Experimental and Thermal Analysis of Heat Flow Path of A Flat Evaporator LHP

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Abstract- *In the present study, a flat plate evaporator LHP with bronze wick is usedto carry out experiments for different heater loads, temperatures are measured at different locations by thermocouples and thermal imaging is carried out to find the temperature distribution in the evaporator region. A thermal mathematical model for the evaporator of LHP is generated using UGNX software. Thermal analysis is carried out for the defined boundary conditions and evaluated the temperature distribution in the system. These estimated temperatures are compared with the experimental data obtained through thermography.*

Keywords- Flat evaporator LHP, bronze wick, thermal imaging, thermal analysis, thermal mathematical model.

I. INTRODUCTION

Loop heat pipe is a two-phase heat exchanging device which utilizes phase change phenomenon (evaporation and condensation) of the working fluid and uses capillary pressure developed in the wick to transfer the heat from evaporator (source) to the condenser(sink) with minimal temperature gradients. Loop heat pipe came into picture to overcome the drawbacks of heat pipe. The orientation of heat pipe is more sensitive to the gravity, as the capillary structure is situated all along its length which causes a higher pressure drop.

The major difference between loop heat pipe and conventional heat pipe is that the porous wick is confined to evaporator section and rest of the Loop is made up of smooth walled tubing which causes a less pressure drop compare to the conventional heat pipe [1].

Wick is a capillary structure which rises the pressure of the liquid by the capillary action.The pressure rise across the wick should be higher than all pressure drops within the loop heat pipe so that the flow of the fluid takes place throughout the loop. Total pressure drop and pressure balance in the loop heat pipe is given by;

$$\Delta P_{cap,\ max} \geq \Delta P_l + \Delta P_v + \Delta P_g + \Delta P_{cond} + \Delta P_{evap}$$ ....*Equation 1*

The following relation must be satisfied at all times for proper LHP operation

$$\Delta P_{total} \leq \Delta P_{cap,max}$$

WOKING PRINCIPLE OF LOOP HEAT PIPE

Loop heat pipe consists of an *evaporator*and a *condenser* that absorbs heat from the heat source and dissipates that heat away respectively; these two components are attached by pipes which forms a loop. A working fluidas a coolantis encapsulated inside this closed loop. The heat from the heat source evaporates this coolant, and these vapoursthen flow through the vapour channel and move towards the vapour line. Vapour line is connected to condenser where the vapours dump this heat and converted into liquid. Figure 1 shows the schematic of a loop heat pipe. The liquid flows back to the compensation chamber through the liquid line. Here, a wick (bronze) is fixed in the evaporator zone, this wick increases the pressure of the liquid by the capillary action which is required for the movementof fluidthroughout the loop. LHP is designed to work at the saturated temperatures of fluid and uses nothing but the heat of vaporization of liquid to transmit the heat from source to the sink. The temperatureacross the wick remains at saturated condition while the temperature inside the compensation chamber is nearly at the saturation point.

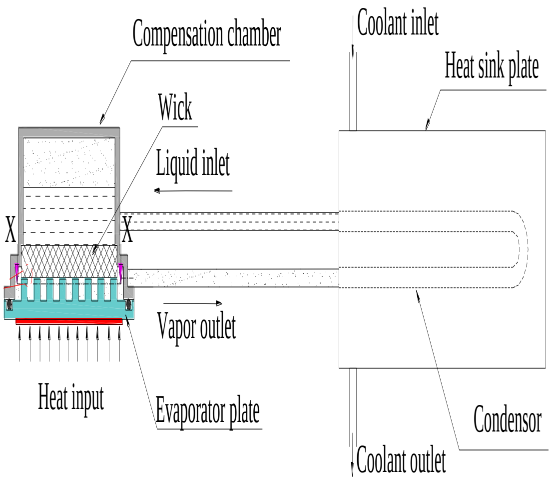


Figure 1: Schematic of Loop Heat Pipe

II. LITERATURE SURVEY

Jentung Ku et al.,[2] studied the operating characteristics and thermo-hydraulic behaviour of LHP. Four peculiar starts up behaviour and overshootwere observed for different conditions of evaporator core and compensation chamber filled with vapors and liquid.

Stephane Launay, Valerie Sartre, Jocelyn Bonjour et al., [3] Worked on the parametric study of loop heat pipe, they concluded that LHP's performance is characterized by its thermal resistance and maximum heat transport capability.

Lin Z, Dongxing Gai, Huan Li, Liu W, Jinguo Yang, Mengmeng Liu et al.,[4] Studied the investigation of the impact of different working fluids on the operational characteristics of miniature LHP with the flat evaporator, they compare the methanol with the acetone as working fluid for the LHP operation and found out that acetone is much better working fluid compare to the methanol for the LHP.

Lin, G, Li, N.,Bai, L., Wen D et al.,[5] Studied the Experimental investigation of a dual compensation chamber loop heat pipe by visualizing the bubble formation inside the compensation chamber of LHP. They observed that bubble formation happens because of heat leakage into the compensation chamberand also insufficient sub-cooling of the incoming liquid.

S. Fukusako, T..Komoriya, N Seki et al.,[6] Conducted an experimental investigation for the transition and film boiling heat transfer of liquid saturated porous bed. They observed that boiling heat transfer is effected by the liquid properties, thermophysical properties of the bead but it doesn't much affected by the depth of the porous medium

L. Mottet, T.Coquard, M.Prat et al.,[7] Studied the three-dimensional liquid and vapour distribution within the saturated capillary evaporator, One peculiar thing was observed that is nucleation or vapour invasion didn't start from the middle point of the wick/casing interface which was assumed to be the hotter point but rather it occurred from the other position which concludes that the assumption of middle point to be the first nucleation site at the wick casing interface wasn't true, vapour invasion could takes place about any point at the wick casing interface which could be the hotter region.

M. Saleem Bashaa, Lalit Bansal, Durgesh Sharma, Saptarshi Basua, Pramod Kumara, Amrit Ambirajan et al.,[8]Studied the bubble dynamics in the compensation chamber of the flat plate loop heat pipe evaporator, temperature profiles for the different heat load was studied and heat transfer coefficient for various heat loads was calculated. According to this paper, at 40 and 60 watts heat loads the trend of temperature profiles are almost same and can be divided into 2 regions namely convective heating zone and nucleation zone (bubble formation).

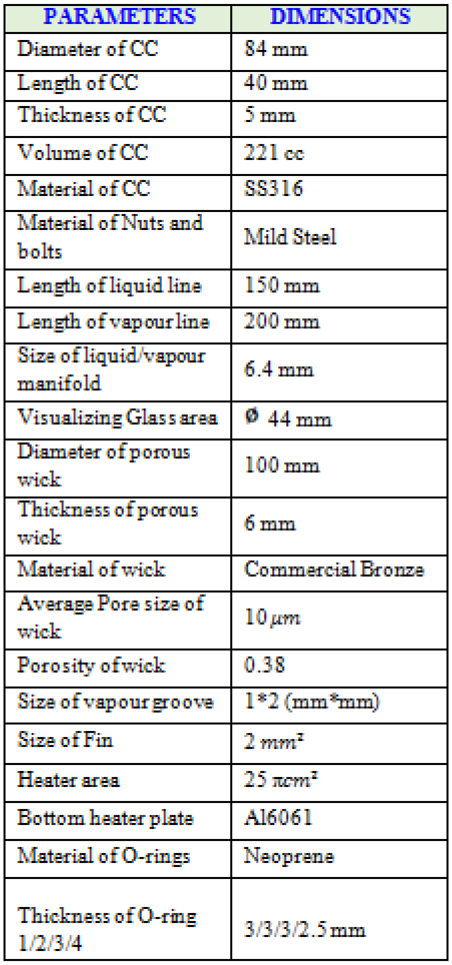
Saleem M Basha, Lalit K Bansal, Saptrashi Basu, Amrit Ambirajan et al.,[9]studied the performance analysis of LHP and bubble dynamics within the CC of LHP, temperature profiles for different heat load namely 40 and 60 watts are plotted to the study the behaviour of the LHP. resistance and heat transfer coefficient across thewick for different heat load are calculated.

Xuan Hung Nguyen, Byung Ho Sung, Jeehoon Choi, et al.,[10]studied on the heat transfer performance for loop heat pipe with circular flat evaporator which concludes thathorizontal orientation proved to be the best design for the LHP, providing robust operation with acceptable heat loads and no oscillation.

He Song, Liu Zhi-chun, Zhao Jing, Jiang Chi et al.,[11]Conducted an experimental study of an ammonia loop heat pipe with a flat plate evaporator. They concluded that thermal resistance of the LHP was mainly affected by the condenser thermal resistance at low heat loads and limited by the evaporator capacity at high heat loads.

III. EXPERIMENTAL SETUP AND METHODOLOGY

In this experiment, only flat plate evaporator is used instead of the complete circuit of LHP. Herewe are interested in studying the operating characteristics, heat flow path of evaporator atdifferent heat loads.



PARAMETERS	DIMENSIONS
Diameter of CC	84 mm
Length of CC	40 mm
Thickness of CC	5 mm
Volume of CC	221 cc
Material of CC	SS316
Material of Nuts and bolts	Mild Steel
Length of liquid line	150 mm
Length of vapour line	200 mm
Size of liquid/vapour manifold	6.4 mm
Visualizing Glass area	Ø 44 mm
Diameter of porous wick	100 mm
Thickness of porous wick	6 mm
Material of wick	Commercial Bronze
Average Pore size of wick	10 μm
Porosity of wick	0.38
Size of vapour groove	1*2 (mm*mm)
Size of Fin	2 mm^2
Heater area	25 πcm^2
Bottom heater plate	Al6061
Material of O-rings	Neoprene
Thickness of O-ring 1/2/3/4	3/3/3/2.5 mm

Mechanicaldetails of Evaporator

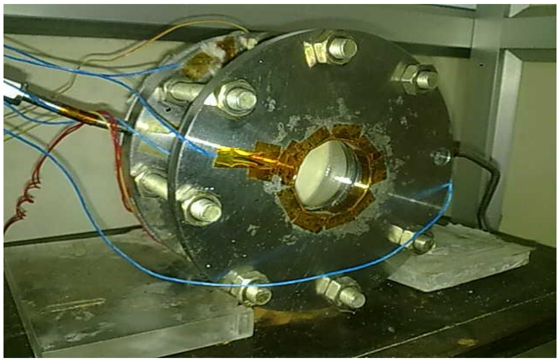
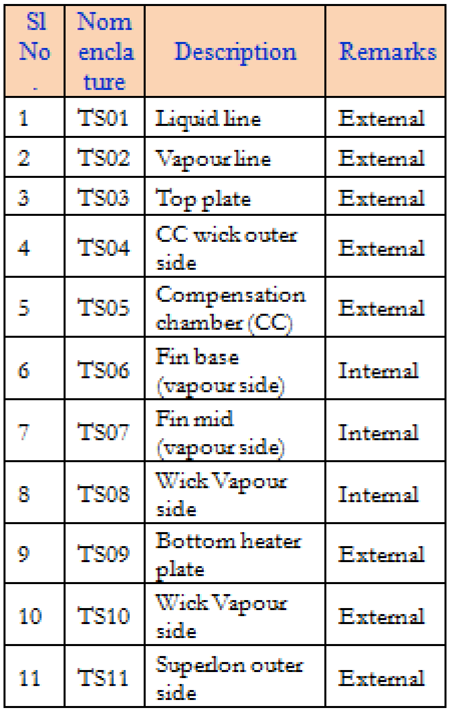


Figure 2: Experimental set up of Evaporator

Figure 3: Evaporator covered with superlon insulation

The assembly of the flat plate evaporator contains the compensation chamber which is bolted with the top plate and bottom heater plate. Figure 2 and 3 shows the evaporator with instrumentation and insulation respectively. In between the compensation chamber and top plate, a glass is inserted which is of Ø 44mm diameter. A heater of maximum rating 120 Watts is mounted on the bottom plate. A reservoir is placed above the evaporator which provides a continuous flow of working fluid to the evaporator for longer operation.

Table 1: List of Temperature sensors



Sl No.	Nomenclature	Description	Remarks
1	TS01	Liquid line	External
2	TS02	Vapour line	External
3	TS03	Top plate	External
4	TS04	CC wick outer side	External
5	TS05	Compensation chamber (CC)	External
6	TS06	Fin base (vapour side)	Internal
7	TS07	Fin mid (vapour side)	Internal
8	TS08	Wick Vapour side	Internal
9	TS09	Bottom heater plate	External
10	TS10	Wick Vapour side	External
11	TS11	Superlon outer side	External

A data acquisition system is provided to record and store the temperatures in the computer. The heater is connected to the battery supply with which heat will be provided to the heater. Vapour line of the evaporator is connected to the reservoir and the reservoir is connected to the evaporator for continuous circulation of the working fluid, Here reservoir is exposed to the atmosphere/surroundings as the vapours from the evaporator line enter into the reservoir it will get condense since reservoir is exposed to atmospheric surrounding and then flows into the evaporator.

A bronze wick with 39% porosity is placed inside the evaporator section of the compensation chamber to develop the required capillary pressure for motion of fluid. The whole evaporator is insulated with the superlon insulation to restrict the heat loss to the surroundings. A thermocouple is also placed at the superlon outer surface to assess its insulating performance. Acetone as the working fluid is selected because it has a good latent heat of vaporization which is quite high as ($519x10^3$ J/kg k) and its compatibility and wetting angle with the wall material is also good.

Acetone is filled into the compensation chamber through the reservoir and vented out the air trapped in the compensation chamber. An IR imaging camera is used to capture the temperature distribution on the outer surface of evaporator. This IR images can be used to validate the data obtained during steady operation of LHP.

IV. RESULTS AND DISCUSSION

Studies for the LHP evaporator are carried out under three categories;

i) **Temperature plots**: under transient and steady operation condition
ii) **Thermal imaging**: under steady operation
iii) **Thermal analysis using UGNX**

These obtained results are analysed for start-up and steady-state operation of LHP and compared with each other.

TEMPERATURE RESULTS

Heater is switched ON and the heater power is adjusted to pre-defined value. Experiments are carried out for 60, 80 and 100W heater powers. Temperature measurements are taken at different locations with the help of 11 T-type thermocouples through a data acquisition system (National Instruments) at 20 samples/minute.

1. Heat load of 60watts

Obtained temperatures for the 60watts are plotted as shown in Figure 4. The experiment is carried out for a duration of 3 hrs. (10800 sec) and plotted as discussed, but for clear visibility of the graph, temperature profiles are plotted for 3000 sec.The temperature profilein general can be divided into two regions/zones which are marked in figure 6

1. Convective heating zone
2. Nucleate boiling zone.

The temperatures rise up to the saturation point of the liquid in the convective heat transfer zone and slight overshoot to superheating of the vapour. Once the nucleation is initiated the temperature is settled to constant values indication the steady-state operation of LHP.

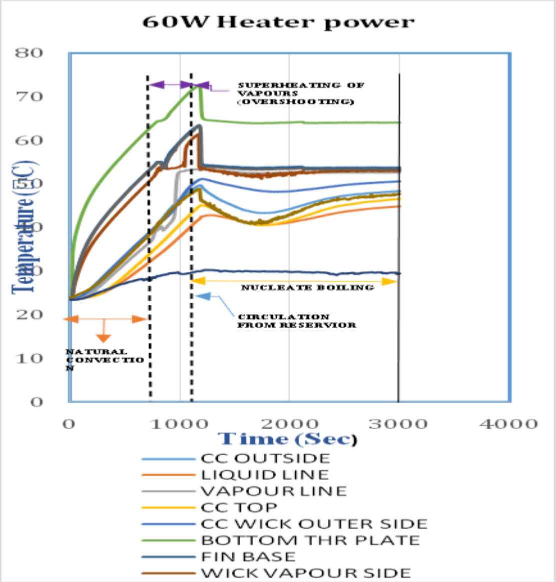


Figure 4: Temperature profile for 60W Heat load

Temperature profiles of bottom heater plate, fin base, fin mid and wick vapour side are following the similar trend but difference lies here in the indication of longer period of stabilization for wick vapour side in the nucleation zone. In the nucleation zone a rise and fall of temperature profile occurred which is called “temperature overshooting” or “serviceability” once liquid starts recirculating from the reservoir temperatures come down and a steady state is reached.

The stabilized period for wick vapour side before overshooting indicates that wick is still full with the saturated liquid and vapour invasion hasn’t started once the temperature goes beyond the saturation point combination of liquid and vapour will be present in the wick. A delay in overshoot for wick vapour side occurred due the fact that thermal conductivity of the wick is lower than the bottom heater plate that is why no sudden overshoot is observed for the Wick vapour side.A slight temperature decrease can be seen before it reaches fully steady state this is due to the initial sub-cooling of incoming liquid from the reservoir.

A sharp rise in the temperatureis observedfor vapour line at the nucleation zone just after overshoot. This sharp rise in temperature occurred due to the flow of superheated vapours through the vapour line which increased the temperature of the vapour line exponentially.

Temperature profiles were decreasing in the nucleation zone before going to steady state which is due to sub-cooling of incoming liquid from the reservoir, initially when incoming sub-cooled liquid of the reservoir mixed with existing liquid in the CC, it creates an overall temperature drop which can be seen in the below graph. After some time when reservoir attaints nearly same temperature as CC (condensation of vapours from the vapour line into in the reservoir increases the overall temperature of the reservoir) temperature will starts to rise again and will go steady state. Temperature on the wick liquid side is uniformly increasing and settling down to steady sate.

2. Heat load of 80watts

The obtained temperatures for the 80watts are plotted below. The temperature profile trends are identical to the temperature profiles of 60W heat load. Only difference observed is the steep increase in the temperature of overshot region. It can be interpreted the overshoot temperature rises as increase in the heat load. This start-up behaviour is significantly influences the design and application of LHP.*The thermal designer should take care such that the allowable electronic temperature should be lower than the temperature in the over-shoot region.*

For vapour line there exists a small overshooting which started just before the recirculation of liquid from reservoir and less temperature drop is observed after mixing of incoming reservoir liquid within the CC which means the sub-cooling of liquid from the reservoir starts to dominate by heat leak from the evaporator core to the CC.

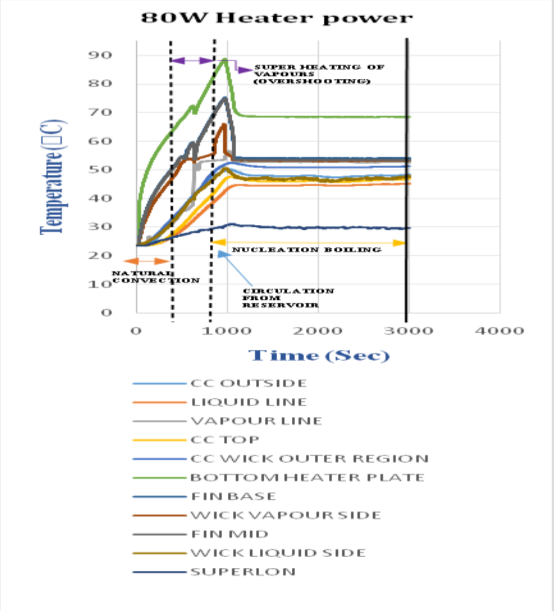


Figure 5: Temperature profile for 80W heat load

3. Heat load of 100watts

The temperature profiles for the 100watts are plotted below, temperature profiles for this heat load are similar to the 80watts and 60watts, a rise in overshoot compare to the previous heat load as expected. The overshoot profile looks border compare to previous heat loadsbecause overshoot is quicker but cooling down of the profile takes longer time as overshoot temperature is higher compared to previous load. In the vapour lineobserved small overshoot profile is more dominated for 100 watts load compare to 80 watts which concludes that higher is heater load more will be overshooting in the vapour line. Less noticeable Temperature drop occurs due to the recirculation of the liquid which means heat leak into the CC is comparatively more dominated for 100 watts load. A slight temperature drop for liquid profile is seen which is due to recirculation of liquid from reservoir but it’s very less compare to the previous heat load.

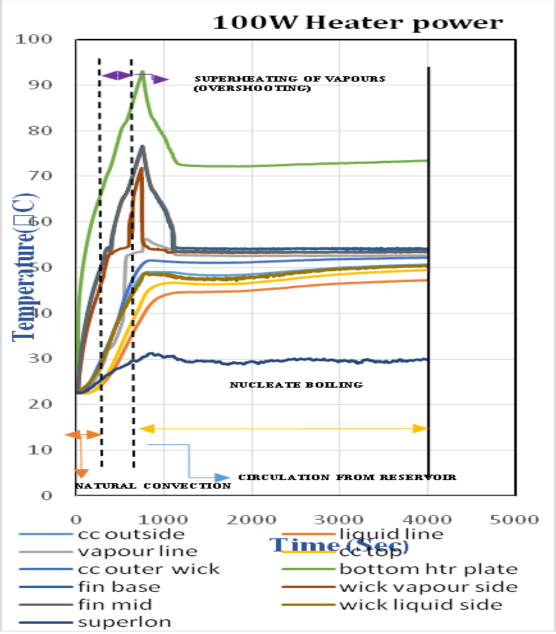


Figure 6: Temperature profile for 100W heat load

IR IMAGING & UGNX ANALYSIS RESULTS

Thermal images are taken for the experimental set up to visualize the heat flow path and to validate the obtained experimental data. These thermal images of the experimental setup are taken without insulation. Four thermal images have been taken at four different locations namely bottom heater plate, top plate and glass to get a clear picture of heat flow path of flat evaporator LHP for 60W load. Figure 9 to 12 shows the temperature distribution for 60W heater power at different regions.

Thermal analysis is carried out using UGNX software for creating the required boundary conditions. Thermal mathematical model (TMM) is generated from the solid model of evaporator. Thermal couplings and boundary conditions are defined. The Solid and TMM models of the evaporator are shown in figures 7&8.

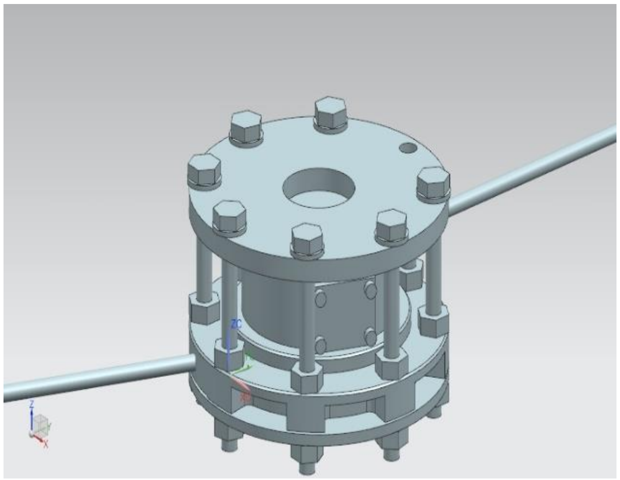


Figure 7: Prepared UG NX model

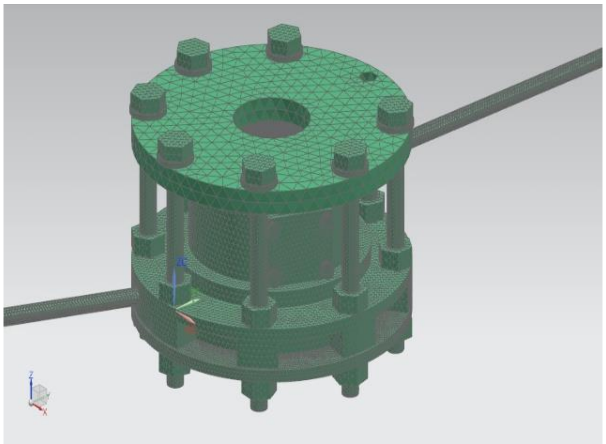


Figure 8: Thermal mathematical model (TMM)

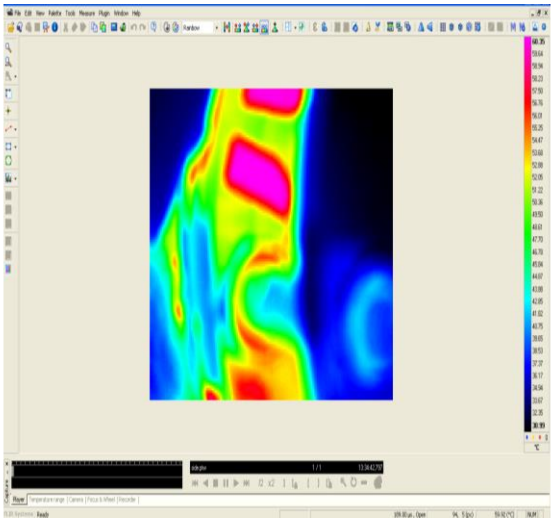
It can be observed that there is significant of heat leak through the bolts connecting from heater plate to the top plate. These heat leak paths have to be minimizing to avoid preheating of fluid before entering the evaporator.

Four different thermal imaging values of LHP is compared with the UG NX thermal model, all the four location temperatures of UG NX model are closely matching with the thermal imaging values and a difference of 4℃ gap is observed which is acceptable. So in conclusion this is the validation of thermal model with respect to thermal imaging at 4 different locations which are found to be in the acceptable range.

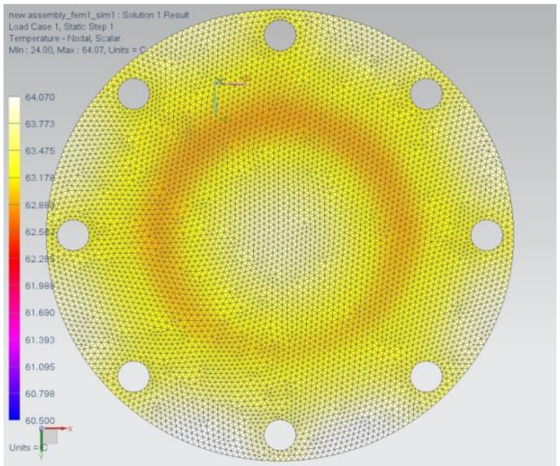
Bottom heater plate

Thermal image of bottom heater plate indicates the highest temperature at the bottom of evaporator which is 60℃ .This temperature value is closer to the obtained experimental value of the bottom heater plate which is around 63℃ . The obtained experimental value is based on the complete insulation of experimental setup so it can justify that without superlon temperature at the bottom of evaporator could be around 60℃ , with this matching of temperatures we conclude that obtained experimental data by the thermocouples are right.

The hotter region at bottom of evaporator is in the middle where we have heater coil and colder region is at the periphery of the evaporator which is around 30℃ . A UGNX numerical model is solved for this case, obtained thermal model temperature 64℃ of bottom heater plate is compare with the experimental data and thermal imaging value, this numerical model gives approximate value of bottom heater plate which is acceptable so in temperatures of experimental value and thermal imaging are matching which indicated that experimental value is correct and thermal model is showing a close value in comparison to thermal imaging and experimental which is acceptable.



IR Imaging

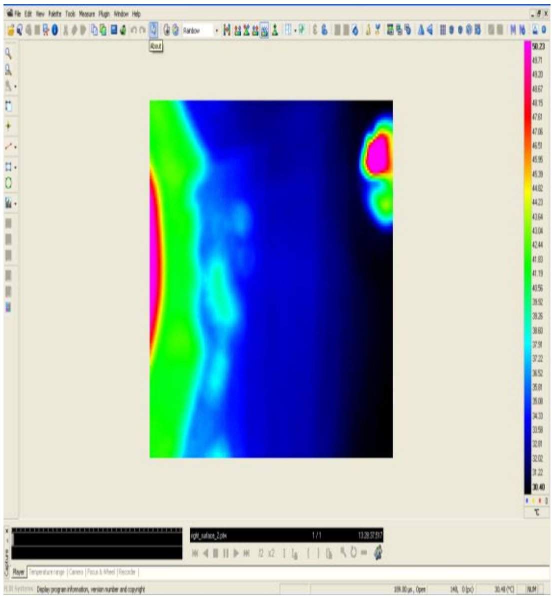


UGNX model

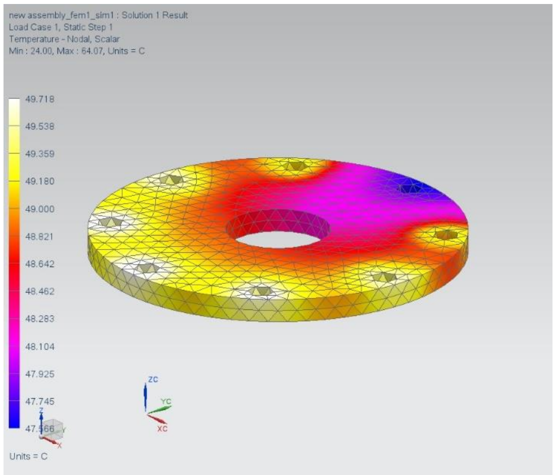
Figure 9: Temperature distribution at the bottom heater plate

Top plate right side

Thermal imaging value of top plate right side is indicating a maximum temperature of 50℃ which is at the bolt-top plate contact, bolt serves as a heat flow bridge in between the bottom heater plate and top heater plate. Heat directly flows from the bottom heater plate through the bolt to the top plate. Thermal model also shows a maximum temperature value of 49℃ which is close to thermal imaging value. Both values of thermal model and thermal imaging are matching with one another, hence thermal model values are correct. Thermal image of top plate and the thermal model of top plate is given below.



IR image



UGNX model

Figure 10: Temperature distribution at the Top plate right side

Top plate left side

Thermal imaging value of top plate left is indicating is indicating a lower temperature in the range of 42℃ which is at the top plate hole not in contact with the bolt, as bolt is not present there is no direct heat flow from the bottom heater plate to the top plate. Thermal model also shows a lower temperature in the range of 47℃ which is acceptable. Both values of thermal model and thermal imaging are close to one another, hence thermal model values can be acceptable, Thermal image of top plate and the thermal model of top plate is given below.

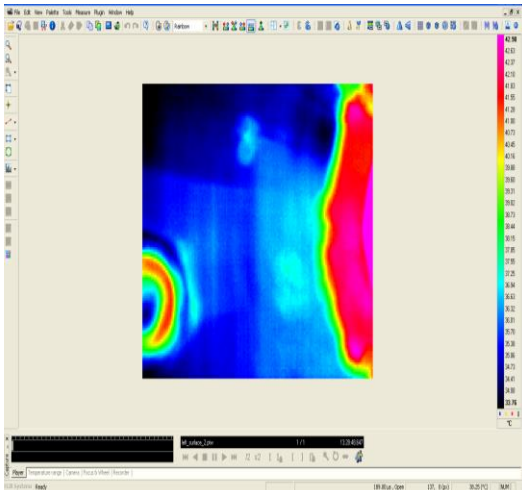
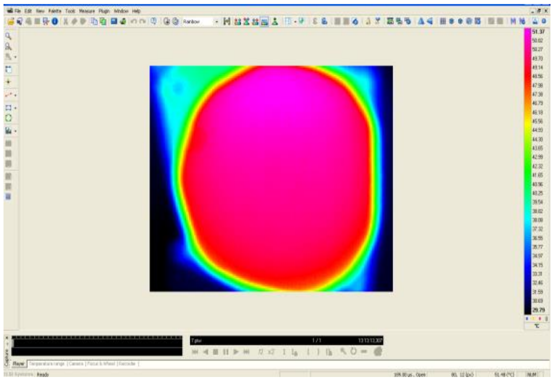


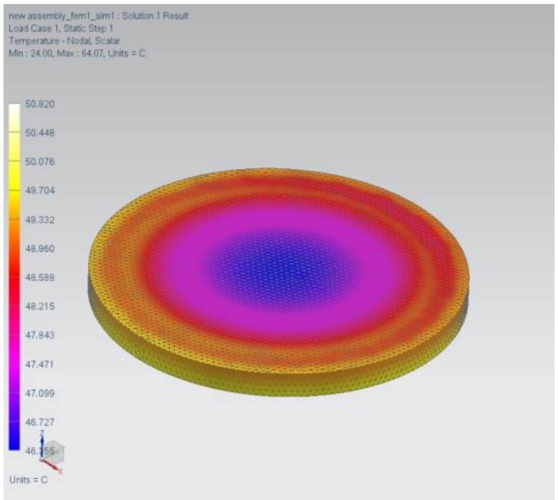
Figure 11: Temperature distribution at the Top plate left side

Glass

Thermal imaging value on the top side of the glass indicating a temperature of 50℃ , thermal model shows a temperature value around 46℃ there is a 4℃ difference between the thermal imaging value and thermal model which is in the acceptable range. Thermal image of top plate and the thermal model of top plate is given below.



IR image



UGNX model

Figure 12: Temperature distribution at the view port (glass)

V. CONCLUSION & FUTURE WORK

Evaporator region of flat plate loop heat pipe is experimentally studied at different heat loads. Temperatures are evaluated at different locations for calculation of heat transfer coefficient across the wick and IR imaging is carried out. Thermal analysis is carried out using UGNX and compared the results. Following are the concluding remarks;

Major achievements and observations:

- Obtained the temperature profile during transient and steady operation of LHP.
- Evaluated the heat flow path in the LHP by heat balance and thermography, and observed good match between the two.
- Observed heat leak path from base plate to acetone through the casing and it can be inferred that there must be isolation to reduce the heat leak.
- At higher heat loads temperature profiles depict two distinct regimes namely, convective heating and nucleate boiling, however, for lower heater power only convective boiling regime exist. So, there exists a critical heat load where the nucleate boiling commences in LHP.
- The temperature profile shows there exists an overshoot in temperature during start-up. Which emphasizes to consider the overshoot temperature while designing the electronics.
- The overshoot temperature rises as increase in the heat load.
- A slight overshoot occursin the vapour line which increases with the heat load.

Future scope:

- Development of the complete circuit of LHP and further study the heat flow by mapping the leakage paths.
- Study of bubble dynamics to evaluate the start-up and steady behaviour of LHP.

The temperature and flow field of the liquid in the near and far field of the bubbles inside the compensation chamber.

ΔPcap	Pressure rise across wick (pa)
ΔPcond	Condenser pressure drop (pa)
ΔPl	Liquid line pressure drop (pa)
ΔPevap	Evaporator pressure drop (pa)
ΔPv	Vapour lone pressure drop (pa)
ΔPg	Pressure drop due to gravity (pa)
CC	Compensation chamber
LHP	Loop heat pipe
TMM	Thermal mathematical model

NOMENCLATURE

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