Cooling For EV and HEV applications

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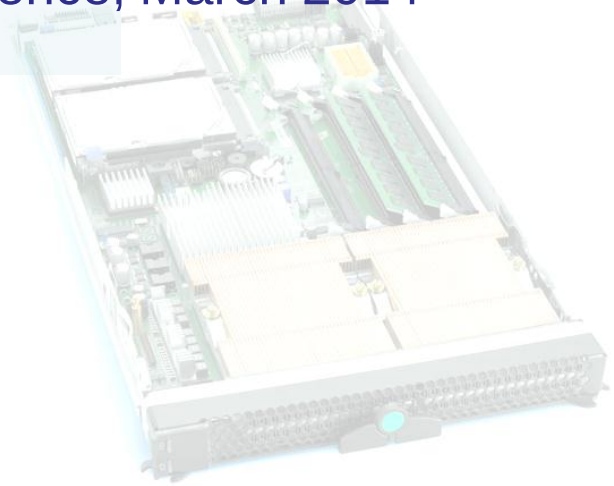
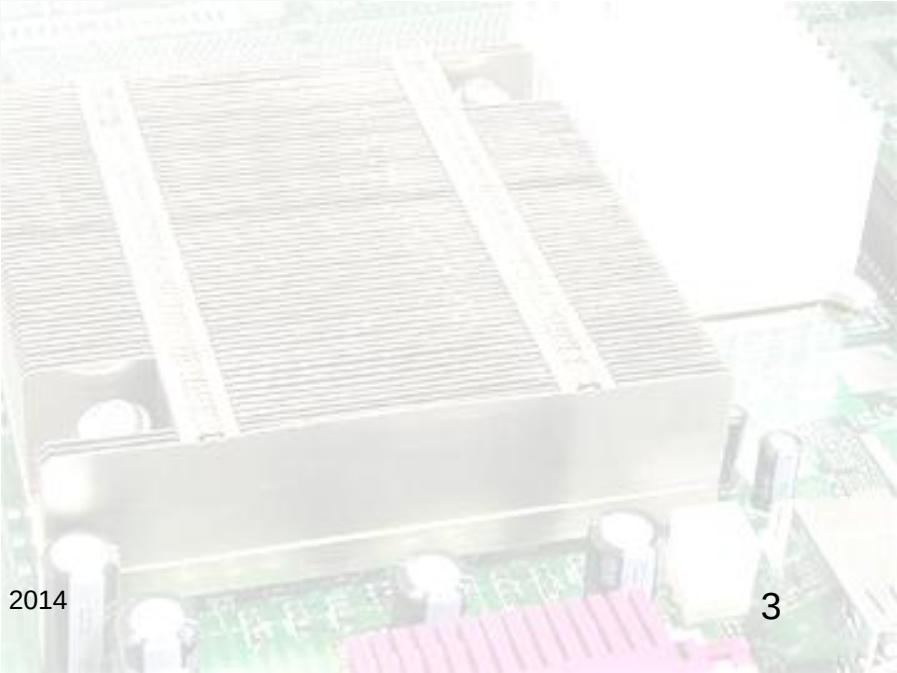


Presentation Outline

- Introduction
  - The importance of effective cooling in EV / HEV's
- Cooling principles and concepts
- New technologies applicable to air and liquid cooling
- Concluding remarks

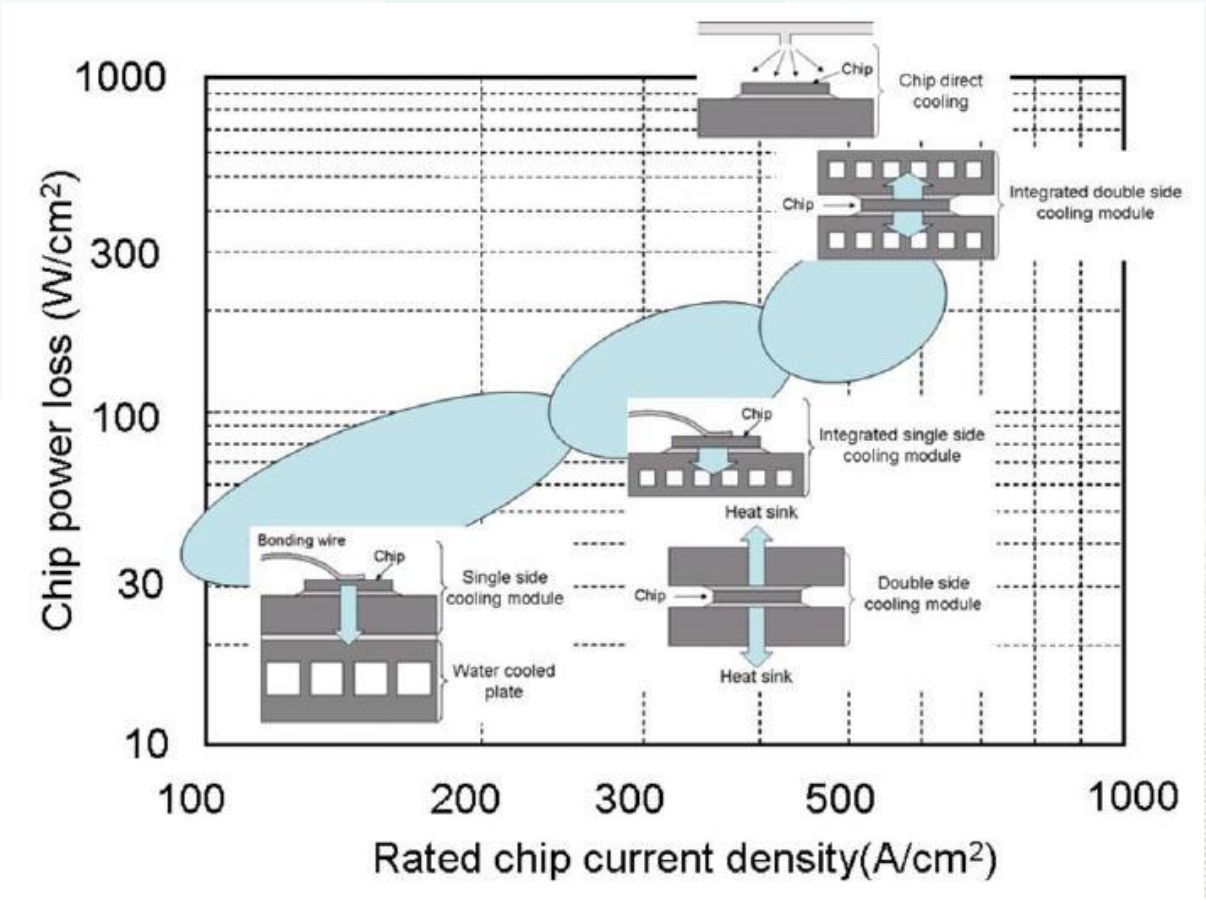
1. Introduction



Introduction

- In EV's and HEV's components such as chargers, drive inverters, traction motors, and energy storage batteries, participate in the power conversion process
- Energy losses during operation cause heat to build up in these components and their temperatures to rise
- The heat must be removed to enable the components to operate at low enough and relatively uniform temperatures to function reliably and maintain performance over a long lifetime
- The role of cooling is to manage damaging thermal effects like high temperatures and large temperature gradients resulting from the energy losses
- This role is vital to the cost, performance and longevity of EV's and HEV's

Power device packaging

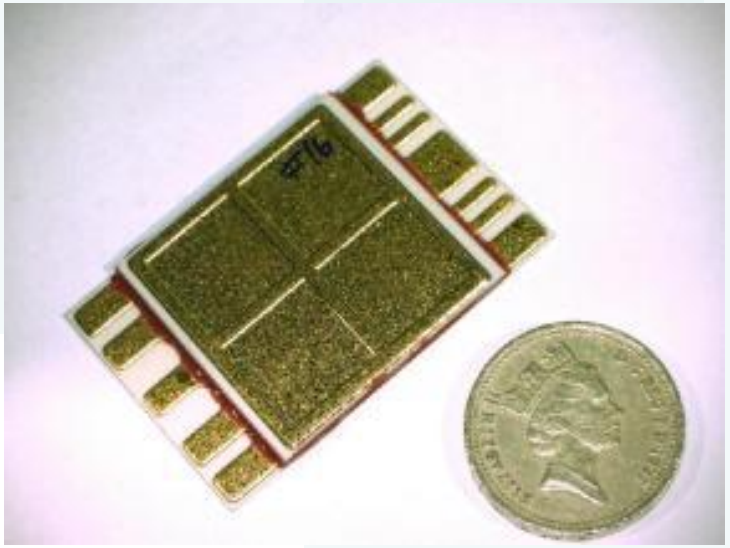


With increasing heat density, thermal interface resistance can become a bottleneck.

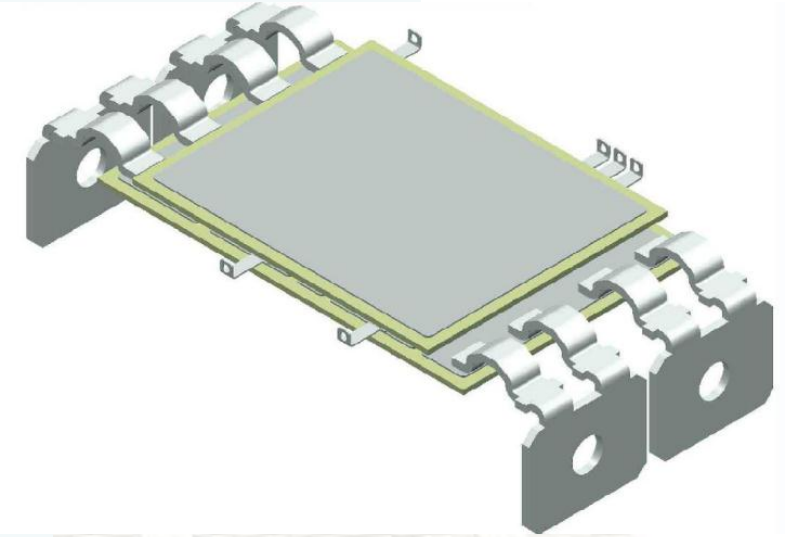
This calls for integrated electrical and thermal packaging so that the number of thermal interfaces from heat source to coolant are minimized.

- Z. John Chen and Ichiro Omura, Power Semiconductor Devices for Hybrid, Electric and Fuel Cell Vehicles, Proceedings of the IEEE, April 2007.

Custom Power Packages



Courtesy Denso



Courtesy Alstom

For EV

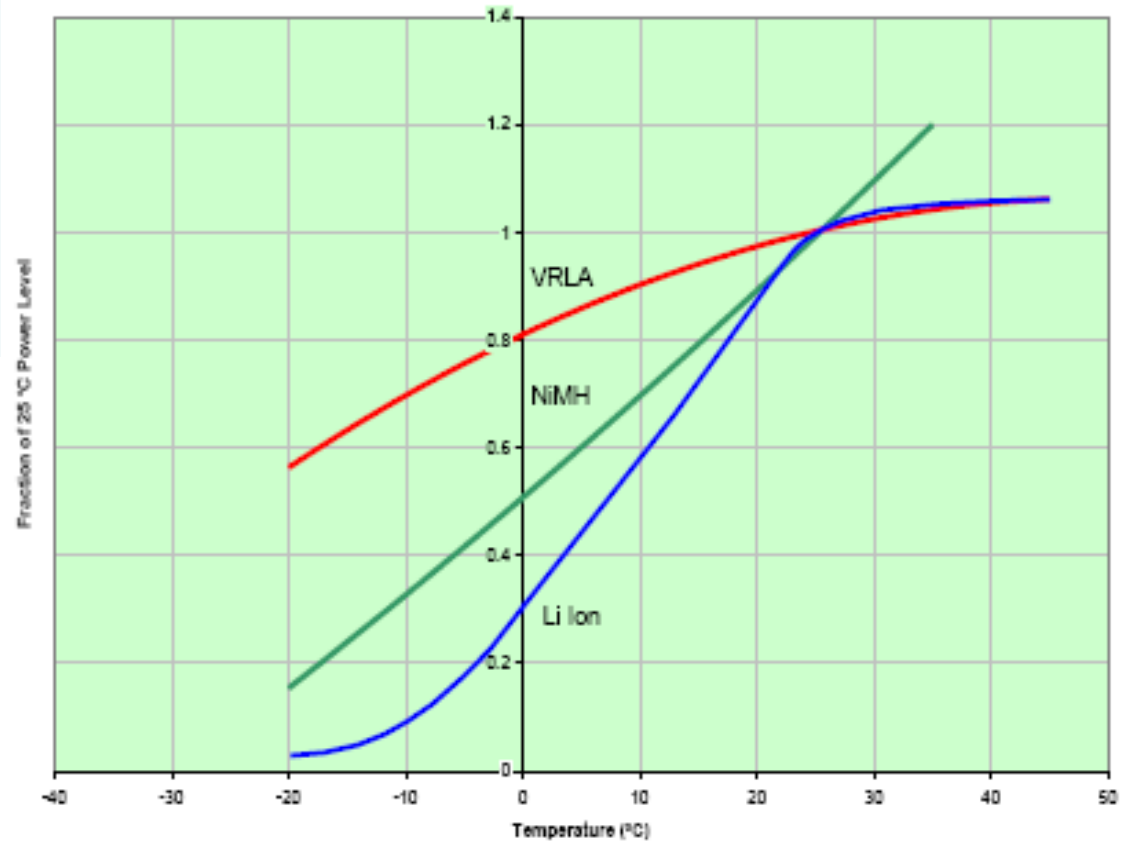
For rail traction

Both these packages minimize material content and are designed with cooling from both sides in mind.

Power semiconductors

- Silicon remains the workhorse material for power semiconductors in EV / HEV
- Wide band gap materials like SiC and GaN will enable lower losses and higher temperature operation in the future. This depends on the development of improved passives and packaging materials. And reduction in cost.
- For now, semiconductor temperatures are limited to about 175 to 200 °C

Effect of Temperature on Battery power



Steven Vance, Parallel-Cell Connection in Lithium-Ion Battery, Kettering University Senior Thesis, Dec 2008

- Both power and energy capacity suffer at low temperatures.
- Risk of damage at high temperatures.
- Batteries need temperature management – not just cooling.
- May be best to tie battery thermal system to the climate control system for vehicle occupants.

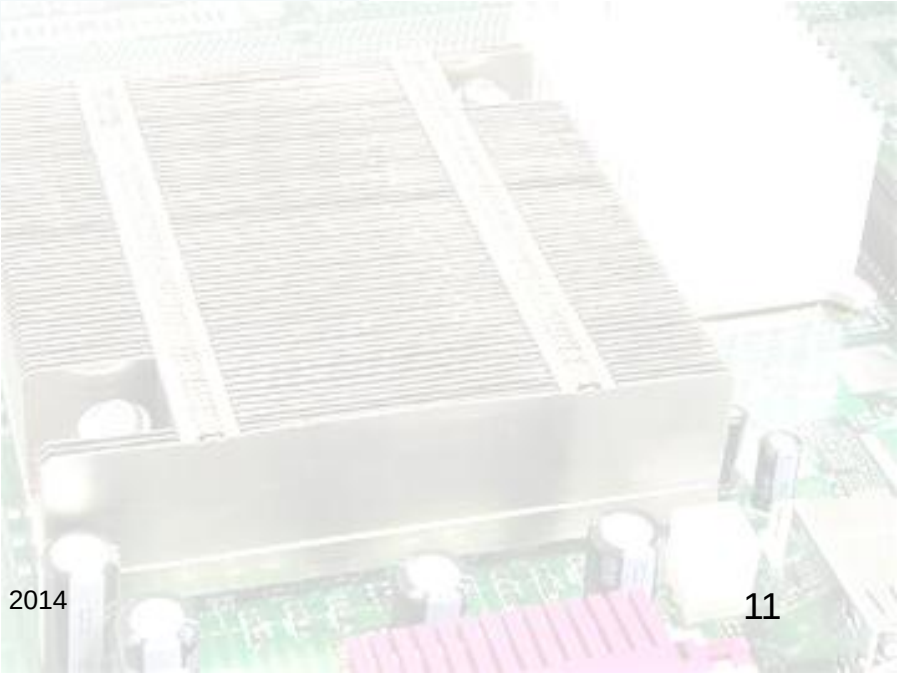
Cooling needed in EV/HEV's and why

- Parts that need only to be cooled
  - Power electronics – reliability
  - Traction motor – efficiency
  - Internal combustion engine - reliability
- Parts that need to be cooled and heated depending on environment
  - Traction power batteries – life, safety, power
  - Occupants – comfort, life support

Importance of effective cooling system

- A more effective cooling system architecture and performance enables:
  - more compact packaging of the power electronics – smaller, lighter
  - higher torque and power output from electric motors – can use smaller, lighter motors for a given job
  - higher charging and discharging rates for batteries and greater energy capacity – faster charging, more traction power, greater range, compact
  - lower parasitic power to operate the thermal management equipment – greater range
  - more space and capacity for people and other mass
  - lower cost and operating cost plus greater reliability

2. Cooling principles and concepts



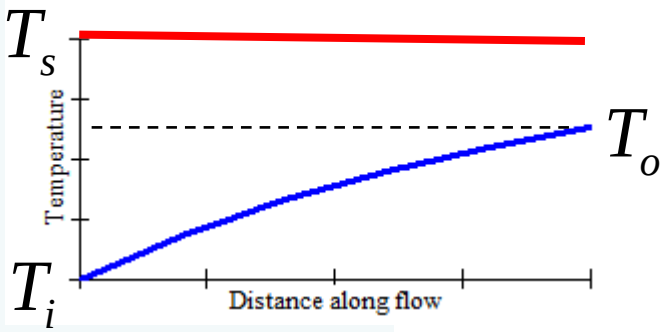
Convection Thermal Resistance

$$R_{sf} = \frac{T_s - T_i}{Q}$$

$$R_{sf} = \frac{1}{C_f \cdot (1 - e^{\frac{-hA_s\eta_s}{C_f}})}$$

$$\varepsilon = (1 - e^{\frac{-hA_s\eta_s}{C_f}})$$

$$Q = hA_s\eta_s(T_s - T_a)$$



Key Variables

C_f = flow heat capacity $\dot{m}c_p$

h = heat transfer coefficient

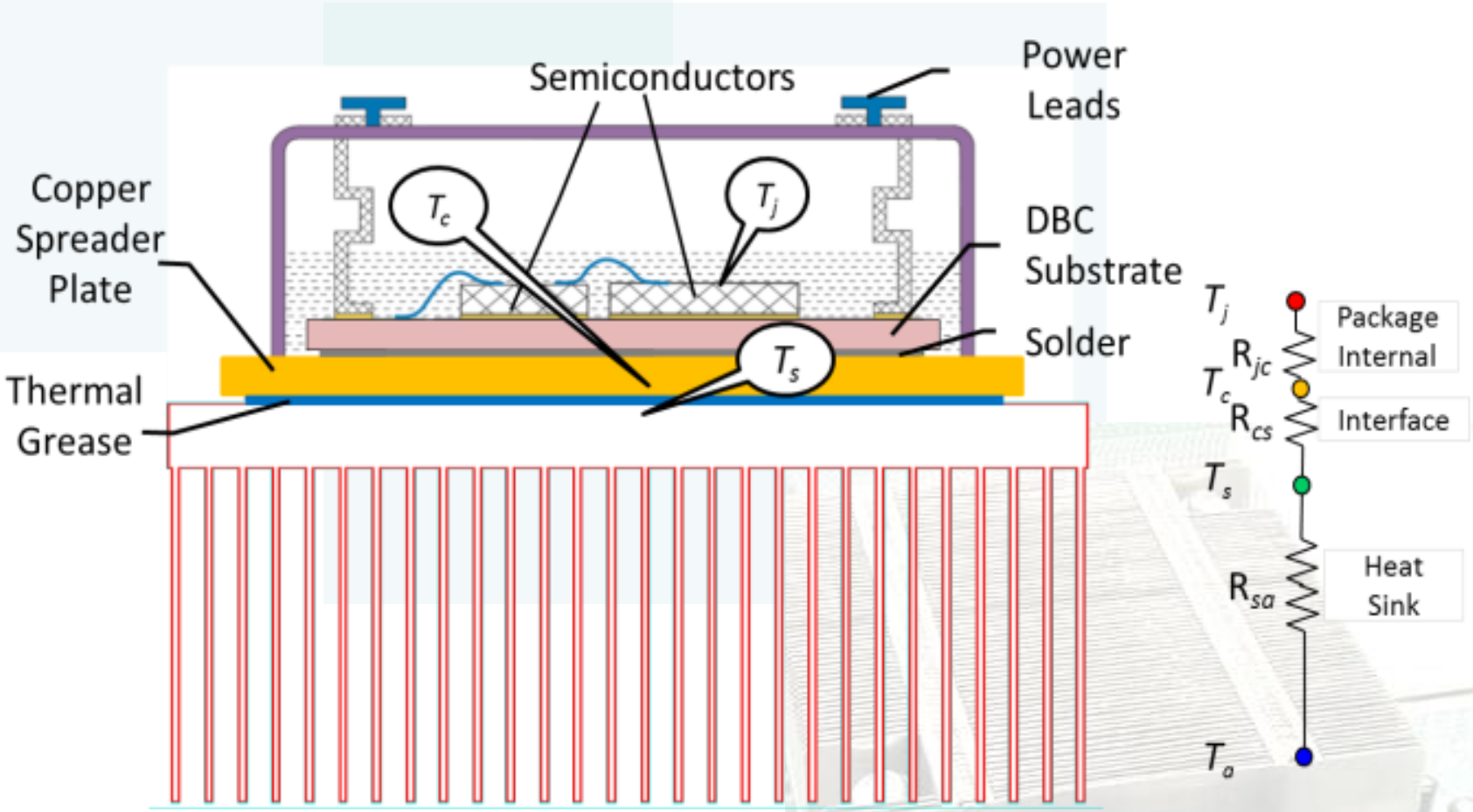
A_s = heat transfer surface area

η_s = surface efficiency (<1)

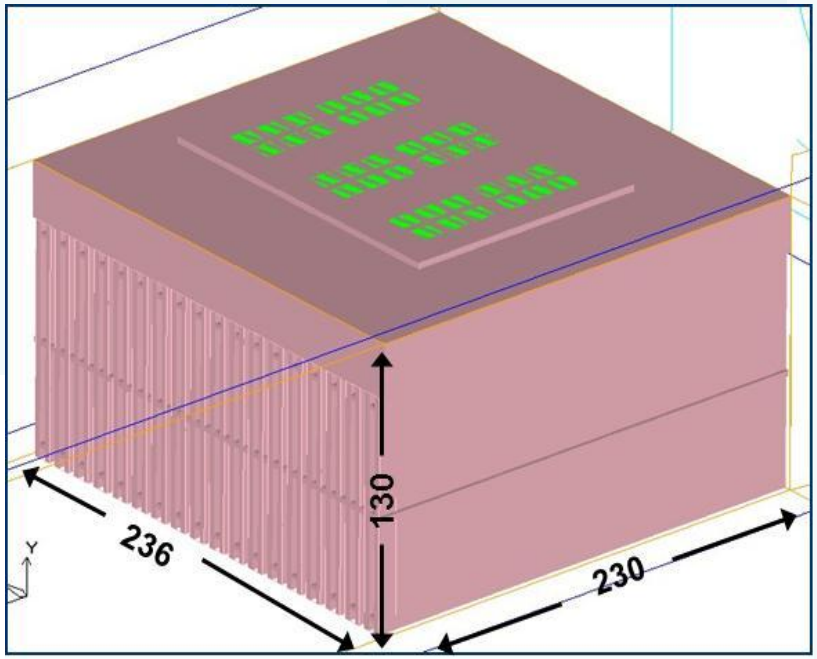
How to improve cooling?

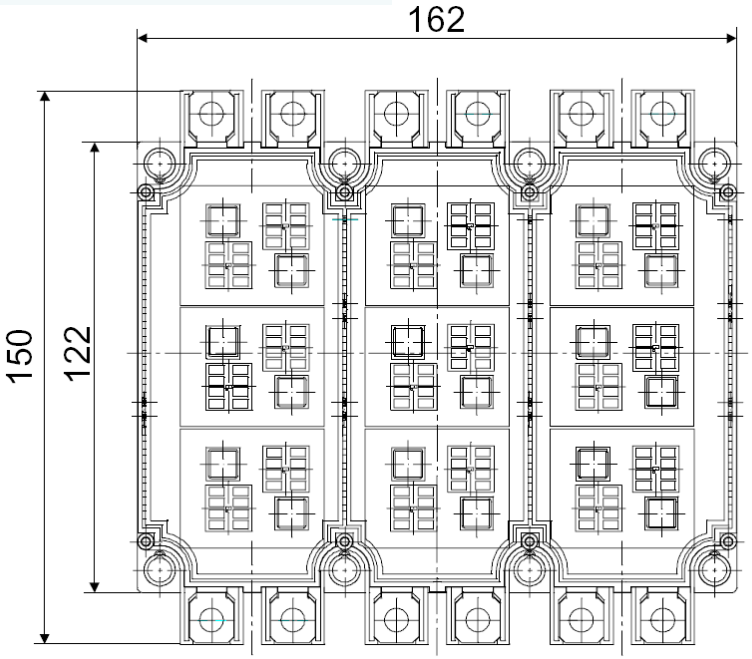
- h – fluid with higher thermal conductivity, turbulence, mixing, smaller channel sizes (e.g. micro-channels)
- A_s – optimize finned surfaces
- η_s – improve heat spreading in the base, use more conductive fins, focus cooling only where needed
- C_f – use higher heat capacity fluid (e.g. water), use latent heat (phase change)

Package Thermal Resistances



Example Air Cooled Solution





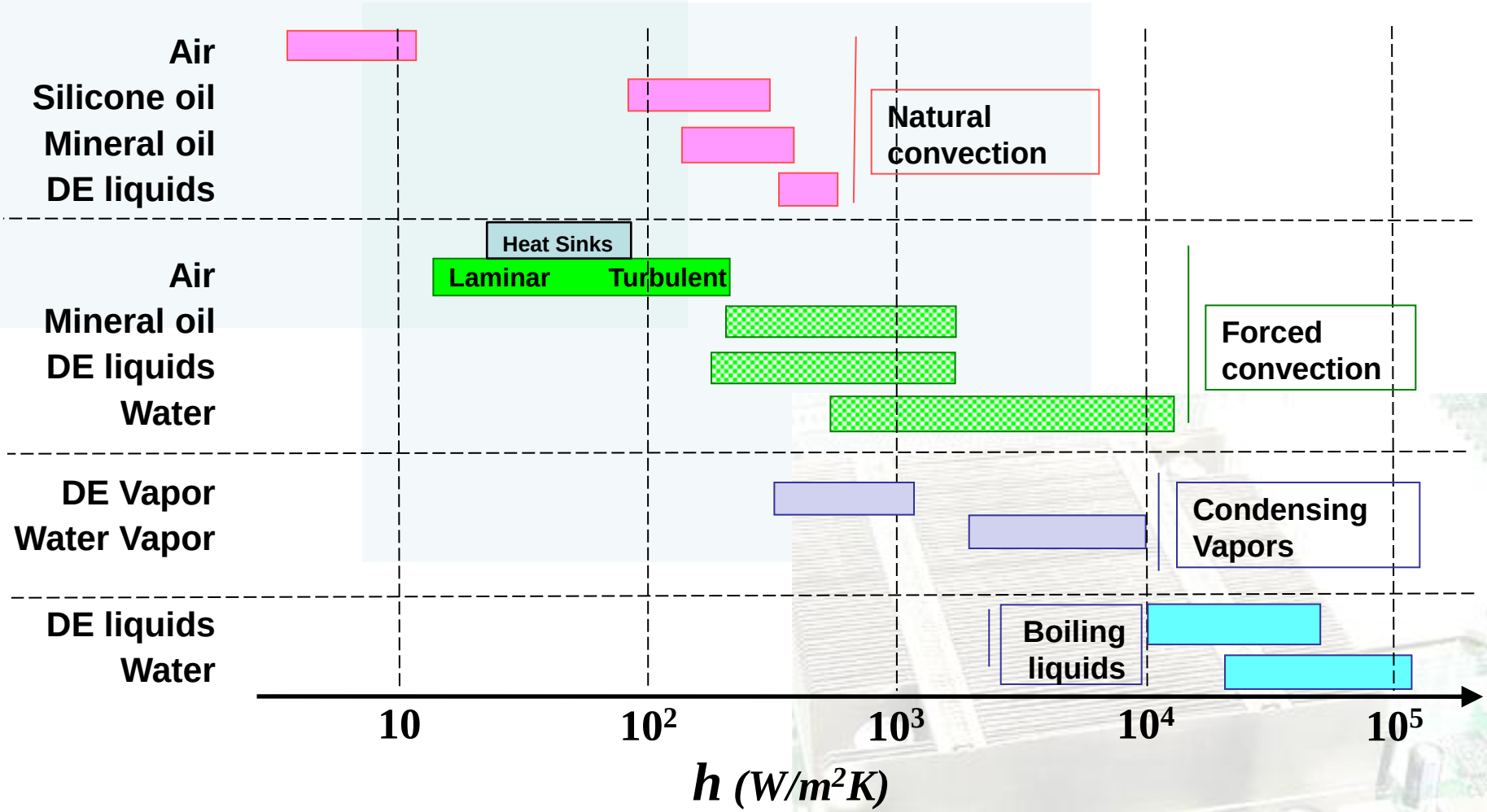
- The heat sink has aluminum base and fins
- Air flow rate through the heat sink = 0.25 m^3/s
- It cools an econo-pack IGBT module dissipating 2 kW of heat

Thermal Resistances in Air Cooled Example

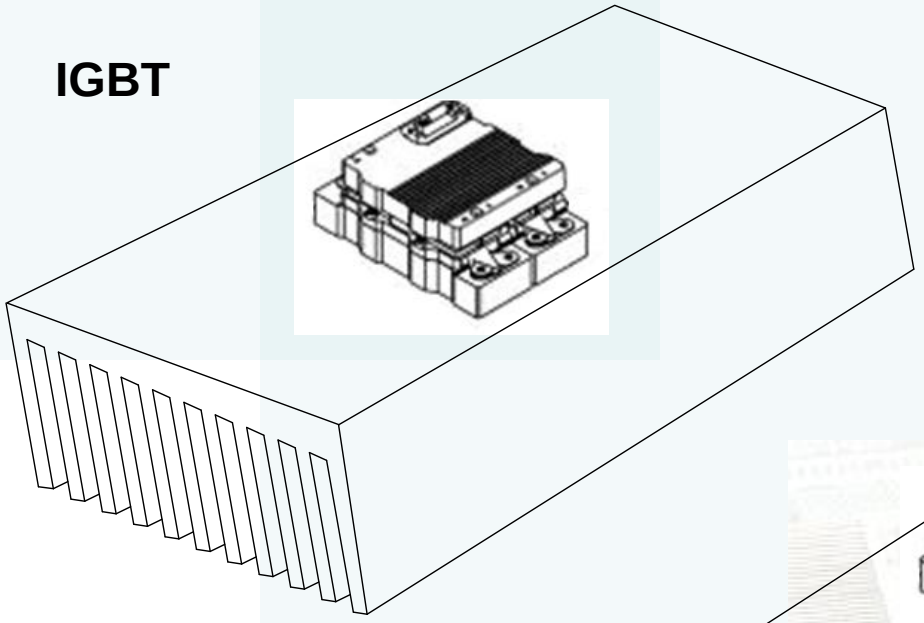
Stack-up layer	Effective Area (~cm^2)	Thickness (mm)	Resistance (^{o}C/kW)	Percent of Total	ΔT at 2kW
Silicon	30	0.2	0.6	1.3%	
Sintered Silver	30	0.1	0.2	0.4%	
Copper plane	35	0.3	0.2	0.5%	= 10 °C
Al-Oxide substrate	45	0.38	4.0	9.7%	
Copper plane	45	0.3	0.2	0.4%	
Solder	45	0.1	0.6	1.3%	
Copper base plate	120	3	0.7	1.6%	= 11 °C
Thermal Paste	120	0.05	4.2	10.0%	
Heat Sink - Base (spreading)	542	20	12.0	28.9%	= 24 °C
Heat Sink - Fins (convective)	542	110	19.0	45.8%	= 38 °C
Total			41.5	100%	= 83 °C

The case for packaging design to eliminate thermal interfaces and a more direct heat path to a better convection cooled surface is compelling.

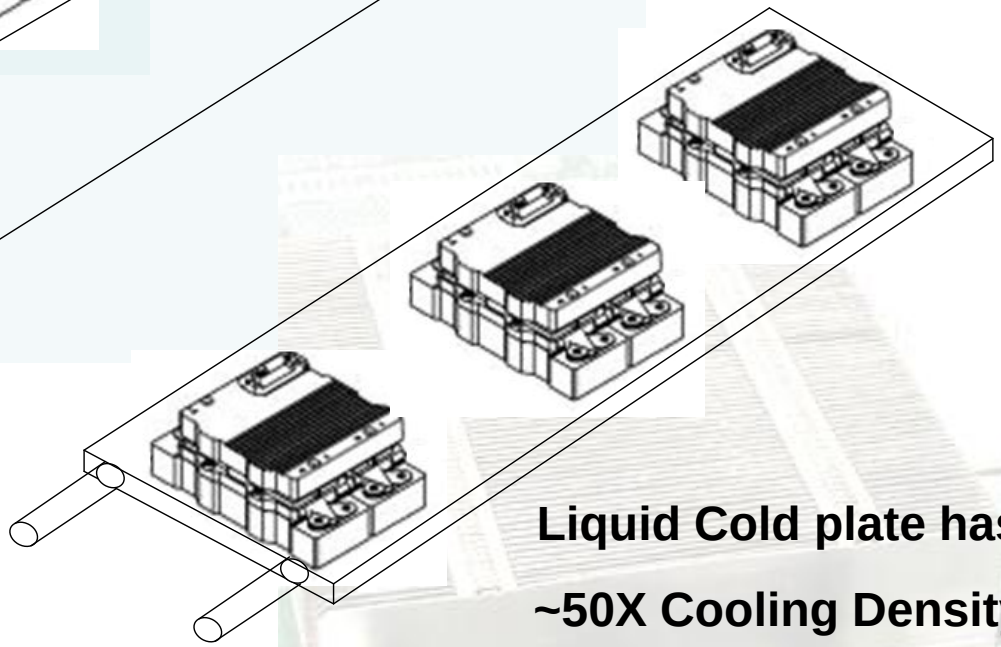
Convection Coefficient



Heat Sink level Cooling Density



Liquid Cold Plate

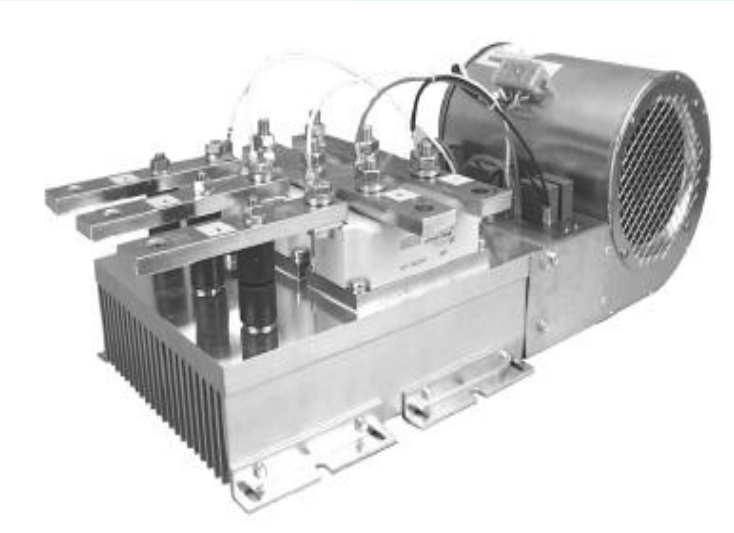


Natural Convection

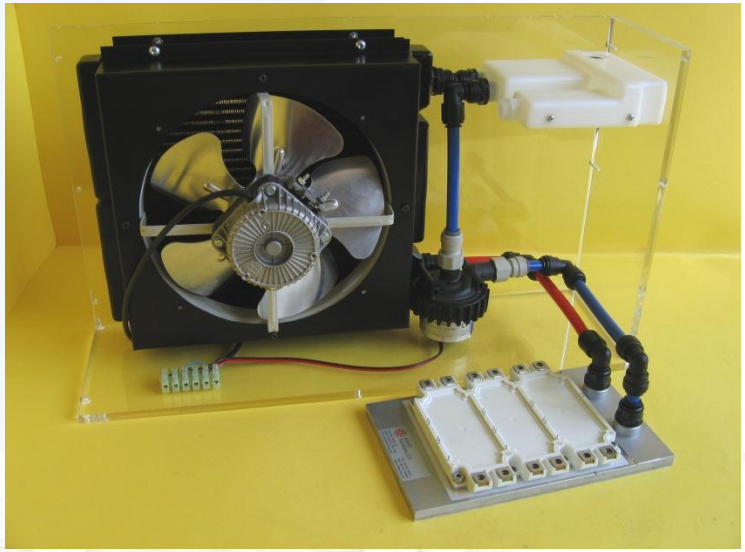
Liquid Cold plate has

~50X Cooling Density

System level cooling density



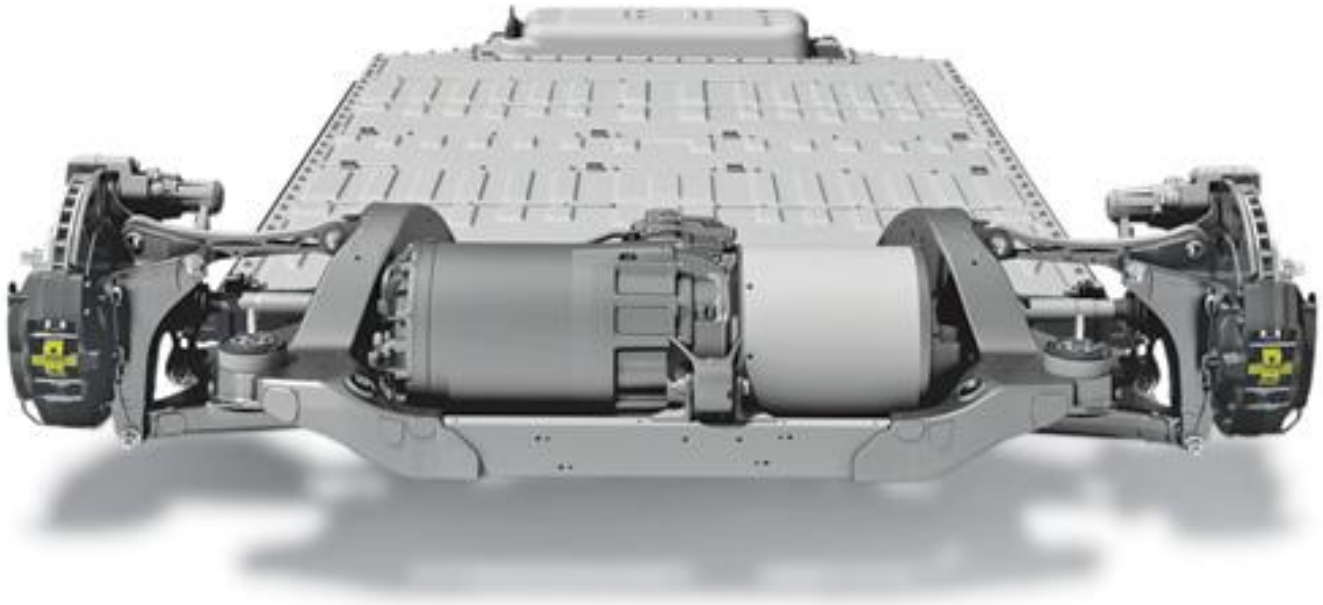
- 600 x 300 x 250 mm
- Weight = 20 kg
- 1.5 kW
- $Rth_{sink\text{-}amb}$ = 40 ˚C/kW



- 500 x 300 x 200 mm
- Weight = 5 kg
- 2 kW
- $Rth_{sink\text{-}amb}$ = 19 ˚C/kW

The case for a liquid subsystem to gather the heat from all the heat sources to the higher level air cooling system (radiator or AC) in the vehicle is compelling.

Tesla Model-S Drive Platform



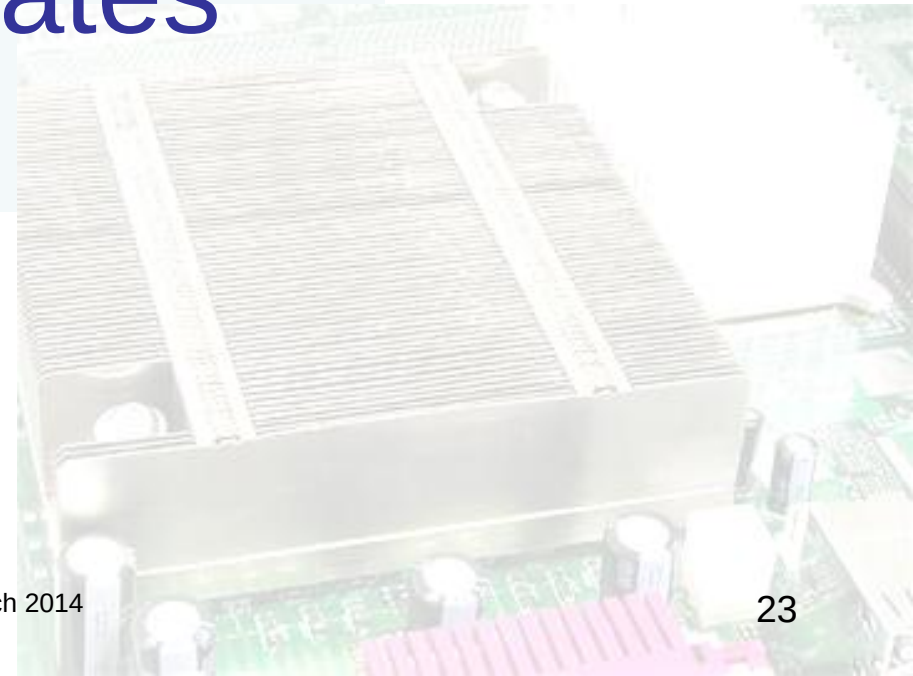
The above example used liquid to cool the battery, the power electronics, and the traction motor. Other recent EV's also incorporate liquid cooling.

3. New technologies applicable to air and liquid cooling in EV / HEV applications

New technologies

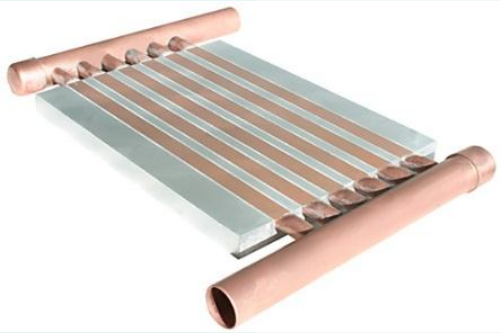
- Liquid cold plates
  - Vortex LCP – high performance flow architecture
  - HSDC – direct cooling of Power Module surface – eliminate interfaces, reduce cost
- Pulsed fluid movers
  - Periodic flow for higher turbulence
  - Lower power consumption – lower parasitic power
- High density die casting
  - Better thermal conductivity while retaining the cost advantages of a near net shape manufacturing process

3a. Liquid Cold Plates



Liquid Cold Plate examples

Single Tube type



Parallel-Tube type

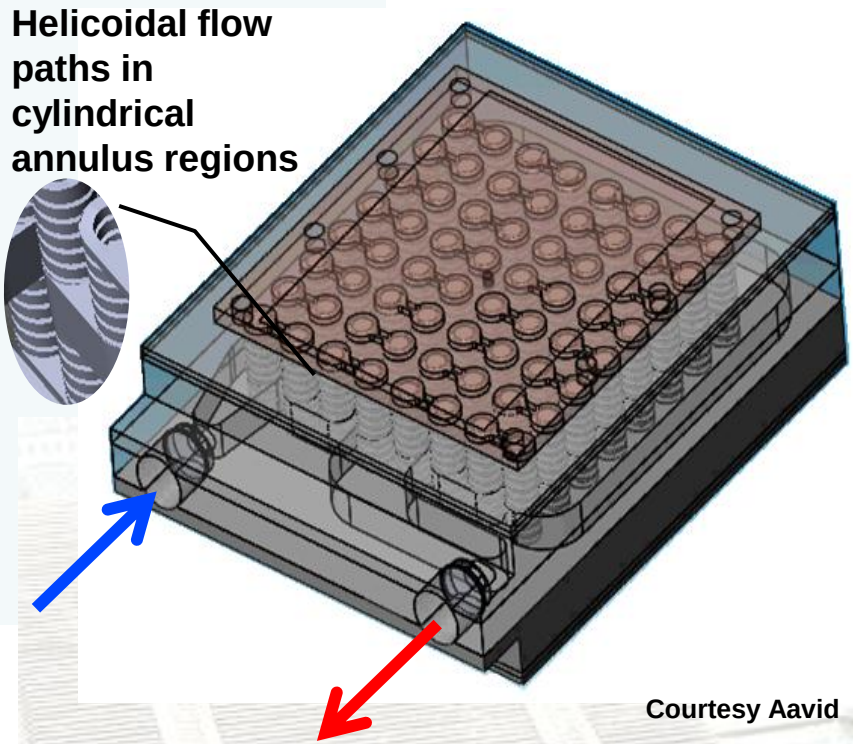
Channel or offset fin Type

Hi-Shear Channel Type

- Wide range of designs are used in industry.
- The best choice depends on the application requirements –ΔP, R_{th}
- We will discuss two new types of cold plates today

Vortex Liquid Cold Plate VLCP

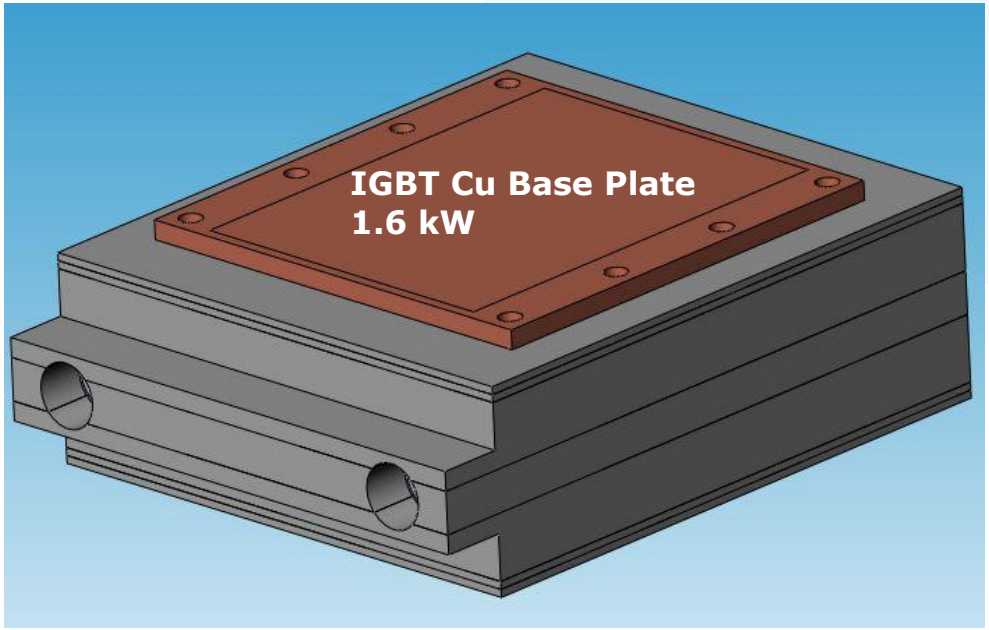
- The technology is developed for cooling systems without filters where flow channels must be > 2mm in size. Size is scalable.
- The liquid flow path is shaped like a helix or “vortex” to promote strong turbulence and mixing and achieve high ‘*h*’ as well as high ‘A_s’
- The overall liquid flow path is normal to the cooled surfaces at the top and bottom
- The cross-section normal to the cooled surfaces is mostly metal for good heat conduction. Modules can be mounted on both sides of LCP.

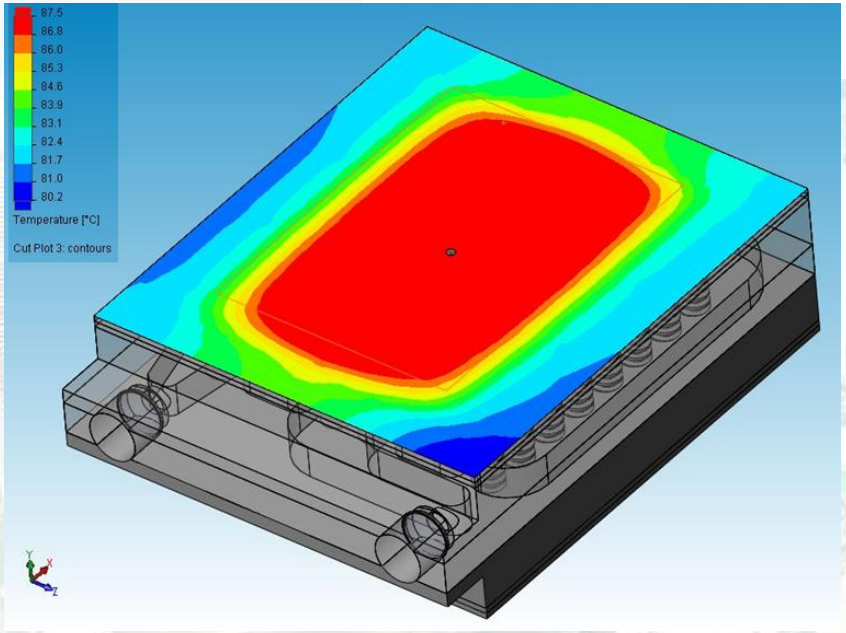


Courtesy Aavid

VLCP for IGBT cooling

- 2 IGBTs, 1600 W each, Tin=80 C, 11 lpm, 50:50 WEG fluid
- Performance of Aluminum VLCP
  - Maximum LCP temperature = 91.5 °C, ϵ=43%
  - LCP thermal resistance = 3.6 °C/kW (7.2 °C/kW each IGBT)
  - Pressure drop = 52 kPa (7.5 PSI)

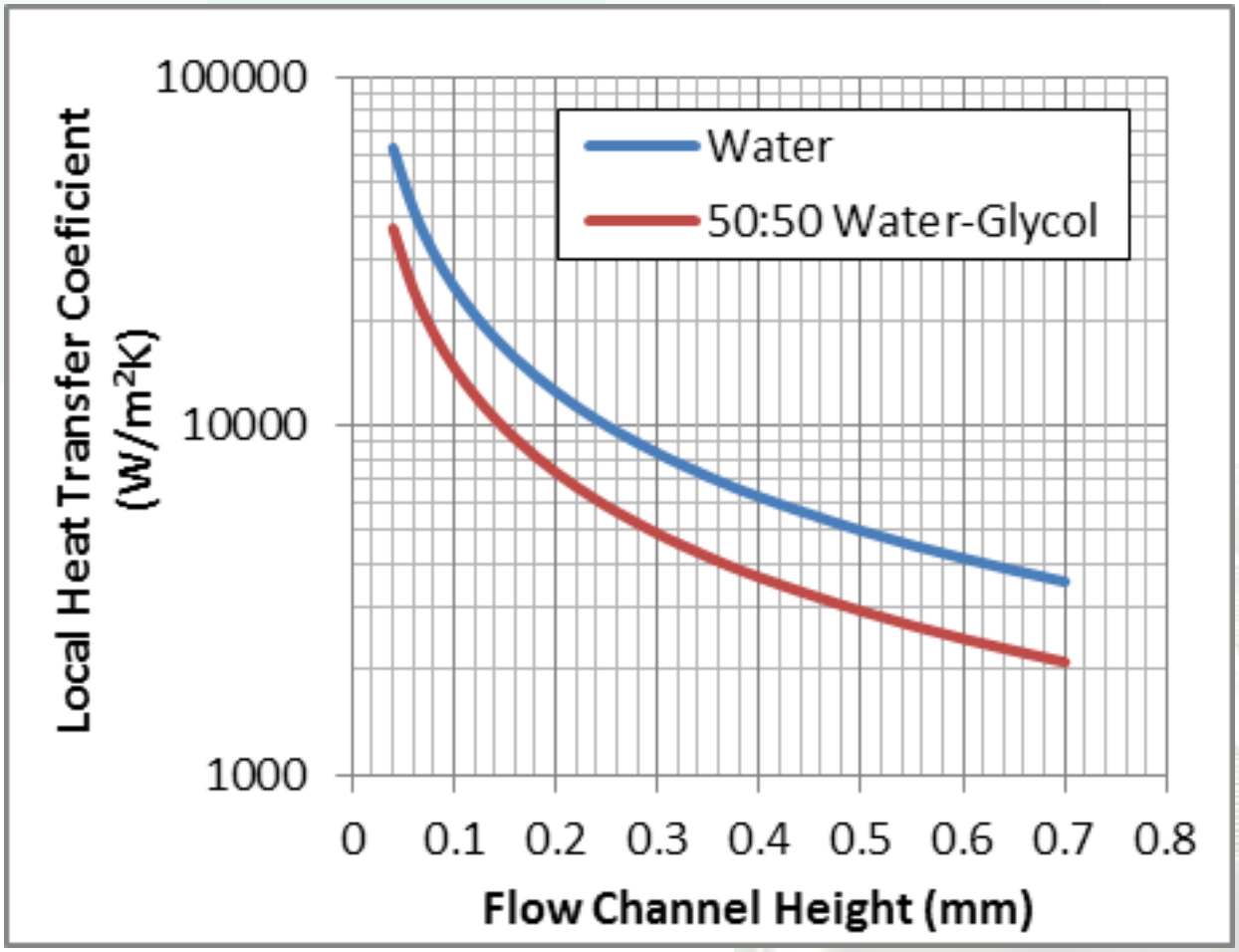




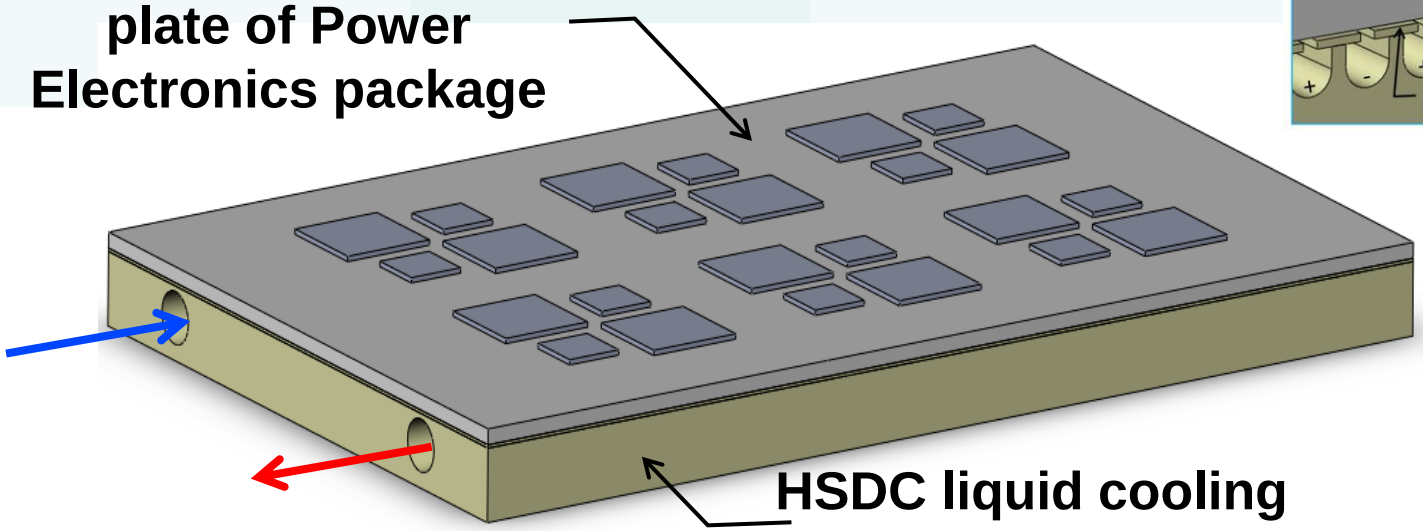
Direct Contact Liquid Cold Plate

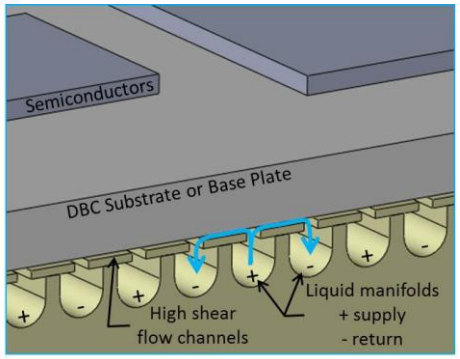
- It is feasible to use micro-channels to just increase ‘h’ and use only the ‘A’ of the base.
- This is because ‘h’ can be increased to a very high number with water based coolants by making the channel height very small – see graph on next page.
- Then the hot component surface can be cooled directly with the liquid rather than by conducting heat into a separate liquid cold plate.
- This concept is named High Shear Direct Contact in reference to the high shear flow in the narrow channel at the heat transfer surface.

Local ‘h’ at cooling surface



Direct Contact Cooling Assembly





HSDC assembly resistances at 5.5 lpm

Stack-up layer	Effective Area (~cm^2)	Thickness (mm)	Resistance (^{o}C/kW)	Percent of Total	ΔT at 2kW
Silicon	30	0.2	0.6	3.4%	
Silver	30	0.1	0.2	1.1%	
Copper	35	0.3	0.2	1.4%	= 10 °C
Al-Oxide	45	0.38	4.0	24.6%	
Copper	45	0.3	0.2	1.1%	
Solder	45	0.1	0.6	3.4%	
Copper base plate	120	3	0.7	4.0%	= 2.6 °C
~~Thermal Paste~~	~~120~~	~~0.05~~	~~4.2~~	~~10.0%~~	
~~Heat Sink - Base (spreading)~~	~~542~~	~~20~~	~~12.0~~	~~28.0%~~	~~= 24 °C~~
HSDC Cold Plate (convective)	120	10	10	61.4%	= 20 °C
Total			16.4	100%	= 33 °C

3b. High Density Die Casting

High Density Die Cast Heat Sinks

- HDDC is a process being developed to manufacture near net shape parts using a die casting like process with better material and thermal characteristics
- HDDC product features can include:
  - high thermal conductivity Al alloys (200+ W/m-K) as well as die cast alloys as needed
  - fine grain structure and no porosity or shrinkage defects due to new process controls during solidification
  - thin, high aspect ratio fin features
  - defect free surfaces with low roughness
  - embedding of copper, graphite, aluminum and other solid materials within the part

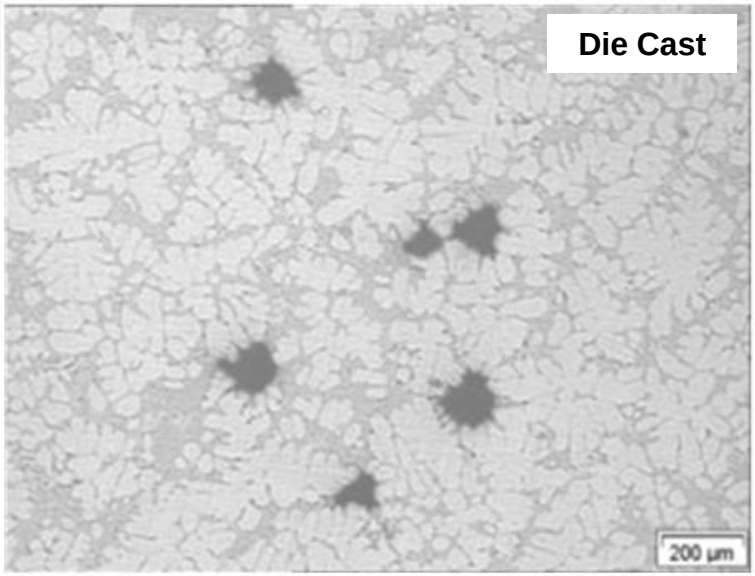
HDDC process capabilities

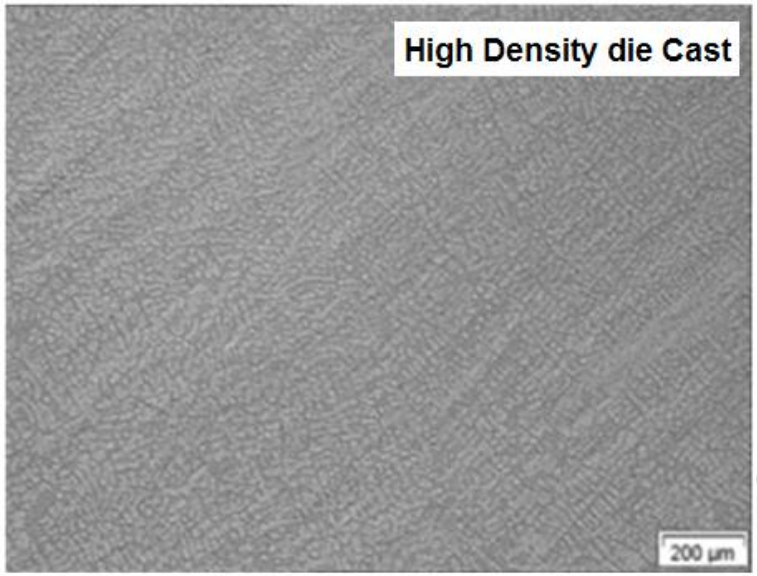
- The process is still in development. This table provides a preliminary comparison for heat sinks with 40-60 mm tall fins.

Description of Feature	Die Casting	HDDC
Fin Geometry (plate, pin etc.)	All types	All types
Minimum Enclosure Wall Thickness (mm)	2-3	1.5
Minimum Fin-to-fin spacing (mm)	5	2-3
Minimum Fin tip thickness (mm)	2	0.8 plate fin 2.0 pin fin
Minimum Fin Taper (degrees)	1	0.5
Porosity (%)	3 - 7	0
3D Near Net Shape Rating (5 is best)	5	4
Surface Quality Rating (5 is best)	2	4
Leak Tightness Rating (5 is best)	2	5
Aluminium Alloys	3XX alloys only	3XX, 11XX, 60XX

Comparison of Microstructure

- Porosity free parts with fine grain microstructure
- Leak tight parts – suitable for liquid cold plates
- (pictures from ~60 mm Φ, 50 mm tall heat sinks)



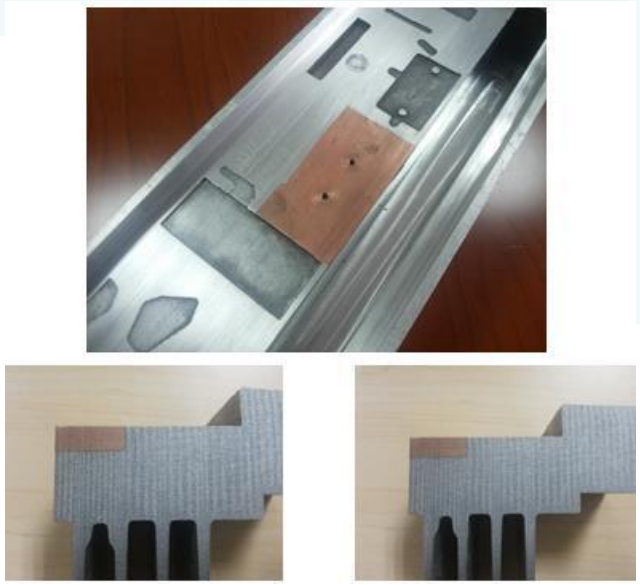


Post HDDC Operations

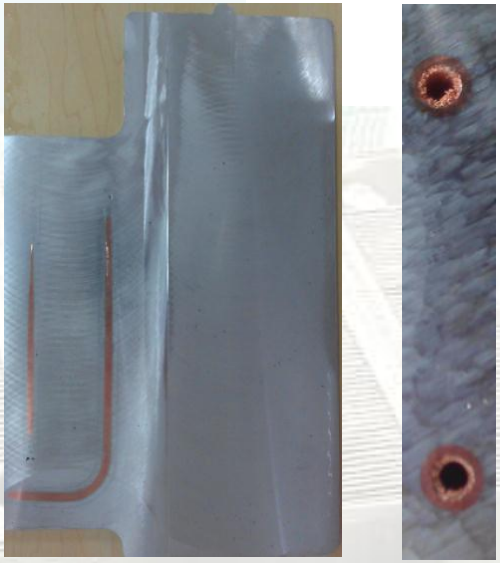
- Machining – OK to penetrate skin layer
- Brazing – robust complex assemblies
- Welding – leak tight enclosures
- Mechanical assemblies – reliable sealing against gaskets
- Surface finishing – anodizing, nickel plating, electro-coating, powder coating, wet painting …

Design Possibilities with HDDC

- Inserts may be imbedded directly into parts – e.g. threaded steel inserts, Al or Cu spreaders, Al or Cu fins etc.
- Process is fast enough to embed high-k graphite fabric
- Early trials with embedded heat pipes also seem promising



Copper heat spreader



Copper heat pipe

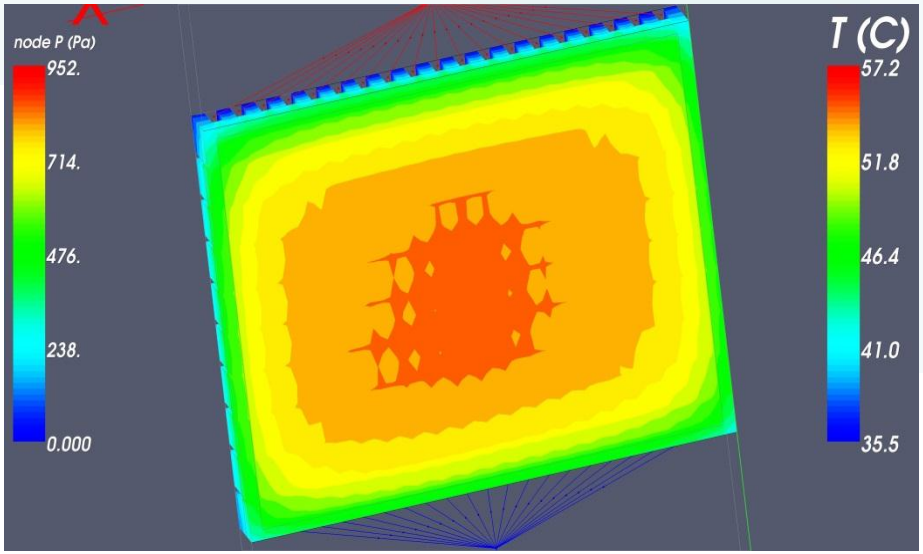
EV / HEV Liquid Cold Plates

- HDDC is particularly suited to make high performance liquid cold plates for EV / HEV applications
  - complex cooling surfaces can be formed at low cost with high thermal conductivity aluminum
  - embedded copper plates can be used to further enhance heat spreading where needed
  - Aluminum brazing or welding processes can be used to make robust and leak tight higher level assemblies

Liquid cold plate performance example

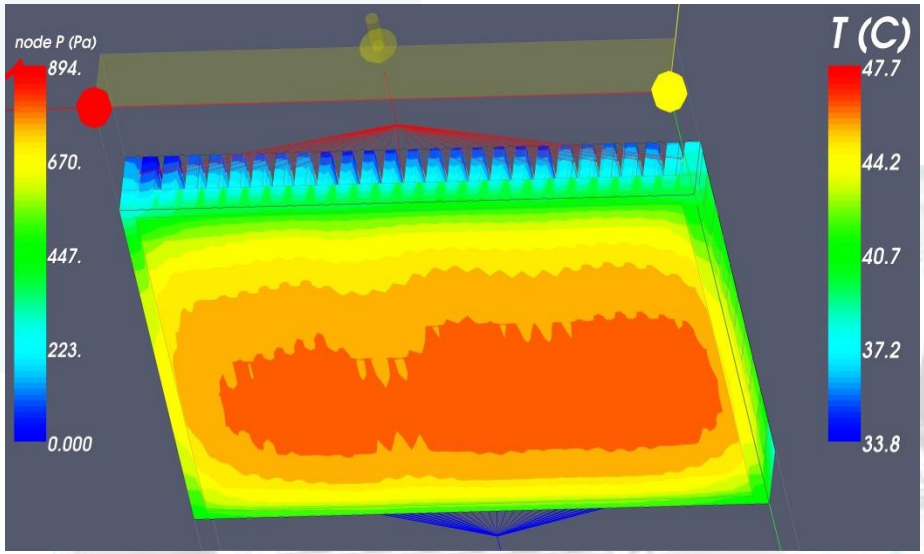
- In suitable applications, HDDC can provide significant reduction in device temperatures and gradients

Traditional Diecasting



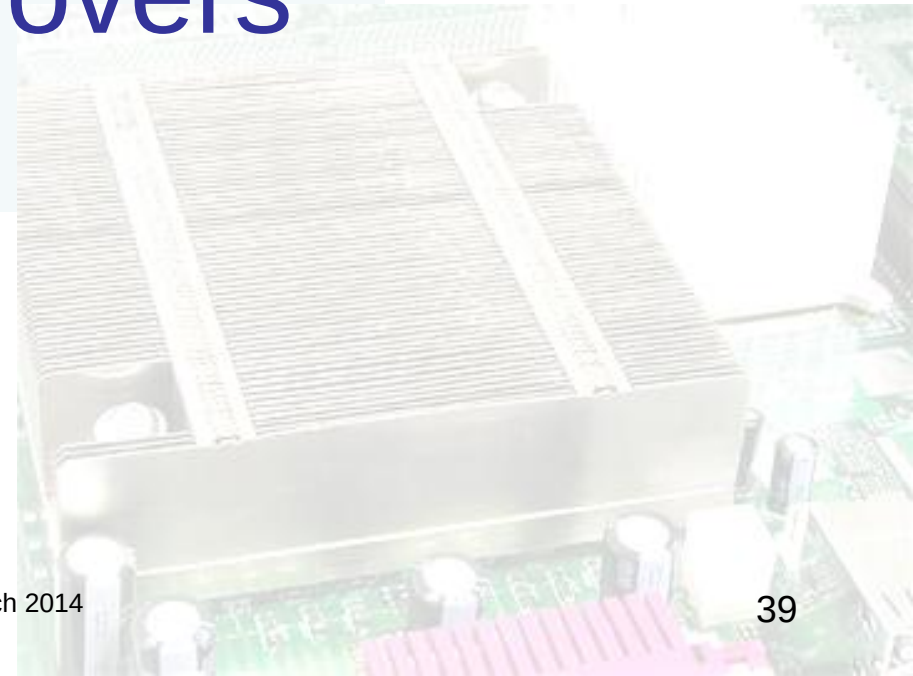
Tmax=57.2 °C, Rth=0.0272 °C/W, Gradient ~ 6 °C

HDDC



Tmax=47.7 °C, Rth=0.0177 °C/W, Gradient ~ 3 °C

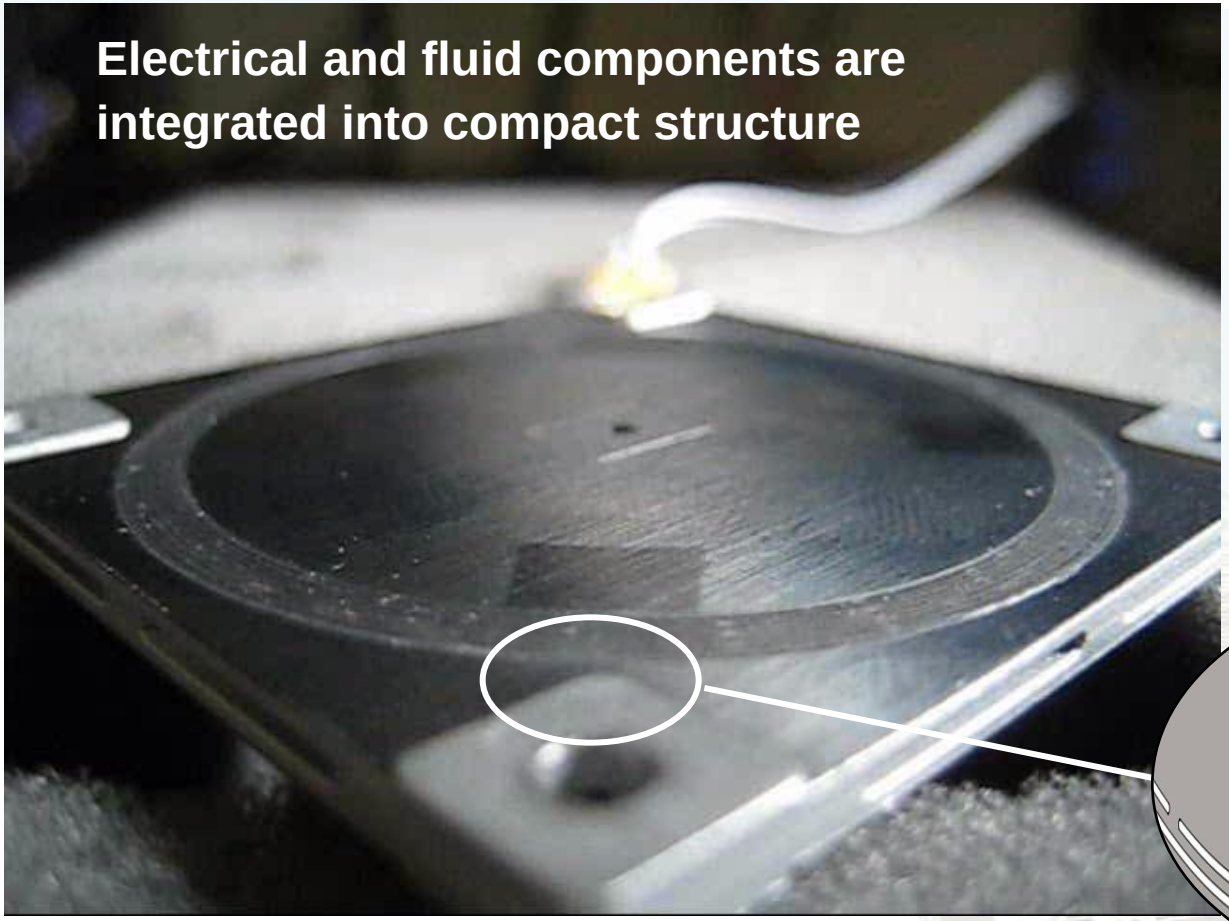
3c. Pulsed fluid movers



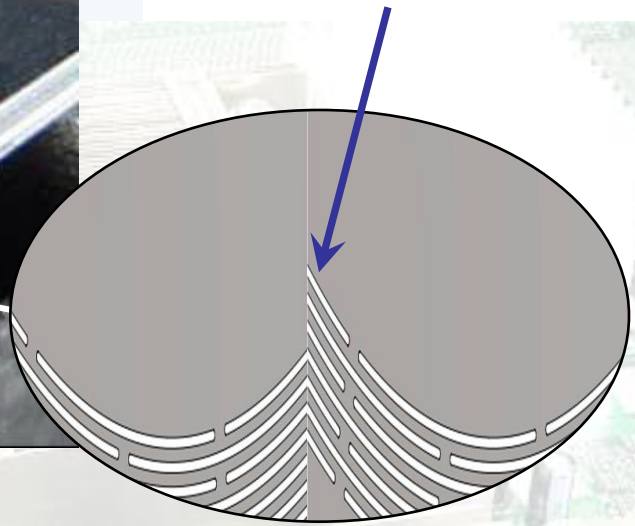
New Positive Displacement Technology

- New high performance fluid mover devices based on oscillating diaphragms:
  - Pulsed air jets
  - Gas compressors
  - Liquid pumps (can pump liquid-vapor mixtures)
- The key attributes of this technology are:
  - Scalability – no loss in performance when miniaturized
  - Flexible form factors – round, square, rectangular …
  - High pumping power densities
  - High reliability – no friction, stresses well below fatigue limit
  - Compact – electrical and fluid components are highly integrated

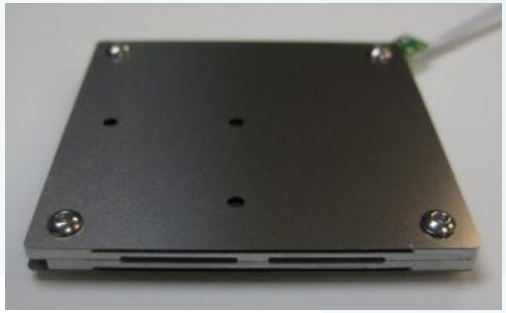
Pulsed fluid mover for air cooling



Matrix spring with overmolded elastomeric seal



Pulsed Air Jets



Application: thin form factors

Dimensions: 50x50x3.4 mm

Package volume: 8.7 cc

Vol displacement/cycle: 6.0 cc

Air pumping power: 50mW

Application: high heat loads

Dimensions: 90x90x29 mm

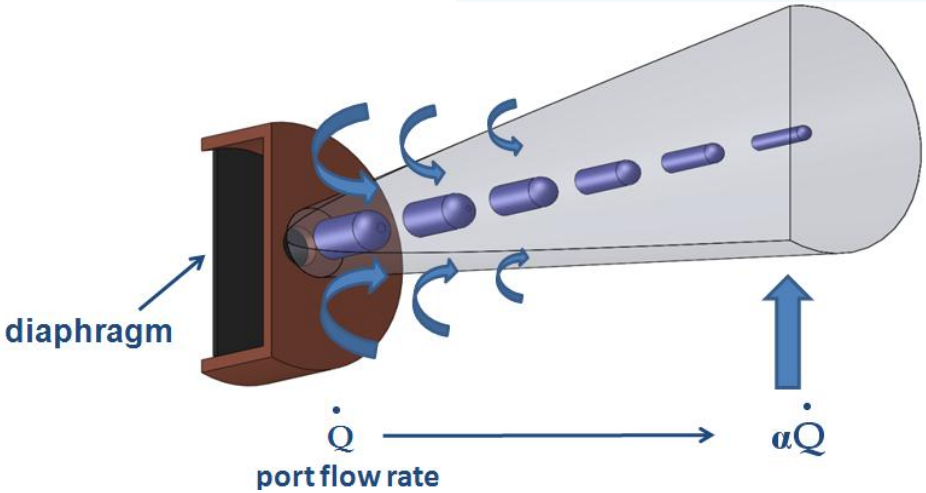
Package volume: 235 cc

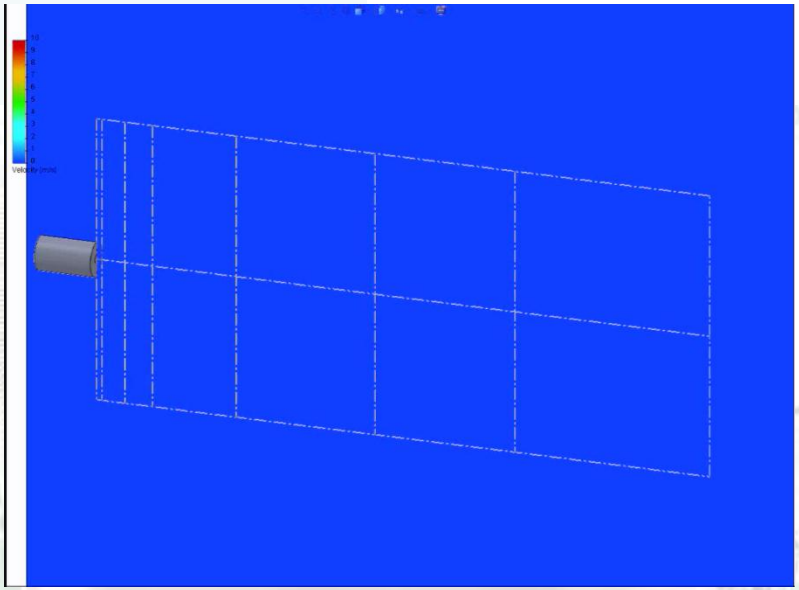
Vol displacement/cycle: 85 cc

Air pumping power: 15W

Pulsed Jet Operating Principle

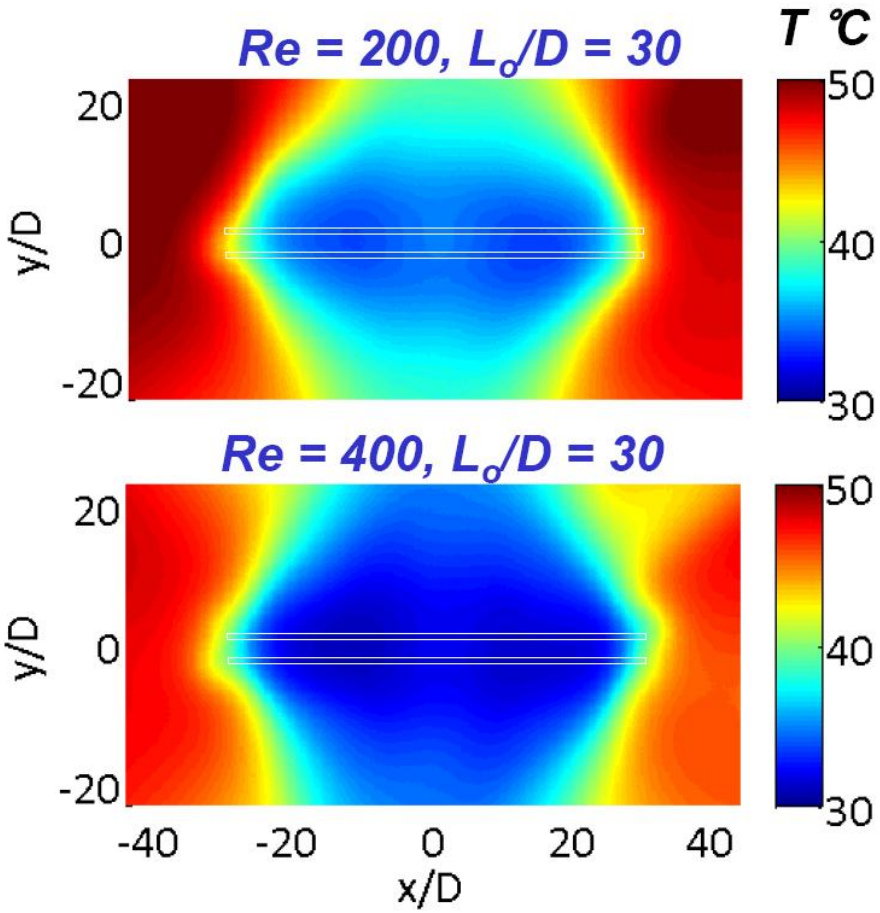
- Actuators eject air pulses (fluid momentum and vorticity)
- Ambient air is “entrained” into the jet via the rotating vortices
- Entrained flow amplification “α” can be 10-30x the actuator’s ejected port flow





Localized cooling with pulsed slot jets

- IR image from the direct impingement of two adjacent pulsed slot jets on a heated surface
- Measured “h” values in the cooled region are up to 20X higher than free convection, 2-3X higher than steady jets



Tim Persoons, Project Review Meeting Report, Nov 2011

4. Concluding Remarks

Conclusions

- Effective cooling in EV / HEV applications influences all design metrics – efficiency, compactness, cost, range, longevity etc.
- Liquid cooling is an effective and even necessary technology for EV/HEV applications.
- The advances in cooling technology described here are based on new production methods, new fluid movers, and enhancement of heat spreading and convection by improving the key parameters that control thermal resistance – 'h', 'A_s', 'C_f', and 'η_s'
- New liquid cooled cold plates are described that enhance 'h' using (a) "vortex flow" and (b) "high shear" fluid channels with direct contact between the liquid and the electronics module.
- New process technology is described to make cost effective high performance aluminum liquid cold plates and embed means to enhance heat spreading
- New fluid mover technology is described to enable enhanced heat transfer coefficients using pulsatile fluid motion in a highly integrated compact design. This improvement allows lower parasitic power draw.

Thank you.

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