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Investigation of Boiling Behaviors in Vapor Chambers in Response to Transient Heat Input Profiles^a

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Abstract

Vapor chambers are being increasingly utilized as passive heat spreaders in various high-power density thermal management architectures. Particularly, in applications involving power electronics packaging, there is a need to understand and predict thermal performance of vapor chambers under different transient heat loads. It is known that boiling could occur in the wick structure of a vapor chamber at the location of heat input if sufficiently high heat fluxes are directly imposed on the chamber wall. Prior experimental studies that characterize the steady state thermal resistance of vapor chambers versus input power can only identify the behavior before and after the transition to boiling. However, because the initiation of boiling is a discrete event that occurs during the transient powering up, it is critical to understand how boiling behaviors will affect the performance of the vapor chamber in response to the transient heat input profile characteristics. Furthermore, currently available transient vapor chamber modeling efforts do not consider the occurrence of nucleate boiling, precluding their usage for applications where boiling is likely to occur. In this paper, we experimentally characterize the occurrence and effect of nucleate boiling in a vapor chamber coupled with an air-cooled heat sink, subject to various transient heat input profiles. The long-time step response behaviors are first studied for ten on-off cycles, at different on-powers, to illustrate the complete temperature response to a steady state in each cycle. For a range of intermediate powers, an interesting phenomenon is observed, where boiling occurs in every alternate cycle; we identify this range as the transition regime of boiling incipience in the vapor chamber. We further investigate the transient response to a pulsed heat input for various on-times ranging three orders of magnitude from 0.1 s to 400 s, and with two duty cycles (0.25 and 0.5), while keeping either the on-power or the average power constant. For a fixed on-power, lower on-times (0.1 s – 2 s) do not cause any boiling, but for longer on-times (≥ 20

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s), cases with lower duty cycles led to occurrences of boiling incipience. Furthermore, for a fixed average power, a higher on-power at a lower duty cycle is more likely to cause boiling, which interestingly leads to an even lower mean steady temperature compared to cases with lower on-power and larger duty cycle. These studies provide insights into the nature of boiling incipience in vapor chambers for their usage under realistic transient input powers mimicking power electronics.

Keywords

Vapor chamber; boiling; transient response; thermal resistance.

Nomenclature

d	duty cycle (-)
f	switching frequency (s^{-1})
I	current (A)
P_{avg}	average power (W)
P_{on}	on-power (in transient tests, W)
Q	input power (in steady state tests, W)
t_{on}	on-time (s)
t_{off}	off-time (s)
t_p	time period (s)
T	temperature ($^{\circ}C$)
U	uncertainty
V	voltage (V)
R	thermal resistance ($^{\circ}C/W$)

Subscripts

air	air flow
$heater$	serpentine resistive heater
$total$	heat sink stack

1 Introduction

Vapor chambers offer an attractive means to spread heat from a localized heat source to a large heat rejection area, and have been utilized for thermal management applications ranging from low power density devices, such as in mobile phones or personal computers [1,2], to high power density embedded heat sink architectures [3]. Next-generation wide-band gap (WBG) semiconductor packaging within hybrid vehicle power electronic systems and radar applications poses a significant thermal design challenge, due to miniaturization driven by space and weight constraints, leading to high device-level power densities. For thermal management in these scenarios, vapor chambers can replace bulky solid metallic heat spreaders due to their high effective in-plane thermal conductivity [4], thus reducing the overall thermal resistance to heat dissipation.

In order to support high heat flux dissipation using vapor chambers, various works in the literature have used thick porous wick structures as evaporator wicks. Here, we review some of these studies and motivate the need to investigate the effect of nucleate boiling under such high heat fluxes. Chen *et al.* [5] studied the usage of an air-cooled heat sink with an embedded vapor chamber for thermal management of a high-power LED pack. The sintered copper evaporator wick was 1.6 mm thick and made with radial re-entrant microchannels inside the porous wick to provide separated flow passages for vapor and liquid flow. The vapor chamber was shown to offer a much lower thermal resistance compared to a copper plate at high powers (> 130 W). In a similar study, Deng *et al.* [6] characterized the performance of a vapor chamber with radial multi-artery wick for high power dissipation > 280 W over 1 cm^2 heater areas. They used a 2.5 mm thick sintered copper wick to support high heat fluxes. The performance of a vapor chamber with a 2 mm thick copper foam porous structure was characterized by Ji *et al.* [7]. The vapor chamber was tested up to a maximum power of 170 W (216 W/cm^2), without the occurrence of dryout, at a thermal resistance of $0.09\text{ }^\circ\text{C/W}$.

Under the application of a high heat flux directly at the wall of a vapor chamber, it is known that nucleate boiling can occur in the internal evaporator wick structure lining the walls. This causes a reduction in the thermal resistance because, compared to purely evaporative mode, the conduction resistance across the saturated wick structure to the evaporating liquid-vapor interface is bypassed [8,9]. The conditions that trigger initiation of nucleate boiling in vapor chambers are not well understood and the process is considered to be probabilistic. Earlier studies involving the characterization of onset of nucleate boiling in capillary-fed wick structures [8,10] have proposed that the process is driven by the wall superheat (temperature rise of the substrate over the saturation temperature), as in conventional boiling processes. Altman *et al.* [11] studied the incipience superheats for sintered wick structures within vapor chambers and found that the superheat for incipience ranged from $20 - 75\text{ }^\circ\text{C}$ above the saturation temperature. In a separate study, Joshi *et al.* [12] and Zhou *et al.* [26] showed the occurrence of nucleate boiling in a vapor chamber (with a 1.5

mm thick evaporator wick) with an air-cooled heat sink. They demonstrated very high heat fluxes ($\sim 450 \text{ W/cm}^2$) could be dissipated without dryout using the thick sintered wick structure. Weibel et al. [13] investigated the repeatability of capillary-fed boiling incipience superheats on monolithic sintered copper samples and observed a wide spread of superheats ranging from $2.1 - 19.8 \text{ }^\circ\text{C}$ on identical samples. This is significantly higher than the superheats observed in pool boiling of water from sintered porous coatings [14,15,16], which are as low as $1.5 \text{ }^\circ\text{C}$. This apparent increase in the capillary-fed boiling incipience superheat was speculated to be caused by the suppression of bubble nucleation in the thin liquid layers sustained in the pore spaces of the porous sample [13].

The performance of vapor chambers is typically characterized under steady state conditions, wherein a specified input power is applied at the evaporator and the system is allowed to reach steady state [17,18]. However, power devices operate in pulsed mode wherein a large power draw occurs over very short times [19]. Future trends in power electronics package design is expected to move toward miniaturization and integration of active and passive devices [20]. Large transient heat loads need to be rejected efficiently to the cooling system to maintain a safe device operating temperature and high reliability. The push toward miniaturization of power modules sacrifices the thermal capacity of the architecture for reduced thermal resistance, which exacerbates this thermal challenge of pulsed systems. Thus, it becomes critical to understand how the behavior of steady state cooling solutions, such as air cooling with embedded vapor chamber heat spreaders, changes when applied to pulsed systems.

There are few investigations in the literature that experimentally study the transient characteristics of heat pipes and vapor chambers. Chen *et al.* [21] studied the transient response of a vapor chamber in conjunction with a plate-fin air-cooled heat sink and used the results to validate their numerical model. Saad *et al.* [22] investigated the transient operation of a copper-water heat pipe with the effect of non-condensable gases. They developed a transient network model to explain the observations. In these studies, the transient behavior of the vapor chamber is intrinsically coupled to the response of the heat sink, which has a significant thermal mass. Patankar *et al.* [23] utilized a method for transient characterization wherein a heat pipe was suspended in air during characterization, to remove any additional thermal mass in order to investigate the standalone transient response for fundamental study. None of these past studies have observed or characterized the occurrence of boiling under transient heat loads.

In the present work, we report experimental characterization of the boiling behaviors in vapor chambers under time-varying input powers. First, the steady state thermal resistance curve of the vapor chamber is obtained. Next, the long-time step response of the vapor chamber is studied for multiple successive on-off heat inputs, at different power levels. In addition, we further study the transient response and boiling behaviors for various cases with different on-times, ranging three orders of magnitude (0.1 s to 400 s) while testing at a fixed on-power or average power.

2 Experimental Methods

2.1 Vapor chamber details

A commercial vapor chamber (Celsia Inc.) is used for all experiments reported in this study. The vapor chamber has overall external dimensions of 100 mm $\times$ 100 mm $\times$ 5.5 mm. The internal sintered powder wick structures on the evaporator and condenser sides are 1.5 mm in thickness, the walls are 0.8 mm thick, and the vapor core is 0.9 mm thick. The commercial vapor chamber device was obtained directly from the vendor and has an internal structure consisting of ribs that provide structural support and fluid return pathways between the condenser and evaporator sides. Additional details and diagrams of the internal structure of the device and the manufacturing process can be found in Refs. [24, 25]. The wick structures are made of sintered copper particles, with a particle size of 75 – 110 microns; an SEM image of the internal wick structure on the evaporator side of the device is shown in Figure 1 (a). In the process of manufacturing the vapor chamber, the target fluid charge is determined based on a measured wick porosity of ~50%. In particular, the filling liquid volume is set to be approximately 50-55% of the porous volume of the wick. A standard degassing procedure is followed before the charging to remove any non-condensable gases from the chamber; a vacuum is drawn on the chamber (10^{-2} – 10^{-3} torr) before the fluid is charged.

Figure 1 (b) shows a photograph of the vapor chamber device. A 10 mm $\times$ 10 mm resistive heater (Mesoscribe^{TM}) with an embedded K-type thermocouple (Omega, ± 0.5 °C) provide heat input to the vapor chamber. The heater is fabricated on the center of the evaporator side using a high-temperature solder for electrical connections. The heater consists of a serpentine resistor pattern printed on the substrate that is sandwiched between two dielectric base/overcoat layers. The heated area from the serpentine pattern is 10 mm $\times$ 10 mm, but the overcoat on top of the heater that is visible in Figure 1 (b) appears larger in size. The surrounding dielectric layer (appears in white in Figure 1 (b)) is made of a low thermal conductivity material and results in a negligible change in the heat input area due to heat spreading.

The resistive heater is powered using a bipolar power supply (Kikisui PBZ40-10; 7 μ sec rise and fall time). A sense line, attached to the heater, compensates for the voltage drop in the lead wires; the power supply thereby directly outputs the voltage drop only across the heater. The maximum allowable temperature for the heater is 300 °C per the manufacturer; at the highest power densities tested (~ 100 W/cm²), the heater temperature was maintained well below this allowable temperature.

2.2 Experimental facility

The steady state and transient behavior of the vapor chamber is tested by attaching it to an aluminum finned heat sink. The air-flow boundary condition on the heat sink side is controlled using an air

jet impingement apparatus. A sketch of the experimental apparatus is provided in Figure 1 (c). The design and operating procedure for the facility are detailed in previous work [26,27] and briefly summarized here. A regenerative blower (Airtech PB1300) supplies air at a constant inlet volumetric flow rate of $\sim 0.01 \text{ m}^3/\text{s}$ (21 CFM) and temperature of $T_{air} = 38 \text{ }^\circ\text{C}$. The air then passes through two flowmeters (King Instrument 7510/7511), which are arranged in parallel with ranges of 0~20 CFM and 0~40 CFM, respectively. The inlet manifold section consists of two air-flow straighteners to provide uniform flow at the jet orifice as shown in Figure 1 (c). A calibrated K-type thermocouple ($\pm 1.1 \text{ }^\circ\text{C}$) is mounted in-line with the jet orifice to measure the inlet air temperature. Cool air flows through the 38.1 mm diameter circular orifice and reaches the main test section, which is fixed on an adjustable positioning stand. The reader is directed to Ref. [26] for additional details on the experimental setup.

In the test section, shown in Figure 1 (d), a straight pin-fin aluminum heat sink is attached to the condenser side of the vapor chamber. The heat sink has a 30×30 array of $2 \text{ mm} \times 2 \text{ mm}$ square pin fins. The fin height is 34 mm and the fin pitch is 4 mm. Stainless steel bolts are used for clamping the overall assembly. A 0.5 mm thick graphite thermal interface material (Laird Tgon^{TM} 810) is placed between the vapor chamber condenser side and the heat sink to reduce the interfacial thermal resistance. The evaporator side of the vapor chamber is insulated with polyetheretherketone (PEEK) to minimize heat loss to the surrounding environment. The heat loss analysis for the test section can be found in Ref. [26]; heat loss is calculated based on a numerical conduction simulation of the test section. The vapor chamber is modeled as a high effective thermal conductivity solid, while the surrounding surfaces are modeled with effective heat transfer coefficients representing air jet impingement (over the heat sink), and natural convection boundaries (outside the insulation). This simulation revealed that the heat loss to the surroundings through the insulation is less than 1%, and is therefore neglected.

Figure 1. (a) An SEM image of the sintered copper particle wick structure on the evaporator side of the device used in the current study (particle size: 75 – 110 μm; porosity: ~50%). (b) A photograph of the vapor chamber used in this study viewed from the evaporator side, with important features of the resistive heater labeled. (c) Schematic diagram of the air-jet impingement facility for testing the steady state and transient response of the vapor chamber. (d) Schematic diagram of the vapor chamber heat sink assembly. (note to the editor: 1.5 columns wide)

2.3 Testing procedure and uncertainty quantification

This section describes the process to conduct the steady state and transient tests. The steady state tests serve as a baseline to understand the relationship between the vapor chamber thermal resistance and input power, which identifies the different evaporation and boiling heat transfer regimes that can occur within the vapor chamber. Once the different regimes are identified, appropriate power levels are selected to conduct transient tests.

For both the steady state and transient tests, the input power is varied by programming the corresponding heat input profile using the power supply software (Kikisui WAVY). The input power, Q , is calculated as,

$$Q = V_{in} I_{in} \quad (1)$$

For a given heat input profile, the air temperature, T_{air} , and heater temperature, T_{heater} , are recorded (NI-9213 DAQ system, National Instruments). For the steady state tests, the heat input is increased in steps and the heater temperature, T_{heater} , is allowed to reach steady state (takes ~15 min) at each step before the data are recorded. The measured parameters are used to calculate the overall thermal resistance, R_{total} , of the heat sink assembly that includes the pin-fin heat sink, thermal interface material, and vapor chamber as,

$$R_{total} = \frac{T_{heater} - T_{air}}{Q} \quad (2)$$

The steady state test is repeated for three runs and the thermal resistance results are shown in Section 3.1.

A typical power electronic device has a transient load. During the power device operation, the switching frequency or period is constant while the on-time is varied by varying the duty cycle. The relationship between switching frequency, on-time, and duty cycle is given by,

$$f_s = \frac{d}{t_{on}} \quad (3)$$

The long-time transient step response of the vapor chamber heat sink assembly is first studied for two runs, for an input power near the occurrence of boiling incipience (observed in the steady state tests). These runs are performed to illustrate that boiling incipience does not occur in a repeatable way, and motivates the need for multiple cycles of heat input to fully characterize the process (see section 3.2).

Next, the long-time step response of the device assembly is investigated for multiple on-off cycles at different on-powers (P_{on}). This is conducted to examine the dependence of boiling incipience on on-powers during the step response temperature signature. The input power is switched on for a given time (t_{on}), followed by switching the power off for a given time (t_{off}). This power step is repeated for multiple cycles at a given value of P_{on} and the test is repeated for different on-powers (see section 3.3).

The transient response is then further studied for a range of on-times spanning three orders of magnitude, at two duty cycles, while either keeping the on-power constant or the average power constant. Note that the data is acquired and recorded at a high sampling rate of 20 ms to capture a reasonable number of data points within a period at the lowest on-time. For the transient tests, at least 10 cycles were recorded at each on-time (see section 3.4).

The uncertainty in the thermal resistance is calculated by considering an uncertainty propagation as,

$$U_{R_{total}} = \left(\frac{U_{T_{heater}}^2}{(T_{heater} - T_{air})^2} + \frac{U_{T_{air}}^2}{(T_{heater} - T_{air})^2} + \frac{U_V^2}{V^2} + \frac{U_I^2}{I^2} \right)^{1/2} R_{total} \quad (4)$$

The uncertainty in the measured heater temperature ($U_{T_{heater}}$) is ± 0.5 °C, per the manufacturer-specified uncertainty. The uncertainty in voltage measurement (U_V) is $\pm 0.05\%$ of the readout value added to the rated value (40 V), per the power supply specifications. The uncertainty in current measurement (U_I) is evaluated as $\pm 0.3\%$ of the rated value (10 A), per the power supply manufacturer.

3 Results and Discussions

3.1 Steady-state thermal resistance

As was described in Section 2.3, the steady state thermal resistance of the heat sink assembly is performed by increasing the input power in steps. Figure 2 shows total thermal resistance as a function of the input power for three separate runs. From this figure, it is observed that the thermal resistance of the vapor chamber generally decreases with increasing power. It can be inferred from the thermal resistance curve that, at low-power operation ($Q < 50$ W), the mode of heat transfer inside the vapor chamber is conduction across the wick that is fully saturated with liquid followed by evaporation from the wick-vapor core interface. The measured thermal resistance is the highest in this region. Increasing the power further causes a reduction in the thermal resistance, which remains nearly constant from $Q = 65$ W onwards. The reduction in the thermal resistance is caused by the initiation of nucleate boiling, which bypasses the conduction resistance across the wick [9]. During this boiling regime ($Q > 65$ W), the thermal resistance is the lowest and further increases in the heat input causes a gradual reduction in the thermal resistance. Dryout is not observed in the range of powers tested in this work; the steady-state dryout limit was observed to be much higher for vapor chambers having the same nominal dimensional tested in prior work [26].

Figure 2. The total thermal resistance of the heat sink assembly as a function of the heat power at steady state. The error bars show the uncertainties in the measured thermal resistances. (note to the editor: 1 column wide)

3.2 Step response to input power near boiling incipience

The occurrence of boiling incipience had to be indirectly inferred from the steady state results in section 3.1. However, boiling incipience in capillary-fed wicks can be directly detected from the transient response to a heat input, as it results in a sudden reduction in the heater temperature [9,13]. From the steady state test, it was evident from the thermal resistance curve that boiling occurs for heat inputs $Q > 65$ W. In this test, to directly detect boiling incipience, the heater power is switched on from $Q = 0$ to $Q = 65$ W in a single step, and the heater temperature is allowed to reach steady state. The procedure is repeated multiple times while allowing the vapor chamber setup to cool to room temperature between the runs. Figure 3 plots the transient heater temperature for two runs that exhibit contrasting behaviors, specifically for a run where boiling does not occur (Run 1) and second subsequent run (Run 2) in which boiling does occur. The onset of boiling in Test 2 is indicated by the sharp reduction in the heater temperature shortly after the power is switched on, as called out in Figure 3. At the same input power, the steady state temperature reached a higher value (85 °C) where there is no boiling compared to when boiling occurs (75 °C). As noted in the literature review, boiling incipience has been shown to occur over a wide range of superheats for capillary-fed sintered wick structures [13], and in commercial vapor chambers [11]. The current observation in Figure 3 indicates that detecting the heat input (or a range of heat input) for boiling incipience in a vapor chamber requires multiple runs or testing with multiple on-off cycles of input power. The results from these multiple runs can then be used characterize the number of incipience events.

Figure 3. A plot of the heater temperature of the vapor chamber over time for two different runs at a step heat input at $Q = 65$ W. The temperature signature in Run 1 does not exhibit the occurrence of boiling; the immediate drop in temperature at onset of boiling is labeled in Run 2. (note to the editor: 1 column wide)

3.3 Response to multiple long-time step inputs

In the following tests, a long time on-off power profile is applied to the heater and repeated for multiple cycles at a given on-power (P_{on}); tests are repeated for different on powers. These results are used to define the range of powers at which boiling incipience is likely to occur.

Figure 4 (a) shows the power profile supplied to the heater. The power is switched on and off for 10 cycles with a duty cycle of $d = 0.5$ and a time period $t_p = 800$ s (i.e., an on-time of $t_{on} = 400$ sec). A long time period is chosen to observe the complete step response of the vapor chamber assembly, which leads to a steady heater temperature, in each of the cycles. The input is then switched off to allow the vapor chamber to cool down before switching the power on again. The test is carried out for increasing on-power levels ranging from $P_{on} = 18$ W to $P_{on} = 100$ W. Figure 4 (b) – (d) shows the characteristic transient temperature responses over five on-off cycles of the vapor chamber (T_{heater}) at different power levels. At $P_{on} = 28$ W, in Figure 4 (b), the temperature monotonically rises to a steady value before the heat input is turned off. No significant change is observed in the subsequent cycles, and no boiling is observed in any given cycle. A similar temperature response is seen for all power levels and cycles in the range $P_{on} < 35$ W. Throughout the intermediate power range of $35 \text{ W} < P_{on} < 65 \text{ W}$, we observe an interesting phenomenon where boiling consistently occurs in each alternate cycle, as should for $P_{on} = 48$ W in Figure 4 (b). In the first cycle, when the input power is turned on, the heater temperature rises until there is a sharp transient reduction in temperature associated with the onset of nucleate boiling. The heater temperature then continues to gradually increase to a steady state before the power is turned off. In the second cycle, there is no occurrence of nucleate boiling and the heater temperature monotonically rises to a steady heater temperature that is higher than in the previous cycle. Boiling then occurs in the third cycle and the temperature response mirrors that of the first cycle. All subsequent cycles consistently exhibit this alternating boiling behavior in every other cycle. For input powers $P_{on} > 65$ W, as demonstrated for $P_{on} = 79$ W in Figure 4 (c), nucleate boiling is observed in all of the cycles. The steady heater temperature at the end of each of the ten cycles is extracted and used to calculate an average thermal resistance value. For the cases where boiling occurs (viz. $35 \text{ W} < P_{on} < 65 \text{ W}$), the steady temperature in each cycle where boiling occurs (5 cycles) is used to calculate the average thermal resistance. Figure 5 shows this thermal resistance plotted against the on-power. From this plot, three separate regimes are identified. The cases that did not exhibit the occurrence of nucleate boiling ($P_{on} < 35$ W) are grouped under the *evaporation regime* in Figure 5; the thermal resistance is highest in this regime. In the intermediate range ($35 \text{ W} < P_{on} < 65 \text{ W}$), the thermal resistance can take one of two values corresponded to whether evaporation or boiling occurs at the end of a given cycle. This is labeled as the *transition regime*. The *boiling regime* is identified for higher powers ($P_{on} > 65$ W) for which nucleate boiling occurs in every cycle; the thermal resistance is lowest in

this regime. It can be concluded that a resistance curve of this nature (based on multiple long-time step input powers) is required to fully characterize the thermal resistance of vapor chambers where nucleate boiling is likely to occur. The occurrence of nucleate boiling in the transition regime of the device seems to be systematic and happens in every alternate cycle.

Figure 4. (a) The on-off step input power profile to the vapor chamber with an on-power, P_{on} . The heater temperature (T_{heater}) is of the vapor chamber is plotted for the first five cycles at (b) $P_{on} = 28$ W, (c) $P_{on} = 48$ W, and (d) $P_{on} = 79$ W. Horizontal lines at the maximum heater temperatures are shown in plots (b) – (d) for comparison. (note to the editor: 1.5 columns wide).

Figure 5. A plot of the thermal resistance for different on-powers (P_{on}). For on-powers at which only evaporation ($P_{on} < 35$ W) or only boiling ($P_{on} > 65$ W) regimes were observed, the average of all 10 cycles is used. For the intermediate range (35 W $< P_{on} < 65$ W), in which alternating boiling and evaporation was observed, the average of both regimes over 5 cycles is shown. (note to the editor: 1 column wide)

3.4 Short on-time boiling behaviors

In the previous section, the long-time step response of the vapor chamber assembly was studied to characterize the occurrence of boiling incipience during the transient temperature change to a steady value in a series of successive pulses. Each test was carried out until steady state, and the occurrence of boiling was shown to lead to a lower steady state temperature during the long-time response. In the current section, we study the effect of shorter on-times (t_{on}) on boiling behaviors, while maintaining either the on-power (P_{on}) or the average power (P_{avg}) constant.

3.4.1 Tests with constant on-power

The first set of tests maintain the on-power (P_{on}) constant at 60 W, which was within the intermediate power range for which the alternating behavior was observed in cyclic on-off testing (Section 3.3). At this intermediate on-power, the on-time is varied over three orders of magnitude from 0.1 s to 400 s. For each on-time, two duty cycles ($d = 0.25$ and $d = 0.5$) were tested (corresponding to average powers of 15 W and 30 W, respectively). Table 1 lists the different testing conditions along with the boiling occurrences that were observed in each test.

At short on-times ($t_{on} = 0.1 - 2$ s), there is no observation of boiling, and the heater temperature reaches a steady, time-periodic regime in which it oscillates about a mean value. For these short times, the average power determines this mean temperature. It is inferred that, because the average power in these cases (15 W or 30 W) is within the evaporation regime (as characterized in Section 3.3), no occurrence of boiling is observed. For larger on-times ($t_{on} = 20$ s – 400 s), the on-power (P_{on}) determines the temperature response. The transient heater temperature response for the on-time $t_{on} = 20$ s is shown in Figure 6 (a) and (b) for $d = 0.25$ and $d = 0.5$, respectively. For the smaller duty cycle case, boiling occurs in only the first cycle, as annotated in Figure 6 (a), but the subsequent cycles do not exhibit this behavior. In contrast, the larger duty cycle case does not exhibit any boiling behavior and the temperature reaches a steady, time-periodic regime similar to the shorter on-times.

The transient heater temperature response for the on-time $t_{on} = 100$ s is shown in Figure 7 (a) and (b) for $d = 0.25$ and $d = 0.5$, respectively. At both duty cycles, boiling is observed to occur in the first cycle. After the first cycle, the duty cycle seems to affect the occurrence of boiling. For $d = 0.25$, boiling occurs in every alternate cycle, but for $d = 0.5$, boiling is not observed in any of the subsequent cycles. This observation suggests that longer off times (allowing the device to cool down further) is somehow associated with the alternating initiation of boiling within the vapor chamber between cycles. For an on-time of $t_{on} = 400$ s, both the duty cycles induce the alternate boiling behavior (note that the case of $d = 0.5$ is equivalent to the on-off testing presented in Section 3.3 for which this behavior was first revealed). The alternating boiling behavior observed in Figure 7 (a) is similar to Figure 4. However, we acknowledge that the physical mechanism behind this behavior in the vapor chamber remains unclear.

Table 1. The transient heat input tests carried out with different on-times at a fixed on-power ($P_{on} = 60$ W), for two duty cycles.

On-time t_{on} (s)	On-power, P_{on} (W)	Duty cycle, d (-)	Average power, $P_{avg} = d \times P_{on}$ (W)	Observations
0.1	60	0.25	15	No boiling
		0.5	30	No boiling
2	60	0.25	15	No boiling
		0.5	30	No boiling
20	60	0.25	15	Boiling occurs only in first cycle
		0.5	30	No boiling
100	60	0.25	15	Boiling occurs in every alternate cycle
		0.5	30	Boiling occurs only in first cycle
400	60	0.25	15	Boiling occurs in every alternate cycle
		0.5	30	Boiling occurs in every alternate cycle

Figure 6. Transient response of the heater temperature (T_{heater}) for an on-power (P_{on}) of 60 W and on-time (t_{on}) of 20 s. The response is shown for duty cycle of (a) $d = 0.25$ and (b) $d = 0.5$. The plots are shown for only the first 1200 s because the temperature signature repeats itself at later times (note to the editor: 1.5 columns wide)

3.4.2 Tests with constant average power

The next set of transient tests were performed with different on-times while keeping the average power constant at $P_{avg} = 60$ W.

Table 2 shows the on-time, average power, duty cycle, and on-power for these set of tests. We note here that in order to maintain the average power at 60 W the on-powers become high, namely $P_{on} = 240$ W (for $d = 0.25$) and $P_{on} = 120$ W (for $d = 0.5$), but not high enough to induce any dryout in the wick structure of vapor chamber, because the steady-state dryout limit is expected to be much higher, based on prior testing [26].

Figure 8 shows the temperature response for $t_{on} = 0.1$ s for the two duty cycles. For $d = 0.25$ ($P_{on} = 240$ W), shown in Figure 8 (a), boiling is initiated early in the transient profile and is seen as a reduction in heater temperature (see inset). After initiation, boiling occurs throughout the remaining cycles and the

steady periodic temperature oscillates around a mean value ($\sim 70^\circ\text{C}$). For $d = 0.5$ ($P_{on} = 120\text{ W}$), Figure 8 (b) shows that boiling is not initiated and thus the steady periodic temperature oscillates around a higher mean ($\sim 80^\circ\text{C}$). This result shows that even if the average power is the same, power cycles having a higher on-power at a lower duty cycle are more likely to cause boiling, and hence can reach a lower mean steady temperature. The same trend is observed for an on-time of $t_{on} = 2\text{ s}$ (but not plotted here for brevity), where for the lower duty cycle ($d = 0.25$) and higher on-power ($P_{on} = 240\text{ W}$), boiling is initiated early on, and the steady periodic temperature oscillates around a mean value of 68°C . This is lower than the mean value of 78°C for the longer duty cycle of $d = 0.5$ ($P_{on} = 120\text{ W}$), for which there was no occurrence of boiling.

Figure 7. Transient response of the heater temperature (T_{heater}) for an on-power (P_{on}) of 60 W and on-time (t_{on}) of 100 s . The response is shown for duty cycle of (a) $d = 0.25$ and (b) $d = 0.5$. (Note to the editor: 1.5 columns wide)

Figure 9 shows the temperature response for the longer on-time of $t_{on} = 20\text{ s}$. For this case, boiling occurs in each cycle of the power profile, irrespective of the duty cycle. In Figure 9 (a), at the shorter duty cycle of $d = 0.25$, within each cycle, there is a sharp reduction in the heater temperature caused by the initiation of boiling. The temperature signature continues to increase within the on-period till the input power is switched off. After the power is turned off in each cycle, there is a very sudden drop in temperature down a certain value, followed by a gradual reduction, and the process repeats for each subsequent power

cycle. The same characteristic behavior is observed in Figure 9 (b) for the longer duty cycle $d = 0.25$ ($P_{on} = 120$ W).

From these results, it is clear that on-power and duty cycle are key factors that determine the initiation of boiling inside the vapor chamber in response to a transient power cycle. At high on-powers and low on-times, boiling may not initiate inside the vapor chamber compared to at the same power with higher on-time. Therefore, in a practical application, it would be favorable to have a vapor chamber designed such that transition into the boiling regime occurs within a desired on-time. While this study puts forth this design objective and shows that the boiling behavior can indeed be repeatedly achieved under certain conditions, it remains unclear how to control and tune this transient behavior of a vapor chamber. However, from the results presented herein, the occurrence of alternating boiling behavior is seemingly related to the discrete boiling incipience event and therefore it is not expected to be unique to the particular the evaporator wick geometry, pore structure, and fill volume investigated here. With this behavior now revealed, future work in this regard can be focused on experimentally evaluating these parametric effects on the occurrence of alternating boiling and exploring methods to mitigate this effect. The alternating boiling incipience behavior revealed for the vapor chamber in this work also has critical implications on the device reliability. For example, if boiling intermittently occurs 50% of time, the sharp drop in device temperature at boiling incipience may cause thermo-mechanical stress that would ultimately result in lower package reliability, even compared to operation at a higher device temperature without boiling.

Table 2. The transient heat input tests carried out with different on-times at a fixed average power ($P_{avg} = 60$ W), for two duty cycles.

On-time t_{on} (s)	Average power, $P_{avg} = d \times P_{on}$ (W)	Duty cycle, d (-)	On-power, P_{on} (W)	Boiling occurrence
0.1	60	0.5	120	No
		0.25	240	Yes
2	60	0.5	120	No
		0.25	240	Yes
20	60	0.5	120	Yes
		0.25	240	Yes

Figure 8. Transient response of the heater temperature (T_{heater}) of the vapor chamber for an average power (P_{avg}) of 60 W and on-time of 0.1 seconds. The response is shown for two cases: (a) $d = 0.25$ ($P_{on} = 240 \text{ W}$), and (b) $d = 0.5$ ($P_{on} = 120 \text{ W}$). (note to the editor: 1.5 columns wide).

Figure 9. Temperature response (T_{heater}) of the vapor chamber for an average power (P_{avg}) of 60 W and on-time of 20 seconds. The response is shown for two cases: (a) $d = 0.25$ ($P_{on} = 240$ W), and (b) $d = 0.5$ ($P_{on} = 120$ W). (not to the editor: 1.5 columns wide)

4 Conclusions

In this paper, we report the boiling behaviors in a vapor chamber subjected to transient heat inputs with heat rejection using an air-cooled heat sink. To study the boiling incipience behaviors, multiple on-off step heat inputs were provided to the vapor chamber, where steady conditions were reached after each step. Three different regimes of operations were noted, a low-power regime ($P_{on} < 35$ W) where boiling never occurred, and transition regime (35 W $< P_{on} < 65$ W), and a high-power regime ($P_{on} > 65$ W) where boiling always occurred during the on time. The transition regime exhibited an intriguing behavior where boiling consistently occurred in each alternate cycle. Within any given cycle, the thermal resistance depended on whether heat transfer occurred by evaporation (higher resistance) or boiling (lower resistance) within the vapor chamber.

Furthermore, to study the effect of the length of the on-times and on-powers on the boiling behaviors and temperature response, various transient pulsed power profiles were investigated. The key observations from these transient cycling tests are:

1. For an intermediate on-power ($P_{on} = 60$ W) and shorter on-times ($0.1 \text{ s} < t_{on} < 2 \text{ s}$), the vapor chamber and heat sink assembly behaves similar to a step response under an average input power ($P_{avg} = d \times P_{on}$). No boiling is observed for these short on-times.
2. For an intermediate on-power ($P_{on} = 60$ W) and longer on-times ($20 \text{ s} < t_{on} < 400 \text{ s}$), the on-power level dictates the transient response. The alternating boiling behavior in each cycle is observed if the device is switched off for a longer time ($d = 0.25$).
3. For an average power of $P_{avg} = 60$ W, and a short on-time ($0.1 \text{ s} < t_{on} < 2 \text{ s}$), boiling occurs for the larger on-power ($P_{on} = 240$ W) (and corresponding lower duty cycle $d = 0.25$), but does not occur for the case of smaller on-power ($P_{on} = 120$ W) (and corresponding larger duty cycles ($d = 0.5$)).

Based on this study, it is evident that the occurrence of boiling in vapor chambers can have a significant impact on the cooling performance of pulsed systems, and transient characterization is critical, even though the technology is mature for operation under steady state conditions. The implications of these transient effects will likely be more pronounced for compact packages that have low thermal resistance from junction to the case. For example, while the steady state performance of the vapor chamber tested herein would be considered adequate for the range of tested powers ($0 - 100$ W), the transient performance of the vapor chamber may not be suitable for pulsed power application within the narrow transition regime ($35 \text{ W} < P_{on} < 65 \text{ W}$) due to the large temperature swings associated with alternating boiling occurrence. This study illustrates that heat spreading technologies that incorporate vapor chambers for pulsed heat loads needs to be judiciously designed considering the steady state heat load, in addition to on- power and duty cycle. Overall, the use of vapor chamber heat spreaders for pulsed loads systems may be challenging due to these competing factors, and one should follow test protocol as presented in this paper to characterize the transient system performance.

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