Influence of Process Parameters on The Thermal Performance of A Single Loop Pulsating Heat Pipe - An Experimental Study

Ch. Sreenivasa Rao and AVSSKS Gupta

Abstract—The continuous demand for smaller and faster microelectronics systems has increased the need for development of more efficient cooling systems. In that direction, development of Heat pipes is proved to be a promising cooling technology for microelectronic systems for the removal of high local heat flux rates and to achieve uniform chip temperatures. The counter current flow between the liquid and vapor phases causes significant entrainment losses in conventional heat pipes and the limitations in conventional heat pipes have led to the development of pulsating heat pipes. The heat transfer mechanism in a PHP is a complex phenomena as it is influenced by multiple factors and no single author could present a comprehensive heat transfer study even as on today. Moreover, the open literature available on single loop PHPs is very limited and hence an attempt is made to verify the influence of diverse process parameters on the flow and heat transfer behavior of a PHP. In the present work, an experimental setup has been built in and conducted experiments in order to understand the behavior of fluid flow and heat transfer characteristics of a single loop PHP without evacuation conditions. The setup is provided with air cooling arrangement at the condenser. The preliminary results highlighting the effect of heat input, working fluid and orientation have been obtained from this experiment. The results highlighted that the PHP yields better fluid flow and heat transfer characteristics in horizontal mode rather its operation in vertical mode. Among all the working fluids considered for PHP operation, Acetone exhibits better transfer characteristics.

Index Terms—Electronics cooling, single loop pulsating heat pipe (PHP), Air cooling, Thermal Resistance, Heat transfer co-efficient

NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Unit</th>
<th>Description</th>
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<tbody>
<tr>
<td>(C_p)</td>
<td>J/KgK</td>
<td>Specific heat capacity</td>
</tr>
<tr>
<td>(D_{crit})</td>
<td>m</td>
<td>Critical diameter</td>
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<tr>
<td>(\dot{m})</td>
<td>kg/s</td>
<td>Mass flow rate of cold water</td>
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<tr>
<td>(Q_{cond})</td>
<td>W</td>
<td>Heat removed in condenser</td>
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<tr>
<td>(Q_\alpha)</td>
<td>W</td>
<td>Input power added</td>
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<tr>
<td>(R_{th})</td>
<td>k/W</td>
<td>Overall thermal resistance</td>
</tr>
<tr>
<td>(T_{c_0})</td>
<td>°C</td>
<td>Avg. condenser wall temperature</td>
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<tr>
<td>(T_{c_in})</td>
<td>°C</td>
<td>Cold water inlet temperature</td>
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<tr>
<td>(T_{c_out})</td>
<td>°C</td>
<td>Cold water outlet temperature</td>
</tr>
<tr>
<td>(T_e)</td>
<td>°C</td>
<td>Avg. evaporator wall temperature</td>
</tr>
<tr>
<td>(F_{cap})</td>
<td>N</td>
<td>Capillary force</td>
</tr>
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<tr>
<td>(A)</td>
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<td>Surface area</td>
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<tr>
<td>(U)</td>
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<td>Uncertainty</td>
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<tr>
<td>(V)</td>
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<td>(I)</td>
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<td>Electric current</td>
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<tr>
<td>(c)</td>
<td></td>
<td>condenser</td>
</tr>
<tr>
<td>(l)</td>
<td></td>
<td>liquid phase</td>
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<td>(v)</td>
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<td>vapour phase</td>
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<tr>
<td>(\sigma)</td>
<td>N/m</td>
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<tr>
<td>(\rho)</td>
<td>Kg/m³</td>
<td>Density</td>
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<tr>
<td>(\varphi)</td>
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<td>Fill ratio</td>
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<tr>
<td>(g)</td>
<td>m/s²</td>
<td>Acceleration due to gravity</td>
</tr>
<tr>
<td>(h)</td>
<td>W/m²K</td>
<td>Heat transfer coefficient</td>
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1 INTRODUCTION

HERMAL management of high power denser microelectronics is a challenging task for present day designers and researches as there are many shortcomings with the available conventional systems. In the light of increased power levels associated with high heat fluxes, the researchers are motivated to develop novel cooling technology for microelectronic systems. Pulsating heat pipes (PHPs) are the promising two phase passive systems developed by Akachi [1] in that direction. Due to their simple structure, small size, cost effective and excellent thermal performance, PHPs have drawn a great deal of attention. The heat influx increases the pressure of vapor plugs at the evaporator and the heat efflux decreases the pressure at the condenser. The differential pressure between the evaporator and condenser would result in the pulsating flow of liquid slugs trapped between the vapor bubbles. Closed loop PHPs enhance the heat transfer majorly in the form of sensible heat rather in the form of latent heat [2-3]. Any typical CLPHP also will be first evacuated and then partially filled with a working fluid. For a capillary tube diameter up to its critical value, surface tension forces are predominant over the gravity forces and the working fluid distributes into the train of liquid slugs and vapor plugs. Beyond critical diameter, the flow becomes stratified. The critical diameter which is a design parameter for a PHP is evaluated from the relation [4].

- Associate Professor, MITS, Madanapalle, Andhra Pradesh - 517325, India, PH-091 9440537402. E-mail: rao_rac@rediffmail.com
- Professor, JNTU College of Engineering, Hyderabad, Telangana - 500087, India, Email: avs_gupta@rediffmail.com
$$D_{\text{crit}} = 2 \frac{\sigma}{(\rho_l + \rho_v) g}$$  

where $\sigma$ is the surface tension of the working fluid, $g$ is the gravitational acceleration and $\rho_l$ and $\rho_v$ are the densities of liquid and vapor phases respectively. The thermo-physical properties of working fluids are evaluated based on their saturation temperature.

Many investigations related to both experimental and numerical studies on PHPs have been reported, as their comprehensive understanding and design is still inconclusive. Experimental works were mainly dealt with flow visualization studies and evaluation of thermal performance under influencing parameters. Numerical studies explained about the flow characterization of slug/plug flows in PHPs.

Gi Hwan Kwon et. al [5] investigated the effect of dual diameter on the flow and heat transfer characteristics of a single turn pulsating heat pipes. The results revealed that a circulating flow was promoted by a dual diameter tube even at lower heat input level and reduced the thermal performance of PHP by 45%.

The performance of a single loop pulsating heat pipe made of quartz glass tube was carried out by Nandan Shah et. al [6] to understand the influence of process variables on the hydrodynamic characteristics and its performance. The studies revealed that for the combination of PHP geometry and working fluid the optimum FR exists within 40-50% and optimum inclination angle exists within 50-70% where the thermal resistance of the loop is minimum.

Thermal performance of a closed loop pulsating heat pipe working on various fluids has been derived by Kammuang et. al [7] in terms of dimensionless numbers. Thermal performance was derived in terms of Kutateladze number (Ku).

Park Yong-ho et. al [8] have explored the measurement of pressure characteristics inside a single loop oscillating heat pipe (OHP) made of copper tube at varied fill ratios. The investigations demonstrated that a fill ratio of 60% yields highest inside pressure magnitude as well as pressure frequency irrespective of any set of operating conditions apart from the attainment of the lowest flow resistance at this fill ratio.

The flow patterns in a PHP were analyzed through visualization studies conducted by Khandekar [9]. The realization of flow visualization studies was done on a single loop PHP developed of copper tubes. The slug flow with a low amplitude of oscillations was observed at lower heat input. Sustainability of annular flow had become very difficult when the fill ratio was increased beyond 70%.

The operating mechanism in an oscillatory capillary tube heat pipe [OCHP] was ascertained by WH Lee et. al [10] through the visualization of flow pattern. For this purpose, the experimental setup made of brass and an acrylic plate with a looped serpentine flow channel of multiple turns was used. Active oscillation of the working fluid was observed at a charging ratio of 40 to 60% and at the inclination angle of 90°.

The inability of check valves and their reliability to deliver expected results in capillary tubes led to the development of loop heat pipes without check valves [11].

Khandekar et.al. [12] demonstrated the existence of multiple quasi – steady states and their characteristics in a PHP by developing an experimental test rig of a single loop PHP made of copper tubes. Three quasi steady states were observed and named as steady state 1, 2 and 3. Extremely poor thermal performance was reported in steady states 1 and 2. The author demonstrated that the steady state-3 was characterized with unidirectional flow pattern with least thermal resistance and allow the PHP to continuously transfer heat in the evaporator and condenser.

Rama Narashimha et. al [13] presented an experimental study on a single turn closed loop PHP. Transient and steady state experiments were carried out for different operating conditions. The results of their experiments showed an intermittent motion of the working fluid at lower heat input.

Naik et. al [14] conducted experiments on a single turn closed loop PHP both in the horizontal as well as vertical orientations for different heat loads. The results revealed that the single loop PHP is found to perform better in the horizontal orientation for all the process variables considered.

Pallavi et. al [15] carried out an experimental study on a single turn vertical closed loop PHP using an azeotropic mixture of water (4.5%wt) and Ethanol (95.5%wt) at a fill ratio of 50%. No measurable difference of thermal resistance is reported by PHP working with an azeotropic mixture of Ethanol and water when compared the PHP performance with Ethanol as the working fluid.

Zhang et. al [16] clarified that the thermal performance of many PHPS was found to be degraded when the inclination angles were increased and some would not even operate at all. PHPS of sufficiently smaller diameter perform better at low inclination angles.

Thus the available literature reveals that not many experiments have been reported on single loop PHPs made of materials other than Copper and Aluminum. Moreover, the suitability of different working fluids with new tube materials such as brass has not been verified. The properties like high ease of bending into curved shapes (malleability), corrosive resistance, cheaper cost, compatibility with most of the working fluids and good thermal conductivity provided an extra edge for brass to be chosen as an alternative tube material. Hence in the present work, the thermal behavior of a single loop PHP made of brass is tested under different operating conditions. Moreover none of the theoretical models developed so far could explain the complexities involved in the flow and heat transfer characteristics in a PHP. Therefore, it has got the necessity of carrying out experimental and theoretical studies to understand the PHP behavior towards the development of more universal theory for pulsating heat pipes.
2 EXPERIMENTATION

2.1 Instrumentation Used in the Experimental Set up

The primary components used in this experimental setup are; copper and glass tubes, silicon rubber tube, a wounded type coil heater and.

Being an excellent conductor of heat, copper is used as the tube material. The copper tube consists of 2 mm inner diameter and 3 mm outer diameter. The tube is bent into a single loop U turn with a radius of 35 mm. The U turn copper tubes are coupled with a glass tube attached between them. The glass tube acts as the adiabatic section and facilitates the flow visualization. The glass tube provided has the length of 50 mm. The glass tube is fabricated of borosil, that could resist up to a temperature of 1200°C. The copper and glass tubes are connected with silicon rubber tube connectors of 2 mm inner diameter. Silicon rubber tube forms a perfect sealing and can resist temperatures up to 400°C.

Eight numbers of K-type thermocouples are used for the measurement of temperature from the PHP. The thermocouples are capable of measuring temperature up to 1000°C. The thermocouples have the wire diameter of 1 mm and four thermocouples each at equal distances are connected in the evaporator and condenser sections. The temperatures at different locations are recorded using a twelve-channel digital temperature indicator.

A coil heater wounded over the evaporator section acts as the source of heat input. The heating element is made of Canthalon (80% Ni and 20% Cr). Teflon tape is wound around the coil to minimize the heat loss between the coil and the heat pipe.

In the experimental setup different working fluids viz., acetone, ethanol, methanol and water are used. The working fluid is filled into the heat pipe using a syringe pump.

2.2 Experimental Procedure

1. The requisite amount of working fluid is injected into the PHP by keeping one end of the non-return valve V1 open (Fig. 1) such that the fluid directly enters the evaporator section.
2. Due to the dominance of surface tension forces, the working fluid distributes into a train of liquid slugs and vapor plugs in the PHP.
3. The required heat input is adjusted and supplied through the power supply unit.
4. A fan is utilized for cooling the fluid in the condenser portion.
5. The device is made to work both in the horizontal and vertical orientations using four different working fluids viz. water, acetone, methanol and ethanol.
6. Experiments of transient nature are conducted and the temperatures are recorded at different locations using the digital temperature indicator. The experiments have been carried out till steady state is reached.

3 RESULTS AND DISCUSSION

Transient experiments have been reported with various working fluids i.e., acetone, ethanol, methanol and water and different temperature variations are recorded with respect to time. The experiments are conducted in the horizontal and vertical positions and have been extended till steady state is reached. In the vertical mode the setup was operated with bottom heating mode i.e. evaporator down and condenser up position.

3.1 Influence of Heat Input on Temperature

Fig. 2 shows the variation of evaporator wall temperature w.r.t time in the horizontal mode for different heat inputs when acetone is used as the working fluid. As the fluid movement starts only after some time of starting the experiment, the bare metallic part of the evaporator gets heated initially. As a result, a rapid increase in the evaporator wall temperature was observed up to 120 seconds. After 120 seconds, the increase in the evaporator wall temperature was slowed down due to the movement of the fluid. Fig. 2 clearly witnesses that the steady state evaporator wall temperature is almost same at higher heat inputs of 14 W and 15 W and slightly low at lower heat inputs of 10 W and 12 W. The time taken to attain the steady state is relatively less at higher heat inputs.

Fig. 3 shows that the condenser wall temperature increases with increase in heat input and is lower at lower heat inputs. Since the fluid movement is observed only after certain time of starting the experiments, the condenser wall temperature was almost same initially and increases only after 120 seconds in case of all heat inputs owing to thermal lag from evaporator section to condenser section.
Even in the vertical mode, similar trends were observed with respect to evaporator wall temperature at the same heat inputs (Fig. 4). It is clearly evident from Fig 2 and 4 that the system is rather fast at all studied heat inputs in the horizontal mode whereas more time is taken in the vertical mode to reach the steady state.

### 3.2 Influence of Working Fluid on Temperature

A typical transient plot showing the variation of evaporator wall temperature w.r.t. time in the horizontal mode for various fluids at 15 W heat input is presented in Fig. 5. Since evaporator wall temperature depends on the boiling point of the fluid, accordingly it is higher for ethanol and lower for acetone. It is also evident from the graph that acetone take less time to attain the steady state compared to the other two fluids.

![Fig. 5 Effect of working fluid on evaporator temperature at Q = 15 W in horizontal mode](image)

The discrepancy in temperature difference between evaporator and condenser w.r.t. time for distinctive fluids at a heat input of 15 W in the horizontal mode of PHP is shown in Fig. 7. The temperature discrepancy between evaporator and condenser witnessed from the figure at steady state is around 21º C for acetone and 48º C for ethanol. Considerably less temperature difference is observed for acetone when compared to other fluids.

![Fig. 7 Effect of working fluid on temperature difference between evaporator and condenser at Q = 15 W in horizontal mode](image)

Fig. 6 shows a similar plot for 15W heat transport capacity, but for condenser wall temperature. It is observed that the condenser wall temperature is lower for ethanol while it is higher for acetone and methanol. This indicates that the movement of the fluid is faster in acetone and intermittent in case of ethanol. The movement of the fluid is faster in case of acetone due to its lower latent heat value. Also the time taken to attain the steady state is less for acetone and ethanol compared to methanol.

Fig. 8 shows the temperature difference between evaporator and condenser at steady state for the same heat input of 15 W with different working fluids in both horizontal and vertical modes of operation of PHP. From the graph it can be concluded that the acetone produces lower temperature difference compared to other fluids in both horizontal and vertical modes. Thus acetone can be taken as the more suitable working fluid for PHP operation.
Fig. 8 Effect of working fluid and orientation on temperature difference between evaporator and condenser at steady state and at Q = 15 W

Fig. 9 Effect of heat input on evaporator temperature for water in horizontal mode

Fig. 10 Effect of heat input on condenser temperature for water in horizontal mode

Experiments are conducted with water in the heat input range of 13 W to 20 W as no fluid movement was observed below the value of 13 W for water. Evaporator and condenser wall temperature plots for water at various heat inputs are shown in Fig. 9 and 3.10. From Fig. 9 it is clear that the variation in evaporator wall temperature w.r.t. time is almost same at distinct heat inputs considered whereas Fig. 10 shows an increase in condenser wall temperature with increase in heat input.

3.3 Influence of Working Fluid on Thermal Resistance

Finally the effectiveness of the heat pipe is indirectly brought in terms of thermal resistance and convective heat transfer co-efficient.

The overall thermal resistance values are evaluated at different heat inputs. A trend of decrement in thermal resistance is noticed from Fig. 11 with the increase in heat input for acetone, methanol and ethanol. Acetone has lower values of thermal resistance at all heat inputs compared to the other fluids. This is due to prevalence of lower temperature discrepancy between the evaporator and condenser sections in case of acetone.

Fig. 11 Effect of working fluid on thermal resistance in horizontal mode

Fig. 12 Effect of orientation on thermal resistance plot for acetone

Fig. 13 Effect of orientation and working fluid on thermal resistance at Q = 15 W

Fig. 12 shows the thermal resistance variation at different heat inputs for acetone both in horizontal and vertical modes. In spite of decreases in thermal resistance both in horizontal and vertical modes with the increase in heat input, higher value of thermal resistance is observed in vertical mode compared to the horizontal mode. This higher value of thermal resistance in the vertical mode is due to the action of gravity and slower and intermittent movement of the fluid observed during the vertical operation of PHP.
Fig. 13 shows the thermal resistance for different working fluids at steady state in both horizontal and vertical modes of operation of PHP. From the graph it can be seen that all the working fluids have lower thermal resistance in the horizontal mode compared to vertical mode. Thus the horizontal mode enables smooth flow of working fluid with higher heat transfer compared to vertical mode.

3.4 Influence of Working Fluid on Heat Transfer Coefficient

The pattern of heat transfer co-efficient for distinct working fluids is described in Fig. 14 with varying heat input in the horizontal mode. Acetone and Methanol shows higher values of heat transfer coefficient at all heat inputs compared to ethanol. This higher value of heat transfer coefficient for acetone and methanol are due to their lower thermal resistance as observed in Fig. 11. It can also be observed from the figure that the increase in heat transfer coefficient with heat input for ethanol is only marginal compared to acetone and methanol.

3.5 Influence of Working Fluid on Bubble Velocity

The variation of speed of the bubble with respect to heat input for different working fluids is shown in Fig. 17. From the figure it is evident that acetone has higher bubble speed irrespective of heat input, whereas ethanol has lower bubble speed. This higher value of speed is due to lower value of latent heat in case of acetone. Further it is interesting to note that the speed of the bubble in case of water is lowest at all heat inputs (Fig. 18).
4 CONCLUSIONS

The following conclusions have been drawn from the experimental conducted on a single loop PHP under air cooling arrangement study.

- The evaporator and condenser wall temperature increases with increase in heat input.
- The fluid movement is faster in horizontal mode at all the heat inputs studied.
- Compared to any other fluids, the time taken to attain the steady state for Acetone is less.
- The thermal resistance of PHP decreases with the increase in heat input in the case of all working fluids.
- Among all the working fluids used, Acetone exhibits lower thermal resistance values.
- The heat transfer coefficient of PHP increases with the increase in heat input in the case of all working fluids.
- Acetone exhibits higher heat transfer coefficient at steady state compared to other working fluids.
- Higher bubble speed is observed for acetone due to its lower latent heat value.
- Slug flow is witnessed by the working fluid at lower input and transition takes place to semi annular flow at higher heat inputs.

REFERENCES