3D Printed Micro-channel Heat Sink Design Considerations

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Raleigh, NC, USA
New generation of airplanes becoming “More Electric”
- Traditional pneumatic and hydraulic systems on airplanes are being replaced with electrical devices
- More electrical equipment is being added to airplanes

Most airplane equipment requires DC power to operate, while generation and distribution is done through 3-phase AC power

Therefore, AC power needs to be converted into DC power
- This is done with power conversion equipment

AC-DC power conversion units are influencing airplane’s generator, wire and filter sizes

Bulky magnetics in AC-DC converters for distribution power and high power motor loads are difficult to cool – driving size and weight

Liquid cooling becomes a necessity.
Pat Wheeler, “The More Electric Aircraft, Why Aerospace Needs Power Electronics”, University of Nottingham, Nottingham, UK

Traditional Airplane

Jet Fuel

Propulsion Thrust (≈ 40MW)

200kW Electric Power

Gearbox driven generators

High pressure air “bled” from engine

Pneumatic 1.2MW

Gearbox driven hydraulic pump

Hydraulic 240kW

Fuel pumps and oil pumps on engine

Mechanical 100kW

Total “non-thrust” power ≈ 1.7MW

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Rationalization of power sources and networks

“Bleedless” engine

**Electrical system power ≈ 1MW**

Majority of load demand on more electric aircraft is from high power motor loads sourced from HVDC (270 Vdc or 540 Vdc)
Liquid Cooling Options

- Liquid-air heat exchanger
- Liquid immersion
- Individual component cooling
- Spray cooling/jet impingement
- Heat pipe
- Cold plate
  - Tubes
  - Machined/casted/3D printed channels
Liquid Cooling Options: Liquid Immersion

Advantages:
- COTS assembly
- Great thermal performance

Disadvantages:
- Lack of reliability
  - Contaminations
  - Leaks
  - Chemical reactions
- More difficult to maintain
- Challenging to repair/upgrade
- Weight issues

http://www.allied-control.com/immersion-cooling
Liquid Cooling Options: Spray Cooling/Jet Impingement

Advantages:
- Great for cooling COTS assembly
- Lower weight
- Hot spot cooling

Disadvantages:
- Lack of reliability
  - Contamination
  - Small pumps
  - Nozzles
  - Leaks
  - Chemical reactions
- More difficult to maintain
- Challenging to repair/upgrade

http://www.frostytech.com/
Advantages:
- Lower Weight
- Simple
- Passive

Disadvantages:
- Cannot transfer heat to longer distance
- Less long-term reliability
- Potential for freezing
- Need additional heatsink

http://www.congatec.com/
Cold plate types:
- Tubes
- Machined/cast channels
- Serial
- Parallel

Advantages:
- High Reliability
- No restrictions to liquid
- Can carry structural load
- Easier to maintain, repair, and overhaul

Disadvantages:
- Need conduction paths
- Position sensitive (see later slides)
Cold Plate Issues

- Serial channel cold plate
  - Harder to route
  - Fluid channel’s dimension is larger
  - Higher pressure losses
  - Liquid temperature rises
  - Cannot provide point of thermal load cooling
  - Relies on solid cold plate material conduction

- Parallel Channeled Cold Plate
  - Complicated calculation and design
  - Need higher precision production (for pressure balance)
  - Need to balance the pressure losses
  - Lower heat exchange rate
Internal air temperature of liquid cooled electronics is often ignored.

Not all heat dissipating components are thermally coupled to cold plate.

The upper surfaces of the thermally coupled components are also releasing heat into internal ambient air.

Components with very small heat dissipation can end up very hot in liquid cooled electronics if not thermally coupled to the cold plate.

Heat released into the internal (box) ambient air needs to be addressed.

If not designed properly, the heat can be released to EE bay from liquid cooled electronics.

Smartly positioning the cold plate as shown can address these problems.
Advantages:
- Light weight
- Small
- Efficient

Disadvantages:
- Connections
- Availability
- Complexity
Liquid Cooled Coil Construction

480 W

110 W

480 W

110 W
Internal “rough” surfaces enhance the heat transfer co-efficiency to liquid.
Transformer coil internal cooling creates uniform temperature distribution. This reduces the hot spot temperature and extends the reliability of the transformer.

<table>
<thead>
<tr>
<th>Component Function Description</th>
<th>Cold Plate Cooling</th>
<th>Individual Component Cooling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coil Outer Surface</td>
<td>116 C</td>
<td>130 C</td>
</tr>
<tr>
<td>Coil Center</td>
<td>140 C</td>
<td>130 C</td>
</tr>
<tr>
<td>Core Surface</td>
<td>72 C</td>
<td>72 C</td>
</tr>
<tr>
<td>Core Center</td>
<td>78 C</td>
<td>78 C</td>
</tr>
</tbody>
</table>
Since the large metal cold plate is no longer necessary, the structure load can be carried by carbon fiber epoxy material.

<table>
<thead>
<tr>
<th>Component</th>
<th>Cold Plate Cooled ATRU Weight</th>
<th>ATRU with Carbon Chassis Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrical Connectors (4 X) and Handles (2X)</td>
<td>1%</td>
<td>1%</td>
</tr>
<tr>
<td>Total Chassis</td>
<td>24%</td>
<td>11%</td>
</tr>
<tr>
<td>Rectifiers Cooler</td>
<td></td>
<td>3%</td>
</tr>
<tr>
<td>Transformer</td>
<td>43%</td>
<td>46%</td>
</tr>
<tr>
<td>Rectifiers X 12</td>
<td>2%</td>
<td>2%</td>
</tr>
<tr>
<td>Input Filter</td>
<td>6%</td>
<td>6%</td>
</tr>
<tr>
<td>Output Inductor</td>
<td>6%</td>
<td>5%</td>
</tr>
<tr>
<td>Output Capacitor</td>
<td>6%</td>
<td>6%</td>
</tr>
<tr>
<td>Status &amp; Output High Frequency Filter CCA</td>
<td>1%</td>
<td>1%</td>
</tr>
<tr>
<td>Bus Bar &amp; Interconnect</td>
<td>4%</td>
<td>4%</td>
</tr>
<tr>
<td>Fluid 62% EGW</td>
<td>1%</td>
<td>1%</td>
</tr>
<tr>
<td>Miscellaneous, Hardware, and Fluid fittings</td>
<td>5%</td>
<td>5%</td>
</tr>
<tr>
<td>Total Weight</td>
<td>100%</td>
<td>90%</td>
</tr>
</tbody>
</table>
Why 3D printing technology?

- **Freedom in Design**
  - No longer bound by traditional machine capabilities
  - Can produce far more complicated geometries
  - No restrictions in hollow structures
  - Small features are possible
  - No crack, void or any other type liquid passages

- **Shorter Development Cycles**
  - Short lead time in manufacturing
  - No tooling is needed
  - Less programming and setup times

- **Future Technology**
  - Additive Manufacturing technology is fast evolving
  - With new technologies and vendors emerging, the cost of production will reduce rapidly
  - Many new possibilities in design
Existing 3D Printing Technology

- Fused deposition modelling (FDM)
- Electron Beam Freeform Fabrication (EBF3)
- Direct metal laser sintering (DMLS)
- Electron-beam melting (EBM)
- Selective laser melting (SLM)
- Selective heat sintering (SHS)
- Selective laser sintering (SLS)
- Plaster-based 3D printing (PP)
- Laminated object manufacturing (LOM)
- Stereo Lithography (SLA)
- Digital Light Processing (DLP)
- New additive manufacturing technologies are emerging
# Technologies and Manufacturers

<table>
<thead>
<tr>
<th>Technology</th>
<th>Manufacturer(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser Sintering</td>
<td>3D Systems Corp., U.S.A.</td>
</tr>
<tr>
<td>Direct Metal Laser Sintering (DMLS), a trademark name for laser sintering tech</td>
<td>EOS, Germany (privately held)</td>
</tr>
<tr>
<td>Selective Laser Melting (SLM)</td>
<td>Renishaw, U.K. (listed on London Stock Exchange)</td>
</tr>
<tr>
<td></td>
<td>SLM Solutions, Germany (privately held)</td>
</tr>
<tr>
<td>Electron Beam Melting (EBM)</td>
<td>Arcam, Sweden</td>
</tr>
<tr>
<td>LaserCUSING, a laser sintering tech</td>
<td>Concept Laser, Germany (privately held)</td>
</tr>
<tr>
<td>Digital Part Materialization (DPM), or what the ASTM considers binder jetting</td>
<td>ExOne, U.S.A.</td>
</tr>
<tr>
<td>Laser Engineered Net Shaping (LENS)</td>
<td>Optomec, U.S.A. (privately held)</td>
</tr>
</tbody>
</table>
Direct Metal Laser Sintering (DMLS)

- Parts are grown micro-layer by micro-layer, with an average thickness of 30 microns.
- The powdered material is distributed by a sliding metal arm on to the printing platform.
- The 3D file directs the 400 W fiber laser to heat the powdered substance layers together at specific points, fusing the particles and transforming the material into solid form.
- The powdered metal is precisely distributed across the build platform with a re-coater arm.
- Proprietary software slices the engineered 3D files into micro-thin layers and controls a 400W fiber optic laser to sinter the exposed layer to the layer before it, fusing the particles and transforming the material into solid form.
The misconceptions of 3D printing are that anything, any design, can be printed
- There are limitations of 3D printing technologies
- These limitations are different from technology to technology
- Not all materials can be used
- Powder based system have more design challenges than wire based
- Liquid bases systems can only print polymers
- Thermoplastic is an easier material to print
- Polymers are much easier to deal with than metal
- Not all metals can be “printed”
- Metal printer needs to be protected by inert gas (Argon)
- Nitrogen is cheap, however, it can change metal properties
DMLS Design Considerations

- **Metals**
  - DMLS can only print metal materials
  - Not all metal materials can be used
  - For a heatsink, metal is the best choice
  - CTE, thermal conductivity, etc
  - Materials that can be welded by laser are the best candidates

- **Material “growth” Direction**
  - This is one of the most important factors during the design
  - Think about how to add materials over a part
  - Sintered material need to “stick” together
  - Laser may penetrate through the metal powders
  - How is the finished part separate from the base matters
# Laser Weldability of Materials

<table>
<thead>
<tr>
<th>Material</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon steel</td>
<td>Welds well. If carbon content &gt; 0.2 % brittle welds.</td>
</tr>
<tr>
<td>Stainless steel</td>
<td>300 series welds well except alloys with $S &gt; 0.05 %$</td>
</tr>
<tr>
<td></td>
<td>400 series welds brittle</td>
</tr>
<tr>
<td>Copper</td>
<td>High reflectivity requires high peak power</td>
</tr>
<tr>
<td>Cu-Be</td>
<td>Welds well but particles hazardous</td>
</tr>
<tr>
<td>Bronze (Cu/Sn)</td>
<td>Reasonable welds</td>
</tr>
<tr>
<td>Brass (Cu/Zn)</td>
<td>Outgasing of zinc prevents good welds</td>
</tr>
<tr>
<td>Aluminium</td>
<td>Pure Al (1xxx) welds well, only a few alloys weld crack free (2219, 3003). Filler material 4047 or combination of alloys may improve result (e.g. 6061 with 4047),</td>
</tr>
<tr>
<td>Titanium</td>
<td>Welds well. Very good shielding with inert gas necessary</td>
</tr>
<tr>
<td>Gold, Silver, Platinum</td>
<td>High reflectivity requires high peak power</td>
</tr>
<tr>
<td>Nickel</td>
<td>Welds well</td>
</tr>
<tr>
<td>Ni based super alloys</td>
<td>Welds well if Ti + Al content &lt; 4 %</td>
</tr>
<tr>
<td>Kovar</td>
<td>Welds well</td>
</tr>
<tr>
<td>Tantal</td>
<td>Welds well. Very good shielding with inert gas necessary</td>
</tr>
<tr>
<td>Molybdenum</td>
<td>Usually welds brittle – may be acceptable where high strength is not required</td>
</tr>
</tbody>
</table>
Cavity Supports
- Can powder support the sintered materials?
- Will a laser penetrate through the powder?
- 45 degree rule is typical
- If holes are not aligned with gravity, diameter of the holes matter
- Recommending dome shaped cavity
  - Top of the dome needs to be rounded

Surface Roughness and small features
- The finished part surface roughness is similar to casting
- 3D print fine threaded hole is not practical due to roughness
- Sharp corners are not practical

Post Process
- Particle blasting, chemical cleaning, machining
- Drill and tap threaded features
- Smooth surface polishing
Additive Manufacturing Method Discussions

- Additive manufacturing method (or 3D printing) will revolutionize the design and manufacturing.
- We are at the early stage of this revolution.
- The “Direct Metal Laser Sintering” may be the best technology today. It will not be the best technology tomorrow.
- There is no “best” technology in additive manufacturing. Only better technology exists.
- The next step in additive manufacturing will be the technology that can produce the part in multiple materials.
- 3D print a traditional design is not the right way to move forward.
- We should rethink about the designs that can take full advantages of the new technology.
Individual component liquid cooling offers the lowest weight solution that will be attractive to airborne hardware electronics industry.

Lower cost, weight & part count. Dramatically improved heat transfer.
The Crane Advantage!

for more information please visit CraneAE.com