A Practical Guide for Using Liquid Two-Phase Heat Sinks

Presenter
George Meyer
CEO, Celsia Inc.
We’ll Answer these Questions

- **Do I Need 2-Phase?**
  - Benefits and consequences of solid materials
  - Some basic rules of thumb

- **Are Vapor Chambers Just Flat Heat Pipes?**
  - Similarities: design, wicks & performance limits
  - Differences: for moving or spreading heat

- **What Size Do I Need?**
  - Heat pipes: diameter, quantity, and shape
  - Vapor chambers: thickness, area, and shape

- **How Do I Integrate Them?**
  - Attaching it to the condenser
  - Mounting it to the heat source/PCB

- **What Should the Heat Exchanger Look Like?**
  - Types of condensers
  - Pros and cons

- **How Do I Model Thermal Performance?**
  - Heat sink ballpark
  - Excel Model
  - CFD analysis
  - Proto testing
When to Use 2-Phase Devices

The Short Answer

- Only when the **design is conduction limited** or
- **Non-thermal goals** such as weight or size **can’t be achieved** with other materials such as solid aluminum and/or copper.

<table>
<thead>
<tr>
<th>Aluminum (baselined at 1X)</th>
<th>Copper</th>
<th>Two Phase</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base thk: 1X</td>
<td>Base thk: 0.5X</td>
<td>Base thk: 0.5X</td>
</tr>
<tr>
<td>Weight: 1X</td>
<td>Weight: 3X</td>
<td>Weight: 2X</td>
</tr>
<tr>
<td>Cost: 1X</td>
<td>Cost: 1.6X</td>
<td>Cost: 1.8X</td>
</tr>
</tbody>
</table>

Even with increased base thickness, may not meet thermal requirements

Copper significantly increases performance, weight & cost. May not meet shock/vibration needs or thermal requirements

Performance can be 5-15% better than solid copper sink with less weight penalty
2-Phase Rules of Thumb

1. 2-phase devices are **incredible heat conductors**.
   - 5 to 50 times better conductivity than aluminum or copper using copper/water 2-phase
   - 1,000 to >50,000 w/mk. Exact figure is primarily dependent on the distance the heat is transported

2. Ideal when heat needs to be **moved** more than 30-50mm
   - Remote fin stacks (heat exchangers) are a perfect example

3. If you’re interested in **spreading** heat to reduce hot spot and/or attach to a local heat exchanger
   - The ratio of heat spreader to heat source should be on the order of 30:1 greater area

4. As with any heat sink, design in an **extra 30%-40% thermal headroom**
2-Phase Similarity: Inner Workings

Heat pipes & vapor chambers transfer heat through the **phase change of liquid to vapor and back to liquid**

Liquid is passively **pumped** from condenser to evaporator **by capillary action**

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**Evaporator**

- Heat Turns Liquid to Vapor that Travels Toward the Condenser (Fin Stack)

**Condenser**

- Cooled Vapor Turns Back to Liquid and Returns to the Evaporator (Heat Source)

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Used for very efficient heat transport & spreading

No noise or moving parts with very high reliability
## 2-Phase Similarity: Wick Structures

<table>
<thead>
<tr>
<th>Sintered Powder</th>
<th>Power Density</th>
<th>Resistance</th>
<th>Orientation</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;500 w/cm²</td>
<td>0.15-0.03 °C/cm²</td>
<td>+90° to -90°</td>
<td></td>
</tr>
<tr>
<td>Good for freeze/thaw and bent shapes</td>
<td>Small heat sources up to 1,000 w/cm²</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Screen</th>
<th>Power Density</th>
<th>Resistance</th>
<th>Orientation</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;30 w/cm²</td>
<td>0.25-0.15 °C/cm²</td>
<td>+90° to -5°</td>
<td></td>
</tr>
<tr>
<td>Main use is for very thin heat sinks due to high evaporator resistance. Limited bending.</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Grooved</th>
<th>Power Density</th>
<th>Resistance</th>
<th>Orientation</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;20 w/cm²</td>
<td>0.35-0.22 °C/cm²</td>
<td>+90° to 0°</td>
<td></td>
</tr>
<tr>
<td>Entry level price / performance must be gravity aided/neutral.</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Evaporator Resistance (Typical Two Phase)

![Graph showing evaporator resistance for different structures](image)

- **Sintered Powder**: Low evaporator resistance, good for high power density applications.
- **Screen**: Moderate evaporator resistance, suitable for medium power density applications.
- **Grooved**: High evaporator resistance, best for low power density applications.
## 2-Phase Device Similarity: Performance Limits

<table>
<thead>
<tr>
<th>Cause</th>
<th>Vapor Pressure</th>
<th>Sonic</th>
<th>Entrainment</th>
<th>Boiling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating well below design temp</td>
<td>Start-up power, low temp combo</td>
<td>Device above designed power input or at low temp</td>
<td>Input power exceeds design</td>
<td>Radial heat flux exceeds design</td>
</tr>
<tr>
<td>Vapor flow prevented</td>
<td>Large internal pressure drop</td>
<td>Condenser flooded with excess fluid</td>
<td>Capillary pump breaks down</td>
<td>Wick dries out</td>
</tr>
<tr>
<td>Change working fluid</td>
<td>Non-catastrophic. Device normalizes as it runs</td>
<td>Increase vapor space or operating temp</td>
<td>Modify wick structure</td>
<td>Increase wick heat flux capacity</td>
</tr>
</tbody>
</table>

**Capillary limit** is the ability of a particular wick structure to provide adequate circulation for a given working fluid.

It is usually the limiting factor for terrestrial applications.
Typical performance limits for various diameters

- The vapor limits are usually only a factor when using flattened heat pipes due to the size reduction in the vapor space.
## 2-Phase Differences: Overview

<table>
<thead>
<tr>
<th></th>
<th>Heat Pipe</th>
<th>Hybrid 1-Piece Vapor Chamber</th>
<th>Traditional 2-Piece Vapor Chamber</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Initial Form Factor</strong></td>
<td>Small diameter tube 3-10mm</td>
<td>Very large diameter tube 20-75mm</td>
<td>Upper and lower stamped plates</td>
</tr>
<tr>
<td><strong>Shapes</strong></td>
<td>Round, flattened and/or bent in any direction</td>
<td>Flattened rectangle, surface embossing &amp; z-direction bendable</td>
<td>Complex shapes in x and y direction, surface embossing</td>
</tr>
<tr>
<td><strong>Typical Dimensions</strong></td>
<td>3-8mm diameter or flattened to 1.5-2.5mm. Length 500mm+</td>
<td>1.5-4mm thick, up to 100mm W by 400mm L</td>
<td>2.5-4mm thick, up to 100mm W by 400mm L</td>
</tr>
<tr>
<td><strong>Mounting to Heat Source</strong></td>
<td>Indirect contact though base plate unless flat &amp; machined</td>
<td>Direct contact. Mounting pressure up to 90 PSI</td>
<td>Direct contact. Mounting pressure up to 90 PSI</td>
</tr>
<tr>
<td><strong>Relative Cost</strong></td>
<td>Very cost effective, but increases quickly with large diameter, custom wick structure, secondary ops</td>
<td>Comparable to 2-4 heat pipes in higher power and/or high heat flux applications</td>
<td>More expensive than 1-piece design due to additional tooling cost and labor time, but large scale production closes the gap</td>
</tr>
</tbody>
</table>
2-Phase Differences: Moving or Spreading Heat?

While there’s no hard line of distinction between the two, think of the difference like this...

**Moving**

- Linear heat flow
- Remote condenser, usually

**Spreading**

- Multidirectional heat flow
- Local condenser, almost always
When *Moving* Heat to a *Remote* Sink

99% of All Applications Use Heat Pipes

- Complex shapes often required
- Easily bendable in any direction
- Readily available in volume
- Will work against gravity ± 45°

Example #1 – *Notebook computer*

2 flattened heat pipes cool 3 heat sources
- With the right thermal modeling, heat sources can be daisy chained onto one device.
- Good example of heat pipe design flexibility.
Example #2 – Small Form Factor PC

Processor cooler that uses the system fan incorporates 4, 6mm heat pipes to move a nominal 100-135 watts to the air stream created by the system fan.

Example #3 – Repeater Housing

Take the heat off of several components and move it to a finned section of a cast housing. It is common to have multiple heat sources on a heat pipe.
When *Spreading* Heat to a *Local* Sink

Heat Pipes are a Good Choice If

- Plenty of air flow
- Lots of room for fins
- Nominal power densities <25 w/cm²
- Normal ambient
- Every penny counts!

**Example #1 – Telecom Equipment Application**

- For moderate performance applications where spreading needs to be augmented, the use of several heat pipes embedded into the base may be sufficient
- The use of heat pipes in the base does not eliminate the conductive losses but will help to reduce them.
When *Spreading* Heat to a *Local* Sink

Vapor Chambers may be the Best choice if

- Z direction (height) is limited
- Power densities are high
- High ambient or low air flow
- **Every degree counts!**

Example #1 – Higher GPU power & density required design modification

One 3mm thick vapor chamber replaced two 8mm heat pipes. 6 degree C better performance and more even heat distribution across heat source surface

- Direct contact to the VC means one less interface and better spreading
- Flat design allows for additional fin area

6 ºC Cooler
When *Spreading Heat to a Local Sink* (continued)

Example #2 – Two versions of the same heat sink

Four flattened heat pipes versus a single vapor chamber

- Four degree C better performance from VC assembly due to direct contact with heat source. Heat source hot spots also reduced

![4.0 °C Cooler](image)

Example #3 – Weight was a critical design factor

Cools six 80 watt ASICs

- Two piece vapor chamber with center cut out for improved weight.
- Heat pipes were not an option due to requirement to thermally link all six ASICS

![Thermal Live 2015](image)
When Moving Heat to Remote Sink

Vapor Chambers are a Good Choice If

- Thermal performance is critical
- Ultra-thin VC can allow for more fin area

Example #1 – Three 450W RGB Laser Diodes for 3D Projector

Three vapor chambers each 70mm W x 300mm L move heat to a common fin stack
- Vapor chambers were used in place of heat pipes to reduce conduction loss
Spreading & Moving – Some Oddballs

Example #1 – Flattened / machined HPs are sometimes used to mimic a vapor chamber
Gaming desktop cooling overclocked processors
- Heat pipes make direct contact with the heat source, eliminating 2 interface layers
- If implemented correctly performance can be good, but cost rises quickly and heat spreading in X direction is still limited

Example #2 – Heat pipes and vapor chamber used in combination
Small form factor desktop PC cooling Core i7 chip
- VC replaced copper mounting plate
- 5 degree better performance than original design with reduced hot spots
Heat Pipe Sizing (copper, sintered wick, water)

<table>
<thead>
<tr>
<th>Diameter</th>
<th>3mm</th>
<th>4mm</th>
<th>5mm</th>
<th>6mm</th>
<th>8mm</th>
<th>10mm</th>
<th>12mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Typical Power Range (W)*</td>
<td>5-20</td>
<td>8-35</td>
<td>11-50</td>
<td>13-65</td>
<td>20-90</td>
<td>24-100</td>
<td>33-135</td>
</tr>
<tr>
<td>Typical Flattening To (mm)</td>
<td>2.0~2.5</td>
<td>2.0~3.0</td>
<td>2.0~4.0</td>
<td>2.0~5.0</td>
<td>2.5~7.0</td>
<td>2.0~3.0</td>
<td>2.0~3.0</td>
</tr>
<tr>
<td>Resulting Width (mm)</td>
<td>3.7~3.3</td>
<td>5.31~4.8</td>
<td>7~5.7</td>
<td>8.6~6.72</td>
<td>11.4~8.8</td>
<td>15.5</td>
<td>18.6</td>
</tr>
</tbody>
</table>

* Power range: Low end = condenser directly below evaporator. High end = horizontal orientation

Challenge – Cool an 85W ASIC by moving heat to a remote fin stack in horizontal orientation

Possible Solutions

Three 5mm Round Heat Pipes vs. Two 6mm Flat Heat Pipes

Comparison

1. 30-40% Thermal Margin 121-142W
2. HP Thermal Capacity (100%) 150W
3. Calculated Therm. Margin 43%
4. Evaporator Stack Height 7mm
**Vapor Chamber Sizing**  (copper, sintered wick, water)

<table>
<thead>
<tr>
<th>Tube Size</th>
<th>16.5mm</th>
<th>19.4mm</th>
<th>25.4mm</th>
<th>30mm</th>
<th>32mm</th>
<th>37mm</th>
<th>43mm</th>
<th>48.4mm</th>
<th>53.5mm</th>
<th>70mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Typical Power Range (W)</td>
<td>50~150</td>
<td>60~180</td>
<td>90~250</td>
<td>120~360</td>
<td>130~390</td>
<td>180~420</td>
<td>220~490</td>
<td>250~550</td>
<td>270~610</td>
<td>360~800</td>
</tr>
<tr>
<td>Typical Flattening To (mm)</td>
<td>2.0~3.0</td>
<td>2.0~3.0</td>
<td>2.0~3.0</td>
<td>2.5~3.5</td>
<td>2.5~3.5</td>
<td>3.0~4.0</td>
<td>3.0~4.0</td>
<td>3.0~4.0</td>
<td>3.0~4.0</td>
<td>3.0~4.0</td>
</tr>
<tr>
<td>Resulting Width (mm)</td>
<td>25.6</td>
<td>30.3</td>
<td>40</td>
<td>46.8</td>
<td>50</td>
<td>57.5</td>
<td>67.4</td>
<td>76</td>
<td>83.5</td>
<td>109.2</td>
</tr>
</tbody>
</table>

* Power range: Low end = condenser directly below evaporator. High end = horizontal orientation

**Challenge** – Cool a 85W ASIC by moving heat to a local fin stack in horizontal orientation

**Comparison**

1. 30-40% Headroom Req. | 130-140W | 130-140W
2. VC Heat Capacity (100%) | 150W | 130W
3. Calculated Headroom | 50% | 30%
4. Evaporator Stack Height | 3.5mm | 3.5mm
2-Phase: Effective Conductivity

- Power & distance transported are modest for most electronics: 1000 to 10,000 w/mK being moved 150-300mm
- For industrial applications where powers are higher and the distances may longer the numbers are typically from 10,000 to as high as 50,000
- Each application for a two phase heat transfer device will have a different effective conductivity. Mainly a function of distance heat is moved

**Thermal Conductivity Estimate**

| width mm | 40.0 | 0.04 | m |
| thickness mm | 2.5 | 0.00 | m |
| total power watts | 150.0 | | |
| total length mm | 200.0 | | |
| heat source length mm | 25.0 | | |
| heat source width mm | 25.0 | | |
| condenser length mm | 200.0 | | |
| condenser width mm | 40.0 | | |
| delta-t Deg. C | 10.7 | | |
| length effective mm | 100.0 | 0.10 | m |
| Delta-t middle heat | 7.2 | °C |
| length effective | 50.0 | mm |
| | 0.050 | m |
Bending & Shaping

Heat Pipes
- Bend radius 3X diameter of heat pipe. Example
- Flatten to 1/3 diameter of original pipe (typical)
- Machining if pipe wall thickness permits. Allows direct contact with heat source

1-Piece Vapor Chamber
- 10mm bend radius along narrow plane
- Flattened to 1/10 – 1/20 diameter of original pipe (typical)
- Surface pedestals of 0.5-1.0mm high available for recessed heat sources

2-Piece Vapor Chamber
- Stamped bend to 1x thickness of the sheet metal, typically done as a ‘step’. Note – steep bends increase vapor pressure drop significantly
- Upper and lower plates are stamped flat.
- Stamped surface pedestals of 3-5mm high available for recessed heat sources
Bending Rules of Thumb

• Spec a straight heat pipe or vapor chamber with 30% thermal margin.
  • Example: A heat load of 70w should use a heat pipe designed with a Qmax of no less than 100w.

• Add total bend radius of the heat pipe/VC. While not perfect this will get you very close to actual.
  • Example: one 90 degree bend and another 45 degree bend = 135 degrees of bend

• For each 10 degrees of bend Qmax will decline by ~0.56%.
  • In our example from above: 135 degree total bend divided by 10 multiplied by 0.56% = 7.6% decrease in Qmax.

• So for our 70w heat source with two bends totaling 135 degrees we’ll need a heat pipe with a Qmax of 100/(1-.076) = 108.2w.
PCB / Heat Source Mounting Options

Clip Style Attachment
- Pros: $ low cost
- Cons: Low pressure- higher TIM resistance

Push Pin Attachment
- Pros: $ low cost, easy Install
- Cons: Low pressure, only good for small heat sink (light weight)

Spring Loaded Screws
- Pros: Higher pressure for better TIM performance
- Cons: hardware can get pricy
## Heat Exchanger Design (Fins)

### Extruded
- **Pros:** 100’s of suppliers, Low Cost
- **Cons:** Somewhat limited in fin ratio

### Formed – Skived, Forged
- **Pros:** more flexible in fin design
- **Cons:** tooling cost can be expensive, $$$ ($$$) cost

### Stamped-folded
- **Pros:** great design flexibility
- **Cons:** $$ tooling cost

### Machined - Printed
- **Pros:** widest design flexibility
- **Cons:** slower process add expense
<table>
<thead>
<tr>
<th>Assembly Attachment</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Soldering</strong></td>
</tr>
<tr>
<td>90% of the time</td>
</tr>
<tr>
<td>Direct copper to copper bonds or nickel plating over aluminum</td>
</tr>
<tr>
<td>VC soldered to a machined forced convection heat sink</td>
</tr>
<tr>
<td>Steel mounting plate soldered to a vapor chamber</td>
</tr>
<tr>
<td>Heat pipes soldered to nickel plated copper blocks</td>
</tr>
</tbody>
</table>
Probably looks very similar to this....

Each modeling method has its own benefits and drawbacks...
Heat Sink Ballpark Calculation

Benefits

• Very Fast (5 min)
• Can do while in a meeting
• Risk level, high or low
• Answers – Is it Remotely Possible?

Method Overview

• For a given heat source (W), max. delta-t, airflow (CFM), and heat sink size…
• Use some rules-of-thumb constants to calculate…..
  • Effective air temperature rise
  • Fin to air resistance
• Add these two together and add a fudge factor to see how much of the available delta-t you used up.
# Heat Sink Ballpark Calculation - Example

**Known**

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Power in Watts (Q)</td>
<td>130</td>
</tr>
<tr>
<td>Max Delta-T (deg C)</td>
<td>45</td>
</tr>
<tr>
<td>Forced Convection (CFM)</td>
<td>16</td>
</tr>
<tr>
<td>Natural Convection (CFM)</td>
<td>2.8</td>
</tr>
<tr>
<td>Heat Sink Dimensions (in)</td>
<td>10.0</td>
</tr>
<tr>
<td></td>
<td>2.0</td>
</tr>
<tr>
<td></td>
<td>1.0</td>
</tr>
</tbody>
</table>

**Rough Calculations**

1. **Effective Air Temp Rise (deg C)**

<table>
<thead>
<tr>
<th>Forced Convection</th>
<th>Natural Convection</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.53</td>
<td>48.75</td>
</tr>
<tr>
<td>2.1*Q/CFM/2</td>
<td>2.1*Q/CFM/2</td>
</tr>
</tbody>
</table>

2. **Fin Area (sq.ft)**

<table>
<thead>
<tr>
<th>Forced Convection (10 per inch)</th>
<th>Natural Convection (4 per inch)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.78 sq. ft. fin area. Count both sides of each fin</td>
<td>1.11 sq. ft. fin area. Count both sides of each fin</td>
</tr>
</tbody>
</table>

3. **Estimate fin-to-air delta-t**

<table>
<thead>
<tr>
<th>Forced Convection (Deg C)</th>
<th>Natural Convection (Deg C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>17.78</td>
<td>222.30</td>
</tr>
<tr>
<td>Q*0.38/Fin area in sq. ft.</td>
<td>Q*1.9/Fin area in sq. ft.</td>
</tr>
</tbody>
</table>

4. **Add #1 and #3 from above and tack on an extra 10 degrees for other resistances**

<table>
<thead>
<tr>
<th>Forced Convection</th>
<th>Natural Convection</th>
</tr>
</thead>
<tbody>
<tr>
<td>36.32 Deg C used of the available 45 deg delta-t</td>
<td>281.05 Deg C used of the available 45 deg delta-t</td>
</tr>
</tbody>
</table>

5. **Ballpark conclusion - heat exchanger using forced convection should work.**
Excel Modeling: Delta-t = 39.2 °C

Benefits

• Low Cost
• Fast & Fairly Easy to Design

Inputs

• Heater: length, width, total power
• Ambient Temp
• Heat Exchanger: fin length, width, height, pitch
• Air Velocity
• TIM 2 Thermal Resistance

Calculations

• Heater: area & power density (w/cm²)
• Heat Exchanger: number of fins, fin area, face area
• Air Flow (cfm)
• Delta-Ts: TIM 2, evaporator, vapor transport, fin to air, air temp rise, total delta-t

Summary

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>TIM2 delta-t</td>
<td>6.4</td>
</tr>
<tr>
<td>Evaporation</td>
<td>1.7</td>
</tr>
<tr>
<td>Vapor Transport (estimate)</td>
<td>3.0</td>
</tr>
<tr>
<td>Fin to Air</td>
<td>19.9</td>
</tr>
<tr>
<td>Air Temperature Rise</td>
<td>8.3</td>
</tr>
<tr>
<td>Total</td>
<td>39.2</td>
</tr>
</tbody>
</table>
CFD Analysis: Delta-t = 37 °C

Benefits

- Auto Optimization of multiple criteria
- Allows you to Focus on Key Design Goals. Weight vs Cost

- Get pretty pictures for presentations
- Answers - Have we Optimized to Meet Goals

- The real value in CFD is more for its optimization flexibility that it is for its improved accuracy vs other methods
  - Fin Pitch & Thickness
  - Base Thickness
  - Type of Metal
  - Type of TIM
  - Air Flow
But, There’s no Substitute for Actual Test Data

Benefits

- Use data to optimize current and future thermal models
- Real data allows you to trouble shoot both product performance and prediction accuracy
- Helps identify variations between design and hardware

- Transitioning from a model to a real part is critical
  - Validate model as early as possible
  - Build and test at various conditions

Delta-t = 41 °C
Excel model, in this case, was more accurate

CFD allowed us to refine fin pitch and thickness

Mean Performance of Final Part
Delta-t = 41 °C

Excel Model
Delta-t = 39.2 °C

CFD
Delta-t = 37 °C

Down & Dirty Ballpark
Delta-t = 36 °C
Q&A --- Thanks for Attending!

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