) which are new entrants in the family of closed passive two phase heat transfer system. This device is a combination of lot of events and mechanisms like bubble nucleation, collapse and agglomeration, bubble pumping action, pressure and temperature perturbations, flow regime changes, dynamic instabilities, metastable non equilibrium conditions, flooding, bridging etc. All contribute towards the thermal performance of a device. But, such a complex operating mechanism is not understood well yet and the present state of the art cannot predict the required design parameters for a given task. The aim of research work presented in this paper is to better understand the heat transfer characteristics of these mechanisms through experimental investigations. Experiments were conducted on a closed loop pulsating heat pipe (CLPHP) made of capillary tube of 2.2mm inner diameter. Water is used as the working fluid. The CLPHP was tested on vertical, horizontal, 30°, 45°, and 60° orientation. The results indicate the thermal performance of this device changes with different filling ratios, orientation, heat input. Better heat transfer performance is obtained at the 60˚ inclination angle at different heat input.

Keywords: Electronics Cooling, Closed Loop Pulsating Heat Pipe, Pressure Pulsations.

1. INTRODUCTION
Pulsating heat pipes (PHPs) are passive two phase thermal control devices. It was first introduced by Akachi et al. [1].In the last decade considerable amount of work has been done out to understand the thermo hydrodynamic characteristics of pulsating heat pipe. Closed loop pulsating heat pipe (CLPHP) is a new addition to the family of heat pipe. Mainly, it consists of a capillary tube bent in several curves joined to the end to end forming a closed loop parallel passages. It has already found some applications in micro- and power electronics applications owing to favorable operational characteristics coupled with relatively cheaper costs. Although grouped as a subclass of the overall family of heat pipes, the subtle complexity of thermo-fluidic transport phenomena is quite unique justifying the need of a completely different research outlook. Comprehensive theory of operation and reliable database or tools for the design of PHPs according to a given micro-electronics-cooling requirement is still an unrealized task A heat pipe is a heat transfer mechanism that combines the principles of both thermal conductivity and phase transition to efficiently manage the transfer of heat between two solid interfaces. They are referred to as the superconductors of heat as they possess an extraordinary heat transfer capacity rate with almost no heat losses. The heat transfer takes place with repeated cycles of condensation and evaporation of the working fluid within a sealed system. Within a heat pipe, there is a hot interface and a cold interface. The hot interface is generally known as evaporator and the cold interface is known as condenser, At the hot interface within a heat pipe, which is typically at a very low pressure, a liquid in contact with a thermally conductive solid surface turns into a vapor by absorbing the heat of that surface. The vapor condenses back into a liquid at the cold interface, releasing the latent heat. The liquid then returns to the hot interface through either capillary action or gravity action where it evaporates once more and repeats the cycle. In addition, the internal pressure of the heat pipe can be set or adjusted to facilitate the phase change depending on the demands of the working conditions of the thermally managed system. In a typical heat pipe, the sealed pipe or tube generally made of a material with high thermal conductivity such as copper or aluminum at both hot

and cold ends. A vacuum pump is used to remove all air from the empty heat pipe, and then the pipe is filled with a fraction of a percent by volume of working fluid (or coolant) chosen to match the operating temperature. Examples of such fluids include water, ethanol, acetone, or mercury. Due to the partial vacuum that is near or below the vapor pressure of the fluid, some of the fluid will be in the liquid phase and some will be in the gas phase. The use of a vacuum eliminates the need for the working gas to diffuse through any other gas and so the bulk transfer of the vapor to the cold end of the heat pipe is at the speed of the moving molecules. In this sense, the only practical limit to the rate of heat transfer is the speed with which the gas can be condensed to a liquid at the cold end. On the respect of thermal distribution, the tube bundle at downside receives heat and the tube bundle upward dissipates heat. So, there may exist an optional adiabatic zone in between this evaporator and condenser zone. This type of heat pipe is essentially a non equilibrium heat transfer device. The performance success of heat pipe primarily depends on continuous maintenance or sustenance of these non equilibrium conditions in the system. The liquid and vapor slug, bubble transport is caused by the pressure pulsations inside the device. Since these pressure pulsations are fully thermally driven, because of the inherent construction of the device, there is no external mechanical power source required for the fluid transport. In a working PHP, there exist temperature gradients between the evaporator and condenser section. These are coupled with inherent real time perturbations, due to Local non-uniform heating and cooling within the evaporator and condenser tube sections, Unsymmetrical liquid vapor distributions causing uneven void fractions in the tubes and Presence of approximately triangular or saw tooth alternating component of pressure drop superimposed on the average pressure gradient in a capillary slug flow due to the presence of vapor bubbles [2].The net effect of all these temperature gradients and perturbations is to create a non equilibrium pressure conditions which in conjunctions with the non-uniform void fraction distribution in respective tubes, is the primary driving force for thermo-fluidic transport. Thus self-sustained thermally driven oscillations are obtained [3, 4].

1.1 Choice of Working Fluids

The experience gained so far by earlier studies [4–10] suggests that the working fluid employed for PHPs should have the following properties:

1.2 High value of (dP /dT)sat

Ensuring that a small change in T_{evap} generates a large corresponding P_{sat} inside the generated bubble which aids in the bubble pumping action of the device. The same is true in reverse manner in the condenser.

1.3 Low latent heat

The two-phase flow characteristics of a PHP apparently suggest that latent heat may also play a vital role in thermal performance, it is quite the contrary. The heat transfer is primarily due to sensible heat transport by the liquid [4,7,9,10] and therefore it may be argued that a low latent heat is in fact more beneficial, aiding quick bubble generation and collapse.

High specific heat: High specific heat is desirable, given the fact that sensible heat is playing the major role in heat transfer in the pulsating mode of PHP operation; although there are no specific studies which explicitly suggest the e□ect of specific heat of the liquid on the thermal performance. It is to be noted that if a flow regime changes from slug to annular takes place, the respective roles of latent and sensible heat transport mechanism may considerably change. The probability of annular flow is high with a combination of high Eötvös number, high heat flux and comparatively low FR (50% or lower). This aspect requires further investigation [10].

1.4 Low surface tension

which in conjunction with dynamic contact angle hysteresis may create additional pressure drop [6,10].

1.5 Low dynamic viscosity

It generates lower shear stress.

In this experiment water is used as the working fluid as its properties are in accordance with the criteria of a good working fluid. Due to its availability, high specific heat, relatively lower surface tension and high change of pressure with the change of temperature makes water the perfect working fluid for this experiment.

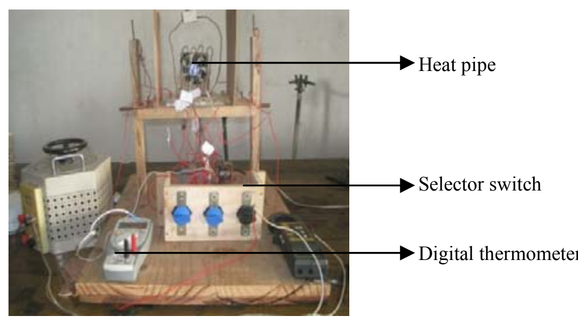

Fig 1. Test section of CLPHP

2. EXPERIMENTAL PROCEDURE

The schematic diagram of the setup is shown in the figure 1. There is a circular heat pipe built using capillary copper tubing with OD 2.3 mm and ID 2.2 mm. the total length of the pipe 155 cm. The tubes are bent on U shape. Two of the bends are located at two extreme ends were kept longer on one side to complete the closed loop circuit through the T connector. For pulsating heat pipe operation distinct liquid slug and vapor bubbles are essential for PHP operation. The formation of slugs in a capillary tube is attributed to the balance of gravity and surface tension forces, leading to the definition of Eötvös number or alternatively the Bond number. The theoretical maximum tolerable inner diameter of the PHP capillary tube is given,

$$D_{crit} = 2[\sigma/g\ (\rho_{liq} - \rho_{vap})]^{½}$$

And $$Eo = (Bo)^2$$

At diameters below this value there is a tendency of surface tension forces to predominate and this assists in formation of stable liquid slugs, an essential prerequisite for PHP operation. As the PHP tube diameter increases the surface tension is reduced leading to stratification of phases. Therefore it seems to follow that a maximum critical diameter the device will stop functioning as a PHP. The device may rather function as a disconnected array of a two phase thermosyphons. After taking the perfect diameter, the experiment would be done on three different orientations. They are Vertical (0^0), 30^0, 45^0, 60^0 angle orientation and Horizontal (90^0). The PHP has to be filled by different amount of working fluid. The general convention is to fill the tube by syringe injector. But on this experiment, the filling ratios are taken different for different orientations. For vertical position, the filling ratios are 28%, 63%, 41.3%, 82.5%, and 100%.For 45^0 positions, the filling ratio is maintained 85.6% and for horizontal position, 82% filling ratio is maintained. After filling the tube on their desired filling ratios, the evaporator section has to be heated by the variac. By changing the variac voltage, different voltage and current are supplied to the evaporator. For heating the evaporator, nichrome wire is coiled in the evaporator and this wire is connected to the variac.

For cooling the condenser a cooling fan is used. It is connected to an adapter circuit. The cooling fan is operated by DC current. So, the adapter circuit is used to convert the AC current to DC current. Generally, the air speed delivered by fan is around 3 m/s. The K type thermocouples are used to monitor the temperature of different position of the heat pipe. The temperature is recorded on a regular time interval. Generally, the time interval is 10 minutes.

3. RESULTS AND DISCUSSIONS

For evaluating the performance, efficiency and understanding the heat transfer characteristics of closed loop pulsating heat pipe, the wall temperature at different points of the CLPHP are measured. The maximum heat throughput is achieved in vertical and inclination heat mode for reaching the average evaporator temperature of 100^0C for water. Thermal resistance are calculated by using equation, thermal resistance = $(T_{evap} - T_{cond})/Q$, then thermal resistances are plotted against heat input.

In vertical mode the vapor bubbles which take up heat in the evaporator grow in size. Their own buoyancy helps them to rise up in the tube section. Simultaneously other bubbles, which are above in the tube, are also helped by their respective buoyant forces. These rising bubbles in the tube also carry the liquid slugs trapped in between them. In this mode of operation there is a natural tendency for the liquid slugs to travel downwards, helped by gravity force, toward the evaporator. Simultaneously the vapor bubbles have the natural tendency to travel towards the condenser helped by their buoyancy. Fig. 2 demonstrates the Comparison of Thermal Resistance vs. Heat Input at different Filling Ratio. In the single-phase mode (100% fill), the liquid could freely circulate in the tube resulting in substantial convective heat transfer. As soon as a small amount of working fluid is sucked out of the device (82.5% fill), it results in the formation of few bubbles in the tubes which hinder the naturally circulating flow. Under the new working condition, the driving force generated due to the density gradient has to overcome additional forces to induce a flow. There new retarding forces are due to (a) the additional frictional resistance (or pressure drop) created due to the head and tail section of the bubble, (b) the buoyancy force which acts on the bubble due to which acts on the bubble due to which it is difficult to bring the bubble in the downward direction against gravity. Between 25-70% filling ratio the device functions in a truly pulsating mode. The thermal performance improves at lower fill charge. The maximum performance was observed at about 25-30% filling ratio for water gave maximum throughput.

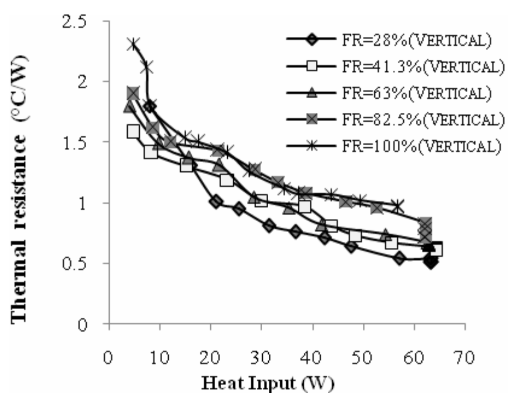

Fig 2. Comparison of thermal resistance vs. heat input at different filling ratio (At vertical position)

In horizontal mode (0 inclinations) of operation, there was hardly any macro movement of bubbles and thermal resistance was almost constant. This strongly suggests that gravity does play a role in the PHP action. Since gravity force is absent, all the movement of bubbles and slugs has to be necessarily done by the pressure forces. These forces are created due to temperature differences, which exist between evaporator and condenser. We have maintained nearly same filling ratio (around 80%) at different inclination. From figure 4 we find that at 60 inclinations closed loop PHP performs better than other position. But comparatively at vertical mode of operation (90 inclinations) it gave maximum heat throughput

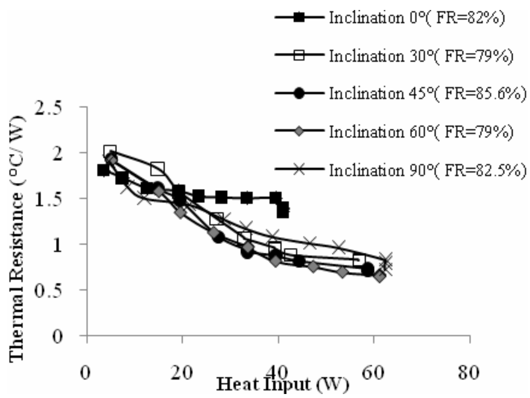

Fig 3. Comparison of thermal resistance vs. heat input at different inclination (Nearly same filling ratio)

Figure 3 shows comparison of thermal resistance vs. heat input at different inclination nearly same filling ratio. A closer look at comparison curve, at 30 inclination closed loop PHP performs better than other position but comparatively at vertical mode of operation it gave maximum heat throughput.

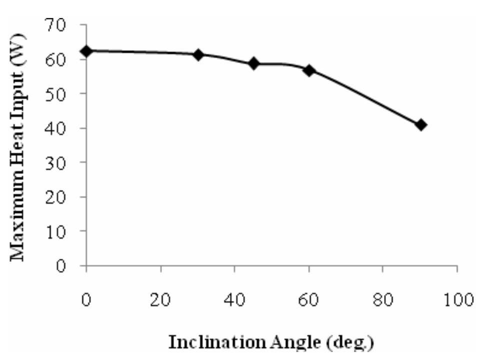

Fig 4. Maximum Heat Input vs. Inclination angle

Figure 4 shows maximum heat input vs. inclination angle nearly at same filling ratio. The maximum heat input increases with decreasing the inclination angle (from vertical position to horizontal position). The maximum heat input was obtained at vertical position. If the same fluid is to be used, the PHP should operate at a higher T_{evap} keeping the T_{cond} constant. This will raise the driving pressure di□erence in the device. If the same T_{evap} is to be maintained then some other working fluid having higher P_{sat} at this temperature as well as a steeper $(dP/dT)_{sat}$ should be used. In general, it is also expected that an increase in number of turns of the device should increase the level of perturbations. This might be a possible solution for better operation.

4. CONCLUSION

From this study some information related to the fundamental characteristics and operational regimes of a PHP were generated. For a given heat throughput requirement, better heat transfer and self-sustained thermally driven pulsating action of the device was observed in the filling ratio ranges from 25–65% for water. Above this range, the overall degree of freedom and the pumping action of bubbles was insu cient for rendering good performance. Below a certain range of filling ratio, partial dryout of the evaporator was detected. The results also indicate that a 100% filled PHP (not working in the pulsating mode but instead as a single phase buoyancy-induced thermosyphon) can thermally perform better than a partially filled pulsating mode device under certain operating conditions. The tested PHP did not operate in the vertical mode constantly for the working fluids tested. The reasons are attributed to fixed number of turns and atmospheric pressures existing at testing conditions. Although the Eötvös number of water was much below the prescribed maximum limit of Eö = 4, gravity forces were definitely seen to a ect the performance. This suggests that, in the vertical mode fluid transport is mainly by the bubble pumping action thereby providing substantial heat transfer. Closed loop pulsating heat pipes are complex heat transfer systems with a very strong thermo-hydrodynamic coupling governing the thermal performance. Di erent heat inputs to these devices give rise to di erent flow patterns inside the tubes. This in turn is responsible for various heat transfer characteristics. The study strongly indicates that design of these devices should aim at thermo-mechanical boundary conditions which result in convective flow boiling conditions in the evaporator leading to higher local heat transfer co-e cients. The inclination operating angle changes the internal flow patterns thereby resulting in di erent performance levels. The best performance is obtained from vertical direction and the worst performance is obtained from the horizontal orientation.

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6. NOMENCLATURE

Symbol	**Meaning**	**Unit**
FR	Filling ratio, V_{liq}/V_{total}	
Q	Heat throughput	(W)
T_{evap}	Evaporator temperature	(°C)
T_{cond}	Condenser temperature	(°C)
σ	surface tension	(N/m)
Eo	Eötvös number	
Bo	Bond number	