



REVIEW OF VARIOUS THIN HEAT SPREADER VAPOR CHAMBER DESIGNS, PERFORMANCE, LIFETIME RELIABILITY AND APPLICATION

Masataka Mochizuki^{a,* †}, Thang Nguyen^b

^a The Heat Pipe, 1-4-33-1022 Shiohama, Koto-ku, Tokyo 135-0043, Japan

^b Fujikura Ltd, 1-5-1 Kiba, Koto-ku, Tokyo 135-8512, Japan

ABSTRACT

The cooling device for computers and electronics is getting smaller and thinner year after year, especially for the mobile handheld device such as smartphone which is the most popular gadget and widely use nowadays. It seems that in the current trend every 6-12 months a new model of smartphone is introduced and it was packed with faster processing processor, memories, and graphics, higher density battery, higher resolution for camera and video and so on. The drawback is the device getting hotter due to the increase of heat dissipation caused by faster computing. The traditional method of cooling by purely metal heat conducting is no longer viable. In the recent year thin heat pipes had been introduced to smartphone for better transfer and spreading the heat for cooling. Thin heat spreader vapor chamber becoming more attractive for smartphone cooling due to its potential superior heat transfer than thin heat pipe. Typically heat pipe or vapor chamber for cooling smart phone is less than 0.4 mm thick. This paper is a review and comparison on the structural design and thermal performance of various thin heat spreader vapor chambers on development or available off the shelves. Discussion on material compatibility, non-condensable gas generation and lifetime reliability of heat pipe and vapor chamber will be also included. Lastly some examples of application presented.

Keywords: Heat pipes; Vapor chamber; Two-phases heat transfer; Smartphone cooling; Non-condensable gas; Life time reliability.

1. INTRODUCTION

The cooling device for computers and electronics is getting smaller and thinner, especially in mobile device like smart phone. In general, the cooling device thickness is less than 0.4mm. Usually, heat pipe and vapor chamber maximum heat transfer is governed by the capillary limit. However, due to the narrow internal space, other limits can be dominated such as viscous, sonic, entrainment or boiling. In this paper the following topics will be discussed - (i) Theoretical calculation for heat transfer limits for case study; (ii) A review and comparison on the structural design and thermal performance of various thin vapor chambers on development or available off the shelves; (iii) Discussion on material compatibility, non-condensable gas generation and lifetime reliability and (iv) Application.

2. HEAT TRANSFER LIMITS

Normally heat pipe and vapor chamber maximum heat transfer is governed by the capillary limit. However, due to the small internal space, other limits can be dominant such as viscous, sonic, entrainment or boiling. Equations and correlations to estimate these limiting factors are listed in Fig. 1 (Yong li, *et al.*, 2016). Authors had assumed that these equations are applicable to flatten heat pipe or vapor chamber configuration. A case study of vapor chamber of length 140mm and width 70mm has been chosen to represent general dimensions of smartphone. Figure 2(a) showed the calculation results of heat transfer limit calculation for water at 60 °C, for these limiting factors against

internal vapor space height. The height is the vapor space without taking account of the wick and container thicknesses. The calculation results indicated that the capillary limit is still a dominant factor, but as the height reduces, the viscous limit can also be a major influence factor. The capillary limit calculation is based on the assumption of sintered copper powder of thickness 0.1mm, approximate 100um powder diameter, 60% porosity, 60 degrees contact angle and water as working fluid. It showed that the limit of the vapor space height is about 0.1mm with maximum heat transfer between 1-6W. Figure 2(b) showed the maximum heat transfer vs. space width, keeping the height constant 0.15mm. As expected if reduced cross sectional area of vapor space then maximum heat transfer would also be reduced.

$$Q_{viscous} = \frac{d_v^2 h_{fg}}{64 \mu_v l_{eff}} \rho_v p_v A_v$$

$$Q_{sonic} = A_v \rho_v h_{fg} \left[\frac{\gamma \lambda T_e}{2M(\gamma+1)} \right]^{1/2}$$

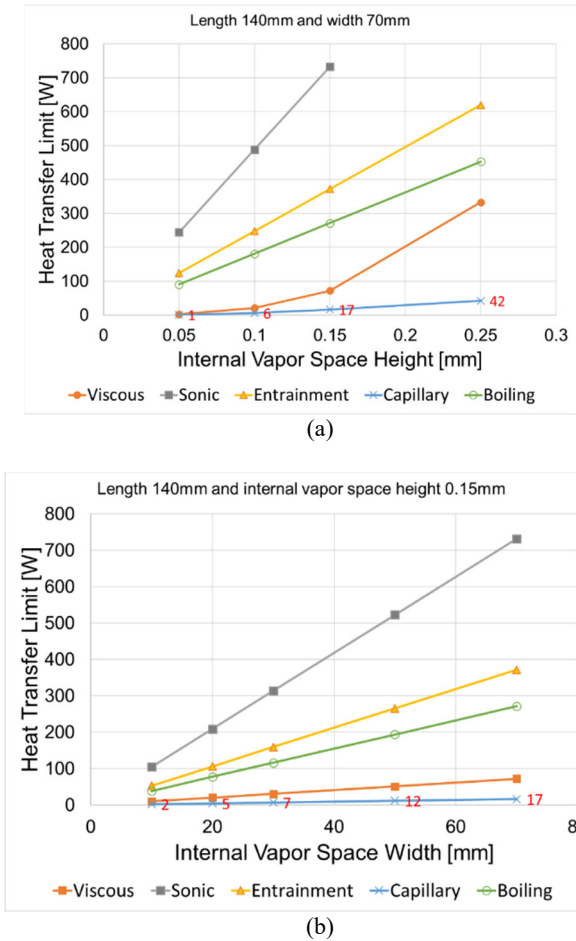
$$Q_{entrainment} = A_v h_{fg} \left(\frac{\rho_v \sigma}{2r_h} \right)^{1/2}$$

$$Q_{capillary} = \frac{2\sigma \cos \alpha}{r_w} \left(\frac{32 \mu_v l_{eff}}{d_v^2 A_v \rho_v h_{fg}} \right) + \left(\frac{\mu_v l_{eff}}{KA_w h_{fg} \rho_l} \right)$$

$$Q_{boiling} = \frac{A_v k_{eff} T_v}{\delta h_{fg} \rho_v} \left(\frac{2\sigma}{R_n} - \Delta p \right)$$

Fig. 1 Heat transfer limits

[†] Corresponding author. Email: mochizuki.masataka@gmail.com



3. EXAMPLES OF VAPOR CHAMBER

There are numerous variety designs of vapor chamber either in development phases or available off the shelves to suit particular need. In this paper, a few vapor chambers are selected to show the variation. Figure 3 is a flexible vapor chamber developed by University of Colorado Boulder and Kelvin Thermal Technologies (Bar Cohen *et al.*, 2015; Ryan Lewis, 2016). They have developed 4 major configurations – (a) PCB-based, 3cm x 3cm with effective thermal conductivities claimed to be higher than 1500 W/mK; (b) Mylar-Aluminum, 5cm x 9.5cm with desired flexibility of highly bendable; (c) Copper-cladded Kapton, 5cm x 9.5cm with the desired flexibility and durability and best thermal performance; and (d) All-polymer 5cm x 9.5cm. The outer casing is Kapton and the inside has nylon spacers and polymer wicking structure. The best thermal performance (case c) of the vapor chamber has a total thermal resistance of about 1 °C/W at heat input of 20 W, and heating area of 1cm x 1 cm.

In the vapor chamber, the wick structure is the most important design because it governs the capillary force which assist to circulate the working fluid, and distribution the fluid within the vapor chamber. Figure 4 shows various hybrid wick structures for the evaporator of the vapor chamber (Hwang, *et al.*, 2010; Sungtaek, *et al.*, 2013). The wick structures are (a) Powder vertical columnar arteries; (b) Powder converging lateral arteries; and (c) Powder bi-porous structure. The main aim of these structures is to distribute the working fluid to the evaporator efficiently. It was found that all these liquid supply structures showed

nearly identical performance. The heat transfer is dominated by the evaporation of the spreading liquid layers.

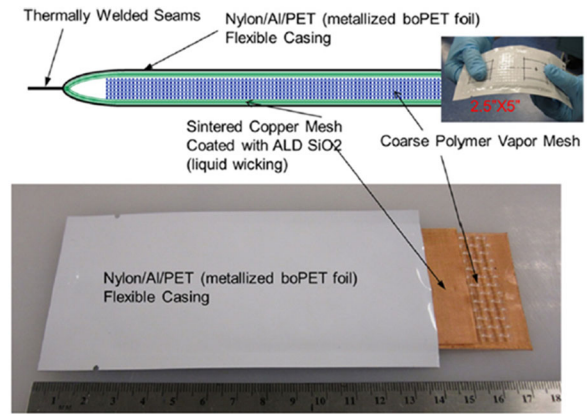


Fig. 3 Flexible vapor chamber

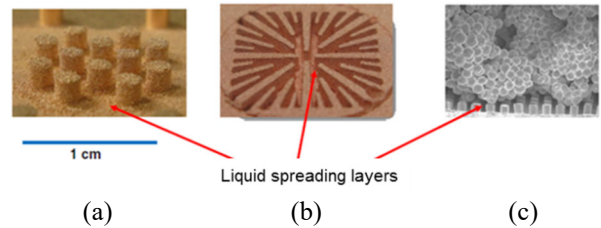


Fig. 4 Hybrid wick structures at the evaporator (a) Vertical columnar arteries; (b) Converging lateral arteries; (c) Powder bi-porous structure

Figure 5 shows the schematic of vapor chamber with copper powder vertical columnar arteries. The vapor chamber has length 120mm, width 70mm, and total height 4.6mm (internal height 2.6mm), and the working fluid is water. The copper powder for the liquid spreading layer and the column are 50um and 150um respectively. It was claimed that for the heating area of 1cm x 1cm, the critical heat flux is about 380 W/cm², and the evaporator thermal resistance is about 0.05 °C/W/cm².

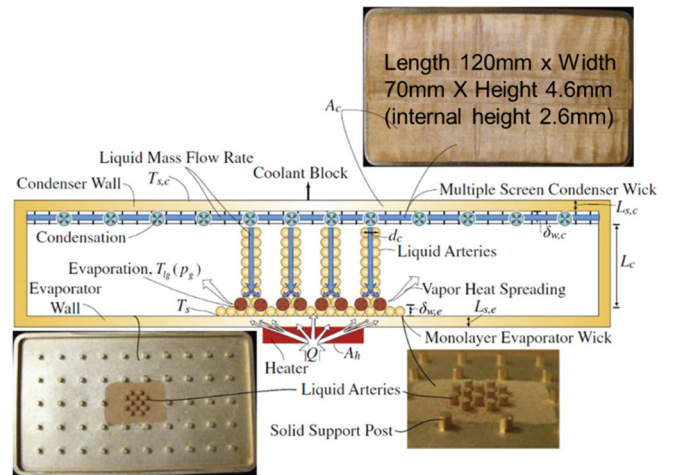


Fig. 5 Schematic of vapor chamber with powder vertical columnar arteries

Figure 6 shows author's vapor chamber. It has length 105mm, width 60mm, and total height 0.35mm (internal height about 0.2mm). Screen mesh was used as wick structure. The pattern of the wick structure varies depend mainly on the location of the heating area. For maximize the performance, it is essential to design the pattern to have the balance and uniform flow distribution of liquid and vapor.

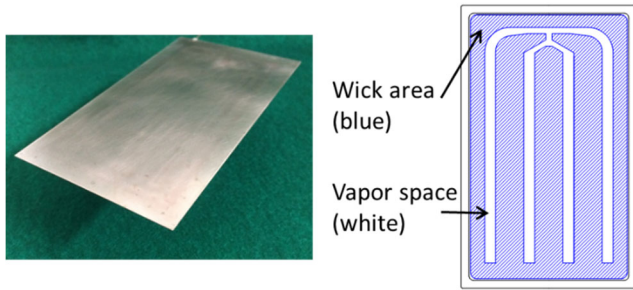


Fig. 6 Vapor chamber #1 developed by M. Mochizuki^a & T. Nguyen^b

Figure 7 shows thermal spreading resistance comparison between thin vapor chamber and the graphite sheet of exact same dimensions. The graphite sheet claimed to have the in-plane thermal conductivity of approximately 800 W/m.K. The spreading thermal resistance (R_{sp}) is defined in Eq. (1). The heating area is 10mm x 10mm located at T2. The test was carried out in a vertical top heat configuration, and natural air convection cooling in a temperature controlled environment. Results in Fig. 7 shows that the vapor chamber spreading is at least 4 times better than graphite sheet.

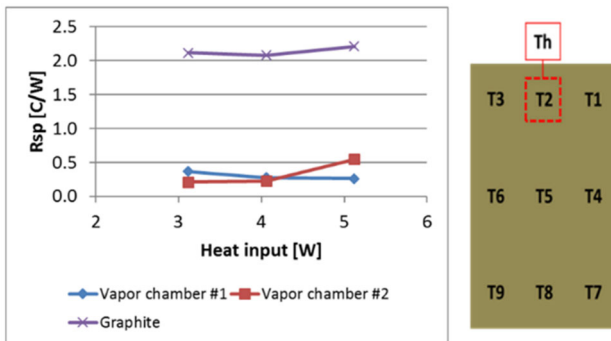


Fig. 7 Spreading thermal resistance comparison between vapor chamber and graphite sheet of same dimensions

$$R_{sp} = \frac{[T2 - average(T1,3,4,5,6,7,8,9)]}{Q} \quad (1)$$

where,
 Q = Heat input [W]
 R_{sp} = Spreading thermal resistance [°C/W]
 $T2$ = Evaporator temperature [°C]
 $T1, T3$ to $T9$ = Condenser temperature [°C]

Figure 8 shows another example of thermal performance comparison between thin vapor chamber and the combination of Copper plate and graphite sheet. The vapor chamber is 100mm x 70mm and 0.4mm thick, whereas Copper plate and graphite sheet has same foot print but with thickness 0.2mm and 0.05mm respectively. The heating area is 10mm x 10mm located at T2. Figure 8(b) shows the vapor chamber can reduce the heat source temperature by about 6-10 °C, and at higher vapor chamber operating temperature gives higher improvement. Figure 8(c) shows the equivalent thermal conductivity comparison in favor of vapor chamber about 4-8 times better. The equivalent thermal conductivity was calculated using Eq. (2). The thermal image in Fig. 8(d) shows that vapor chamber helps spread the heat uniformly compared to the large temperature gradient of the Copper plate & graphite sheet.

$$K_e = \frac{QLe}{[average(T1,2,3) - average(T4,5,6)]Wt} \quad (2)$$

where,
 K_e = Equivalent thermal conductivity [W/mK]
 L_e = Equivalent thermal conductivity length [m]
 Q = Heat input [W]
 $T1$ to $T6$ = Temperature of the evaporator top surface [°C]
 t = Thickness of the vapor chamber or total thickness of the copper plate & graphite sheet [m]
 W = Width of the vapor chamber or copper plate / graphite sheet [m]

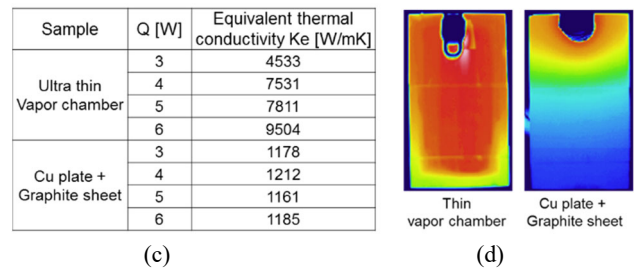
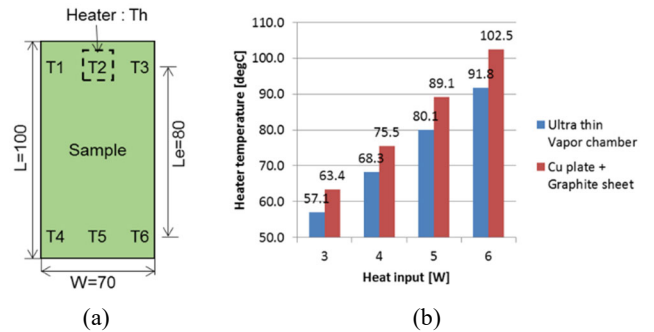


Fig. 8 Vapor chamber #1 developed by M. Mochizuki^a & T. Nguyen^b

Figure 9 shows a good summary of various vapor chamber performance by Bar Cohen *et al.*, (2015). The abbreviation TGP means Thermal Ground Plane which operational principle is exact the same as vapor chamber. The summary indicated that the vapor chamber equivalent thermal conductivity is better than any known best material thermal conductivity.

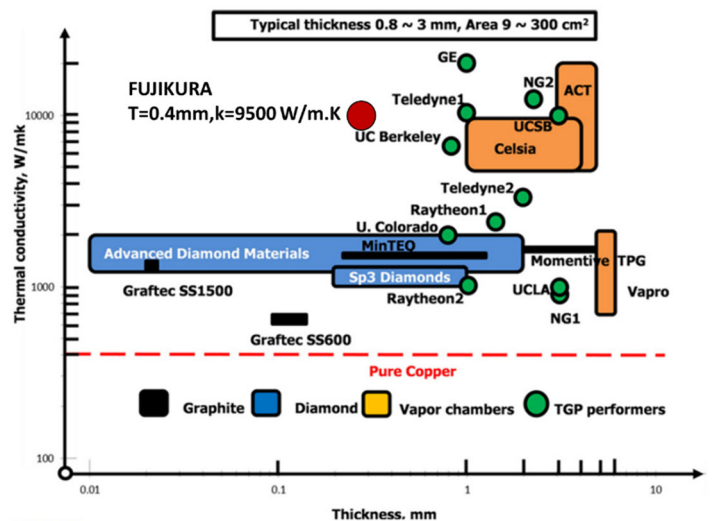


Fig. 9 Summary of vapor chamber performance

4. LIFE TIME RELIABILITY

Heat pipe and vapor chamber are simple passive devices, and which are totally sealed and have no moving parts, therefore one would expected long life reliability, and it would be so if manufacturing correctly. Their life reliability can be degraded by the followings - the internal of the device is unclean; gases present due to improper vacuum and filling of working fluid; Incompatible of material and working fluid; Impurity of material and working fluid. In long term operating their thermal performance can be degraded as a result of (1) chemical reaction that generate non-condensable gases and/or (2) corrosion and erosion of the container and wick. The non-condensable gases (NCG) accumulate in the heat pipe or vapor chamber, forming a diffusion barrier to vapor flow and effectively reducing the condenser area available for heat transfer.

Table 1 Comparison of surface area ratio

| | Heat pipe diameter 6mm; length 140mm, wall thickness 0.3mm. | Heat pipe diameter 2mm, length 140mm, wall thickness 0.3mm. | Heat pipe diameter 2mm, flatten to 2.9mm, length 140mm, wall thickness 0.1mm, internal height 0.4mm. | Vapor chamber length 140mm, width 70mm, internal height 0.2mm. |
|---|---|---|--|--|
| Internal surface area [m ²] | 2.375 x 10 ⁻³ | 6.158 x 10 ⁻⁴ | 7.56 x 10 ⁻⁴ | 1.966 x 10 ⁻² |
| Internal volume [m ³] | 3.206 x 10 ⁻⁶ | 2.155 x 10 ⁻⁷ | 7 x 10 ⁻⁸ | 1.96 x 10 ⁻⁶ |
| Ratio surface area to volume | 741 | 2857 | 10800 | 10029 |
| Ratio to dia. 6mm | 1 | 3.9 | 14.6 | 13.5 |

The NCG can greatly affect the performance of vapor chamber since the ratio of surface area to internal space is large in comparison with traditional heat pipe. Table 1 shows a particular case study comparison between thin vapor chamber (0.2mm internal height) and 6mm round heat pipe – in this case the ratio of surface area to internal volume for vapor chamber can be a magnitude order higher than the round heat pipe. The more surface areas the higher chemical reaction between material and working fluid.

It is anticipated that most gas quantity generated at initial time as shown by Murakami *et al.*, (1987). Figure 10(a) shows that most of gas quantity generated at the initial time, and very limited gas generation thereafter. These data were collected from Copper-water axial grooves heat pipe which has diameter 6.35mm and total length 250mm (heating length 50mm). There were total 60 samples tested at accelerated temperatures 40, 60, and 160 °C. If the initial NCG generation can be removed, then it is expected that there will be little or no NCG in long term operating. To demonstrate this phenomenon, Murakami tested the heat pipe at the initial and measured temperature drop of heat pipe, then re-evacuated heat pipe and tested again. The results are shown in Fig. 10(b) that heat pipe temperature drop remained constant after air re-evacuation.

For computer, power devices, and electronic application, most of the vapor chamber would be made of copper and compatible working fluid water. Working fluid water was chosen due to its high latent heat and performance merit in the operating range 50-150°C applicable to computing devices. Also water is a friendly fluid to the environment. As mentioned before for the mobile devices, vapor chamber need to be thin and light which can be a problem for mechanical structure integrity due to copper material is soft. Therefore, a harder material which is compatible with water would be required. One of suitable material is Nickel.

In order to estimate the life time of Nickel-water combination, the Arrhenius correlation in Eq. (3) is used. The notations are - Ea is activation energy (Joules); K is Boltzman constant (8.625 x 10⁻⁵ eV/°K); Ttest is test temperature (°K); and Tuse is operating temperature (°K). Table 2 (Anderson, 1973) shows the activation energy for various

material and fluid combination from the past literature. For Nickel-water combination the activation energy is about 10.3 x 10⁻²⁰ Joules.

$$\text{Accelerator factor} = e^{(-Ea/K)*(1/T_{test}-1/T_{use})} \quad (3)$$

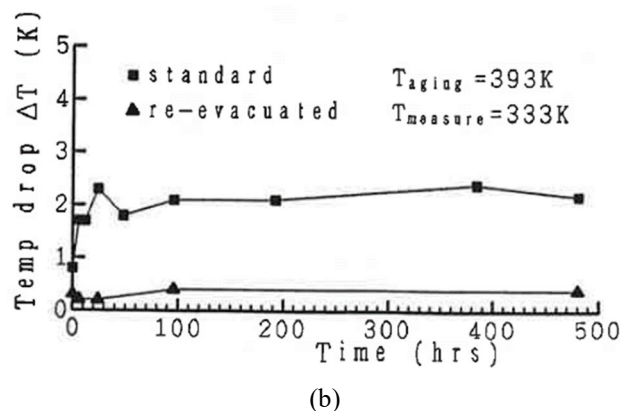
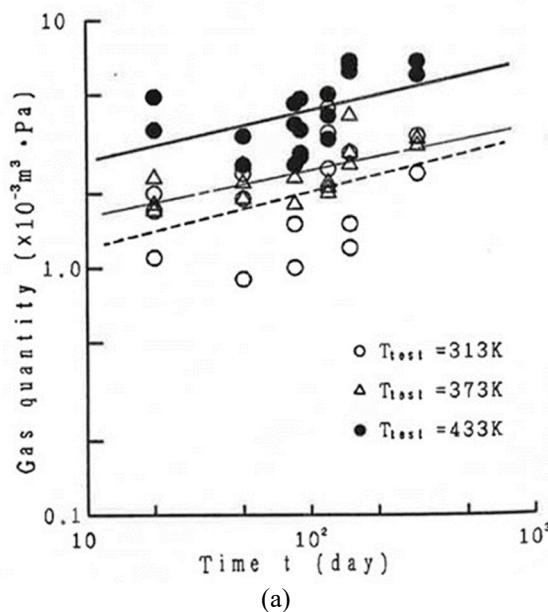


Fig. 10 Heat pipe copper-water life test data

Table 2 Activation energy for various material and fluid combination

| Material | Environment | Temperature (°C) | Activation Energy (10 ⁻²⁰ Joules) |
|----------------------|--------------------------------|------------------|--|
| Mild steel | Air | below 570 | 31.3 |
| Stainless steel | Oxygen | 550-650 | 20.6 |
| Iron | Oxygen | 350-450 | 15.7 |
| Aluminum | Oxygen | 400-600 | 25.9 |
| Uranium | Air | | 15.3 |
| Nickel | Oxygen | 310-345 | 13.8 |
| Nickel | Oxygen | 360-440 | 14.6 |
| Nickel | Oxygen | 500-1000 | 24.2 |
| Mild steel | 5-20% NaOH | 250-355 | 10.4 |
| Mild steel | 10% HCL | 40-80 | 10.1 |
| 18/9 Stainless steel | H ₂ SO ₄ | -100 | 8.63 |
| 304 Stainless steel | Distilled water | 38-149 | 8.29 |
| Iron | 10% HCL | 40-90 | 3.37 |
| Lead | 10% HCL | 40-110 | 6.81 |
| Aluminum | 70% HNO ₃ | 10-120 | 8.47 |
| Uranium | Water | | 5-10 |
| Nickel | Distilled water | 36-81 | 10.3 |

By use of Eq. (3) and assumes the operating temperature of 60 °C for a continuous life time of 5 years, then the accelerated test time required for various temperature is show in Fig. 11. For example – If test at

elevated temperature of 100 °C, the accelerating factor is about 10 times, and the test time required is about 4000 hrs. Whereas, if test at elevated temperature of 160 °C, the accelerating factor would be about 180 times, and the test required is about 250 hrs.

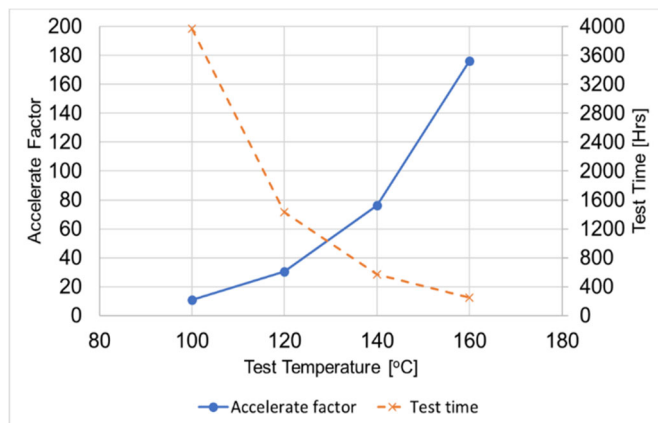


Fig. 11 Accelerator factor vs. temperature & time for Ni-water

5. APPLICATION

Figure 12 shows general cooling technologies for cooling computer and electronic products. Heat pipe is now a commodity for cooling in computer desktop, laptop and ultrabook. In some cases, vapor chamber would be used if high performance heat dissipation required. Figure 13 shows examples of thin heat pipe use for cooling thin platform products such as computer tablet and smart phones. The thin heat pipe thickness is in the 0.5mm level. The introduction of the 5G network smart phone device in 2019, which would require higher dissipation, and possibly thin heat pipe is not efficient to transfer the heat away, unless multiple heat pipes are used. Recently, a smart phone company (LG) intends to use vapor chamber, as shown in Fig. 14, to more efficiently spread the heat in X-Y direction since it has larger surface area. This type of thin vapor chamber cooling solution may become necessary for thin high power devices.

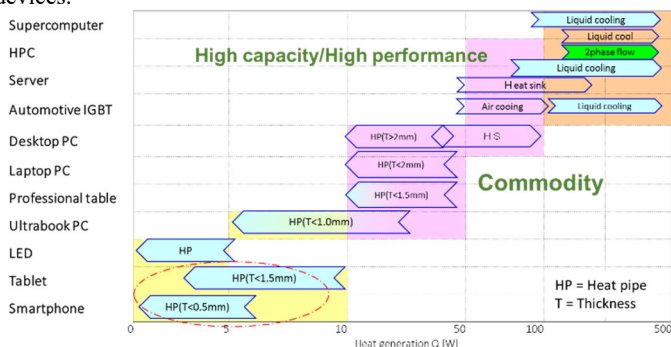


Fig. 12 General cooling technologies for computer and electronics products

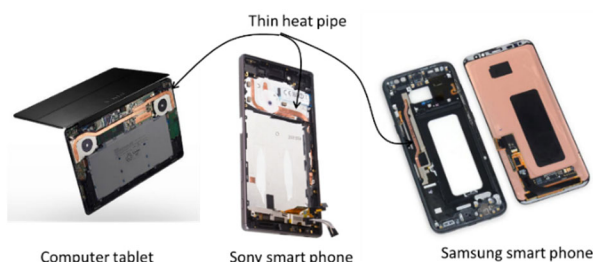


Fig. 13 Examples of use thin heat pipes for cooling thin platform products such as computer tablet and smart phone (images from internet)

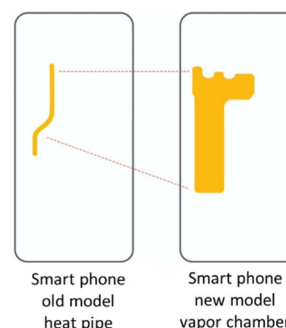


Fig. 14 Potential use of vapor chamber for 5G smart phone (image from internet)

6. CONCLUSIONS

- The minimum internal space height is limited to about 0.1mm (ie. Minimum vapor chamber thickness about 0.3mm, assuming 0.1mm thickness for top and bottom plates. Required further investigation on how to integrate wick into 0.1mm plate total thickness).
- The maximum heat transfers for 0.1mm space height vapor chamber would be only few watts.
- For the current design and manufacturing of thin vapor chamber 0.3mm thick, it is unlikely that there will be any significant improvement in the thermal performance. Maybe a nano-structure wick, improvement in hydrophilic in the evaporator, and hydrophobic in the condenser, are required for further performance enhancement.
- When the internal space height reduces, other limits such as viscous limit can have significant effect on heat transfer capability, therefore these limits need to be calculated and considered in the design.
- Vapor chamber equivalent thermal conductivity or heat spreading performance is much better than any known heat spreading / conducting material for the same form factor.
- Expectation is that thin vapor chamber may become increasingly necessary for cooling thin high power devices.
- Non-condensable gas (NCG) can have a profound bad effect on thin heat pipe and vapor chamber since the internal surface is large but internal volume is small, therefore, small amount of NCG can occupy large volume ratio.

REFERENCES

Anderson, W.T., 1973, "Hydrogen Evolution in Nickel-Water Heat Pipe," *AIAA 8th Thermophysics Conference*, July 16-18, USA.

Bar-Cohen, A., Matin, K., Jankowski, N., and Sharar, D., 2015, "Two-Phase Thermal Ground Planes: Technology Development and Parametric Results," *Journal of Electronic Packaging*, **137**, 010801. <http://dx.doi.org/10.1115/1.4028890>

Boreyko, J.B., and Chen, C.H., 2013, "Vapor Chambers with Jumping-Drop Liquid Return from Superhydrophobic Condensers," *International Journal of Heat and Mass Transfer*, **61**, 409-418. <http://dx.doi.org/10.1016/j.ijheatmasstransfer.2013.01.077>

Hwang, G.S., Nam, Y., Fleming, E., Dussinger, P., Ju, Y.S., and Kaviany, M., 2010, "Multi-Artery Heat Pipe Spreader: Experiment," *International Journal of Heat and Mass Transfer*, **53**, 2662-2669. <https://doi.org/10.1016/j.ijheatmasstransfer.2010.02.046>

Li, Y., Zhou, W., He, J., Yan, Y., Li, B., and Zeng, Z., 2016, "Thermal Performance of Ultra-Thin Flattened Heat Pipes with Composite Wick Structure," *Applied Thermal Engineering*, **102**, 487-499.

<http://dx.doi.org/10.1016/j.applthermaleng.2016.03.097>

Mochizuki, M., 2019, "Micro and Miniature Heat Pipes and Vapor Chamber for Cooling Electronic Devices," *8th International Symposium on Micro & Nano Technology*, April 26-28, Qingdao, China.

Murakami, M., Arai, K., and Kojima, Y., 1987, "Statistical Prediction of Long-Term Reliability of Copper-Water Heat Pipes from Accelerated Test Data," *6th International Heat Pipe Conference*, May 25-29, Grenoble, France.

Ryan Lewis, 2016, "Ultra-Thin Thermal Ground Planes," *Kelvin Thermal Technologies*, ATW, Denver.

Sungtaek, J.Y., Kaviany, M., Nam, Y., Sharratt, S., Hwang, G.S., Catton, I., Fleming, E., and Dussinger, P., 2013, "Planar Vapor Chamber with Hybrid Evaporator Wicks for the Thermal Management of High-Heat-Flux and High-Power Optoelectronic Devices," *International Journal of Heat and Mass Transfer*, **60**, 163-169.

<http://dx.doi.org/10.1016/j.ijheatmasstransfer.2012.12.058>