The Constrained Vapor Bubble Experiment – Interfacial Flow Region

Akshay Kundan, Peter C. Wayner Jr., **Joel L. Plawsky**
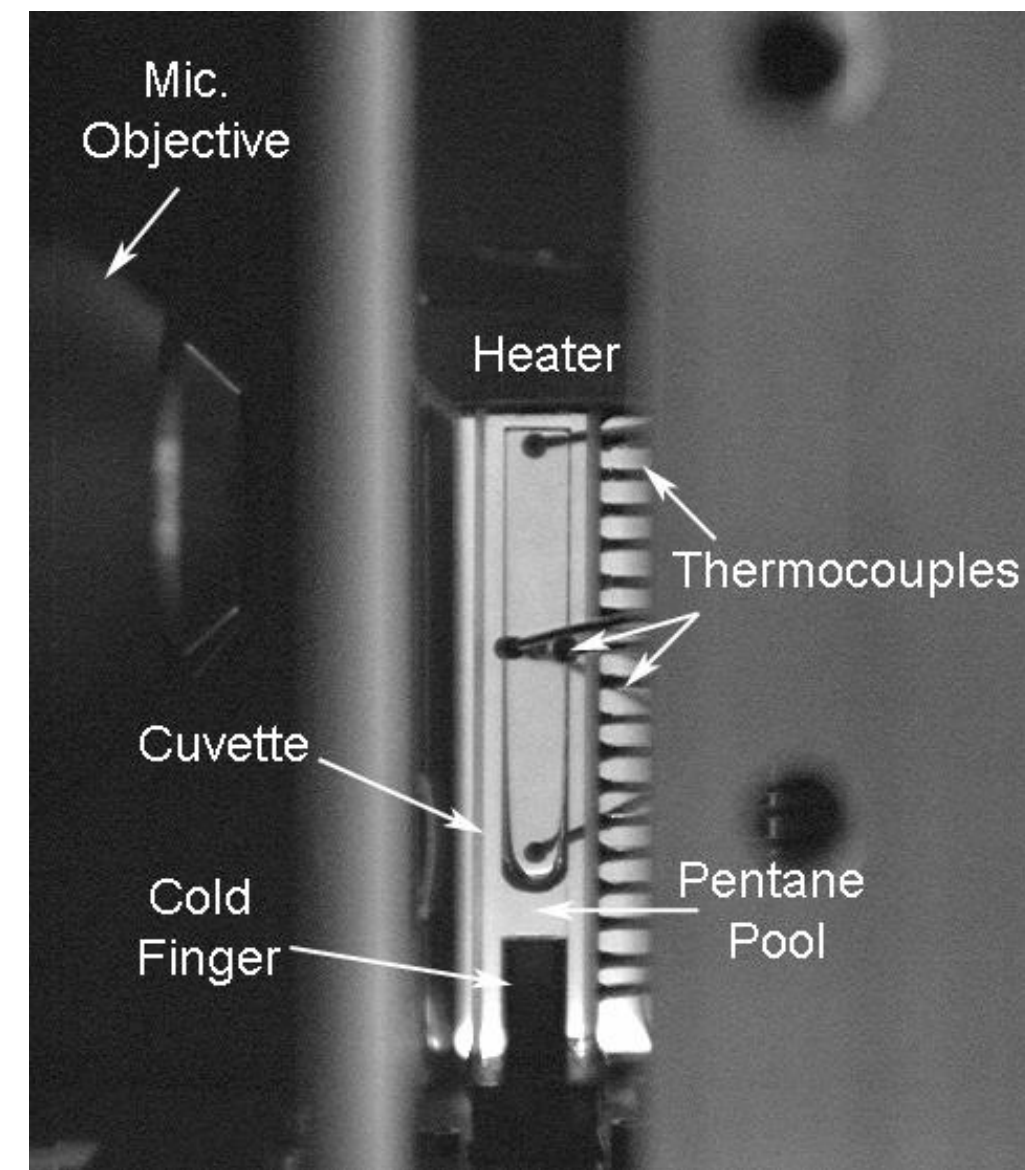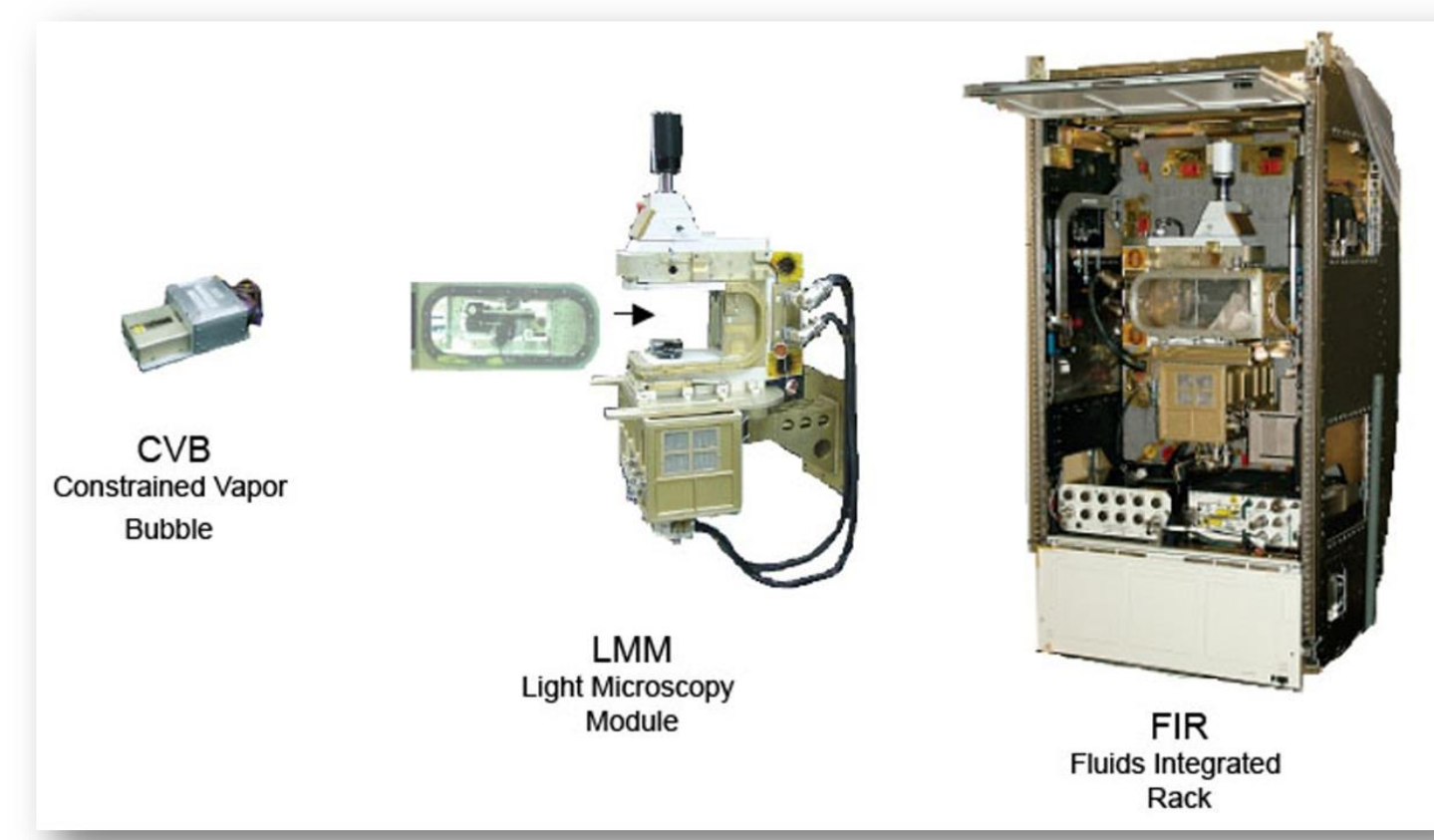
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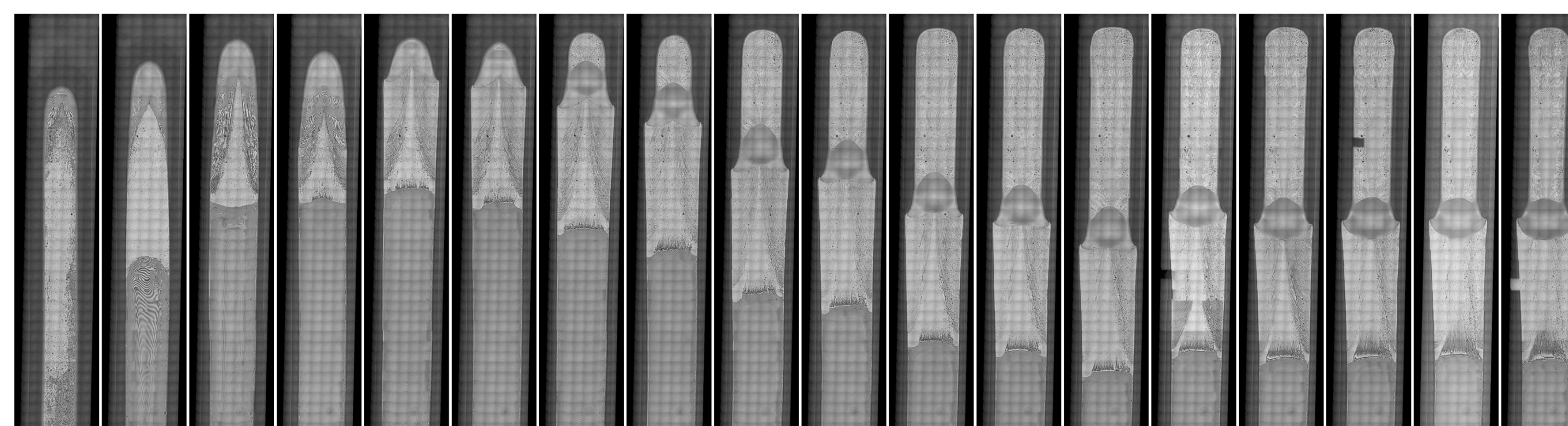
Introduction

Surveillance Image

Experimental set-up

- A bubble constrained by the walls of a solid.

- A transparent wickless heat pipe flown in the ISS

- 3mm x 3mm ~ 20 - 40 mm long (inside dimensions), size developed to have low Bond number.

- Study the fluid physics and determine the liquid and vapor distribution.

- Completely modular design.

Experimental Results

Composite image 40 mm µg run

- Heat pipes are predicted to dry-out as power is increased. [1-2]

- Opposite behavior of dry-out i.e. flooding observed at heater end from 0.7W onwards in microgravity [3].

- Formation of a thick layer of liquid near heater starts from 0.7 W – 3 W called Interfacial flow region

- Beyond 2.2 W, the interfacial region reaches a constant length, arresting further penetration of liquid down the axis of the heat pipe.

Experimental Results
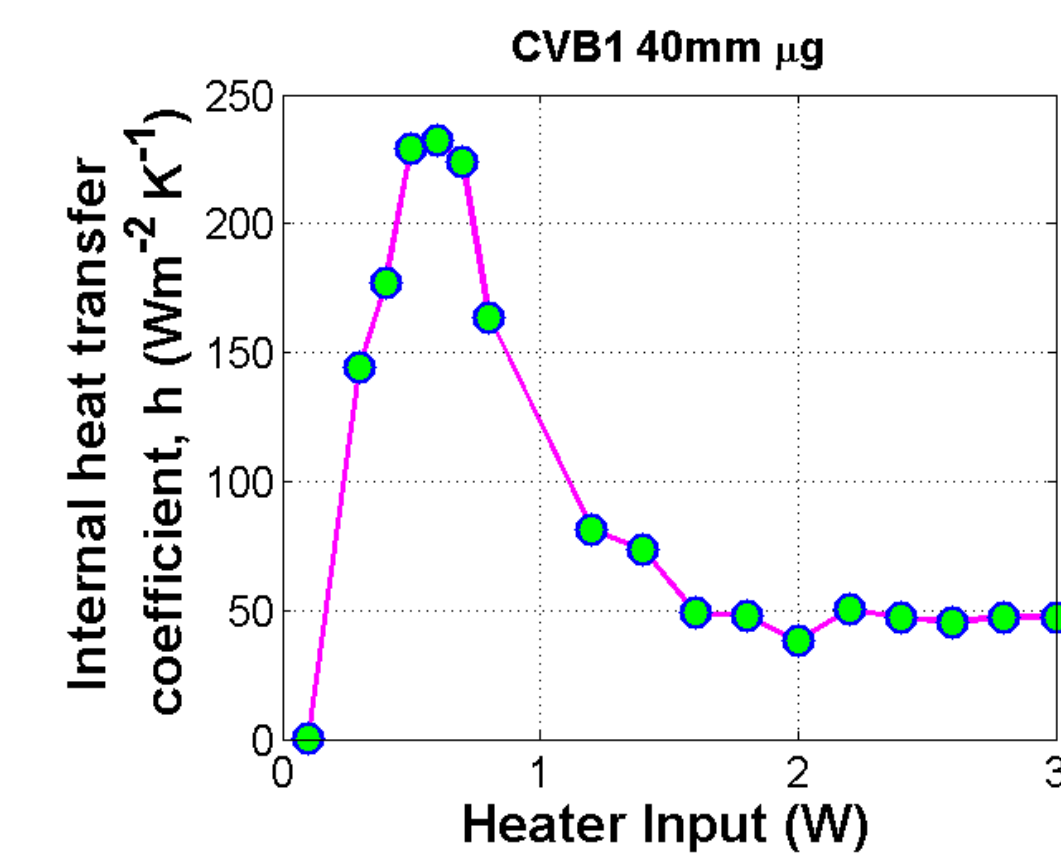

Interfacial flow region
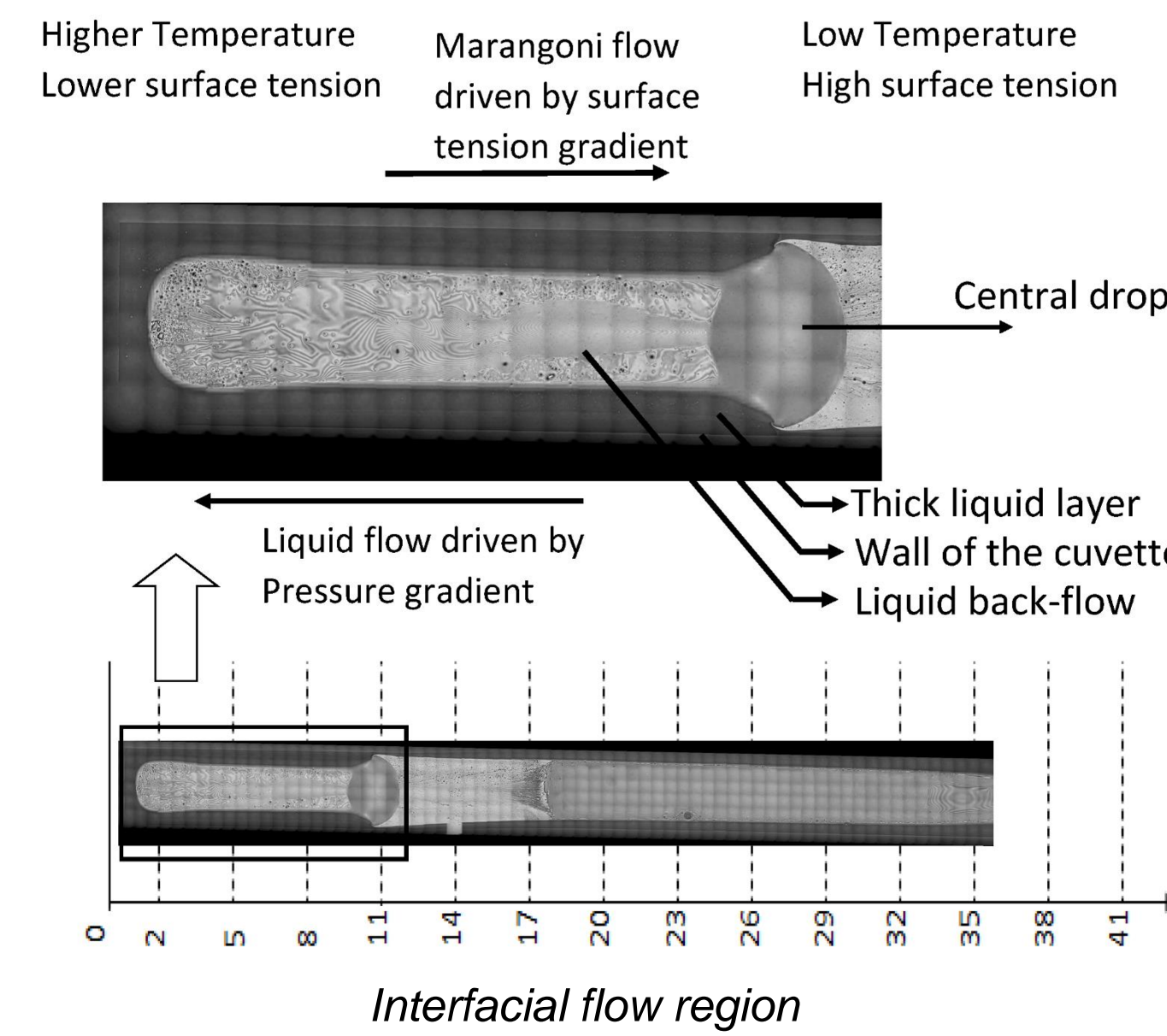
- The Marangoni stress forces liquid from the heater end to the cooler end.

- Capillary pumping forces liquid from the cooler end to the heater end.

- The flow combination leads to a pinch point and a central drop that collects the excess liquid.

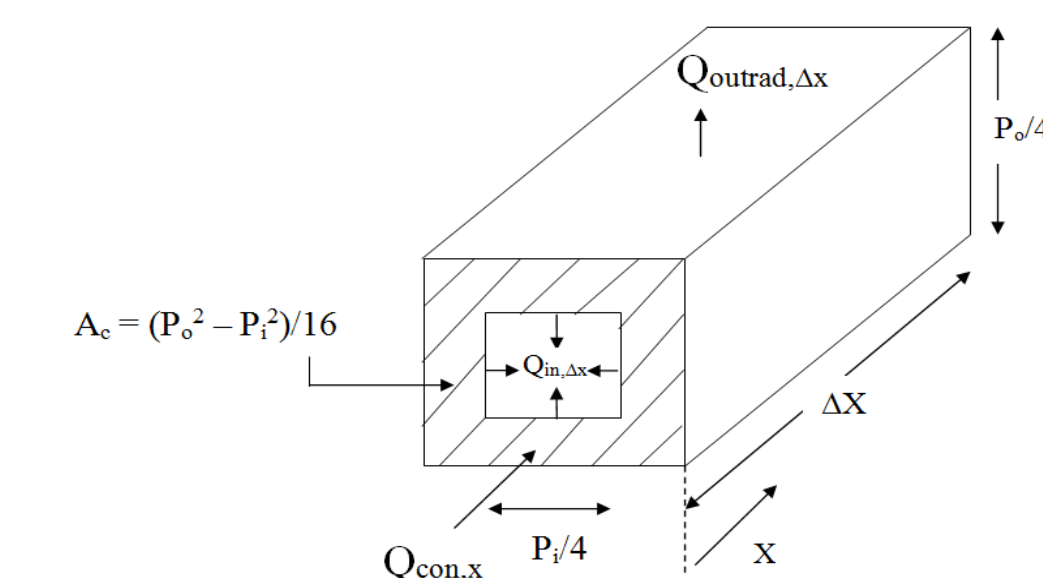- Increase in vapor space at 3 W hints at a new operation regime.

- Extra heat input is compensated by back flow and then evaporation of liquid in the vapor region.
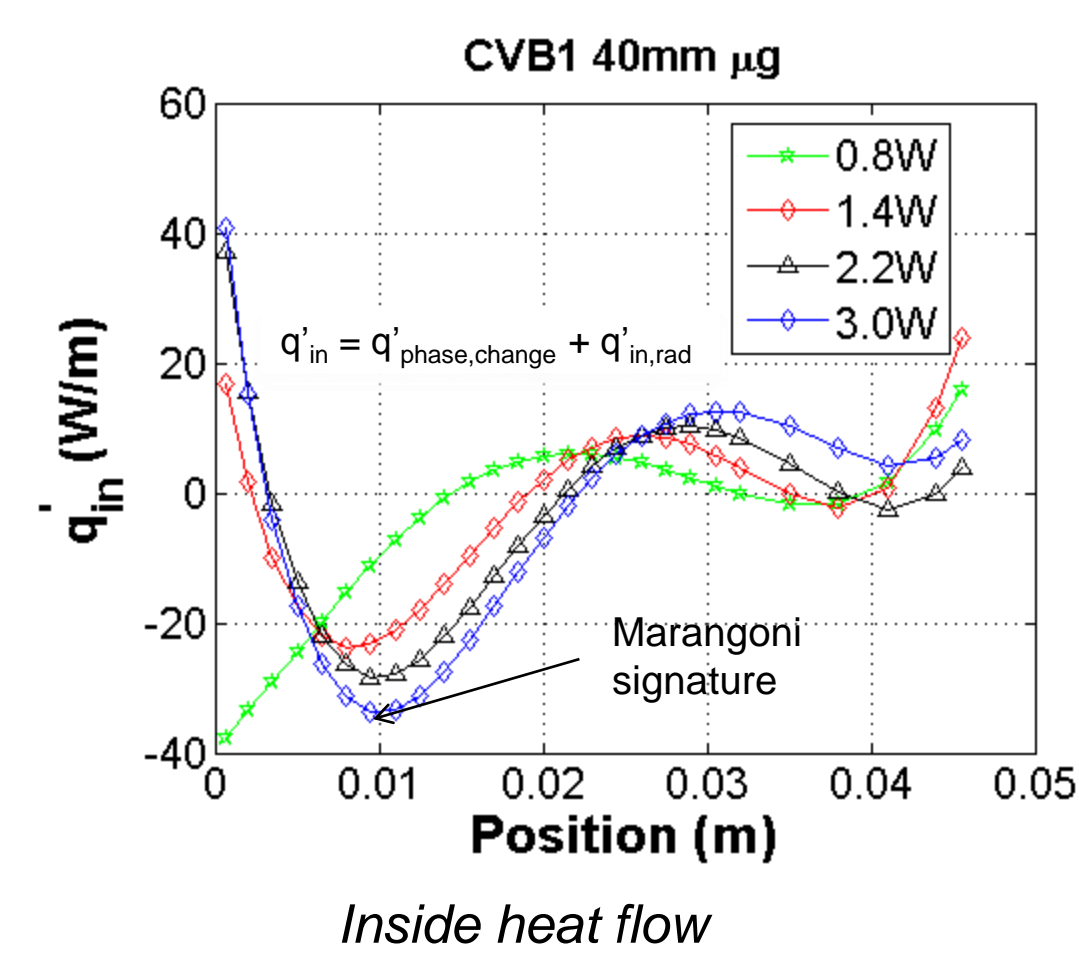
Mathematical Analysis

$$k_{silica}A_{silica}\frac{d^2T}{dx^2} - h_{inside}P_{inside}\left(T - T_{vapor}\right) - \sigma\varepsilon_{silica}P_{outside}\left(T^4 - T_{surroundings}^4\right) = 0 \qquad (1)$$

1D model for heat flow [4]

$$q'_{in} = q'_{cond} + q'_{outrad} \qquad (2)$$

Inside heat flow

- Maximum internal heat transfer coefficient at 0.7 W

- Interfacial flow starts from 0.7 W, results in increased resistance to heat transfer and thus, decrease in internal heat transfer coefficient.

- A constant internal heat transfer coefficient from 2.2 – 3W is consistent with the arresting of interfacial flow region.

- Bending curve near the heater end - a signature of 'Interfacial flow region'.

- The Marangoni signature coincides well with the location of central drop at high power inputs.

- Beyond 2.2 W heat input, the temperature gradient at 10-12 mm of heat pipe is not sufficient to offset the capillary flow and movement of the junction vortex down the axis is arrested.

- Increased heat input is dissipated to the surroundings as outside radiation.

- A balance between an increased evaporation rate due to thick liquid film and outside radiation results in a constant heat transfer coefficient.

Conclusions

- The internal heat transfer coefficient of the CVB can be correlated to the presence of the Interfacial flow region.

- The competition between capillary and Marangoni flows causes 'Flooding' near the heater and not a 'Dry-out' region.

- The growth of the interfacial flow region growth is arrested at higher power inputs.

- 1D heat model confirms the presence of 'Interfacial flow region' and its growth.

- Visual observations are essential to understanding the heat pipe's performance.

References

1. Savino, R., and Paterna, D., "Marangoni effect and heat pipe dryout", *Phys. Fluids,* 18, 118103, (2006).
2. Yang, L., and Homsy, G. M., "Steady three-dimensional thermocapillary flows and dryout inside a V-shaped wedge", *Phys. Fluids,* 18, 042107, (2006).
3. Kundan, A., Plawsky, J.L., Wayner, P.C., Jr., Chao, D.F., Sicker, R.J., Motil, B.J, Lorik, T., Chestney, L., Eustace, J. and Zoldak, J., "Thermocapillary phenomena and performance limitations of a wickless heat pipe in microgravity.", *Phys. Rev. Lett,* 114, 146105 (2015).
4. Kundan, A., Plawsky, J.L., and Wayner, P.C., Jr., "Thermophysical characteristics of a wickless heat pipe in microgravity – Constrained vapor bubble experiment", *Int. J. Heat Mass Transfer,* 78, pp. 1105-1113, (2014).

Future Work

- Understand the role of cooler temperature on the growth of the interfacial flow region and the magnitude of the interfacial forces

- Develop higher dimension model to predict the interface temperature gradient and the velocity profile in the interfacial flow region.

- Improve theoretical models [1,2] to predict the flooding behavior observed in CVB experiments.

Final goal is to cool critical space craft components to enable long-term manned missions.

Applications

- LED lamps, Desktops, laptops.
- Hubble Space Telescope, Mars Rovers.
- Very important for space applications.

Acknowledgements