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Akshay Kundan, Thao T. T. Nguyen, Joel L. Plawsky, Peter C. Wayner, Jr., David F. Chao, and Ronald J. Sicker

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**CONDENSATION ON HIGHLY SUPERHEATED SURFACES: UNSTABLE THIN  
FILMS IN A WICKLESS HEAT PIPE**

Akshay Kundan

The Howard P. Isermann Department of Chemical and Biological Engineering  
Rensselaer Polytechnic Institute  
Troy, NY, 12180.

[akshaykundan@gmail.com](mailto:akshaykundan@gmail.com)

Thao T. T. Nguyen

The Howard P. Isermann Department of Chemical and Biological Engineering  
Rensselaer Polytechnic Institute  
Troy, NY, 12180.

[nguyen.thaoche@gmail.com](mailto:nguyen.thaoche@gmail.com)

Joel L. Plawsky\*

The Howard P. Isermann Department of Chemical and Biological Engineering  
Rensselaer Polytechnic Institute  
Troy, NY, 12180.

[plawsky@rpi.edu](mailto:plawsky@rpi.edu)

Peter C. Wayner, Jr.

The Howard P. Isermann Department of Chemical and Biological Engineering  
Rensselaer Polytechnic Institute  
Troy, NY, 12180.

[wayner@rpi.edu](mailto:wayner@rpi.edu)

David F. Chao

NASA Glenn Research Center  
Cleveland, OH, 44135.

[David.F.Chao@grc.nasa.gov](mailto:David.F.Chao@grc.nasa.gov)

Ronald J. Sicker

NASA Glenn Research Center  
Cleveland, OH, 44135.

[Ronald.J.Sicker@nasa.gov](mailto:Ronald.J.Sicker@nasa.gov)

\*Corresponding Author: [plawsky@rpi.edu](mailto:plawsky@rpi.edu)

## **ABSTRACT**

A wickless heat pipe was operated on the International Space Station to provide a better understanding of how the microgravity environment might alter the physical and interfacial forces driving evaporation and condensation. Traditional heat pipes are divided into three zones: evaporation at the heated end, condensation at the cooled end, and intermediate/adiabatic in between. The microgravity experiments reported herein show the situation may be dramatically more complicated. Beyond a threshold heat input, there was a transition from evaporation at the heated end to large-scale condensation, even as surface temperatures exceeded the boiling point by 160 K. The hotter the surface, the more vapor was condensed onto it. The condensation process at the heated end is initiated by thickness and temperature disturbances in the thin liquid film that wet the solid surface. Those disturbances effectively leave the vapor “superheated” in that region. Condensation is amplified and sustained by the high Marangoni stresses that exist near the heater and that drive liquid to cooler regions of the device.

**KEY WORDS:** Marangoni flow, Condensation, Evaporation, Heat pipe, Instability, Disjoining Pressure.

## 1. INTRODUCTION

A heat pipe is a device of high thermal conductance used to transport heat over long distances in high heat flux applications. It is an ideal environment for studying how interfacial phenomena affects evaporation and condensation processes. Heat pipe technology has been extensively studied [1-4]. Many articles on micro [2-12], macro heat pipes [13-15] and V-shaped grooves [16, 17] have been published. The phenomena limiting the performance of heat pipes have been discussed theoretically [18 -21], demonstrated using temperature and pressure measurements [22-24], and directly visualized in some cases [25]. In any system sustaining large temperature gradients, Marangoni stresses, driven by surface tension differences, arise and may significantly alter flow fields and the processes of evaporation and condensation. Theoretical studies have shown that if enough Marangoni stress is generated in a heat pipe, it should lead to dry out of the hot end and the device will reach its capillary limit earlier [18-20]. Recently, microgravity experiments demonstrated that large Marangoni forces may have the opposite effect and lead to flooding of the heater end, not dryout [26].

The origins of flooding stem from observations of condensation on subcooled surfaces by Hijikata and Himeno [27] and meniscus evaporation on superheated surfaces by Argade et al [28]. The former found that certain binary vapor mixtures would condense in the form of droplets or streaks even though the two liquids are completely miscible and the vapors of the pure fluids should undergo film-wise condensation. The authors called the phenomenon, pseudo-dropwise condensation. As explained by Hijikata, Fukasaku, and Nakabeppu [29], the drops were formed by Marangoni flows. Local concentration gradients altered the interfacial tension between liquid and vapor leading to drop formation. Related phenomena occur in ultra-thin films of pure liquids exposed only to temperature gradients leading to film rupture and drop formation [30] or oscillations in a meniscus [31, 32].

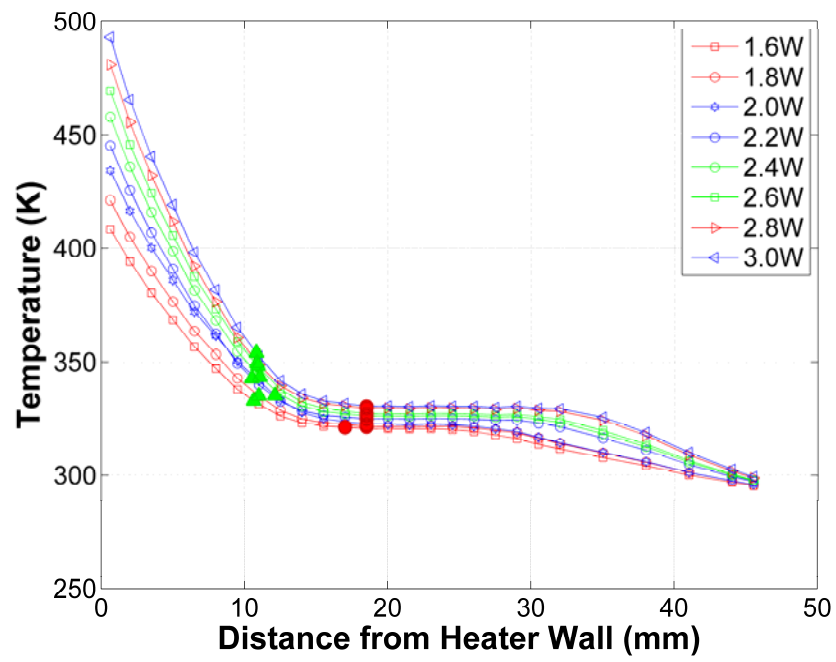
Here, we demonstrate that condensation of the working fluid on the superheated surface of a wickless heat pipe in microgravity first appears beyond a threshold thermal load to the device and is the source of the flooding phenomenon reported earlier [26]. As we increase the thermal load and raise the temperature at the heated end, the amount of condensed liquid increases. Condensation occurs even as surface temperatures exceed the boiling point by over 160 K. This condensation process arises, is sustained, and is amplified by Marangoni flows.

At this point, we are reporting on a phenomenon for which we have yet no absolute explanation, just snippets of previous models that may help point to an explanation. The purpose of this note was to present the one curious observation to the community, that as we increased the heat input into the device, we see evidence of increased condensation on the heated surface rather than the expected evaporation and dryout.

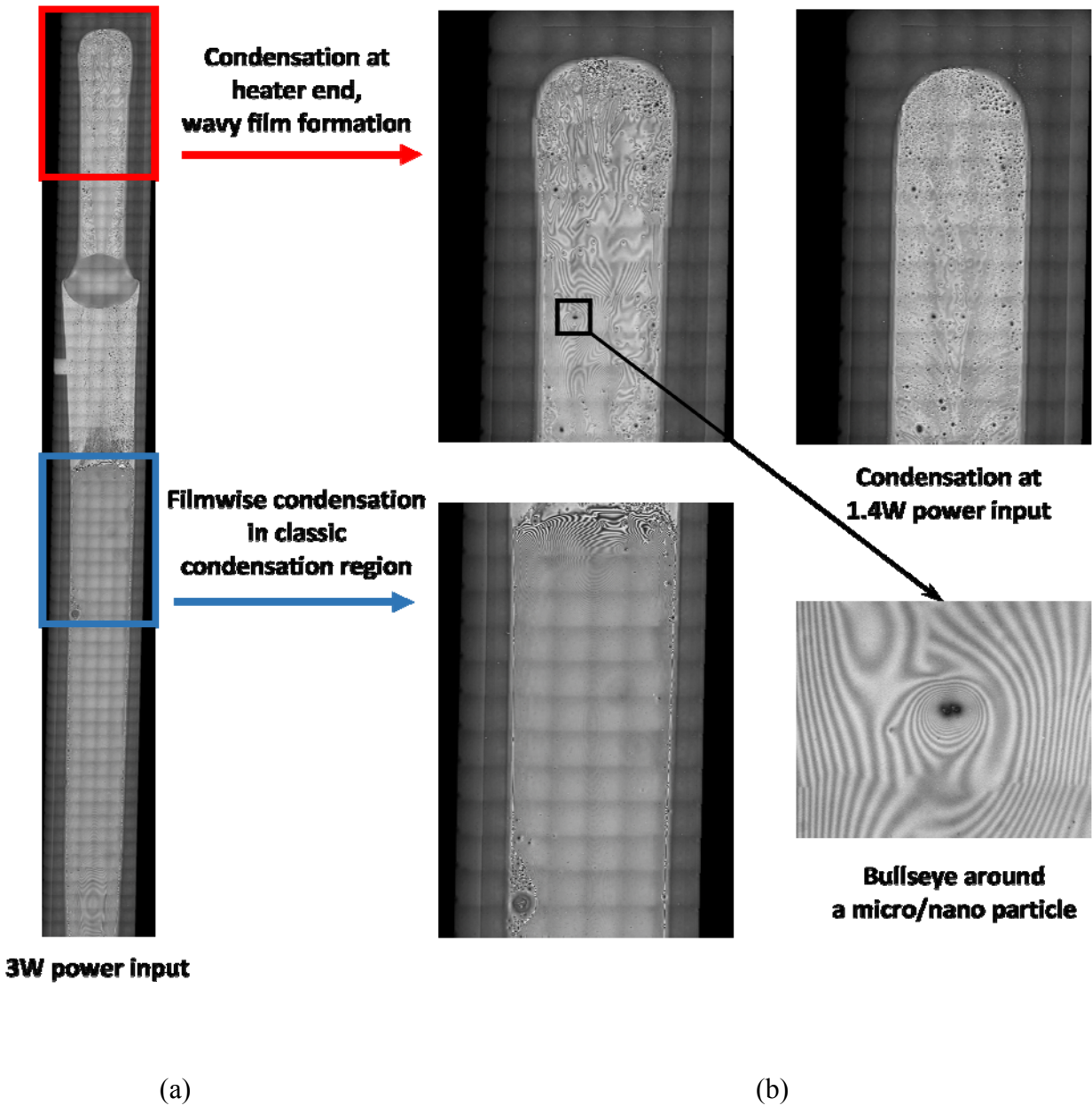
## **2. EXPERIMENTAL MEASUREMENTS**

The Constrained Vapor Bubble (CVB) experimental system aboard the International Space Station consisted of a silica cuvette partially filled with pure pentane. A constant heat input was supplied to the heater end, and the cooled end was kept at constant temperature by a cold finger. Thermocouples were installed along one of the walls of the cuvette to measure the temperature profile and interferometry was used to map the liquid film thickness profiles. The experimental details have been described in previous publications [26, 33-37] and a synopsis is given in the Supplemental Information section [38].

Figure 1 shows the temperature profiles in a 40 mm, microgravity CVB experiment carried out using a cold finger temperature of 292 K and electrical power inputs to the heater of 1.6 to 3W. Beyond 3W, the heater temperature exceeded the safety limit of 523K for operation on the space station. The red circles represent the condensation points calculated, using the Antoine equation and experimental pressure measurements [38]. They are a measure of the average vapor temperature. The green markers are the location of the central drop obtained from the vapor-liquid interface images [26] and are the points of maximum evaporation. At positions beyond the green markers, toward the cooled end, the system operates as a classic heat pipe.



**Figure 1:** Temperature profile along the heat pipe.



**Figure 2:** (a) The interfacial flooding region in the 40 mm microgravity CVB runs [35]. The composite images are comprised of 522 individual microscope frames. (b) Film-wise condensation in the traditional condensation region (lower image) versus the uneven, wavy, film condensation observed near the heater end at 3 and 1.4W power inputs respectively (upper images). The density of fringes is larger at 3W compared to 1.4 W indicating more liquid accumulating on the surface. The bullseye image shows pentane condensing around a microparticle(s).

### 3. RESULTS AND DISCUSSION

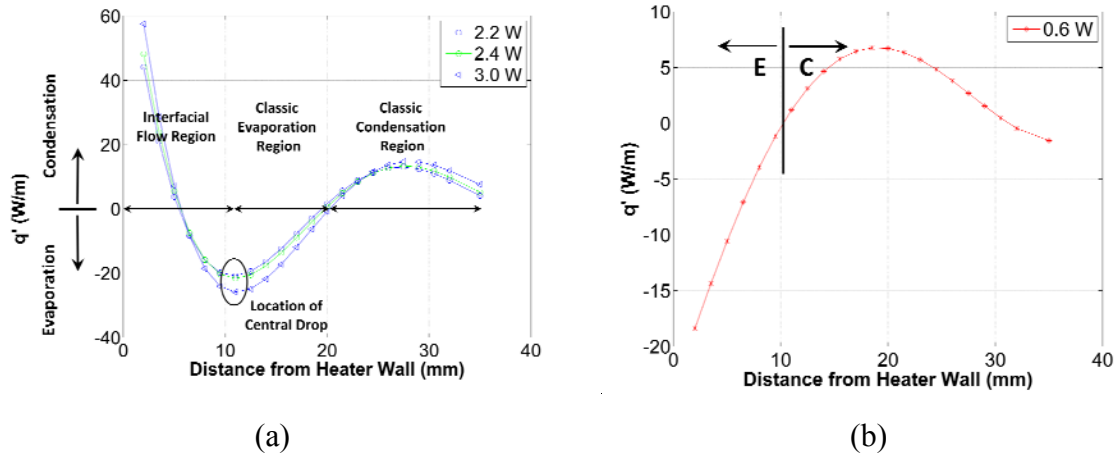
The liquid distribution within the CVB can be divided into several regions as seen in Figure 2a [35]. The interfacial region is located between the heater end and the "central drop" and first appears at a power input between 0.6 - 0.7 W. At larger power inputs, the temperature gradient was high enough to generate a significant Marangoni flow that drove the liquid away from the heater end. Instead of the heater end becoming dry, liquid accumulated there and reduced the performance of the heat pipe [26, 34]. In the sharp corners of the device, the competition between the capillary return flow and the Marangoni flow formed a junction vortex leading to a thick liquid "drop" that formed on the flat surface of the cuvette. The balance between the capillary pressure gradient and the Marangoni stress prevented the interfacial region from penetrating further down the heat pipe at power levels in excess of 2.2 W [35]. This can be clearly seen in Figure S2b.

In addition to flooding the corners with liquid, the flat surface of the heat pipe in the interfacial region became covered by a wavy, film of liquid as highlighted in Figure 2b. Though hard to see in Figure 2a, as the images at 1.4 W and 3.0W in Figure 2b show, this film became thicker as the heat load was increased. The images suggest that condensation occurred at the heater end, even at temperatures more than 160 K above the normal boiling point (red symbols in Figure 1).

We used the temperature data from Figure 1 in conjunction with similar data from an evacuated version of the heat pipe to perform a one-dimensional thermal analysis of the heat flow inside the heat pipe [33]. The results are shown in Figures 3a and 3b where the internal heat flow per unit length is plotted versus distance from the heater wall. The negative values in the figures represent net heat loss from the interior wall of the heat pipe while the positive values indicate net heat gain. At power inputs below 0.6 - 0.7 W where the interfacial region had yet to develop (Figure 3b), we observe only heat loss in the region within 1 cm of the heater wall. We attribute this to evaporation of the liquid there. Once the interfacial region appeared, we observed heat gain near the heater wall whose magnitude grew with the heat input. While we first thought the heat gain was due to increasing radiative exchange with the heater wall, the interference images and growth of the liquid film on the flat portions of the device suggest that the heat gain was due to condensation of vapor in that region. The 5 - 6 mm nearest the heater



wall, where  $q'_{in}$  was positive, coincides with the region where we observed the wavy thin film of liquid on the flat surface (Figure 2b). In addition, the temperature gradient in this region mimics what is observed in the classic condensation region as shown in Figure S2a.



**Figure 3:** Heat flow to (positive) or from (negative) the internal surfaces of the heat pipe associated with condensation or evaporation respectively. (a) High power inputs indicating condensation at the heater end; (b) The heat flow associated with a 0.6 W power input where the interfacial region has not yet developed. The E and C symbols refer to the traditional heat pipe evaporation and condensation regions.

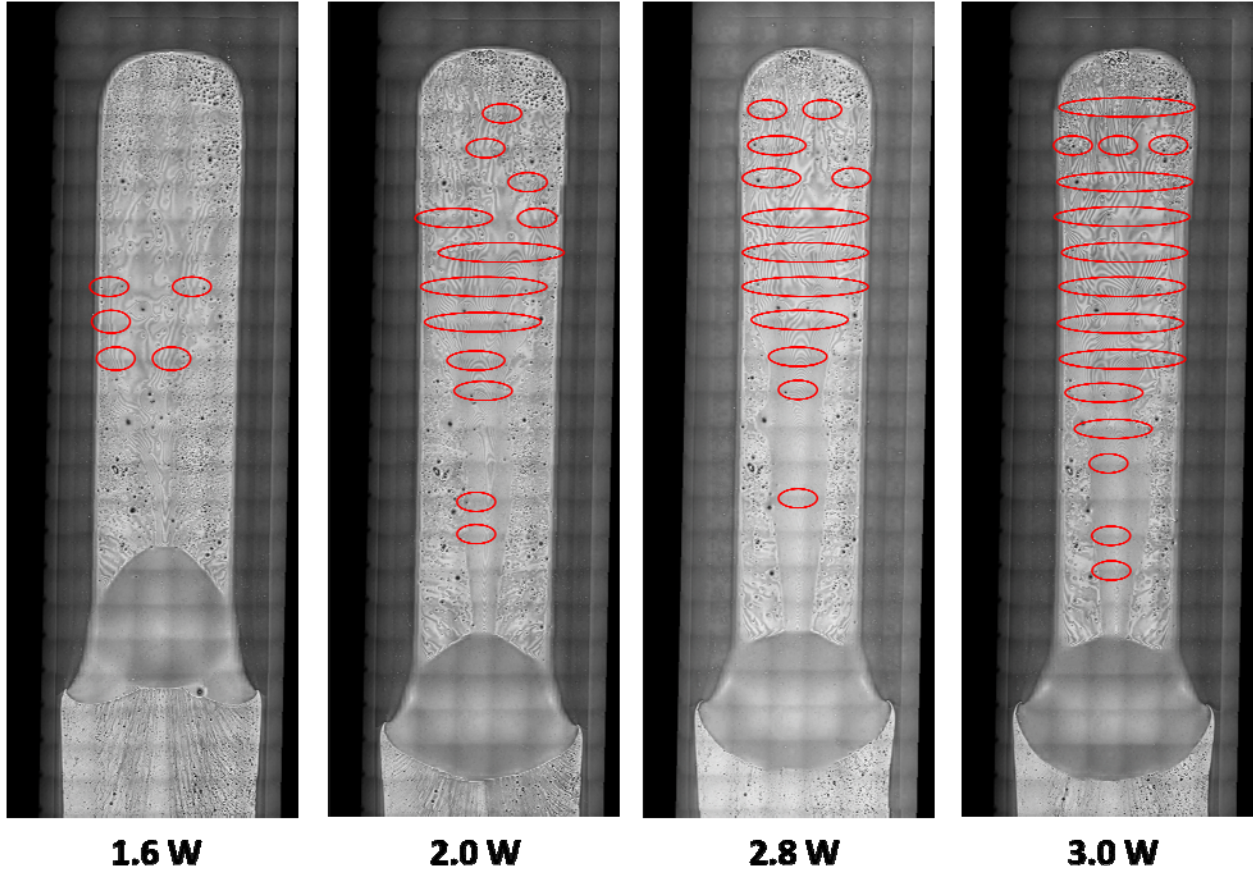
Traditionally, a heat pipe is divided into three consecutive regions: an evaporation zone near the heater, an intermediate or adiabatic zone if the device is insulated, and a condensation zone near the actively cooled region. The images and thermal analysis of the CVB indicate that at least in microgravity, the situation may be more complicated. The "normal" evaporation zone could be split into a condensation region followed by an evaporation region. There may be an additional, thin evaporation zone on the heater wall upstream of the condensation zone, but we were not able to image that portion of the device.

For a perfectly wetting fluid like pentane on a fused silica surface, only film condensation should occur. Film condensation does occur in the region nearer the cooled portion of the device as shown in the lower image of Figure 2b. The film thickness increases monotonically as one approaches the cooled end. By contrast, the region of condensation near the heater end is uneven

and at times patchy, suggesting that the physics of the condensation phenomenon involved there is different from that governing the classic condensation region. Temperature gradients along the main axis of the heat pipe can exceed 4000 K/m, while from the center to the edge, they are approximately 750 K/m, enabling strong Marangoni flows from the heater to the cooler end and from the center of the heat pipe toward its edges. The corner flooding in the interfacial region is fed by condensation on the flat surfaces and the flow of that condensate from the center to the edges of the heat pipe.

The remaining question is what drives the condensation at such high surface temperatures? Using the Augmented Young- Laplace Equation, the temperature jump at the vapor-liquid interface in the thin film regions of this system was shown to be on the order of  $10^{-5}$  K [35]. Small perturbations to this temperature jump would be sufficient to disturb the "equilibrium" and lead to evaporation or condensation within the film [28, 40]. This small perturbation can be created by a change in interfacial curvature that arises from surface roughness variations, liquid composition variations or, micro/nanoparticles present on the flat surface that were left over from device fabrication. These particles can be seen in Figures 2a and 2b.

At the very high temperatures near the heater, the unevenness of the wall surface and vapor-liquid interface results in large spatial and temporal perturbations to the film thickness of the kind discussed by Hijikata et al. [27, 29]. The high temperature gradients near the heater drive the condensed liquid in the interfacial region down the axis of the heat pipe and toward the corners. This prevents the thin film from achieving a steady-state, keeps the disjoining pressure higher than the capillary pressure, and amplifies and sustains condensation in that region.



**Figure 4:** Interfacial flow region where the ovals highlight regions showing frame-to-frame fringe discontinuities at various power inputs in microgravity. The number of discontinuities increases dramatically with increasing thermal load to the heat pipe.

While we see spatial variations in the film thickness, there are also temporal variations that contribute to the condensation. 10× composite images are shown for 1.6 W, 2.2 W, 2.8 W and 3.0 W in Figure 4. Each image is composed of 552 individual frames stitched together, mapping the entire surface of the cuvette. A complete mapping can take 2-3 hours and more details can be found in the Supplemental Information section [38]. As the whole composite image is comprised of individual images taken at a particular, fixed, frequency, any abrupt discontinuities within the fringe patterns from frame-to-frame indicate that the film thickness has changed within the time required to move the microscope stage one frame. Such instabilities are shown and highlighted in Figure 4. Oscillations in the film thickness are observed moving down the axis of the heat pipe and the frequency, or number, of these oscillations increases with

increasing power input. These instabilities lead to more condensation in the interfacial region and ultimately an increase in the adsorbed thin film on the flat surface.

In the context of thin film stability [30 – 32] for a perfectly wetting fluid, the stabilizing effects are due to the capillary and the disjoining pressures, while vapor recoil, gravity, and the Marangoni stresses tend to destabilize the film. Using models for thin film stability developed and summarized in [41] and a perturbation analysis, we found that the liquid film becomes unstable for wavenumbers,  $k$ , greater than zero if:

$$\frac{1}{\sigma h_0} \left( \frac{3\alpha_T \Delta\sigma}{2k_T} + \frac{A}{2\pi h_0^3} + \rho g h_0 \right) > k^2 > 0 \quad (1)$$

The details of how the equation was derived and the nomenclature used can be found in the Supplemental Information [38]. Here,  $A$  is the Hamaker constant and  $A < 0$  for a perfectly wetting fluid like pentane. Therefore, the thin film is unstable if:

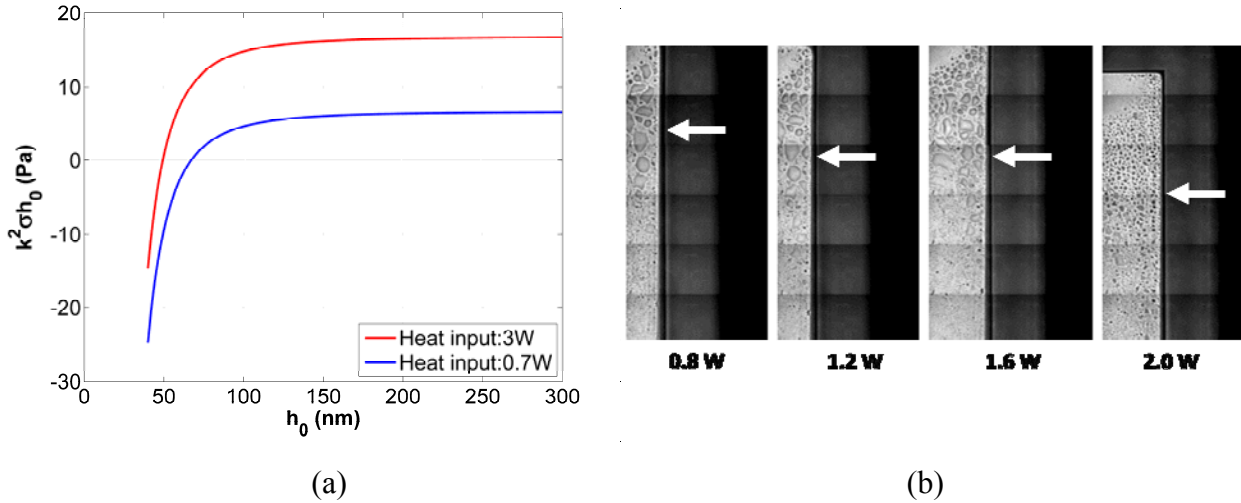
$$\underbrace{\frac{3\alpha_T \Delta\sigma}{2k_T}}_{\text{Marangoni Stresses}} > \underbrace{\frac{|A|}{2\pi h_0^3}}_{\text{Disjoining Pressure}} - \underbrace{\rho g h_0}_{\text{Gravitation}} \quad (2)$$

The Marangoni term depends on the superheat,  $\Delta\sigma = \gamma \Delta T_0$ . Therefore, at a given film thickness, there is a critical superheat,  $\Delta T_{0,C}$ , above which the film becomes unstable:

$$\Delta T_{0,C} > \frac{2k_T}{3\alpha_T \gamma} \left( \frac{|A|}{2\pi h_0^3} - \rho g h_0 \right) \quad (3)$$

In Figure 5, we plot the value of  $\sigma h_0 k^2$  as a function of liquid film thickness,  $h_0$ , for power inputs of 0.7 W and 3.0 W. These cases correspond to surface temperatures that were 20 K and 160 K above the normal boiling point of pentane at the pressures existing inside the device. 0.7 W represents the power input where instability is first observed, and 3.0 W [34] is the point where the safety limits of the experiment were reached. The gravitational component is always on the order of  $10^{-3}$  Pa or less and so it has a negligible influence on the stability. Gravity

does influence the overall performance of the device in 1-g by restricting the return flow of liquid to the heater end. The Marangoni component in Figure 5 starts to exceed the disjoining pressure component at a film thickness of 67 nm at 0.7 W, and 49 nm at 3 W. The first dark interference fringe visible in Figure 2 occurs at a film thickness of 100 nm when  $\lambda = 546$  nm light is used for illumination. Thus, whenever a fringe can be seen on the flat surface of the device near the heater end, the Marangoni component exceeds the disjoining pressure component and the film should be unstable as shown in Figure 5. At a superheat,  $\Delta T_0 \sim 160$  K, and  $h_0 \sim 100$  nm, the magnitude of the Marangoni component is approximately 17 Pa and the disjoining pressure is about 2 Pa.



**Figure 5:** (a) Scaled wavenumbers defining film stability as a function of film thickness. The surface superheat at 0.7 W was 20K and at 3.0 W was 160 K. Instability occurs when  $k^2 > 0$  and this occurs at a thickness above 49 nm at 3W and 67 nm at 0.7W. The values for the physical parameters were based on the average temperature at the heater end (heater wall to central drop), and were taken from the NIST database for pentane (<http://webbook.nist.gov/chemistry/fluid/>) and [42]. The Hamaker constant was estimated for pentane-on-silica using Lifshitz theory. The value of the heat transfer coefficient was taken from [34] and was calculated based on the models used to generate Figure 3. (b) 1-g images of the heater end of the CVB showing condensation effects at the heater end. Condensation appears dropwise due to very little return flow in the corners. Full images can be found in the Supplemental Information section [38].

As shown in Figure 5b and in Figure S3, the phenomenon also appears in 1-g, if one knows to look for it. However, since the return flow of liquid is meager in 1-g, there is little vapor to condense at the heater end and the phenomenon appears as if pentane were a partially wetting fluid. Thus, it can be easily confused with surface contamination. The droplet density increases and the droplet size decreases with increasing heat input, indicating that it is likely not surface contamination or fluid impurities adsorbing on the surface. The liquid was tested upon returning the device to Earth and was shown to be free of contaminants that might have caused partially wetting behavior.

#### **4. CONCLUSIONS**

Unexpected condensation of liquid on a large scale at the heater end of a wickless heat pipe was observed and analyzed. Small perturbations to the interfacial temperature jump due to the variations in film thickness effectively superheated the vapor and caused the condensation to occur even at temperatures 160 K or more beyond the boiling point. The condensed liquid was driven down the main axis of the heat pipe and from the center of the heat pipe to its edges by strong Marangoni stresses. This led to flooding of the heater end of the device. The thin film within the interfacial/flooded region was spatially and temporally unstable leading to more condensation as the wall temperature was increased. These phenomena also occur in a 1-g environment but are easily mistaken for the effects of surface contamination.

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