EXPERIMENTAL INVESTIGATIONS OF FLAT PLATE OSCILLATING HEAT PIPE

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1. Abstract

Heat transfer management is present issue which is progressively increasing importance in line with technology. Effective thermal management is needed to serve to the present trends of power & flux level of upcoming micro devices. This research describes the experimental investigations of the flat plate oscillating heat pipe (FP-OHP) as new entry in the family of two phase heat transfer system. As a unique heat transfer device, flat plate oscillating heat pipe has been considered have a smart prospect due to its advantages: simple structure, low cost, and outstanding heat transfer capability. A number of theoretical studies and experimental investigations have been carried out on the closed loop flat plate oscillating heat pipe (CLFP-OHP) in the past decades. However, due to the complex working mechanism of CLFP-OHP, the effect of operational parameters, working fluids and geometrical parameters on the thermal performance CLFP-OHP has not been completely revealed so far. As per available literature, there is a need of data which shows the effect of operational parameters, working fluids and geometrical parameters on the thermal performance of CLFP-OHP. Also, limited investigations are reported for the application of CLFP-OHP in different electronic components. Therefore, based on research gap, above mentioned aspects were studied independently through the experimentations followed by application. The experimental methodology has been described, which includes outline of the experiments, experimental setup, temperature measurements and flow visualization of CLFP-OHP. In the present research, the CLFP-OHP was investigated with different operational parameters (charge ratio, orientation, and heat load) working fluids (acetone, DI water, ethanol, and methanol) and geometrical parameters (channel size and shape). To achieve the investigations, four different experimental series have been organized, developed, and tested. The thesis gives detailed discussion on various parameters. In order to investigate the effect of these parameters, parallel channels were machined onto the pure copper plate to form CLFP-OHP. First, influence of operational parameters on the thermal performance of CLFP-OHP has been investigated. FP-OHP with different charge ratios from 20% to 70% and orientations such as vertical (90°), 60°, 30° and horizontal (0°) have been used to study the effect of operational parameters. It was observed that the enough charge ratio is required to sustain the oscillation motion of working fluid in CLFP-OHP. The lowest thermal resistance is achieved for 60%

charge ratio for CLFP-OHP. It can be found that the orientation other than the vertical (90°), the thermal resistance is always higher, indicating poor performance of CLFP-OHP in other orientation as compare to vertical orientation. Second, effect of working fluids on CLFP-OHP performance was studied. Four different working fluids such as acetone, DI water, ethanol and methanol were used. The best thermal performance was observed by acetone with charge ratio of 60% in the vertical orientation. Third, influence of channel size and channel shape on CLFP-OHP performance was investigated. The objective of this investigation is to understand the influence of channel size with square cross section of 2×2 mm^2, 5×5 mm^2 and influence of channel shape with square to circular on the thermal performance of CLFP-OHP. It is noted that the smaller channel size 2×2 mm^2 is more favorable to CLFP-OHP. It is concluded that when the working fluid charged in square channel CLFP-OHP, the two phase heat transfer is definitely much higher than for the equivalent circular channel. The CLFP-OHP application on electronics component such as MOSFET (metal oxide semiconductor field effect transistor) was identified to improve thermal management of electronics systems. The objective of this application is to improve dissipation of heat produced by MOSFET during operation and to decrease thermal resistance of the same by providing cooling device using CLFP-OHP. The MOSFET cooling device has been developed with CLFP-OHP. With the development achieved so far, the future for the CLFP-OHP seems quite promising.

2. Brief description on the state of the art of the research topic

As modern systems become smaller and more densely packed, the demands for effective heat transfer devices increases. All new design coming up in the field is with higher power dissipation levels. In addition, total power is not the only problem; power per unit area (heat density) is growing in to it. Moore et al. [1] suggested that the semiconductor transistor density doubles in every 18 months. These advancements are directly related to the power dissipation. Due to more access to computers, consumer electronics, internet and telecommunication power dissipation management has become a challenge. To answers the future issues and projections, technological development is likely to be the only savior. In the way of ongoing development, the requirements from the heat transfer devices are low thermal resistance, high heat transfer capabilities, compatibility, reliability, miniaturization, and low cost. With these requirements in mind, new heat transfer devices are continuously being developed. Continued stringent requirements led to the development of two phase heat transfer device such as heat pipes. The different heat pipes have played a significant role in many applications. The flat plate oscillating heat pipe (FP-OHP) is unique concept patented by Akachi [2, 3], which seems to meet all the requirements. The FP-OHPs have already found applications in electronic components due to its unique characteristics coupled with low cost [4]. Although the FP-OHP is a subclass of the family of heat pipes, the working mechanism is definitely unique. Oscillating heat pipe exists as continues capillary tube arrange in a serpentine manner, namely tubular oscillating heat pipe (T-OHP).

Fig. 1 closed loop flat plate OHP

In recent time [5-7], the closed loop flat plate oscillating heat pipe (CLFP-OHP) as shown in Fig.1 is developed to overcome the limitations of the T-OHP (limited application, low heat dissipation in space).

The CLFP-OHP is made on the different materials. The micro channel has been machined on to the base metal plate. The thin sheet is used to cover the CLFP-OHP. The hydraulic radius of the channel is made small to allow working fluid to oscillate in CLFP-OHP. The CLFP-OHP consists of evaporator, condenser and adiabatic sections. The working fluid is partially charged in CLFP-OHP followed by heat load at evaporator section. This results in the growth of vapor plugs in the evaporator section. Enlarged vapor plugs push the liquid slugs towards the condenser section. The condenser section cools down the vapor plugs, and vapor pressure reduces. The growth and contraction of vapor plugs result in an oscillating flow of liquid slugs and vapor plugs in CLFP-OHP. The heat transfer is a kind of sensible heat form within liquid slugs and latent heat form in vapor plugs [8-11]. Currently, CLFP-OHP has growing research interest for improving the thermal performance of various heat generating systems. The thermal performance of the CLFP-OHP is greatly affected by the various parameters, which can be categorized into three groups: (1) operational parameters [12-15]; such as charge ratio, orientation and heat load, etc. (2) working fluids [16-18] and (3) geometrical parameters; size of channel and shape of channel, etc. [10, 19-21].

The charge ratio is defined as the ratio of charged working fluid volume to the total volume of the CLFP-OHP. The charge ratio has a meaningful effect on the heat transfer performance of the CLFP-OHP. The amount of liquid slugs and vapor plugs depends on the charge ratio.

The orientation has significant influence on the thermal performance of CLFP-OHP. When the orientation of CLFP-OHP is changing, the influence of the orientation on thermal performance is very obvious. The input heat load is also very important operational parameter for the thermal performance of the CLFP-OHP. The effect of the heat load on CLFP-OHP is mainly embodied at two aspects: the startup heat load and the relationship between the heat load and thermal performance of the CLFP-OHP. Among the numerous methods to improve the thermal performance of CLFP-OHP, the most effective one is to select an excellent working fluid [5]. The physical properties of the working fluid, such as wettability, latent heat, surface tension, specific heat, viscosity etc. have profound effects on the thermal performance of CLFP-OHP [5]. The different response of CLFP-OHP with different working fluids is the results of effects of various thermo-physical properties of the working fluids. It is necessary to know the effect of individual working fluids on the thermal performance of CLFP-OHP. It has been observed that geometrical parameters can affect the thermal performance of the CLFP-OHP. However, the thermal performance of the CLFP-OHP was not investigated in detail according to channel size. The size of channel is an important parameter which greatly affects the transition of flow patterns and the distribution of working fluid, especially when the shape of the channel is not circular, such as square and triangular, the effect of the corners on oscillatory motion of working fluid is more obvious [5]. The optimum conditions of the operational parameters, such as the charge ratio and heat load, tend to vary according to the channel size [5]. The shape of the channel is the essential factor that should be considered during designing CLFP-OHP. As so far, the researches on the effect of effect of shape of channel on CLFP-OHP are very limited. But its positive impacts on the heat transfer performance of CLFP-OHPs are attracting more attention.

3. Definition of the Problem

CLFP-OHP is a recent advancement in the area of thermal management. Researchers have reported heat transfer capacity of CLFP-OHP. The oscillation motion of working fluid seems to be dependent on various parameters. A completely new research work is required to understand the effect of various parameters on the thermal performance of CLFP-OHP. This research work aims to understand the effect of the various parameters on the thermal performance of CLFP-OHP.

4. Objective and Scope of work

The existing literature of CLFP-OHP covers its capacity to transfer higher loads, while the influences of various parameters are not reported so far. Hence, the effect of operational parameters, working fluids, geometrical parameters, and application of CLFP-OHP still need to be explored to understand the working mechanism of CLFP-OHP. The main objective of present research work is to investigate the above parameters on thermal performance of CLFP-OHP. The selection of the CLFP-OHP parameters play important role in effective thermal management. Based on research gap the objectives of the proposed work as follows:

- To investigate influence of operational parameters such as charge ratio, orientation, and heat load on the thermal performance of CLFP-OHP.
- To understand the startup characteristics of different working fluids such as DI water, acetone, methanol and ethanol.
- To know the effect of different working fluids such as DI water, acetone, methanol and ethanol on the thermal performance of CLFP-OHP
- To find the effect of geometrical parameters on thermal performance of CLFP-OHP.
- To develop the application of CLFP-OHP on MOSFET (Metal Oxide Semiconductor Field Effect transistor)

To address these objectives the scope of the present work is identified as follows:

A. Effect of operational parameters

These parameters are important for CLFP-OHP and that is reflected in resulting better thermal performance. The effect of charge ratio, orientation and heat load is studies in the present work.

B. Effect of working fluids

The working fluid decides the initial thermal performance of CLFP-OHP. The selection of best working fluid for the CLFP-OHP is essential of effective thermal performance. Therefore, different types of working fluid will be investigated to understand the effect of working fluid on thermal performance of CLFP-OHP.

C. Effect of geometrical parameters

The geometrical parameter consists of the size of the channel and shape of the channel. The geometrical parameter governs the circulation of the working fluid in the CLFP-OHP. Hence, the different size of the channel and shape of the channel are investigated.

D. CLFP-OHP heat transfer device for MOSFET (Metal Oxide Semiconductor Field Effect transistor)

The MOSFET (Metal Oxide Semiconductor Field Effect transistor) heat transfer device using CLFP-OHP will be investigated. Also, the comparison of conventional heat transfer device with CLFP-OHP heat transfer device will be elaborated.

5. Original contribution by the thesis.

The unique CLFP-OHP test section is developed to investigate the effect of operational parameters on the thermal performance of CLFP-OHP. The appropriate set of operational parameters obtained and same can be recommended to develop CLFP-OHP. Different working fluid such as DI water, acetone, methanol, and ethanol were investigated to understand the startup characteristics and thermal performance of different working fluid. Working fluid is the first stage of development of CLFP-OHP that decides the initial condition of the process. Hence, startup characteristics and thermal performance were understood for the better understanding of the CLFP-OHP. The channel size and the channel shape were used to find the effect of geometrical parameters on the thermal performance of CLFP-OHP. The 2×2 mm^2 channel size and square channel are recommended among the 5×5 mm^2 channel size and circular channel shape in the CLFP-OHP to obtain the best thermal performance. The CLFP-OHP MOSFET cooling device has proved an effective method to obtain enhanced heat transfer from MOSFETs. Use of CLFP-OHP in MOSFET cooling resulted in reduction of the thermal resistance of device. This CLFP-OHP MOSFET cooling device approach has enabled CLFP-OHP application in electronic components, which resulted into improvement in the thermal management of electronic component. The experimental procedure is developed for evaluating important parameters and selecting working fluid to achieve best thermal performance. These methodologies can be applied at initial stage where the manufactures want to use CLFP-OHP in thermal management of electronic device. The CLFP-OHP MOSFET cooling device has demonstrated significant reduction in the thermal resistance and enhancement in the thermal performance.

6. Methodology of Research and Results

6.1 Methodology of Research

Four series of CLFP-OHP experiments were conducted in the present investigations.

In series 1, CLFP-OHP experiments were conducted for different operational parameters such as charge ratio and orientation from 10 to 120 W heat loads to find influence of these parameters on the thermal performance of the CLFP-OHP. The list of operational parameters is tabulated in table 1. The CLFP-OHP geometry and working fluid were kept same for all the experiments in series 1.

Table 1 Series 1 CLFP-OHP Operational Parameters

Type of Study	Sample ID	Charge ratio (%)	Orientation	Heat Load	Channel Profile	Channel Size (mm^2)
Effect of charge Ratio	F1	20 30 40 50 60 70	Vertical (90°)	10-120	Square	2 × 2
Effect of orientation	F1	60	Vertical (90°) Inclined (60°) Inclined (30°) Horizontal	10-120	Square	2 × 2
Effect of charge ratio with varying orientation for a given heat load	F1	40 50 60 70	Vertical (90°) Inclined (60°) Inclined (30°) Horizontal	100	Square	2 × 2

Series 2 experiments covered the effect of working fluids on thermal performance of CLFP-OHP. The detail of working fluid is presented in table 2.

Table 2 Series 2 CLFP-OHP Working Fluid

Type of Study	Sample ID	Working fluid	Charge ratio	Orientation	Channel Profile	Channel Size
Effect of working fluid	F1	DI Water Ethanol Methanol Acetone	60	vertical	Square	2 × 2

In series 3, the effect of geometrical parameters such as size of the channel and shape of the channel is investigated. Operational parameters such as charge ratio and orientation were kept constant in series 2 and 3. The list of geometrical parameters is tabulated in table 3.

Table 3 Series 3 CLFP-OHP Geometrical Parameters

Type of Study	Sample ID	Channel Size	Working fluid	Charge ratio	Orientation	Channel Profile
Effect of channel size	F1	2 × 2	Acetone	60	Vertical	Square
	F2	5 × 5				
Type of Study	**Sample ID**	**Channel Shape**	**Working fluid**	**Charge ratio**	**Orientation**	**Hydraulic radius**
Effect of channel shape	F1	Square	Acetone	60	Vertical	0.61
	F3	Circular				

In series 4, application of CLFP-OHP was tested on MOSFET (Metal Oxide Semiconductor Field Effect transistor). Operational parameters and geometrical parameters both were kept same in series 4.

6.1.1. Development of CLFP-OHP test section

The CLFP-OHP test section was made of pure copper with parallel channel machined by the vertical milling machine. The hydraulic radius of 2 × 2 mm^2 square channel is within range of calculated maximum hydraulic radius of the channel. The evaporator section, condenser section, and adiabatic section was 30 × 70 mm^2 respectively. Copper charge tube was used to charge the working fluid in the CLFP-OHP. The CLFP-OHP test section is sealed with transparent acrylic sheet. The holes are machined on copper heating block to house the 3 cartridge heaters (Ø6.5 × 60 mm) to form evaporator section of CLFP-OHP. Each cartridge heater contains capacity of 100 W. The thermal paste (Omegatherm) was applied to the circumferential gaps between the heating block and cartridge heaters to reduce the contact resistance. The evaporator section of CLFP-OHP was heated by copper heating block. The heat sink has inlet and outlet connection for water. The condenser section was in direct contact with a copper cooling block which was cooled by a constant-temperature cooling source. The CLFP-OHP test section was fabricated by a vertical milling machine. The overall size of copper plate is 93 mm × 70 mm × 5 mm. The CLFP-OHP test section was then sealed from top with an acrylic plate using a fasteners and silicone gel. The transparent acrylic plate of 3 mm was used for flow visualization of working fluid in the heat pipe.

6.1.2 Experimental apparatus

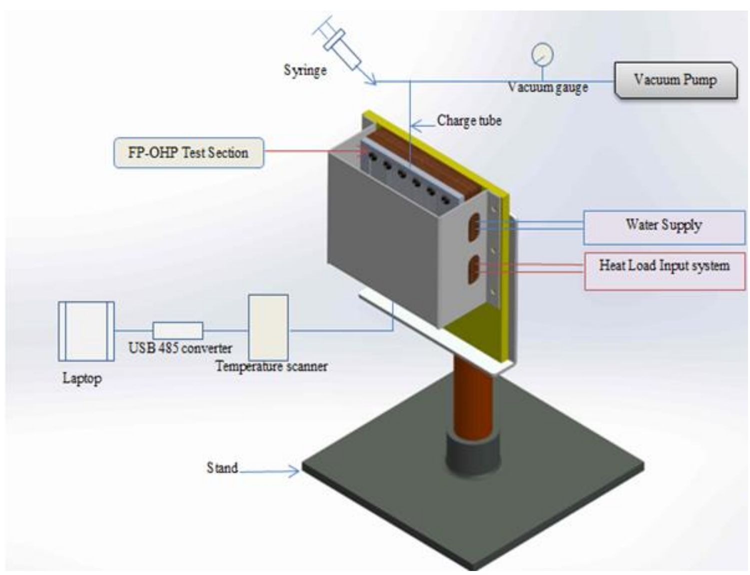

Fig.2 Experiment set up

The experimental setup is shown in Fig.2. It consists of a CLFP-OHP test section, heat load input system, water supply, temperature scanner, USB 485 coveter, laptop, and stand. Heat load input system is used to control heat load to the evaporator section by adjusting voltage and current to the cartridge heaters. Total six K-Type thermocouples of ± 0.5 °C accuracy were used to measure temperature responses. The thermocouples are attached on both sides of CLFP-OHP to measure the temperature at various locations. For all temperature measurements, K type of thermocouple of diameter 1.5 × 90 mm long by Senswell make were used. Two thermocouples were used to measure the evaporator section temperature; two thermocouples each were placed in the condenser section and on adiabatic section to measure the average temperature respectively. The CLFP-OHP test section was mounted on a tiltable stand. A filling valve was connected to the charged tube to charge the working fluid. MASIBUS make data scanner used to record temperature data to the laptop through USB 485 converter. The temperature scanner has an accuracy of 0.1 %. The temperature data logging to the laptop was interfaced through by MASIBUS software. To charge the CLFP-OHP to a specified charge ratio, the test section was vacuumed to a pressure of 0.01mbar, by using a mechanical rotary vacuum pump. Then after, a specified amount of working fluid charged into the CLFP-OHP by using a medical syringe. The heat load to the evaporator section was adjusted after the CLFP-OHP test section reached to steady state condition. A constant heat load was applied to evaporator section via copper heating block and the condenser section was cooled via copper water cooling block with the inlet water temperature at 25°C (±0.1°C). The flow visualization of working fluid was carried out video camera. After confirming the constant temperature of all the K-Type thermocouples mounted in the CLFP-OHP test section, the heat load input system switched on and desire heat load was applied through variable transformer. The experiment procedure was repeated for all investigations.

7 Results and Discussion

7.1 Effect of operational parameters

7.1.1 Effect of charge ratio

The CLFP-OHP was charged with different charge ratios from 20% to 70% in steps of 10% in vertical orientation. In present work, an effort has been made to resolve the critical charge ratio of acetone for CLFP-OHP. The CLFP-OHP failed to start-up when it was charged at the lowest charge ratio up to 30%. The phenomenon of dry-out was observed in CLFP-OHP for 20% and 30%. It is found that the stronger oscillation motion of liquid slugs and vapor plugs in the CLFP-OHP at 60% charge ratio. The CLFP-OHP with a charge ratio of 40% does not decrease the thermal resistance after 90 W as compared to the other charge ratio. These results indicate a poor performance at 40% charge ratio after 90 W. It reveals that enough charge ratio is required to sustain the oscillation motion in CLFP-OHP. It was found that the CLFP-OHP is working when the charge ratio above 50%. The 70% charge ratio gives better performance as compared to other charge ratios, except 60% charge ratio. The best thermal performance was observed for 60% charge ratio at 100 W heat loads. The lowest thermal resistance of 0.39 °C/W is achieved for 60% charge ratio.

7.1.2 Effect of orientation

The heat transfer performance of CLFP-OHP is very noticeable when the orientation is changed from vertical orientation (90°). In this investigation, four orientations were tested from vertical (90°) to horizontal (0°) in steps of (30°). The charge ratio of 60% is used in this study, which has lower thermal resistance as compared to other charge ratios. Experimental results exhibited better performance in the vertical orientation. In the vertical orientation, the liquid slugs and vapor plugs oscillated more during operation and resulted in stronger oscillation motion of acetone in CLFP-OHP. At 100 W heat loads, thermal resistance of vertical orientation (90°) was 35 % lower than the 60° orientation and 62% lower than the 30° orientation.

7.1.3 Effect of charge ratio with varying orientation

The thermal performance of CLFP-OHP can be varying when the working conditions are different with charge ratios and heat loads. An effort has been made to know the effect of charge ratio with varying orientation for 100 W. The CLFP-OHP was tested with charge ratios 40% to 70 % in steps of 10%, with orientations changed starting from vertical orientation (90°) in the sequence of 90°-60°-30°-0°. For each orientation 20 min was allowed so as to steady state condition before moving over to the new orientation. It can be inferred that the thermal resistance of 60% charge ratio was the most favorable across all the orientations.

7.2 Effect of Working fluids

7.2.1. Startup characteristics of CLFP-OHP

The influence of working fluids on the startup characteristics and on the thermal performance is still untouched. In this investigation, 60% charge ratio and vertical orientation of the CLFP-OHP was used. The 60% charge ratio and vertical orientation were found to be the best operating parameters in previous investigations. Startup characteristics involve the beginning of two-phase flow for the estimation of the thermal performance of the CLFP-OHP at lower heat load. Acetone, methanol, ethanol and DI water are used as pure fluids. Input heat load is not observed sufficient for working fluid to generate vapor bubbles and hence this zone is considered as oscillation free zone. The smallest zone width is observed for acetone and largest for DI water. For DI water and ethanol, this heat load is not sufficient to generate vapor bubbles until it reaches 50 W and 40 W respectively. Therefore, water has delayed startup time, highest startup heat load compared to other working fluids. Specific heat of acetone, ethanol and methanol are nearer to each other. But ethanol has 78 °C boiling temperature which is higher than methanol and acetone. Therefore, it requires more heat load to start the oscillation. So, ethanol has delayed startup time and higher heat load compared to acetone and methanol. Acetone has lower viscosity is favorable due to small shearing force leads to minimum flow resistance. Therefore, acetone has less startup time compared to methanol.

7.2.2 Thermal performance of CLFP-OHP for different working fluids

The thermal performance of CLFP-OHP with different working fluids is investigated at heat load 10-120 W. With the increase in heat load from startup heat load, the thermal resistance of acetone and methanol is rapidly decreased compared to DI Water and ethanol. The same trends were observed for DI water and methanol when the heat load is increased beyond 50 W. The lowest thermal resistance for acetone was calculated as 0.39 (°C/W) at 100 W and for DI water as 0.65 (°C/W) at 140 W. It was observed that higher the temperature difference between the evaporator and condenser, lower was the thermal resistance. Hence, thermal performance was observed to increase with the increase in heat load irrespective of working fluids. The increase in heat load supports the operating parameters which increase oscillating motion in square channel CLFP-OHP. Higher the oscillation motion, lower will be the CLFP-OHPs thermal resistance. The thermo-physical properties of acetone; lower boiling point, lower dynamic viscosity, higher dP/dT ratio, make it more suitable working fluid for effective heat transfer as compared to other working fluids. The dry-out condition was not observed for given heat load and 60% charge ratio for all the working fluids. It is concluded that thermal resistance is observed lower for acetone compared to all other fluids due to the suitability of its thermo-physical properties to initiate oscillatory motion in CLFP-OHP.

7.3 Effect of geometrical parameters

7.3.1 Effect of channel size

The objective of this investigation is to understand the influence of channel size on thermal resistance of CLFP-OHP with square cross section of 2×2 mm^2 and 5 x 5 mm^2. The thermal resistance of 5 x 5 mm^2 channels showed higher value at the heat load of 100 W because the pressure fluctuation at evaporator and condenser sections became small with the flow types change from more oscillation to less oscillation of liquid slugs and vapor plugs. At the 5 x 5 mm^2 square channels, the heat transfer is decreased as compared to 2 × 2 mm^2 square channels due to insufficient heat load with 5 x 5 mm^2 square channels. At the heat load of 10 W, oscillation motion occurred relatively early with 2 × 2 mm^2 square channel sizes. The thermal resistances were the lowest at the 2 × 2 mm^2 square channels due to the increased oscillation motion and decreased working fluid resistance. It is noted that the two phase flow of working fluid plays an important role to enhance the heat transfer in CLFP-OHPs attributed by small channel sizes.

7.3.2. Effect of channel shape

The effect of different channel shapes on the thermal resistance of CLFP-OHP is analyzed. The oscillating motion of working fluid in CLFP-OHP depends on the channel shapes. In order to understand the effect of channel shape, the hydraulic radiuses of square and circular shape are kept same. The square channel CLFP-OHP obtained up to 35% lower thermal performance in terms of thermal resistance than the circular channel. It is noted that the square channel CLFP-OHP can manage higher heat load than the circular channel CLFP-OHP. This is due to fact that the square channel shapes allowed the working fluid to pass along the channels. It is postulated that when the working fluid charged in square channel CLFP-OHP, the two phase heat transfer is definitely much higher than for the equivalent CLFP-OHPs circular channel. It is noted that the CLFP-OHP with square channel shape has an advantage in terms of oscillation motion of working fluid over the circular channel shape.

7.3.3 Thermal conductivity of CLFP-OHP

A new thermal performance indicator, CLFP-OHP thermal conductivity is used in assessment of heat transfer capability of device. The thermal conductivity of CLFP-OHP increases with the increasing heat loads at heat source section. The reason is that the heat load is proportional to thermal conductivity of the CLFP-OHP, and the temperature difference between evaporator and condenser section. The thermal conductivity of CLFP-OHP is between 867 and 3205 W/m °C. For comparison, the thermal conductivity of CLFP-OHP is increased by factor of 8.7% in comparison with that of pure copper (401 W/m °C). It is noted that the thermal conductivity of the CLFP-OHP is more than that of high purity copper, which is attributed to oscillation motion of liquid slugs and vapor plugs in the CLFP-OHP between the evaporator and condenser sections.

7.4 Thermal performance of CLFP-OHP MOSFET cooling device

The CLFP-OHP MOSFET cooling device was developed to study the thermal performance of CLFP-OHP application. The temperature difference between evaporator and condenser sections indicating oscillation motion of working fluid in device. The heat load accumulation made the saturation pressure high enough to drive the vapor plugs and liquid slugs oscillation motion, and the acetone from the bottom was pushed to the condenser section. It observed that the thermal resistance of device decreases with increase in the heat load. Hence the thermal resistance of CLFP-OHP MOSFET cooling device should easily surpass the traditional cooling heat sink device.

8. Achievements with respect to objectives

Objectives	Publication/Patent
To identify research gap through literature review	Frontiers in Heat and Mass Transfer (I.F.1.24)
To investigate effect of operational parameters	Journal of Heat Transfer, ASME (I.F.=1.47)
To understand influence of working fluids	Experimental Heat Transfer, Taylor & Francis Group (I.F.=2.00)
To find effect of geometrical parameters	Journal of Brazilian Society of Mechanical sciences and Engineering, Springer (I.F.=1.743)
To develop the CLFP-OHP application	Patent

9. Recognition during research work

Recognition	Journal Name	Publication	Impact Factor
Reviewer	International journal of Heat and Mass Transfer	Elsevier	4.346
Reviewer	Journal of Low Temperature Physics	Springer	1.491
Grant Received for Patent			
Grant type	**Grant number**	**Amount**	**Date**
SSIP-GTU	201921003211	25000	25/1/2019

10. Conclusion

The major conclusions of this thesis can be summarized as follows:

- The operational parameters such as charge ratio, orientation and heat load exhibited dependence on the thermal performance of CLFP-OHP.
- The CLFP-OHP failed to start-up when it was charged at the lowest charge ratio up to 30%. The phenomenon of dry-out was observed in CLFP-OHP for 20% and 30%. Also, the results indicate a poor performance at 40% charge ratio after 90 W. This is due to the fact that there are too many vapor plugs in the channels and it is very hard to maintain the stable oscillation.
- It was found that the CLFP-OHP is working when the charge ratio above 50%. The best thermal performance was observed for 60% charge ratio at 100 W heat loads. The lowest thermal resistance of 0.39 °C/W is achieved for 60% charge ratio.
- Experimental results exhibited better performance in the vertical orientation. In the vertical orientation, the liquid slugs and vapor plugs oscillated more during operation and resulted in stronger oscillation motion of acetone in CLFP-OHP.
- It was observed early oscillation motion in acetone and methanol as compared to DI water and ethanol. This is due to that the (dP/dT) value of acetone and methanol is high as compared to water and ethanol. The high value of (dP/dT) ratio reveals that a small change in temperature can generate a large pressure difference. Therefore, DI water has delayed startup time as compared other working fluid.
- The optimum channel shape and channel size of CLFP-OHP were square and 2×2 mm^2, respectively. With the heat load of 100 W, the lowest thermal resistance was achieved to be 0.39 °C/W. The flow pattern of liquid slugs and vapor plugs determined the thermal performance of FP-OHP which improved with the 2×2 mm^2 square channels.
- The MOSFET cooling device is able to transfer the heat with acetone as working fluid in vertical orientation through natural convection.

10. Publications

International Journal Publication: Springer, Taylor & Francis Group, ASME and Scopus based Journal

[1] K. Mehta, N. Mehta, and V. Patel, "Experimental investigation of the thermal performance of closed loop flat plate oscillating heat pipe," *Experimental Heat Transfer,* pp. 1-19, 2020. 10.1080/08916152.2020.1718802

[2] K. Mehta, N. Mehta, and V. Patel, "Influence of the channel profile on the thermal resistance of closed-loop flat-plate oscillating heat pipe," *Journal of the Brazilian Society of Mechanical Sciences and Engineering,* vol. 42, p. 123, 2020/02/15 2020. 10.1007/s40430-020-2213-x

[3] K. Mehta, N. Mehta, and V. Patel, "Effect of Operational Parameters on the Thermal Performance of Flat Plate Oscillating Heat Pipe," *Journal of Heat Transfer,* vol. 141, pp. 121802-1-8, 2019. 10.1115/1.4044825

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Patent

[8] K. Mehta and N. Mehta, "MOSFET cooling device with flatplate oscillating heat pipe," India Patent, 2019.

Conference Paper

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