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Operational characteristics of a miniature loop heat pipe with flat evaporator

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Abstract

This paper specifically addresses the thermal characteristics of the miniature Loop Heat Pipe (mLHP) with the flat disk shaped evaporator, 10 mm thick and 30 mm in diameter, for the thermal control of the compact electronic equipments. The loop was made of copper with nickel wick and water as the working fluid. Detailed study was conducted on the start-up reliability of the mLHP at high as well as low heat loads. It was found that the device was able to start-up at input power as low as 5 W, however the start-up time was very high at such heat loads. During the testing of mLHP under step and random power cycles, the thermal response presented by the loop to achieve steady state was very short. At low heat loads, thermal and hydraulic oscillations were observed throughout the loop. The amplitudes of these fluctuations were very high at condenser inlet and liquid line exit. It is expected that the extent and nature of the oscillations occurrence is dependent on the thermal and hydrodynamic conditions inside the compensation chamber. Overall, the effect of these oscillations on the thermal performance of the mLHP was not very significant. In the horizontal orientation, the device was able to transfer maximum heat load of 70 W with evaporator temperature below $100 \pm 5\,^{\circ}\mathrm{C}$ limit. The thermal resistance (R_{mLHP}) of the mLHP lies between 0.17 to $5.66\,^{\circ}\mathrm{C/W}$.

Keywords: Loop heat pipe; LHP; Heat transfer; Thermal performance; Miniature loop heat pipe; mLHP; Flat evaporator; Thermal control

1. Introduction

At present, different cooling alternatives [1] are available for the thermal management of the electronic devices. An optimum choice depends on the number of factors, to name few, thermal performance, reliability index, acoustic issues, cost of manufacturing, future potential and scope for miniaturization. In the domain of two-phase technology, a Loop Heat Pipe (LHP) [2] can be considered as one of the potential candidates for cooling compact electronics with high powered microprocessors. A LHP consists of an evaporator, with fine pored wick structure, and a condenser section connected with separate vapour and liquid flow lines. It uses latent heat of evaporation and condensation to transfer heat, and relies on the capillary pressure generated by the wick structure for the circulation of the working fluid around the loop. Different operational characteristics and the design architectures of LHPs have been studied by researchers [3] worldwide which have classified the unique features of these devices as high heat capacity, reliable operation at adverse tilts in gravity field and heat transfer over long distances.

LHPs are worldwide accepted as passive cooling devices in space applications [4]. Presently, these devices are being investigated to define their potential in the thermal control of the consumer based electronics [5,6]. Majority of these efforts are devoted to the design of the miniature loop heat pipes (mLHPs) which can be easily integrated inside the compact enclosure of the electronic equipment. Unlike conventional heat pipes, loop systems provide wide flexibility in the design of the evaporator and condenser sections. mLHP with the cylindrical [7, 8] as well as flat evaporators [9–12] have been developed and tested successfully. Flat evaporator can be considered as an optimum design for compact enclosures as it provide relatively more scope for design miniaturization. Similarly, depending on the heat removal conditions condensers of different design and

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Nomenclature

ΔP	Pressure difference	Pa	cap	capillary
R	Thermal resistance	°C/W	cond	condenser
T	Temperature	°C, K	cl	condenser line
V	Volume	m^3	eg	evaporator grooves
$Q^\bullet$	Applied heat load	W	evap	evaporator
x	Liquid fraction	%	g	gravity

Greek symbols

ε	Porosity	%	l	liquid

Subscripts

cc	compensation chamber
ll	liquid line
v	vapour
vl	vapour line
w	wick

shape like fin and tube type, concentric tube type, collector type and coil on plate type can be incorporated in the mLHP [13].

The research and development on the loop heat pipes is linked with the understanding and improvement of the low power start-up process, steady state performance and transient response of the device to different power cycles [14]. Start-up phenomenon in the LHP largely depends on the pre-start situation inside the loop. Depending on the pre-start-up liquid distribution inside the evaporator and compensation chamber, four different types of start-up behaviour can result [15]. It was established that start-up situation with ready liquid–vapour interface inside the evaporation section is the most favourable one whereas the condition when the liquid–vapour interface exists on the liquid absorbing face of the wick and the evaporation section is flooded with liquid is the most difficult and requires relatively large heat load density for successful start-up. Particularly, at very low heat loads the LHP presents start-up issues [16] due to the intensive heat flow from the evaporation zone to the compensation chamber. These start-up issues are more pronounced in the miniature LHP owing to the thin wick structure which increases the back heat flows (also called as heat leaks).

In the operating mode, the performance issues are mainly concern with the occurrence of the large vapour superheating and thermal oscillations phenomena in certain range of input power particularly at low heat load. In this case, the degree of superheat is determined by the temperature difference between evaporator and compensation chamber which is mainly dependent on applied heat load, vapour fraction inside compensation chamber, liquid charging ratio, physical and thermal characteristics of wick and working fluid. The thermal oscillations are characterised by the continuous fluctuations in the temperature at different locations of mLHP and thus inability of the evaporator to attain stable operating conditions. These oscillations are expected to result from the thermal and hydrodynamic interaction between the compensation chamber, condenser and evaporator section [17,18].

The main objective of the present study was to design and investigate the start-up phenomenon and steady state performance of the flat evaporator miniature loop heat pipe with copper body, nickel wick and water as working fluid. Copper–water combination is chosen for the present investigation due to the viability and acceptability of such a system for electronic cooling applications. The present research also endeavours to test the compatibility of the nickel water system for loop heat pipe applications. A miniature LHP with the flat disk shaped evaporator, 10 mm thick and 30 mm diameter, and fin and tube type condenser was developed. Temperature oscillations associated with the passive loop systems were also explored in detail.

2. Experimental prototype and test procedure

An experimental prototype of miniature LHP (mLHP) as shown in Fig. 1(a) was constructed for carrying out the present investigation. The evaporator was made in the shape of the flat disk with the active diameter of 30 mm and thickness of 10 mm. Such a shape of the evaporator is very optimum for the successful integration of the mLHP in the compact electronic equipments like notebooks which has a constraint on the maximum available thickness of the thermal device. There were fifteen longitudinal grooves machined on the inside of the evaporator active heated zone which behave as a vapour removal channels and also provide heat to the skeleton of the porous structure through conduction process. The evaporator was made from pure grade of copper that provide superior thermal conductivity (398 W/m K) and minimal heat spreading resistance from the source to the evaporator face. Fig. 1(b) illustrates the cross section of the evaporator assembly showing the location of the vapour channels, wick structure and integrated compensation chamber. For LHPs, the coupling of the evaporator and the compensation chamber in a single structure does not necessitate any pre start-up procedures for priming the capillary structure that are required in the capillary pumped loops. Sintered nickel wick of 3 mm thickness, 3–5 µm mean pore radius and 75% porosity provided the thermal as well as hydraulic linkage between the evaporation zone and the compensation chamber. Here, the evaporation zone is formed at the evaporating face of the wick including the interface of the wick with the internal wall of the heating zone. In order to avoid any bypass of vapour from the evaporation zone to the compensation chamber, an O-ring seal (Fig. 1(b)) was used around the wick. The compensation chamber basically covered the entire liquid absorbing face of the wick which guarantees continual wet-

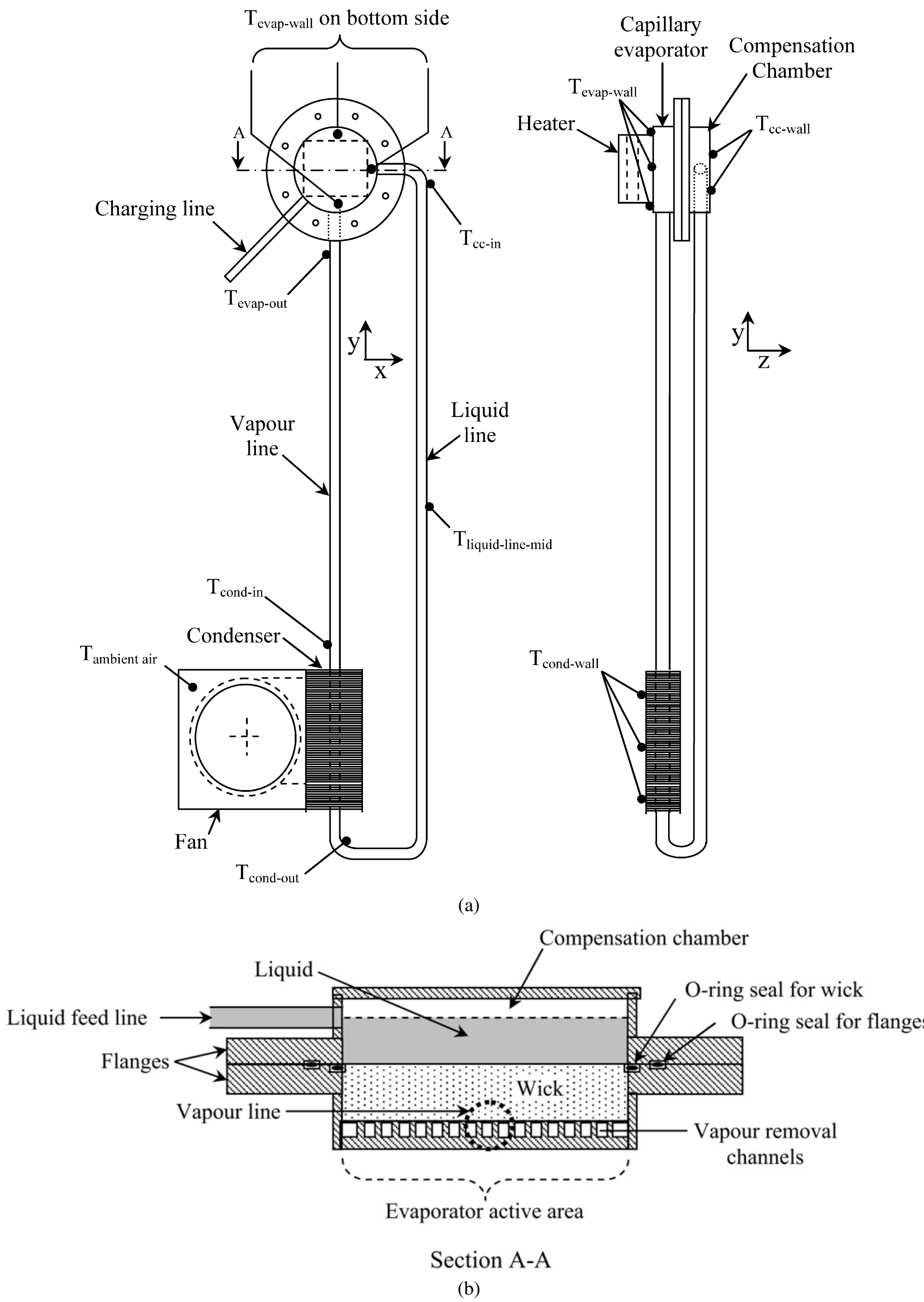


Fig. 1. Schematics of the experimental prototype and test set-up for the mLHP. (a) Top and side view of the mLHP showing the details of the evaporator and condenser section, and the placement of the thermocouple points. (b) Cross section of the mLHP evaporator.

ting of the wick matrix. In addition to this, the compensation chamber acts as a liquid reservoir and accommodates the extra liquid inventory displaced from the other parts of the loop during start-up and transient operating conditions. It receives liquid from the condenser via liquid line. As the compensation chamber is directly linked to the evaporator therefore it dictates the saturation conditions inside the loop to large extent [18,19]. At any given heat load, the saturation temperature of the compensation chamber is influenced by its heat exchange with the evaporator, ambient and incoming liquid from the condenser.

The mLHP condenser was fin-and-tube type with the total length of 50 mm and cross section of 10 mm × 20 mm for each fin. A centrifugal fan was used to dissipate heat from the condenser to the ambient by means of forced convection of air with temperature of $22 \pm 2\,^{\circ}\mathrm{C}$. The heat transport zone (i.e. vapour line) of the mLHP was 150 mm in length and 2 mm internal diameter. For the return of the condensate to the evaporator, a liquid return line with the total length of 290 and 2 mm internal diameter was used. For the purpose of minimising heat losses to the ambient, the loop was thermally insulated using fibre glass insulation. The mLHP body and transport lines were made from pure copper. Water was used as the heat transfer fluid. To avoid any consequences of Non Condensable Gases (NCGs) generation inside the mLHP, proper care was taken in cleaning the components before assembling and during charging of the loop with the working fluid. The cleaning procedure includes heating the components inside the furnace at 150 °C for 30 minutes followed by acid washing and soaking inside hot water. mLHP was hermetically sealed by brazing the joints and providing an O-ring seal between the evaporator flanges. For charging, the loop was first evacuated and then filled with the predetermined quantity of the distilled, deionised and degassed water stored under vacuum condition.

In order to test the thermal performance of the mLHP, a heat load simulator in the form of copper block with two embedded cartridge heater and active area of 25 mm $\times$ 25 mm was used. The active area of the heater was able to cover most of the heat acquisition face and therefore provides uniform mode of heating to the evaporator. A digital power meter with accuracy of ± 0.1 W was used to measure and control the input power to the heat simulator. Fourteen T-type thermocouples with ± 0.5 °C accuracy were used to measure the temperature at different locations of the mLHP. Fig. 1(a) also shows the placement of the thermocouple points. For the determination of the evaporator, condenser and compensation chamber temperature, the average reading of the thermocouples installed on their external wall was taken. All the instruments were connected to the Keyence Thermo Pro 3000 data acquisition system which helps to monitor and record the test data from the mLHP prototype at a time interval of every 5 seconds.

In this phase of experiments, mLHP was operated in the horizontal orientation with the evaporator and condenser at the same level in the gravity field. Tests conducted on the mLHP explored the start-up behaviour and transient response of the loop to the changing heat loads. Start-up of the loop evaporator was attempted at both low as well as high heat loads within the operating regime which was decided by the maximum permissible temperature of the heat source taken as 100 ± 5 °C for electronic cooling applications. For the successful start-up to occur, the initiation of the fluid circulation around the loop and development of the constant temperature profile at the evaporator and across the vapour line was deemed necessary. Start-up time is the time interval needed to acquire the steady thermal and hydraulic conditions in the mLHP following the application of heat load. Profile testing of the mLHP for 5 W step increase as well as for abrupt changes in the input power was done.

Thermal resistance offered by the mLHP (R_{mLHP}) from evaporator to condenser external surface was used to access the heat transfer performance of the device. R_{mLHP} was calculated as:

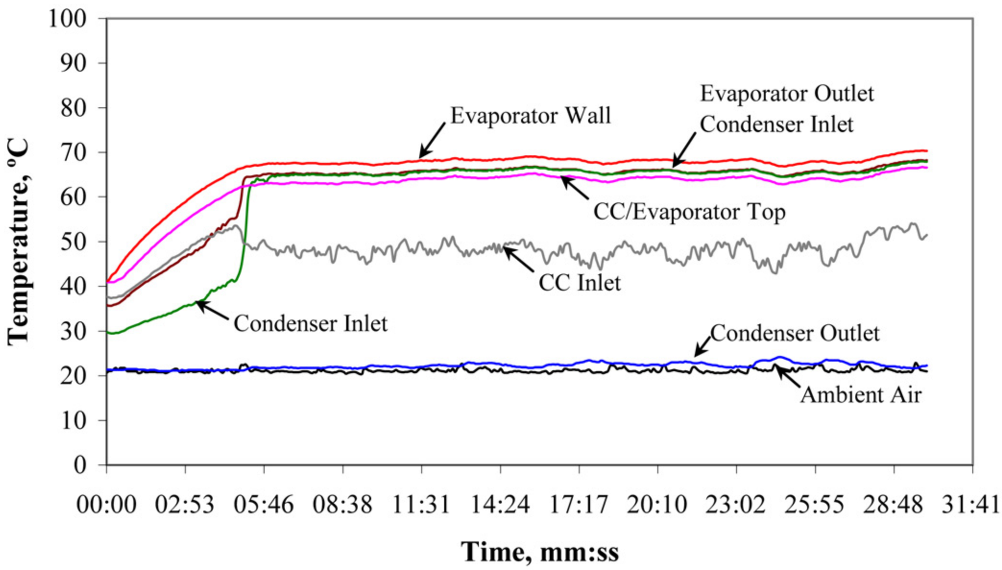
$$R_{\text{mLHP}} = \frac{(T_{\text{evap}} - T_{\text{cond}})}{Q^{\bullet}} \tag{1}$$

where, T_{evap} is the external temperature of the evaporator active zone which was measured by taking mean of the temperatures from the thermocouples fixed on the evaporator external surface ($T_{\text{evap-wall}}$). T_{cond} is the condenser temperature calculated by averaging the readings from the condenser inlet temperature ($T_{\text{cond-in}}$), condenser fin temperatures ($T_{\text{cond-wall}}$) and condenser outlet temperature ($T_{\text{cond-out}}$). $Q^{\bullet}$ is the applied heat load.

3. Result and discussion

3.1. Start-up tests

The start-up phenomenon is very critical in evaluating the design and reliability of the mLHP for the thermal control of the electronic device. Fig. 2 shows the start-up of the mLHP at heat loads of 10, 30 and 50 W, respectively. It is clear from the start-up trends that the mLHP was able to achieve steady state conditions at both low and high heat loads within the range of applied heat load. The start-up profiles demonstrated by the loop for different heat loads is more or less similar except that the notable rise in the condenser outlet temperature was noted with the increase in the heat load. It is observed that for low heat loads, the condenser is able to cool the liquid condensate to near ambient temperature. This is due to the large portion of the condenser being employed for subcooling purpose. Contrary to this, at high heat loads the active or two phase length of the condenser increases that reduces the subcooling portion. As a result, at high values of input power, the temperature of the liquid at the condenser outlet is higher than the ambient which was around 50 °C at 50 W. The condition for the successful start-up was to achieve stable temperatures throughout the mLHP after the heat load is applied which is shown by horizontal temperature contours in Fig. 2. From the comparison of the start-up profiles, it is noted that the start-up time required for low heat loads is more than that for high heat loads. The start-up phenomenon involves satisfying two main conditions that includes; (1) clearing of liquid from evaporator grooves, vapour line and part of condenser; and (2) setting up required pressure difference across the wick that is necessary to circulate the working fluid around the loop. For the loop, the start-up time is the actual time required to accomplish these processes. The first condition is achieved by the vapour generated inside the evaporator which helps to displace liquid from grooves, vapour line and portion of condenser and accumulate it inside the compensation chamber. In this case, the rate of the vapour generation inside evaporation zone affects the time needed to achieve this condition. At low heat load, the vapour generation process inside the evaporation zone is very slow which increases the start-up time. For high heat load, the intensive generation of the vapour takes place from the evaporating meniscus that results in early initiation of the fluid circulation and thus start-up procedure. In order to realise second condition, development of steady temperature difference across the wick is necessary. The thermal gradient across wick depends on hydraulic losses inside loop except wick structure, thermal characteristics of wick and hydrodynamic conditions inside compensation chamber that includes vapour fraction, parasitic heat load from evaporator, liquid flow rate from condenser and heat loss to ambient. It should be noted that completion of the first condition is must to lay grounds for



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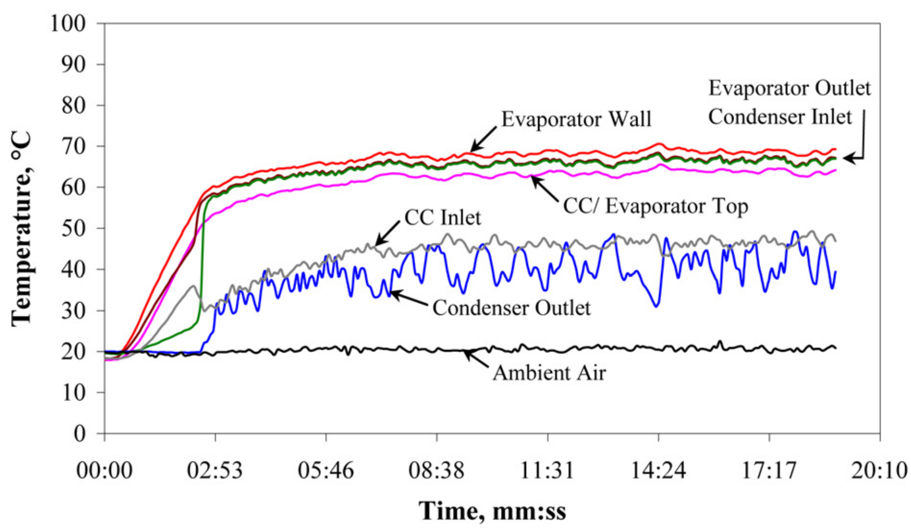

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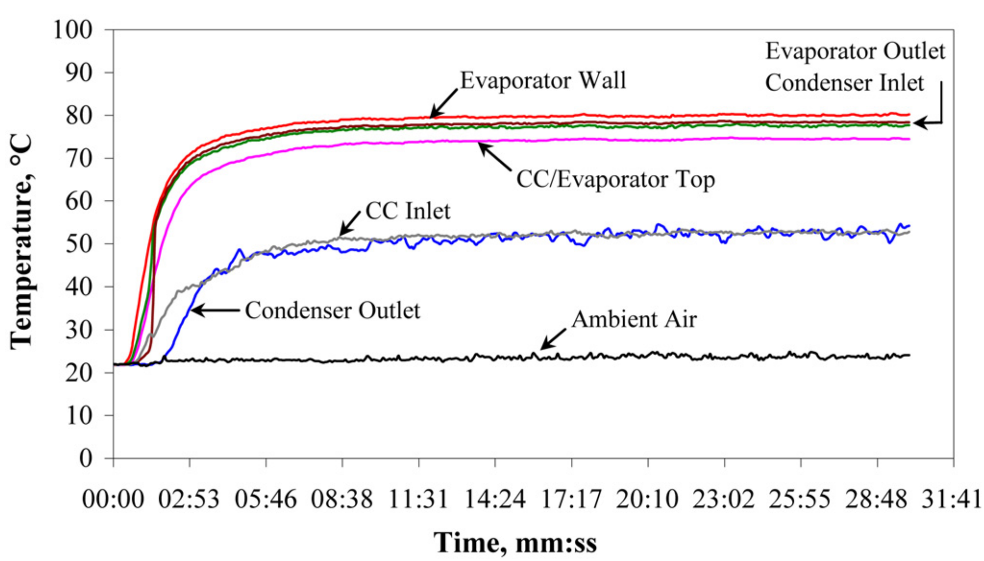


(c)

Fig. 2. Start-up of the mLHP at different heat loads. (a) Input power = 10 W. (b) Input power = 30 W. (c) Input power = 50 W.

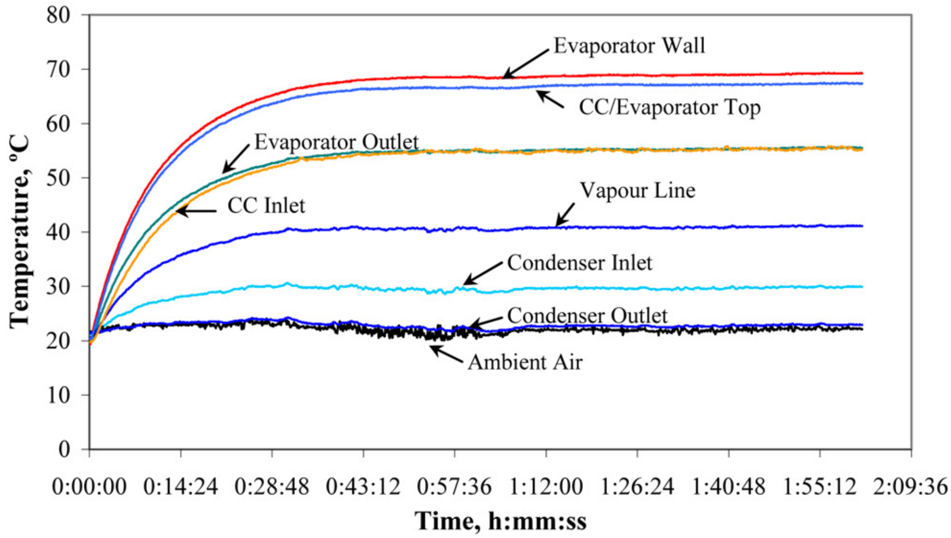


Fig. 3. Start-up of the mLHP at a low heat load of 5 W.

satisfying the second condition. The net outcome of fulfilling these conditions is attainment of stable evaporating meniscus at the wick-wall interface so as to generate sufficient capillary pressure in accordance with the condition expressed by Eq. (2). Such an interface auto-regulates the contact angle and thus capillary pressure for any change in the total pressure loss during loop operation which can be due to variation in heat loads or tilt angle of mLHP in gravity field.

$$(\Delta P)_{\mathrm{cap}} = \Delta P_{\mathrm{v}} + \Delta P_{\mathrm{l}} + \Delta P_{\mathrm{g}} \tag{2}$$

As presented in Fig. 2, for 10 W input power, the start-up of the loop took approx 5 minutes while for 50 W the start-up process occurred in less than 3 minutes. Pre start-up conditions inside the evaporator and compensation chamber also effects the start-up time required by the loop. It is favourable to have liquid–vapour interface already present inside the evaporator for the early initiation of the evaporation after heat load is applied, and flooded compensation chamber to minimise heat leaks and thus assist in the rapid setting of stable temperature gradient across the wick. Both the factors will help to minimise the time taken for start-up. It should be noted that pre start-up fluid allocation inside the loop is quite random due to the large quantity of unbound liquid present in the mLHP. As a result, loop can show different modes of start-up behaviour [15] at the same operating conditions.

Fig. 3 presents the start-up of the mLHP at heat load as low as 5 W. The loop was able to achieve steady state conditions at the evaporator. However, the time required for the start-up process is more than 25 minutes which is quite high when compared to the time required for high heat load tests. The anomaly in the low power start-up process is clearly visible from the large difference of 25 °C in the evaporator outlet and condenser inlet temperatures, and similar temperature trends for evaporator outlet and compensation chamber inlet. Both the factors are clear indicative of large heat flows from the evaporation zone to the compensation chamber. At low heat load, very small portion of condenser is required for condensation of vapour and thus most of the condenser is occupied with liquid phase. As a result, the liquid inventory present inside the compensation chamber is low which increases the vapour fraction inside the chamber. The presence of low liquid charge inside the chamber decreases its heat capacity and thus increases its temperature under the influence of back conducted heat from evaporator. As the irregular surface of porous structure provides very favourable nucleation sites, the vapour bubbles can be formed on the liquid absorbing face of the wick at low heat loads. This was verified by conducted a visual experiment in which the transparent acrylic was used for top cover of the evaporator/chamber and loop was operated at 5 W heat load. In the experiment, a number of nucleation sites were observed on the top face of the wick at low heat load. It was experienced that with the increase in heat load, the vapour bubbles collapses which can be due to elevation in operating pressure and increase in liquid inventory inside chamber that reduces the degree of liquid superheating and thus bubble formation tendency. At low liquid charge inside chamber, these nucleation sites can result in local dry-outs of the wick structure which provides the low resistance path for vapour flow from evaporator to chamber. Such a back flow was experimentally observed when the loop was charged with insufficient liquid inventory. The result was an indefinite increase in the evaporator temperature leading to the total failure of the loop operation. In the present case, the probability of the vapour bypass through the wick is phase out by the stable temperature of 41 °C at the middle of vapour line, and the condenser outlet temperature close to ambient due to complete subcooling of condensate. Also, the definite temperature difference between the evaporator and compensation chamber body supports the argument.

The charging ratio of the liquid inside the loop plays an important part in prevention the start-up failure of the mLHP device. In particular, the liquid inventory should be sufficient to provide proper wetting of the capillary structure before the heat load is switched on. In order to satisfy this requirement, proper consideration has to be given to the compensation chamber volume and liquid charge inventory. As for the compensation

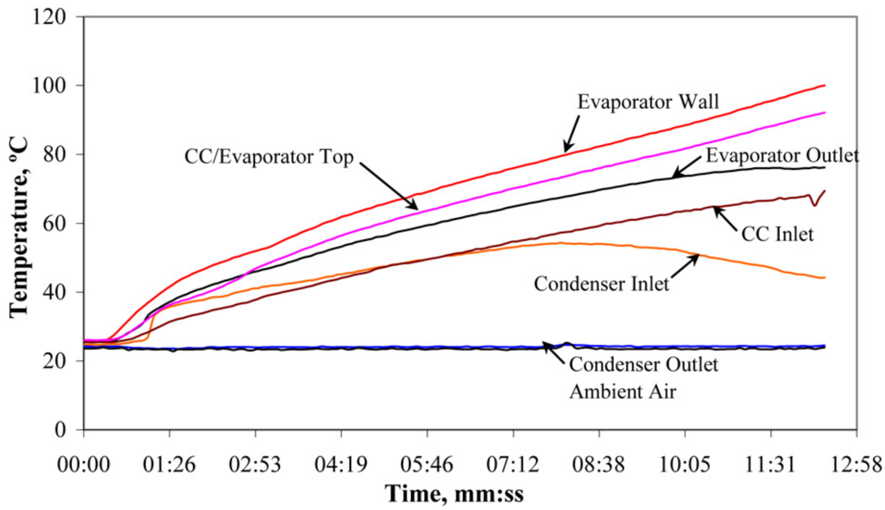


Fig. 4. Start-up failure of the mLHP evaporator at 20 W input power due to the insufficient liquid inventory inside the loop.

chamber volume, it should be large enough to accommodate the liquid charge displaced from the evaporator vapour channels, vapour line and part of the condenser. In the present case, compensation chamber was sized such that its internal volume is approximately equal to the internal volume of the loop. In the LHP, considerable part of the liquid is present in the unbound state throughout the loop. As the testing was done in the horizontal orientation, therefore it is expected that liquid can be distributed in the entire loop volume. Under such circumstances, it is always desirable to guarantee some minimum quantity of the working fluid inside the compensation chamber to keep the wick saturated with the liquid. In order to establish the optimum liquid charge, a number of trials were conducted by varying the charged quantity of the liquid from 30 to 80% of the loop internal volume. It was experimentally observed [20] that in cold state, liquid charge from 50 to 80% was acceptable for the reliable start-up and steady state operation of the loop. For lower charge ($< 50\%$), there were consequences of wick dry out due to inadequate liquid inside the compensation chamber where for higher charge ($> 80\%$), the active condenser area was not sufficient for heat removal. The thermal performance of the mLHP was best with 80% charge which account for 50% liquid fraction inside the chamber. This is due to the presence of bulk liquid inventory inside the compensation chamber that helps to increase heat capacity of chamber and provides better wetting of the wick structure. To ensure optimum liquid fraction (50% or above) inside chamber, the charged quantity of the liquid was determined by using Eq. (3).

$$V_{\mathrm{l}} = V_{\mathrm{eg}} + \varepsilon V_{\mathrm{w}} + V_{\mathrm{vl}} + V_{\mathrm{cl}} + V_{\mathrm{ll}} + x V_{\mathrm{cc}} \tag{3}$$

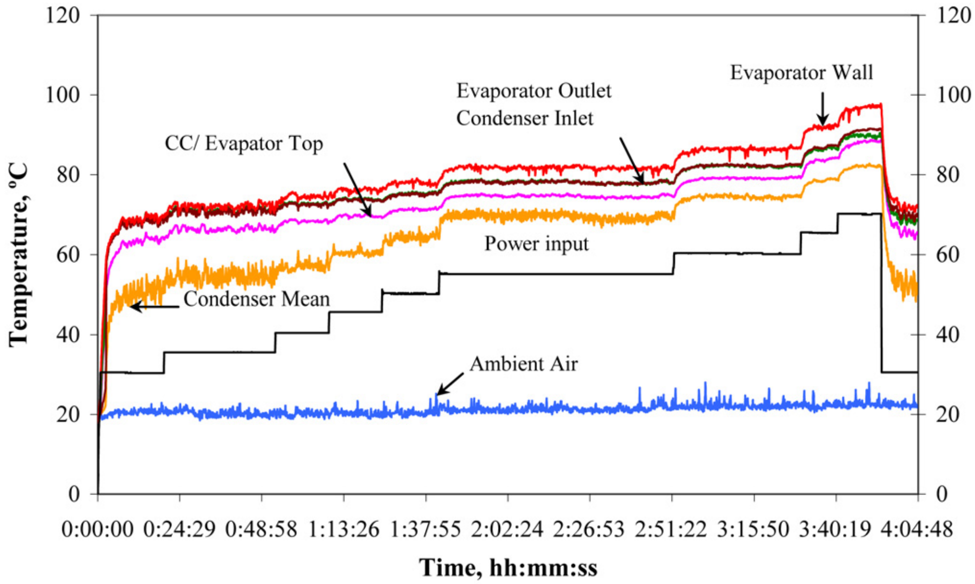
where x is the liquid fraction inside the compensation chamber.

Although, the start-up was also possible with lower charging ratio but the reliability of the start-up process was low in such cases. Fig. 4 shows the start-up failure of the mLHP, with 30% charge ratio and operating at 20 W, due to the insufficient liquid inventory inside the compensation chamber. Even though the fluid circulation is initiated in the start but the evaporator temperature is not able to stabilise throughout the test. The dry-out of the capillary structure is evident from the drop in the condenser inlet and evaporator outlet temperatures, and continuous rise in the compensation chamber inlet temperature which is due to the bypass of vapour from evaporation zone to the compensation chamber viz. wick structure. These types of start-up failures were not observed for liquid charge ratio above 50% of loop volume.

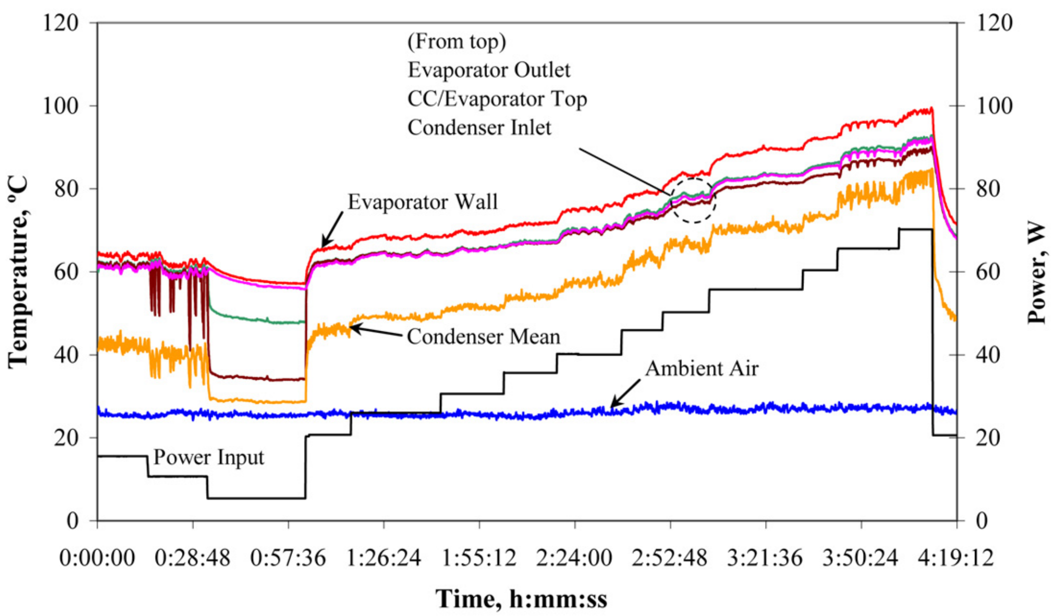
3.2. Performance tests

The mLHP was operated under different heat load cycles to validate its operational reliability and transient response to the changing heat loads. In these tests, the heat load was either varied in fixed steps, i.e. step loading or it was changed in variable fashion, i.e. random loading. Here, the basic aim was to imitate different modes of power cycles that can be encountered in the real working scenario of the electronic microprocessor. In the test run as presented in Fig. 5(a), the heat load was increased in increments of 5 W. Similarly, in test run shown in Fig. 5(b), the heat load was first decrease from 15 to 5 W and then increase from 5 to 70 W in steps of 5 W. For the second type of loading sequence as shown in Fig. 5(c), the heat load was changed in random order with power cycle of 50-20-60-10-15-10-5-20-80-75-40 W in sequential order. This type of power loading sequence is very important to validate the capability of the mLHP to handle the transient heat loads encountered during the continuous operation of the electronic device. It can be observed that for all the tested heat profiles the mLHP performed very efficiently and presented very fast response to the step as well as random changes in input power. For each run, the steady state was achieved within short transient period of 2 to 3 minutes following the change in the input heat load.

It is observed from Fig. 5 (a) and (b) that for input power less than 35 W, the increase in the evaporator wall temperature for each step increment in heat load is relatively small. Any increase in heat loads beyond 35 W produces a more linear and steep rise in the evaporator temperature. This heat load de-



(a)

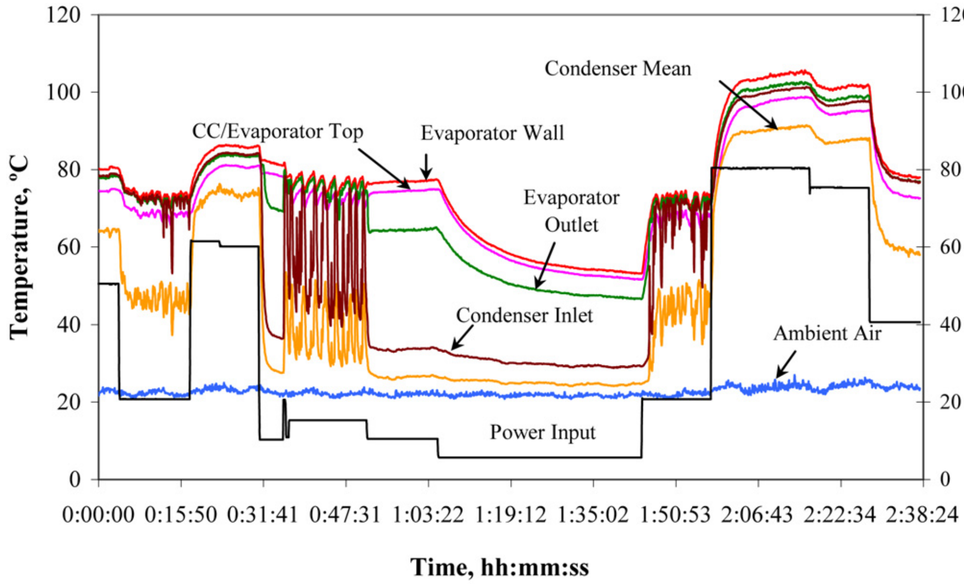


(b)

Fig. 5. Performance testing of the mLHP at different power cycles. (a) 5 W step power loading from 30 to 70 W. (b) 5 W step power loading from 15 to 5 W and 5 to 70 W.

pendence of the mLHP operating temperature is very unique to the passive loop systems and is related to the amount of parasitic heat loads from evaporator to compensation chamber, liquid inventory inside compensation chamber and mass flow rate of incoming liquid from condenser. At low heat loads, as the mass flow rate of vapour is small therefore majority of the condenser is occupied with the liquid and compensation chamber is only partially filled. With the increase in the input power, the mass flow rate of vapour increases that will now require large area of condenser for phase change process. In order to claim area of condenser, the vapour displaces the liquid from the condenser to the compensation chamber. This accumulation of the liquid inside the compensation chamber helps to increase the heat capacity of compensation chamber and thus decrease the effect of the heat leaks from evaporator to compensation chamber on the chamber temperature. As the compensation chamber temperature dictates the evaporator temperature. Consequently, the operating temperature of the mLHP displays small deviations with the increase in input power. It is estimated that complete filling of the compensation chamber is accomplished around 35 W. With further increase in input power, the mLHP function in a constant conductance mode like a conventional heat pipe and presents a monotonic temperature trend.

The mLHP was able to transfer maximum heat load of 70 W while maintaining the evaporator temperature within



(c)

Fig. 5. (*Continued.*) Performance testing of the mLHP at different power cycles. (c) Random power loading cycle of 50-20-60-10-15-10-5-20-80-75-40 W.

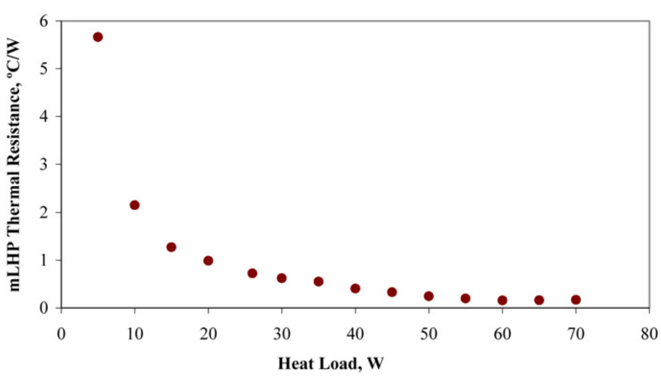


Fig. 6. mLHP thermal resistance versus applied heat load.

$100 \pm 5\,^{\circ}\mathrm{C}$ which is the maximum permissible temperature for electronic microprocessors. For heat load in the range of 5 to 70 W, the thermal resistance of the mLHP (R_{mLHP}) lies between 0.17 to 5.66 °C/W as presented in Fig. 6. Minimum value of 0.17 °C/W for R_{mLHP} was achieved at 70 W.

3.3. Temperature oscillations

Fig. 7 shows the start-up and steady state operation of the mLHP at 15 W with the temperature oscillations present throughout the loop. In this oscillation mode of operation, the loop evaporator achieved a quasi-static state with the evaporator temperature fluctuating within narrow limit of $\pm 3\,^{\circ}\mathrm{C}$. It is observed from the plot that the frequency of occurrence for these oscillations is same at different locations but the amplitude is relatively different. Particularly, the extent of the fluctuations is very high at the condenser inlet and condenser outlet. It is interesting to note that the phase difference between temperature oscillations increases as we move from the evaporator outlet to the compensation chamber inlet. This phase difference represents the time lag associated with the fluid flow from evaporation zone to the compensation chamber in close loop.

These temperature oscillations are expected to be outcomes of the fluctuations in the returning subcooled liquid temperature (from the condenser) which in turn causes the oscillation in the heat leaks (from the evaporator to the compensation chamber). The oscillations in the returning liquid temperature is obvious from the large fluctuations in the condenser outlet and liquid line temperatures, furthermore the changes in the heat leaks is clear from the swing in the evaporator and compensation chamber wall temperatures. As the heat load increases, the periodic increase in the vapour mass occurs. The condenser is not able to condense all the vapour mass and provide enough subcooling to the condensate. As a result, hot liquid is displaced from the condenser to the compensation chamber which is indicated by the rise in condenser outlet and liquid line temperature. Due to the addition of hot charge inside the chamber the extent of heat leaks increases which reduces the latent heat expended in the formation of vapour thereby reducing the mass of vapour produced. Now, the condenser is able to accommodate all the produced vapour and provide necessary subcooling to the liquid returning to compensation chamber. This reduces the heat leaks to the compensation chamber and increases the heat load inside the evaporation zone thus increasing the vapour charge again. This process is repeated indefinitely and manifests itself in the form of temperature oscillation. The oscillations in the heat leaks was experimentally verified by monitoring and comparing the applied heat with the heat dissipation in the two-phase (or constant temperature) portion of the condenser. In this case, the difference between the applied and dissipated heat load gives the heat leaks from evaporator to the compensation chamber, ignoring the effect of the heat losses to the ambient as the mLHP was thermally shielded using fibre glass insulation.

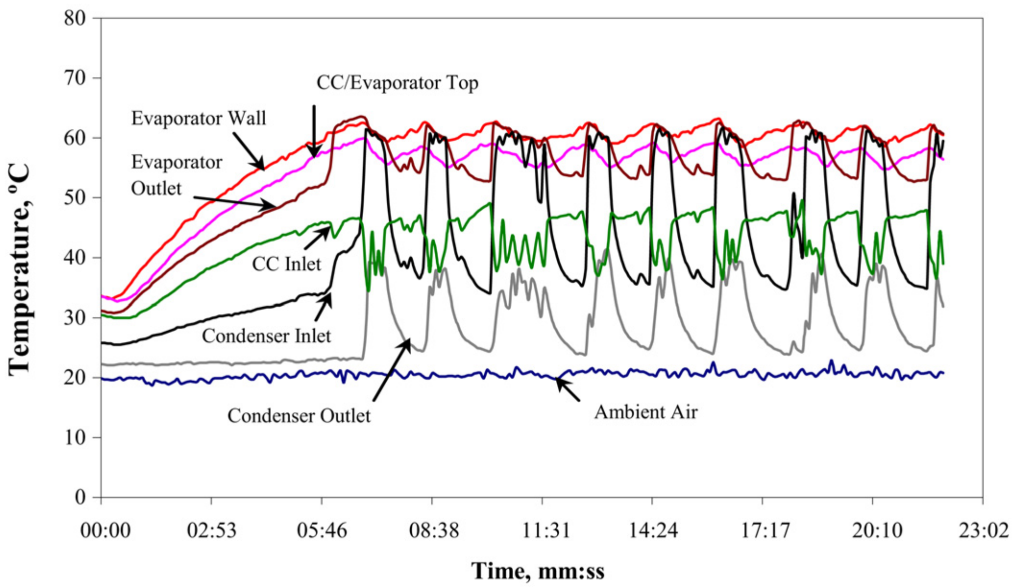


Fig. 7. Temperature oscillations observed at 15 W input power.

In the present tests, these oscillations were noted at low to moderate heat loads from 10 to 20 W. From Fig. 5 (a) and (b), it is observed that the oscillations are not notable for input power below 10 W and above 20 W. It is anticipated that the appearance and disappearance of the oscillations is associated with the distribution of the liquid between the compensation chamber and the condenser which inturn affects the heat leaks and subcooling of the returning liquid. Within the range of input heat load, the mLHP is observed to operate in three different modes. At low heat loads (i.e. < 10 W), large temperature differences exist between evaporator and condenser section thereby commencing high resistance mode of operation (Fig. 3). Oscillations do not occur for heat load < 10 W as the generated vapour mass at such low heat loads is quite small which is readily condensed inside the condenser and the condensate is provided with sufficient subcooling thereby preventing the occurrence of temperature fluctuations. For heat load > 10 W and < 20 W, oscillation mode of operation is presented (Fig. 7). For heat load > 20 W, the mLHP offers normal or low resistance mode of operation in which the heat is transferred from source to sink with minimal temperature differences (Fig. 5).

Fig. 8 shows frequency and amplitude plot for the condenser inlet and liquid line exit temperatures while the mLHP is operating in the oscillatory mode. With the increase in heat load from 10 to 20 W, it was noted that the frequency of the oscillations increases while the amplitude decreases. This damping effect is provided by the accumulation of the displaced liquid from the condenser into the compensation chamber. In other words, the increase in the liquid fraction inside the compensation chamber helps to dampen the oscillations. For low heat loads, the liquid quantity inside the compensation chamber is low or the vapour fraction is high. This reduces the heat capacity of the compensation chamber and thus increases the effect of heat leaks from the evaporator to the compensation chamber. As a result, the intensity of the oscillations increases. Contrary to this, with progressive increase in heat loads, the liquid inventory inside the compensation chamber increases that decreases the effect of heat leaks thereby reducing the temperature oscillations. From Fig. 8, it is clear that the oscillations in the liquid line are quite dominant whereas for the condenser inlet the fluctuations exist for only very narrow range. It should be noted that in oscillation mode, the mLHP was able to perform its intended functions as a heat transfer device quite effectively though with quasi-static operating conditions.

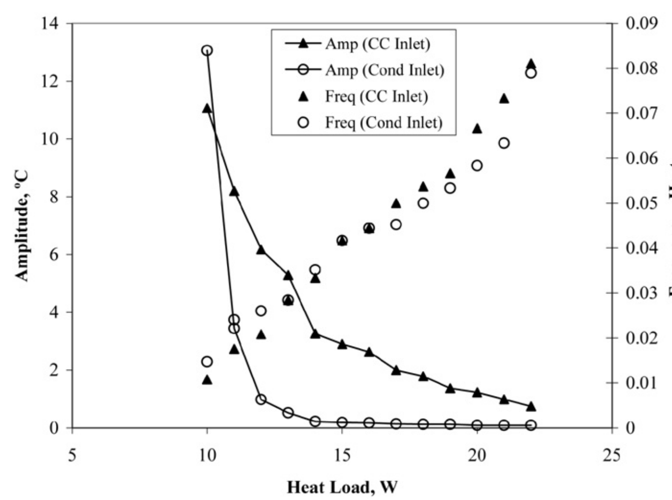


Fig. 8. Amplitude and frequency of the temperature oscillations observed at condenser inlet and liquid line exit at different heat loads.

In the present tests, the loop did not showed any notable degradation in the thermal performance or symptoms of Non-Condensable Gas (NCG) collection inside the compensation chamber or condenser. In addition to this, visual inspection of the nickel wick and loop internal surfaces did not provide any evidence of colour patches due to metal oxidation. Nickel and water system can be considered compatible as supported by the present facts however further tests are needed to validate the long term compatibility.

4. Conclusions

In this paper, experimental investigation of the miniature loop heat pipe with flat disk shaped evaporator, 30 mm in diameter and 10 mm thick, and copper–water configuration was conducted. The main outcomes of the study can be summarised as follows:

- The mLHP was able to achieve stable evaporator conditions for low as well as high heat load start-up. However, the start-up time increases with the decrease in the value of the applied heat load. For very low heat load, the start-up time was very high and large temperature difference existed between evaporator and condenser temperatures.
- While operating under different power loading cycles, the mLHP presented very fast response to the changes in the input power and was able to achieve steady state within short transient period of 2 to 3 minutes.
- The device was able to achieve minimum thermal resistance (R_{mLHP}) of 0.17 °C/W at 70 W while maintaining the evaporator temperature within allowable limit of 100 ± 5 °C for electronic cooling purposes.
- Thermal and hydraulic oscillations were observed throughout the loop for input heat load in the range of 10 to 20 W. The amplitude of the oscillations was very high at the condenser inlet and liquid line exit but the occurrence frequency was same all over the loop. Such temperature oscillations are expected to be the outcome of the fluctuations in the heat leaks from the evaporator to the compensation chamber and subcooled liquid temperature.
- With the increase in heat load, the frequency of the oscillations increases and the amplitude decreases. Beyond 20 W, the oscillations were not prominent at any location of the mLHP.
- The compensation chamber is the most critical component of the loop heat pipe and its hydrodynamic state dictates the extent and the nature of the temperature oscillations for the input heat load. However, the effect of these phenomena on the thermal performance of the mLHP is very minimal.
- Overall, the thermal characteristics of the copper–water mLHP, tested in this experiment, can be considered acceptable for the thermal control of the compact and high powered electronic devices.
- The present tests support the chemical compatibility of the nickel and water system however long term experiments may be needed to validate the system completely.

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