PROGRESS REPORT

1. Project Title: Development of Novel Low Cost Heat Spreader for High-Power Monolithic Microwave Integrated Circuit (MMIC) Amplifiers	**DST No: IMP/2018/001167**
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3. Co-PIs(Name & Address): Dr. Arul K Prakash Professor arulk@iitm.ac.in Indian Institute of Technology Chennai, I.I.T. Post Office Chennai, TAMIL NADU-600036 Prof. B S Murty murty@iitm.ac.in Indian Institute of Technology Chennai, I.I.T. Post Office Chennai, TAMIL NADU-600036	**Date of Birth:**

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4. Broad area of Research: Electronics and Communication Systems (Hardware Design, System Software), Combat Engineering Systems (Aircrafts and Submarines, Battle Tanks, Autonomous Systems, Armaments and Engineering Support Systems) **4.1 Sub Area:** Thermoelectric materials, including for waste heat recovery, advanced power electronics devices, reliability evaluation of Gallium Nitride semiconductor structures.	

5 Approved Objectives of the Proposal:

To develop a prototype of a novel, thin and compact heat spreader that would cool high power MMIC amplifiers without any external cooling liquid. The minimum capabilities of the device would be to maintain the temperature of the MMIC less than 150°C removing about 20W from a size of 5mm x 5mm. The thickness of the device would be a few mm and the length a few cm, the exact values to be an outcome of the design process.

The utility of the product will be in maintaining the operating temperatures of high power MMIC (as well as other high power electronics) below the temperature beyond which the efficiency of the IC drops, without the use of any external cooling fluids in an environment when very limited space is available. The device will use a porous wick, filled with a liquid which will boil at one end of the device attached to the IC, transfer the heat by becoming gas and flowing to the other end and then condense at the cool end and again percolate through the wick to the hot end due to capillarity with no external pumping.

The novelty of the proposed product will be the use of directed porous media with a continuous variation of pore size so that high flow of gases as well as film percolation of liquid will be allowed with minimum resistance resulting in high heat flux as well as operability in a large range fluxes. The directed porous media is planned to be made with aligned micro copper tubes sintered to each other.

Date of Start: 15/01/2019	**Total cost of Project:** 11518600/-
Date of Completion: **15/01/2023**	**Expenditure as on:** **15/01/2023**
	Capital: NA

6 **Methodology: 1500 char (Half page):**

Literature survey: The existing research done in this area, the designs of the heat spreaders developed so far, as much as available, will be first studied to review the present understanding of the design process, the suitable CTE matched materials, the structure of the evaporator, condenser, wick and other issues in the development of the spreader. An effort to understand the current understanding of the physics behind the various processes involved, like boiling in porous media, condensation, percolation through wicks etc. would be undertaken.

A lumped model that captures the physics of the various sub-processes like boiling in the evaporator, vapour transport, condensation in the condenser, and percolation through the wick and heat losses will be developed. Such a model will predict the heat flux for a given combination of the design parameters of the spreader, namely the wick material and its porosity, the length of the spreader, the material of the casing, the type and amount of working fluid and its properties, the areas and porosity of the condenser and evaporator region etc. Once the overall design parameters are obtained by the lumped modelling, the geometric details of the evaporator, condenser and the wick that maximizes the flux will be found out by CFD analysis. The finalized design parameters will be used for fabrication and testing of the device.

We will create different wick structures like Cu sintered power, sintered aligned arrays of Cu capillary tubes as well as mixture of these two. A chamber, partially filled with the working fluid and maintained at saturation conditions, whose pressure and temperature could be monitored would be made. Heating and cooling arrangements for the working fluid to be maintained at saturation temperature at atmospheric pressure would be provided. This chamber will be used to test various configurations of wick structures and copper micro tube bundles. These experiments will help in choosing the wick/ Cu tubes that has the highest mass flux, the highest critical heat flux and the highest percolation. For various heat fluxes into the wick the boiling, percolation and condensation in the wick will be studied, observations of the wick surface with an IR and ordinary camera through the borescope will also be done. Based on these, the final wick design will be chosen and the prototype fabricated by encasing the wick in a conductivity matched casing. In discussion with AMPL the appropriate casing material will be chosen. Some of the possible materials for the casing include Cu, Cu-Mo alloy, Al Nitride or Titanium. The effect of various fill fractions will also be studied.

7. **Salient Research Achievements:**

   a. **Summary of Progress: 5000 Char (3 page)**

1. The procurement of IR camera is in the tender stage. The delay occured since the earlier tender got cancelled after opening since GoI changed the tender regulations in between. The tender closes on August 25th and the order is expected to be placed within few days.
2. The induction heating mechanism to seal the heat pipe is procured.

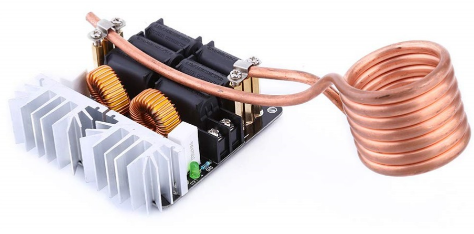


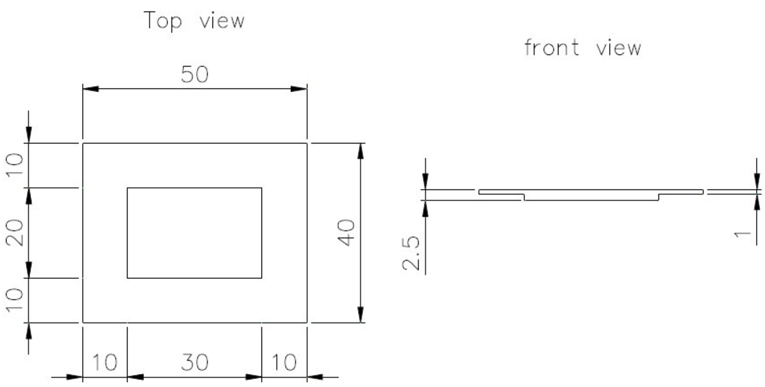
Figure 1, Induction heater driver and coil for sealing vacuum chamber

3. Two varieties of spherical copper powder are procured for making sintered porous media.

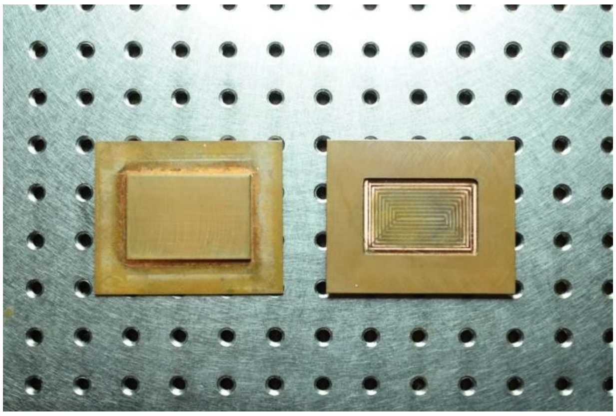
(a) (b)

Figure 2 Spherical copper powder; (a) 15-45 microns diameter and (b), 50 to 150 microns diameter.

4. A copper cavity for enclosing the porous media is fabricated. This is a test rig prior to the cavity by Direct bonded copper (DBC) sheets (a sandwich of aluminum nitride and copper). The thin slices of porous media will be brazed to the inner walls of this heat pipe chamber. The chamber will be evacuated, filled with the required amount of charge and sealed using a two hole method. The vapor chamber will be sealed with an Sn96 Ag4 alloy using induction heating. A thin 400 nm film of Nickel is to be coated on copper to facilitate induction heating of solder and a 10 nm gold plating will ensure perfect soldering joints. These coatings on the first prototype are under progress in IIT Madras campus itself via vapour deposition methods.



(a)



(b)

Figure 3(a)Schematic of the copper cavity for enclosing sintered porous media,

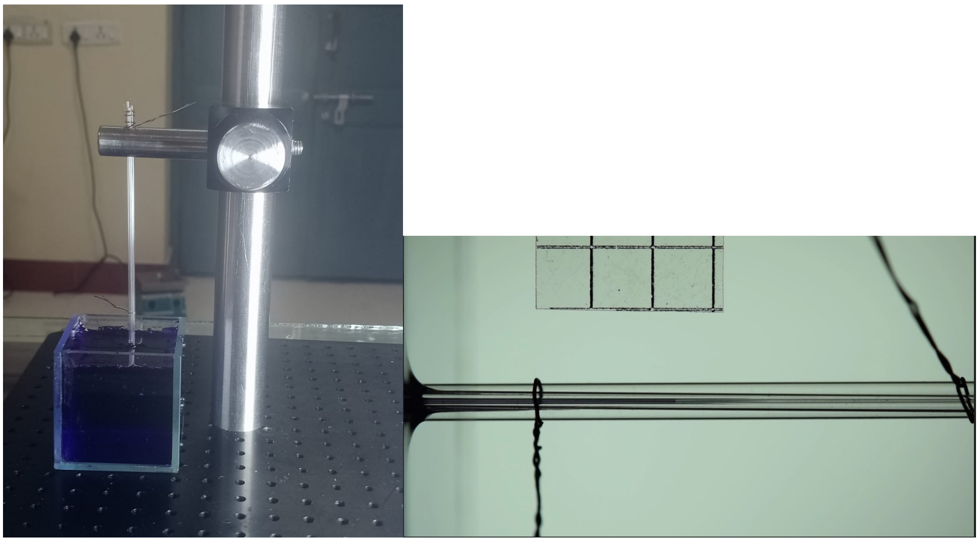
all dimensions are in mm. (b) Copper cavity made to enclose sintered porous media

5. A vacuum charging unit is under design/fabrication stage. The vacuum pump to create the vacuum inside vapor chamber is procured

Figure 4 Vacuum pump for evacuating non condensable gases from vapor chamber.

6. The sintering of porous media at various pressure, temperature and time is in progress through a collaboration with metallurgy department of IIT Madras using a spark plasma sintering machine **Dr Sinter 5000 SPS.** The graphite dies for the sintering process is under fabrication by an agent in Pune.

7. A basic study of capillary rise with in the interstices of glass capillary tube array was conducted as design input to the heat pipe with directed porous media. Three glass tubes of outer diameter 1.38mm are bundled together and the capillary rise in the interstitial gap is measured.



(a) (b)

Figure 5 The setup to measure the capillary rise in interstice. A video is recorded and velocity of corner rise is estimated through image processing. (a) shows the measurement setup and (b) represents the closeup video of dye rising in the interstitial channel.

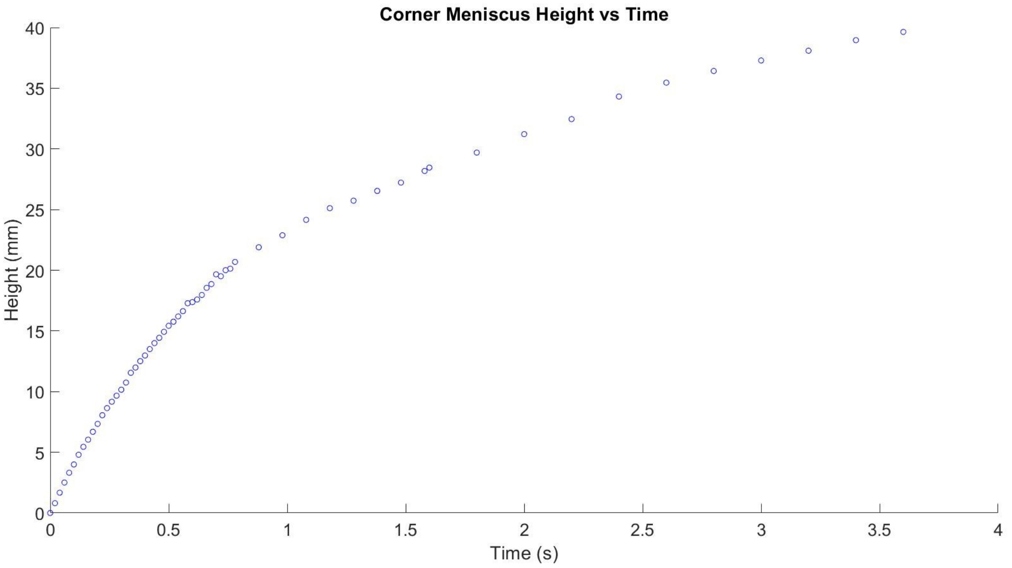
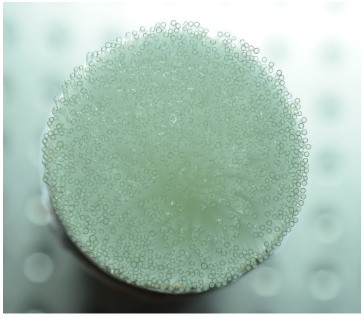
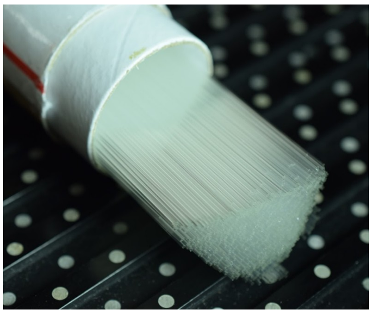


Figure 6 Capillary height with time for water in an interstice formed three tubes of 1.38 mm outer diameter.

8. Fine glass tubes are procured to study the dynamics of capillary rise in interstice of tube bundles. Currently the experiments with these small tubes are progressing.



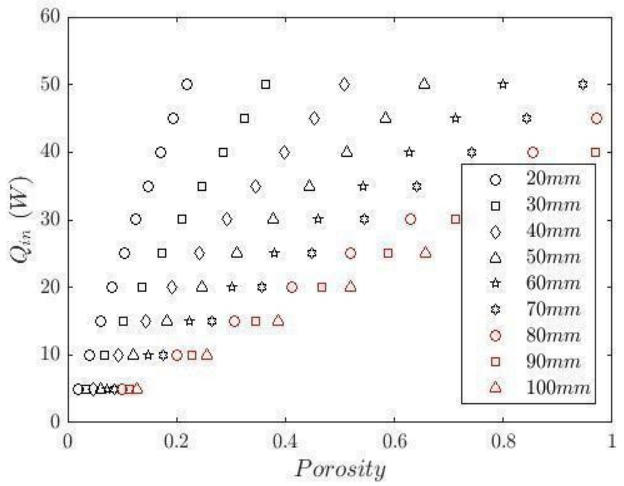
(a)



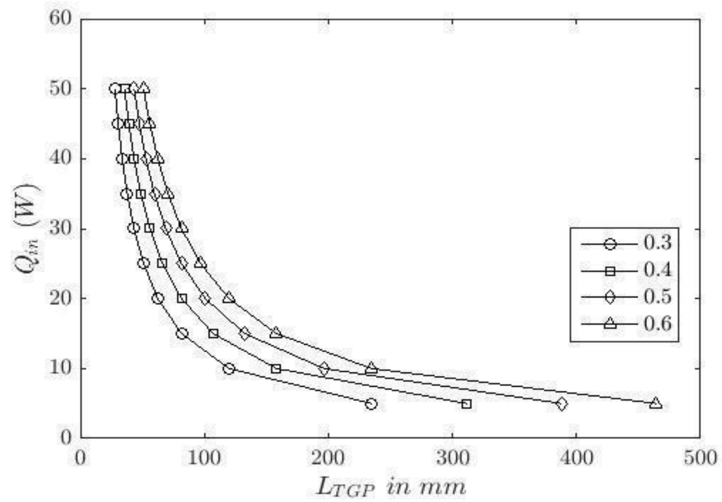
(b)

Figure 7 Glass capillary tubes with (a) outer diameter 0.7 mm and (b) inner diameter 0.5 mm

9. A lumped parameter design code was developed for porous media with sintered copper powder. The obtained dependence of the heat flux on the length of a heat pipe, for various porosities, is shown in figure 8(a). Figure 8(b) shows the dependence of the heat flux on the porosities for different lengths for the same case. From such an analysis we can now choose the porosity and the length to maximize the heat transfer for a given set of geometrical constraints.



(a)

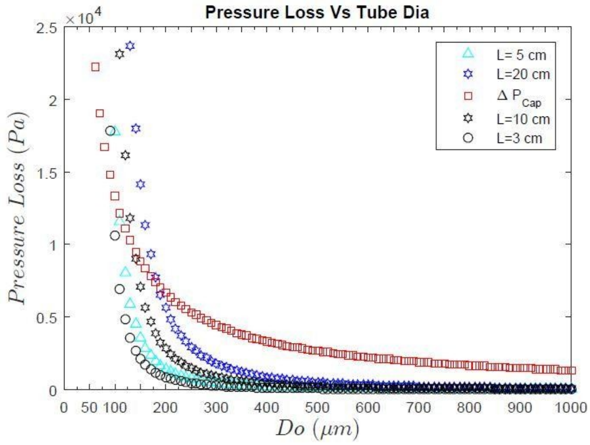


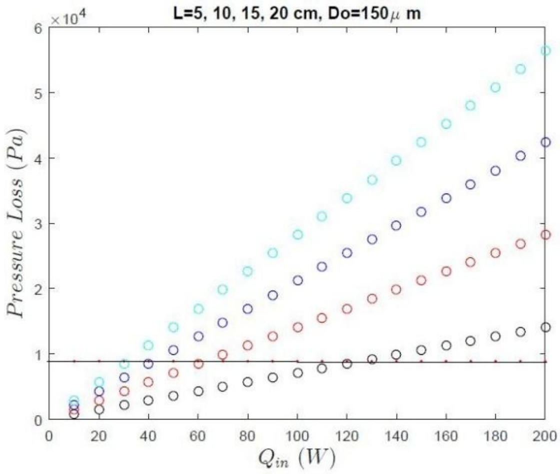
(b)

Figure 8. Design curves for a heat pipe with sintered porous media. (a), variation of flux with maximum possible length for various porosities; (b), variation of flux with porosity for various lengths of the heat pipe.

10. The lumped parameter design analysis code for directed porous media based heat pipe, which uses an array of copper micro capillary tubes was developed for the case of complete filling of the interstices. The pressure loss for liquid flow through interstitial channels to supply the required flux, assuming that the supplied flux is entirely carried away by evaporative flux, was compared to the capillary pressure in the interstice. Figure 9(a) shows the variation of the viscous pressure loss against tube diameter varying from 50 to 1000 microns for various tube lengths 5cm, 10cm, 15cm and 20cm respectively. The capillary pressure limit is also shown. The study shows that there is an optimum value of tube outer diameter below which dry out will happen. Micro tubes with outer diameter varying from 100 to 200 microns are found to be best for our purpose as per these estimations. Figure 9(b) shows the

variation of pressure loss vs input heat flux for 150 microns tube diameter; figure 9(c) shows the same for 250 microns tube diameter. The horizontal line in the figures represents the capillary pressure limit. This study will give us an estimate for the maximum possible length for various tube diameters.





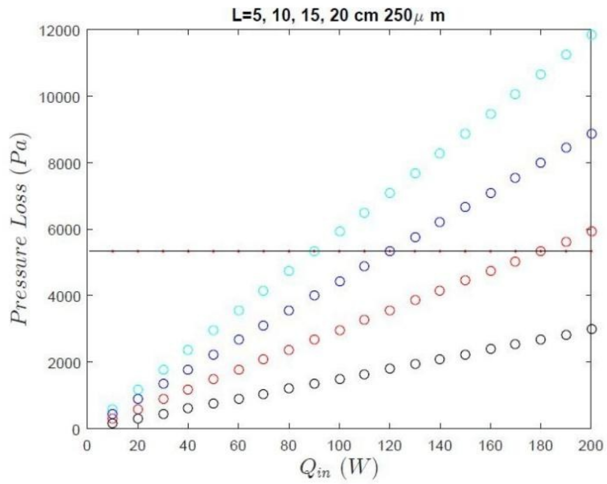


Figure 9. (a)The variation of viscous pressure loss vs tube outer diameter for different tube lengths varying from 5cm to 20 cm for a fixed heat flux of 50 W. Squares represent capillary pressure. (b) The variation of pressure loss vs input heat flux for 150 microns tube diameter. The horizontal line shows the capillary pressure. The black symbols represent 5cm, red 10cm, blue 15 cm and cyan 20cm of tube length respectively. (c) Same as (b) for 250 microns tube diameter. The horizontal line represents the capillary limit. The black symbols represent 5cm, red 10cm, blue 15 cm and cyan 20cm of tube length respectively.

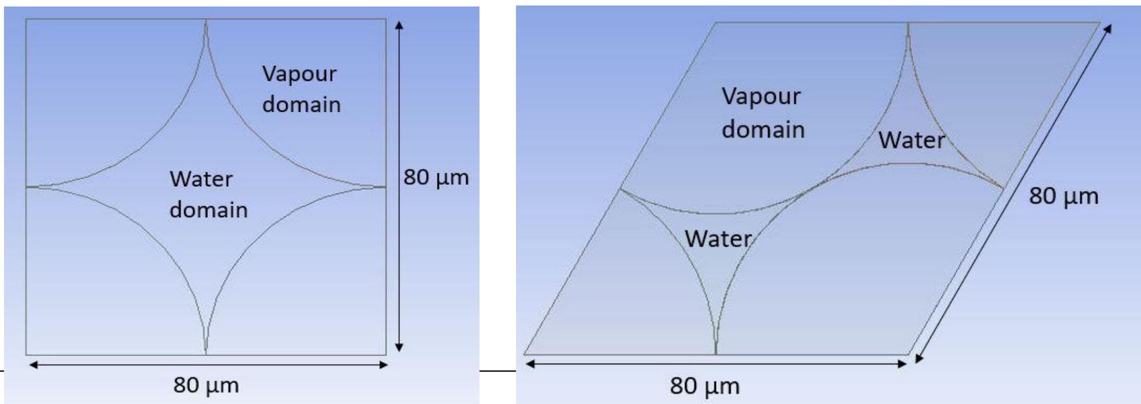
11. For the case of partially filled interstices we extended the lumped parameter model by including considerations of film evaporation. We made a model to estimate the evaporative velocity from a thin film and estimated the area of evaporation in each interstitial film. We found that the evaporative mass flux near the tip of interstice was found to be less than the supply mass flux through the film cross section due to capillarity; this implies that the capillary corner rise in interstices is capable of supplying the needed evaporative mass flux and that the film will not dry out. To check the flux balance, the total available heat was distributed to each interstice and compared with the evaporation flux from interstitial films. The evaporative flux flux was found to be much higher, implying the high heat load capability of the configuration.

12. While initial testing was conducted using four different media made out of 20 micron, 50 micron, 70 micron and 100 micro sphere diameter made out of brass, we noticed that the wetting properties are very poor for brass due to its high contact angle with water. Due to this, the sintered porous media is to be made in copper since copper has a very low contact angle.

Figure 10: Sintered porous blocks with pour size varying from 20 to 100 microns.

13. A multi-phase heat transfer simulation code is being developed in OpenFOAM platform to study the relative performance of various porous media. The design outputs from the lumped analysis and literature survey is being used for this. Initially, a cavity, with a homogenized porous media, was modelled. Then flow through a cavity with bottom part being porous media was simulated and validated. Energy equation was added later to these simulations to validate the heat transfer solutions.

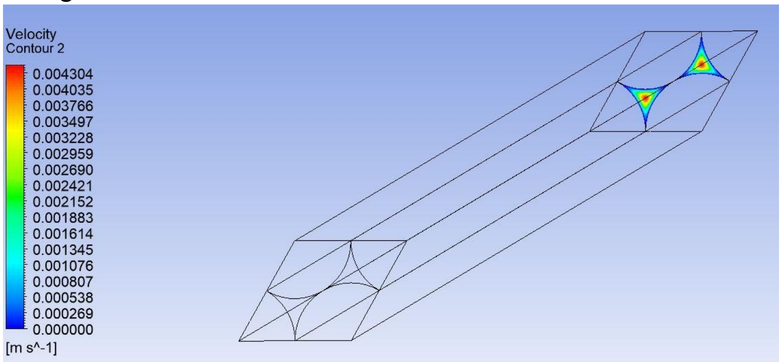
14. Flow through the actual geometry between capillary tubes was modelled. To study the flow and heat transfer in the two possible arrangements shown below in figure 11, two different types of unit cells were created and meshed in ANSYS. For a counter flow arrangement of water through the interstices and water vapour through the tubes flow and heat transfer in both the arrangements were solved using FLUENT solver. The outlet temperature for water and water vapour are lesser, and the total surface heat flux for inner pipe is more, in the staggered tube arrangements (case (b) in figure 11) as compared to case (a). Therefore, it is



(a) (b)

Figure 11: Cross sectional view of unit cell of capillary tube with two types of arrangements (a) and (b).

concluded that the design (b) is better for our requirements. Figure 12 shows the velocity contours at the ends and in addition it shows a 3-D design of a unit cell of the capillaries which are 5 cm in length.



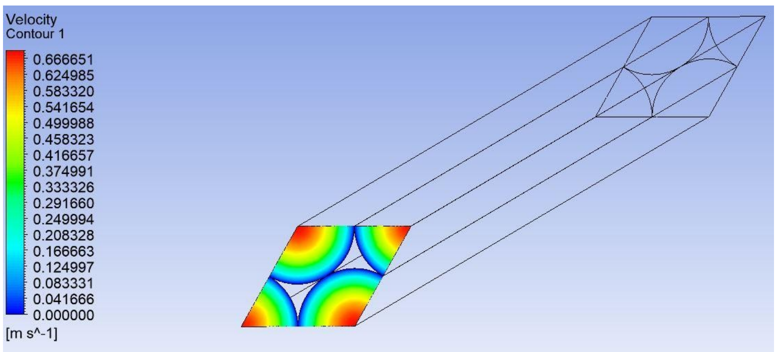


Figure 12. (a) Velocity contour at outlet for (a) water and (b) water vapour

15. To simulate the 2-phase flow in such interstices with evaporation and condensation, Volume of fluid (VOF) model solver is used in OpenFOAM with energy equation, surface tension model to account for capillary dynamics and Kistler Dynamic contact

angle model. The phase change model proposed by Hardt et.al. with the interfacial heat transfer equation given by Schrage et. al. and the interface is assumed to be at the saturation conditions For phase change phenomena, it becomes important to locate an accurate position of the interface., which is achieved by a contour-based interface reconstruction algorithm. The phase change models with dynamic contact angle models were validated by simulating condensation of water over a flat plate.

16. Using this multiphase solver, we are now simulating the actual flow in the interstices of the capillary tube array. The figure 13 shows the geometry of one interstice cross section with refined mesh near the boundaries. Due to symmetry only one third part of the above geometry, shown in Figure 14, which is of 5 cm in length and has a 40 micrometer radius of curvature, is taken for the simulation. The total number of cells are around 10 million and the 1st mesh near the wall is 1 µm. We start the simulations with interstice filled with 2 mm height of liquid column at time t=0. The temperature at the wall boundary is linearly varied with the height of the interstice. The liquid remains at 70° C initially. Boundary condition at symmetry wallis taken as $\partial\varphi / \partial n = 0$ where φ can be velocity, pressure and temperature and n is the normal to the boundary. The value of any property parallel to the boundary is taken to be the same on both the symmetric walls. The boundary conditions at other faces are tabulated below. These simulations are now ongoing.

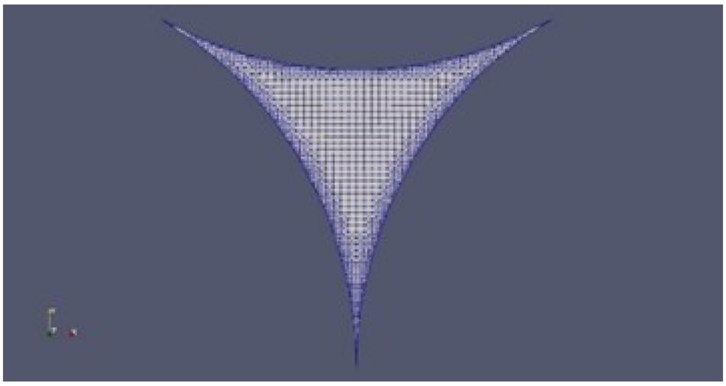


Figure 13: Cross section of one interstice of a unit cell of staggered arrangement

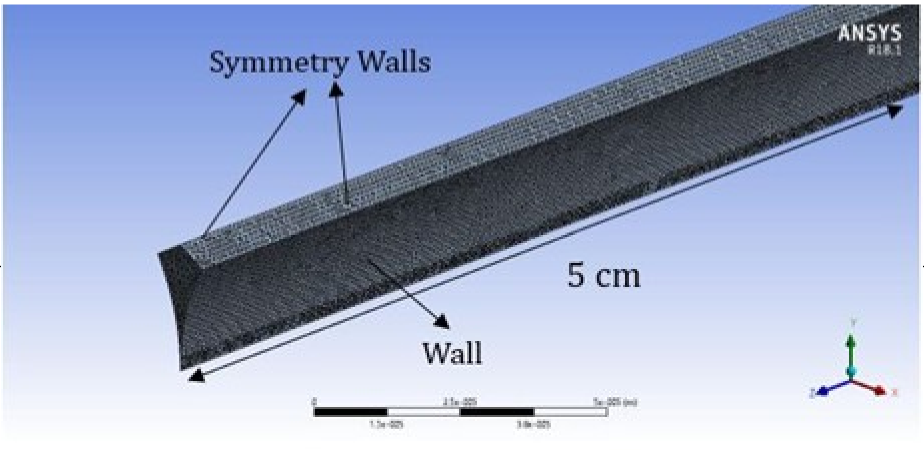


Fig 14: 3-D view of one third portion of the interstice

Parameter	Boundary Name	Condition
Velocity	Inlet	$\partial w/\partial z = 0$ and all other velocity (u and v) gradients in streamwise direction are zero.
	Outlet	Inlet-outlet condition
	Walls	No-slip condition
Pressure	Inlet	Zero gradient, $\partial P/\partial z = 0$
	Outlet	Atmospheric pressure
	Walls	Zero normal gradient i.e., $\partial P/\partial n = 0$ Where *n* is normal to the wall
Temperature	Inlet	70° C
	Outlet	120° C
	Walls	T(°C)=70+1.666*z Height from bottom =z (in mm)

References:

1.) V. A. F. Costa , L. A. Oliveira , B. R. Baliga & A. C. M. Sousa, **Simulation Of Coupled Flows In Adjacent Porous And Open Domains Using A control-volume Finite element Method**, *Numerical Heat Transfer*, *Part A: Applications: An International Journal of Computation and Methodology*,2004; 45:7, 675-697

2.) X. B. Chen, P. Yu, S. H. Winoto, H. T. Low, **Forced Convection Over a**

Backward-Facing Step with a Porous Floor Segment, *Numerical Heat Transfer, Part A: Applications: An International Journal of Computation and Methodology*, 2008; 53:11, 1211-1230

3.) S. Hardt a, F. Wondra, **Evaporation model for interfacial flows based on a continuum-field representation of the source terms**, *Journal of Computational Physics*, 2008;227 :5871–58951

4.) Christian Kunkelmann, Peter Stephan, **CFD Simulation of Boiling Flows Using the Volume-of-Fluid Method within OpenFOAM**, *Numerical Heat Transfer, Part A: Applications*, 2009; 56:8, 631-646

7.2 New Observations: 1500 Char (Half page):

The new observations as of now include the maximum length of the heat spreader for a given heat flux and porosity of copper sintered powder, shown in Figure 8. Similar results for the heat pipe using sintered tubes, shown in figure 9, are also new. The measured capillary rise in interstices of micro capillaries in figure 6 is also new.

7.3 Innovations: (5 lines 250 char):

The main innovation will be the use of an ordered micro-tube porous media, oriented in the direction of flux. In such a case the tube holes allow the vapor to escape fast while the tube walls with reducing gap and towards the point of contact of the tubes help in fast spreading of the liquid film in between these tubes. The structure thus allows faster percolation due to the preponderance of corners aligned in the direction of fluid transport and easy transport of vapor from evaporator to condenser. Such a structure could be combined along with the conventional sintered porous structure in the evaporator and condenser regions as well, or continued in the evaporator and condenser regions by providing vertically aligned tubules at the evaporator and the condenser ends.

7.4 Application Potential:

7.4.1 Long Term

The technology can be used for high heat flux electronic chip cooling for any aerospace or defense systems, especially where wide band semiconductors are implemented and high gravity conditions are prevailing. Apart from aerospace and defense applications, this product can be used for any other cooling applications in electronics industry like laptops, and other devices.

7.4.2 Immediate

The immediate application will be for situations where high gravity flight conditions exists and where reliable compact cooling techniques are crucial. For instance, the heat generated in wide band semiconductors where micro wave spectrum is used for communications need this type of reliable cooling technology without moving components. The immediate application of this design will be in the MMIC supplied by AMPL to DRDO to be used in Agni missiles.

7.5 Any other None

Research work which remains to be done under the project (for on-going projects) :

1. Fabrication of the prototype of heat pipe with sintered Cu powder: After characterising the particle size of the newly procured copper powder using the SEM facility at IIT Madras, it will be sintered to make sheets of 2mm thickness and required dimensions in a spark plasma sintering furnace. Porous media of different porosity and permeability will be made by changing the sintering temperature, pressure applied and sintering duration. Porosity of the sintered porous media will be estimated using SEM images.

The sintered porous layer will be brazed to the casing and the enclosure evacuated, filled with required amount of change and sealed. The vacuum sealing unit is in the fabrication phase.

2. Completion of the lumped parameter design of the heat pipe with directed porous media, made with array of Cu capillary tubes. Film evaporation considerations are to be included into the present lumped parameter design code for heat pipe with capillary tubes, so that the heat pipe can be designed for partial filling of the interstices between the tubes. The code is expected to give length and diameter of tubes for various filling ratios and heat fluxes.

3. Basic studies on the capillary rise, evaporation and condensation in directed porous media made of capillary tube arrays. Initial studies on capillary rise in the corners of an array of glass tubes have thrown up new results that are unexplainable by the present theories. Further studies on the capillary rise, evaporation and condensation in such tube arrays will be done which will give predictive models to be used in the design of the heat pipe with capillary tube array.

4. Fabrication of heat pipe that uses directed Cu porous media made out of array of capillary tubes: Copper tubes of 200 microns and 400 microns outer diameter will be bonded together by low pressure sintering and then packed in a copper cavity to make the heat pipe. Same evacuation, filling and sealing procedure will be then conducted.

5. Testing of the performance of the heat pipe prototypes: Once the heat pipe is made, a small heater will be connected at one end of the heat pipe and a heat sink to the other end. Two thermocouples will take the temperature measurement and the efficacy of the flat heat pipe can be quantified with this. Once a successful configuration and fill ratio of working fluid are obtained, the cavity will be made using direct bonded copper sheets to match the thermal expansion of electronic chips.