

# Dropwise Condensation in Vapor Chambers

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## Abstract

Electronic devices continue to shrink in size while dissipating more heat. The size of the air cooled heat sinks required to remove this heat has increased while the size of the heat source has decreased. These trends have resulted in large conduction gradients across the base of the heat sinks, resulting in decreased thermal performance. A passive and reliable method of minimizing the spreading resistance in air cooled heat sinks is to embed a vapor chamber in the base of the heat sink. A vapor chamber is a two-phase heat transfer device that uses capillary forces to isothermally circulate a working fluid at saturated conditions. Provided that the vapor chamber is circulating fluid properly (within its capillary limit) the thermal resistance of the vapor chamber is limited by the evaporating and condensing processes in the vapor chamber. Much attention has been paid to the evaporating process since the heat flux of the evaporating process is generally many times higher than that of the condensing process. However, heat fluxes in the condensing regions of vapor chambers have risen to the point where they can't be neglected. Described here is a novel method of improving the condensation performance in vapor chamber devices by using self-assembled monolayers to promote dropwise condensation. In other applications, dropwise condensation has been shown to improve the condensation heat transfer coefficient by an order of magnitude over the typical filmwise condensation surfaces found in vapor chambers. Presented here are condensation test data comparing the performance of filmwise and dropwise condensation surfaces in vapor chambers.

## Keywords

Dropwise Condensation, Vapor Chambers, Self-Assembled Monolayers, Thermal Management, Electronics Cooling

## Nomenclature

|            |   |
|------------|---|
| $h$        | Heat transfer coefficient               |
| $k$        | Copper thermal conductivity             |
| $L_{2-1}$  | Distance from between thermocouples     |
| $L_{2-s}$  | Distance from thermocouple 2 to surface |
| $q''$      | Heat flux                               |
| $T_1$      | Temperature at thermocouple 1           |
| $T_2$      | Temperature at thermocouple 2           |
| $T_s$      | Condenser surface temperature           |
| $T_\infty$ | Temperature of saturated fluid space    |

## 1. Introduction

As the electronics industry continues to push processor performance, the amount of power utilized by these devices grows [1]. System integrators face challenges in thermal management as consumers continue to demand smaller, more portable, and more rugged devices. For these devices to maintain a nominal operating temperature, the thermal management techniques involved must also continue to become more efficient and compact. An important process in the current thermal management architecture involves spreading the heat generated from these small electronics devices over a larger area so the heat can be dissipated to the ambient through traditional air cooled heat sinks [2]. The use of two-phase heat transfer devices such as heat pipes and thermosyphons to help spread heat has become common [3]. As the overall device package shrinks the area for the heat sink also decreases, causing larger thermal gradients and heat fluxes through the condensing sections of the two-phase heat transfer devices. A need arises for technologies resulting in a decrease in condenser thermal resistance without additional power consumption or moving parts.

For the past 60 years dropwise condensation has been studied for its ability to produce heat transfer coefficients an order of magnitude higher than filmwise condensation [4]. The mechanism of dropwise condensation is still debatable and much discrepancy exists in the literature on this topic [5]. However, the ability of dropwise condensation to increase heat transfer coefficients over filmwise condensation is well established. Research into dropwise condensation is inspired by economic incentives attainable if the heat transfer coefficients of dropwise condensation can be sustainable [6]. However, only recently have researchers been able to create surfaces which can maintain their properties and sustain the dropwise condensation mode over time [7].

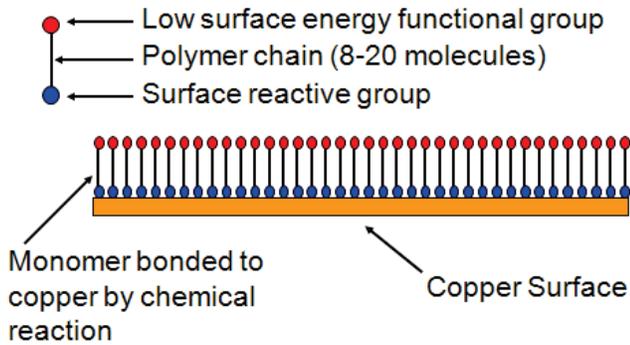
In industrial processes, hydrophobic coatings are typically plagued by surface pollutants that result from the impure chemicals used in the processes. These pollutants tend to plate/cover the hydrophobic condensing surfaces over time. When this occurs, the wetting properties of the surface are determined by the wetting properties of the various surface pollutants. These surface pollutants tend to be hydrophilic, resulting in a transition from dropwise condensation to filmwise condensation. In this paper, dropwise condensation is studied for application in closed two-phase heat transfer devices such as heat pipes and vapor chambers. In these systems the working fluid is pollutant free. Since these devices are closed for the entire duration of their lifetime, no surface pollutants will be introduced to the system during normal operation. Therefore, it is expected that dropwise

condensation can be maintained in heat pipes and vapor chambers as long as the coating does not wear or degrade.

One method of modifying the wetting properties of a surface is to use self-assembled monolayers (SAMs). SAMs have the advantage that they are one molecule thick, and therefore do not add appreciable thermal resistance to the condensing surface. Even though they are so thin, they can completely alter the surface properties of a metal to the desired wetting property. In this paper, the condensation surface of a copper vapor chamber was modified using a thiol based SAM to make the condensing surface hydrophobic. Thiol based SAMs were chosen because they create strong covalent bonds with copper. The strong nature of the covalent bond allows the coating to survive for long periods of time. Currently life testing of the coatings used in this study is ongoing.

## 2. Surface Preparation Background

Using the SAM technique involves chemically reacting a molecule with a short polymer chain to a surface as demonstrated in Figure 1. The chemical used in these types of surface preparations are typically polymer chains with a backbone that ranges from approximately 8 to 20 carbon atoms long [8-9]. On one side of the polymer chain is a reactive functional group, capable of forming a chemical bond with a surface. In this study the copper surfaces were prepared using a thiol (or sulfur) reactive group. It should be pointed out that the coating used in this process differs from typical surface coverings, as the chemical bond between the molecule and the metal surface is of a permanent nature.



**Figure 1** Illustration of non-wetting surface preparation using self-assembled monolayer technique. While one end of the molecule chemically reacts with the surface, the hydrophobic (non-wetting) side of the molecule points away from the surface creating a surface that is entirely non-wetting.

The other end of the polymer chain is a surface group with low surface energy, such as a methyl  $-CH_3$  or fluoryl  $-CF_3$  group. Surfaces with low energy are considered hydrophobic or non-wetting. SAMs form a one layer thick coating very readily because of the self-extinguishing nature of the reaction. Since the thiol (reactive) end group only reacts with the copper surface, and not the hydrophobic end group, the process cannot continue after one layer is created. The result

of the SAM process is a surface which is chemically altered possessing only the surface properties of the hydrophobic functional end group of the molecule.

The copper surfaces tested in this study were prepared with a heptadecafluoro-1-decanethiol SAM. The surfaces were first polished until an optical quality (mirror) surface was attained. The surfaces were then ultrasonically cleaned with methanol. The native copper oxides on the surface were removed with nitric acid. The surface was then exposed to a solution to create hydroxyl groups on the copper surfaces. The SAM was then created by placing the surface in a dilute solution of IPA and heptadecafluoro-1-decanethiol overnight. The surface was also rinsed with IPA and blown dry with nitrogen after every step of the preparation. Immediately after preparation the contact angle was visually inspected at various locations on the lid to be  $\sim 110^\circ$ , consistent with previous observations.

## 3. Experimental

A vapor chamber possessing a dropwise condensation surface was fabricated. In the development effort, multiple vapor chambers were fabricated and “opened” to assure that the coating was intact after fabrication. Figure 2 shows droplets placed on the condenser surface after fabrication.



**Figure 2** Droplets were placed at multiple locations on the vapor chamber lid to test for hydrophobicity.

The performance improvement attributable to the dropwise condensation coating was then experimentally tested. A vapor chamber prototype was specially modified to acquire accurate heat transfer coefficients in the condenser. This extra effort is required since the  $\Delta T$  from the wall to fluid space is often very low ( $< 2^\circ C$ ) with dropwise condensation.

The condensation lid of the vapor chamber was made thicker than a normal vapor chamber lid to allow for accurate measurement of the heat transfer coefficient on the vapor chamber inner surface. The thicker lid allowed for the drilling of two holes in the condenser surface that were used to extrapolate the surface temperature of the condensation surface and perform conduction calorimetry. Conduction calorimetry was performed by using Fourier’s Law to calculate the heat flux at each location. By using the two thermocouple measurements at each location, the distance between the thermocouples and the known thermal conductivity of copper, the local heat flux was calculated using Equation 1. Using Equation 2, the surface temperature was extrapolated. The local heat transfer coefficient could

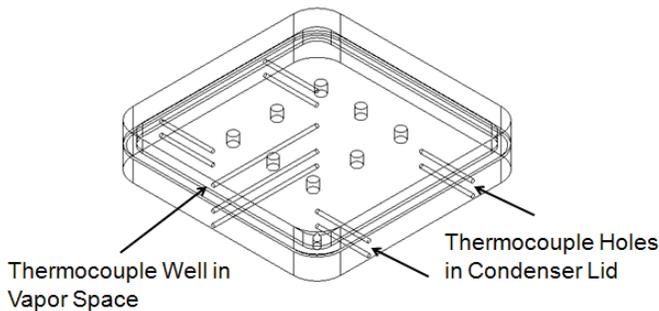
then be calculated using the locally measured heat flux, surface temperature and saturated fluid temperature.

$$q'' = k \frac{T_2 - T_1}{L_{2-1}} \quad \text{Equation 1}$$

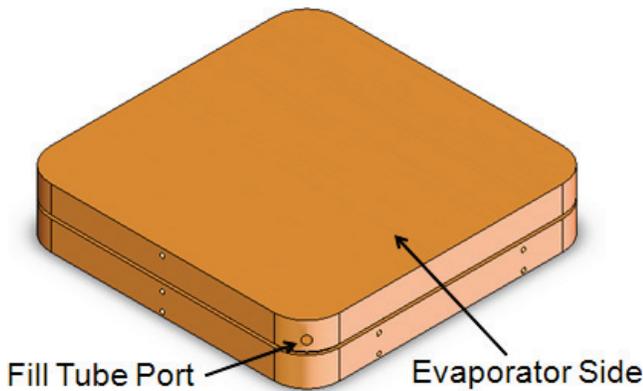
$$T_5 = T_2 + q'' \frac{L_{2-s}}{k} \quad \text{Equation 2}$$

$$h = \frac{q''}{T_\infty - T_s} \quad \text{Equation 3}$$

A diagram showing the location of various thermocouples in the vapor chamber is shown in Figure 3. Two (2) holes were drilled at five (5) locations in the lid to extrapolate the surface temperature and determine the local heat fluxes through the lid. The dimensions of the vapor chamber heat input areas were 5.08cm x 5.08cm. The heat input (evaporator) and heat removal (condenser) sections were equally sized in this experiment to exaggerate heat fluxes in the heat removal regions.



**Figure 3** A solids model showing the location of thermocouple required to measure the surface temperature and heat flux (through conduction calorimetry) are shown. Also shown is a thermocouple in the fluid space to measure the saturated fluid temperature.



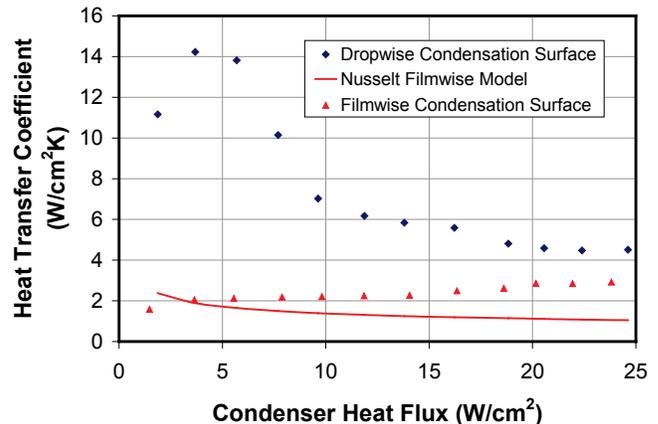
**Figure 4** A solids model of the tested 5.08cm by 5.08cm vapor chamber is shown.

#### 4. Data and Results

The vapor chamber was tested in a gravity aided orientation with the condenser surface perpendicular to the ground. A baseline vapor chamber with a filmwise condensation surface was also fabricated and tested. The vapor chambers were tested with the saturated vapor temperature set to 70°C. The average condenser heat fluxes tested ranged from 2W/cm<sup>2</sup> to 25W/cm<sup>2</sup>.

Measured heat transfer coefficients for the filmwise and dropwise condensation surfaces are shown in Figure 5. The data shown are the numerical average of the five (5) local heat transfer coefficients measured. The filmwise condensation data is also compared to the Nusselt filmwise condensation model [4] in Figure 5.

The dropwise surface resulted in condensation heat transfer coefficients that were ~4 times higher than model predicted filmwise condensation and ~2 times higher than the tested filmwise surface. The disagreement between the filmwise condensation model and the filmwise condensation test data is likely due to surface conditions. Organic contamination on the filmwise surface is likely to result in a transitional dropwise/filmwise surface that is consistent with the test data. However, it is expected that the transitional (part dropwise/ part filmwise) surface that was likely present would eventually transition to completely filmwise and result in the predicted filmwise condensation performance. In another study conducted on copper surfaces where visualization of the surface was possible, the filmwise data matched very well with the model [10]. In that work, the test setup allowed for stringent cleaning of the surface and more control over the copper oxide growth conditions.



**Figure 5:** Gravity aided condensation heat transfer coefficient data for a vapor chamber with a dropwise condensation surface is shown. Filmwise data are also compared to predictions from the Nusselt model for filmwise condensation.

The dropwise condensation performance was also not as beneficial as expected. In the same study referenced above, an 8-10 times improvement in heat transfer coefficient was measured with dropwise condensation over filmwise

condensation. It is suspected that the degradation of the surface around the perimeter may have contributed to the measured performance degradation. This effect should be minimized when a larger vapor chamber is fabricated, and the perimeter defects aren't as important.

## 5. Conclusions

Self-assembled monolayer coated condensation surface were tested in vapor chamber heat transfer devices suitable for commercial electronics cooling. A well instrumented vapor chamber was fabricated and tested to take accurate condensation heat transfer coefficient measurements. A filmwise and dropwise condensation vapor chamber was experimentally tested. The dropwise condensation mechanism demonstrated superior performance over conventional vapor chambers with a 4 fold improvement in heat transfer coefficient performance over predicted filmwise condensation performance. Dropwise condensation performance is expected to be even higher if the quality of the self-assembled monolayer coating can be maintained on the perimeter of the vapor chamber during sealing.

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