Direct Jet-Impingement Cooling Solution

Presenter: Antonio Pappaterra

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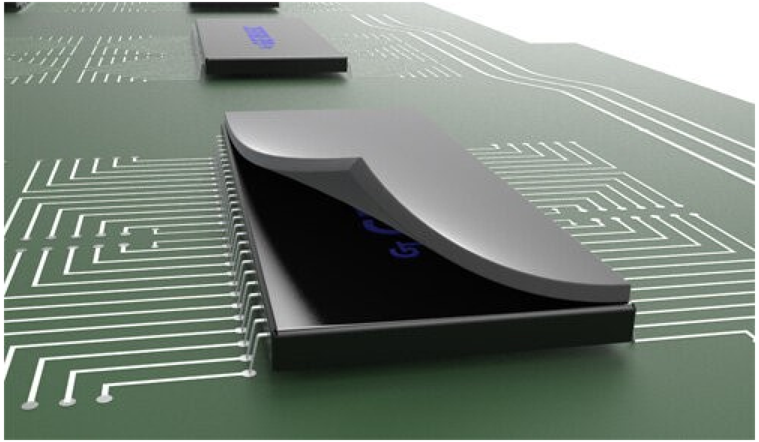
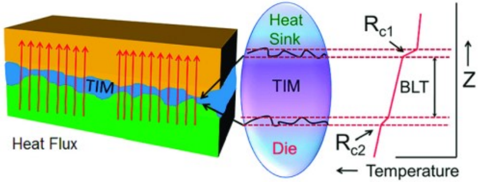
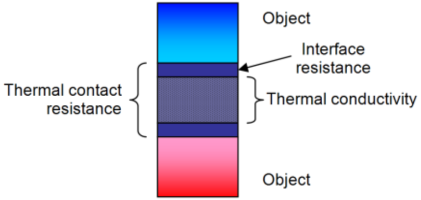
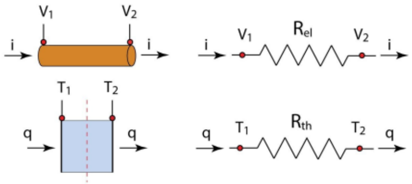
TIM (thermal interface material) limits → Direct jet-impingement









- Low Thermal conductivity (material)
- Contact thermal resistance at interfaces

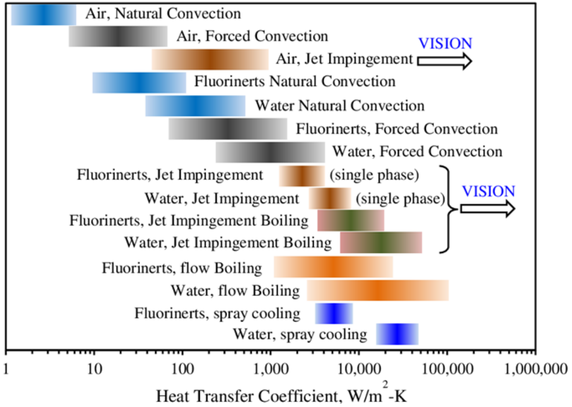
Thermal barrier

$$\textit{convection:} \quad q_{conv} = h\Delta T$$

$$\textit{conduction:} \quad q_{cond} = k\frac{\Delta T}{L}$$

$$R_t = \frac{L}{kA}$$

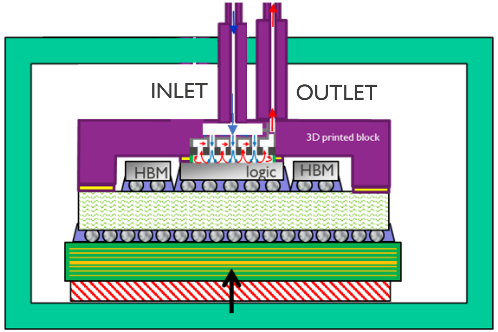
where
k is the materials conductivity [$W.m^{-1}.K^{-1}$]
L is the plane thickness [m]
A is the plane area [m^2]

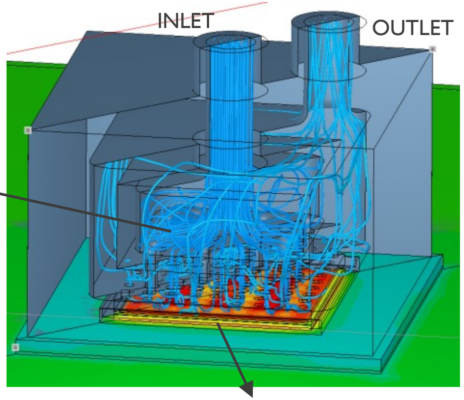


- Jet-impingement higher htc than traditional forced convection

(boundary layers are much thinner, and often the spent flow after the impingement serves to turbulate the surrounding fluid)

Direct Liquid Jet-Impingement Cooling Solution for AD HPVC





Glycol-water coolant mixture

P=300W
(20x20 die)

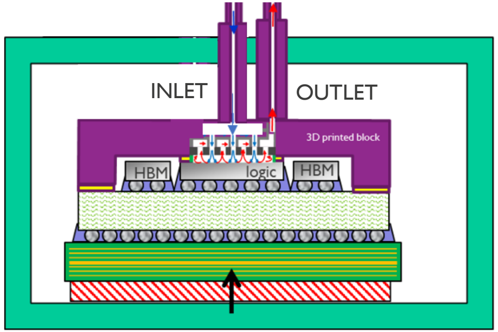
- Liquid cooling
- Direct Jet-Impingement (no TIM)
- Lidless
- Enhanced heat path

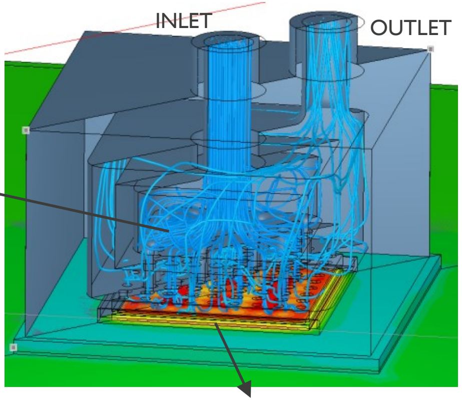
<u>Hot Condition:</u>
- Tamb= 85degC
- Tfluid_inlet= 65degC
- VFR= 5 l/min

<u>Cold Condition:</u>
- Tamb= -40degC
- Tfluid_inlet= -30degC
- VFR= 1 & 0.8 l/min

- Tmax < 105degC
  (Ambitious target 90degC)
- Pdrop< 250 mbar

Direct Liquid Jet-Impingement Cooling Solution for AD HPVC

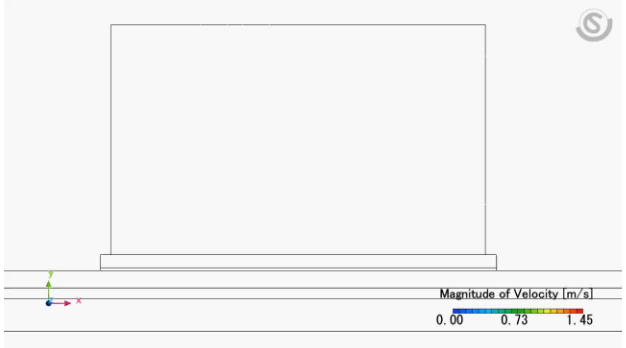


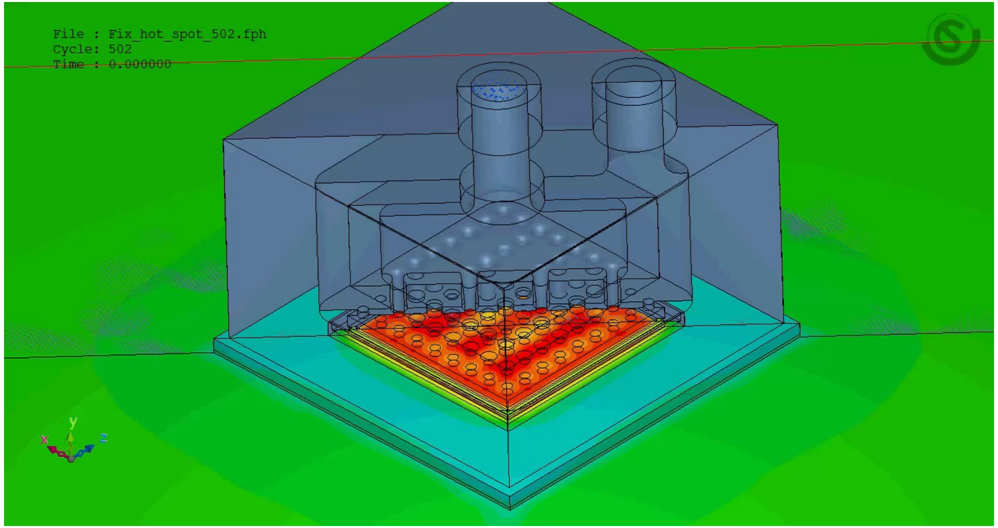


Glycol-water coolant mixture

P=300W
(20x20 die)

Post-processing CFD animations





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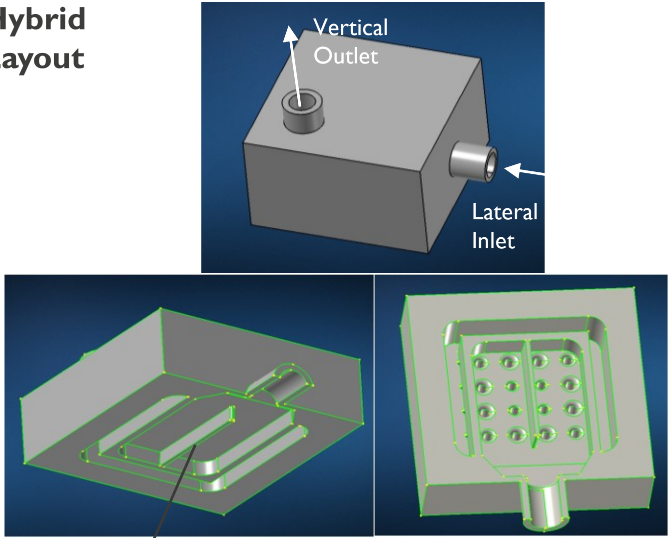
Concept study: why a vertical layout (inlet/outlet)?

Hybrid Layout

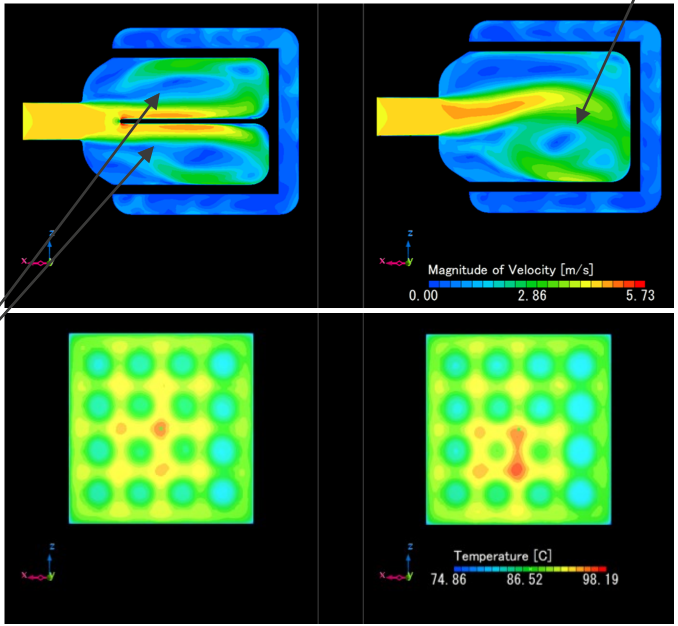


Horizontal Cross Section

Introduced middle fin
(optional)

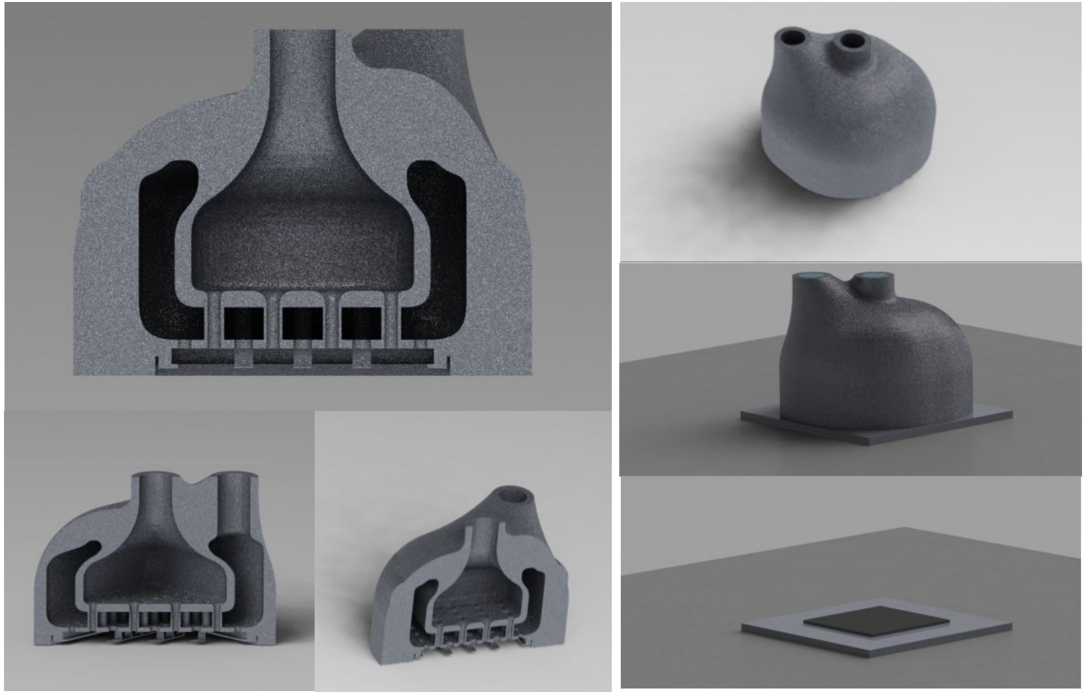
Main "Tumble" Vortex

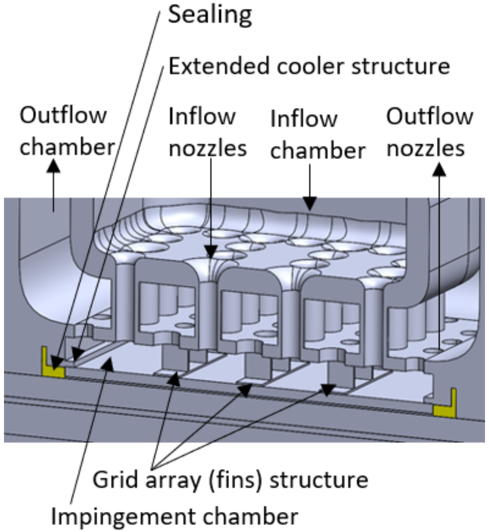
Two minor
"Tumble"
Vortices



- Single die (20x20mm)→ Small on-plane surface
- Difficult distribution fluid among nozzles (vortices) → Hot-Spots in the middle
- Pressure drop (90deg deviation) > 250mbar
- Volume/External encumbrance (with pipes/connectors) → Other elements on-plane

Final cooler design





Main Features:

- Dimensions 35*35*26.5mm
- N.34 inflow nozzles (“x” diameter)
- N.47 outflow nozzles
  - N.36 with “x” diameter
  - N.11 with “y” diameter (bigger)
- 5mm Inlet/Outlet ports inner diameter
- Grid array (fins) structure

Overall CFD setting

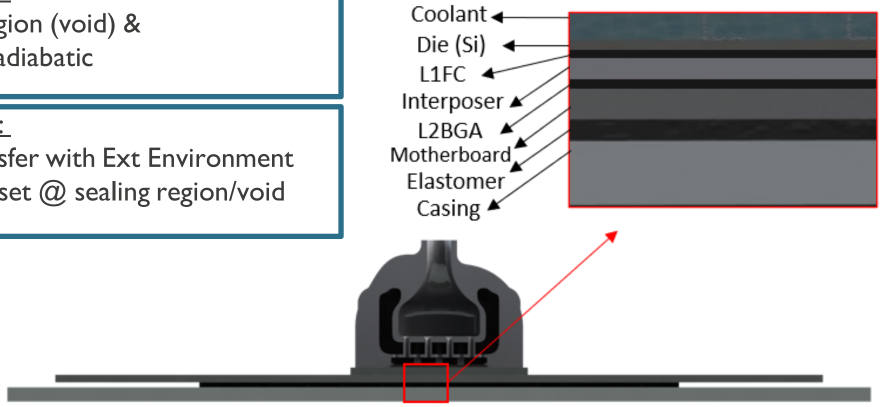
Turbulence model: *K-w SST (ref. paper)*
Turbulence BC: *preliminary analytical calculations*
- *Intensity*
- *Length scale*

Liquid: *Glycol-water (58%) → Temp. dependent properties*
Power: *300W (bottom die)*
VFR, Tfluid & Tamb: *Based on "Hot Condition" (previous slide)*

Condition n.1:
- Sealing region (void) & ext walls adiabatic

Condition n.2:
- Heat transfer with Ext Environment
- 1 W/m-k set @ sealing region/void

Solid Material Properties Assigned

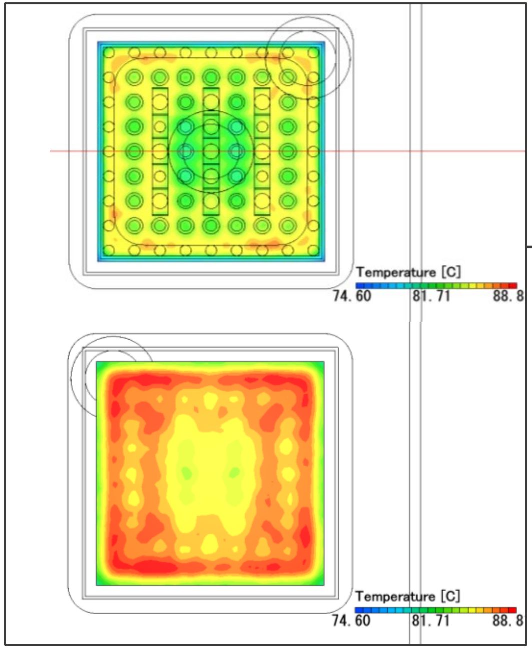


Turbulence model	Computational cost (time required)	Impingement jet transfer coefficient prediction	Ability to predict secondary peak
k-ε	★★★★ Low cost	★ Poor: Nu error of 15–60%	★ Poor
k-ω	★★★★ Low–moderate	★★ Poor–fair: anticipate Nu errors of at least 10–30%	★★ Fair: may have incorrect location or magnitude
Realizable k-ε and other k-ε variations	★★★★ Low	★★ Poor–fair: expect Nu errors of at least 15–30%	★★ Poor–fair: may have incorrect location or magnitude
Algebraic stress model	★★★★ Low	★★ Poor–fair: anticipate Nu errors of at least 10–30%	★ Poor
Reynolds stress model (full SMC)	★★ Moderate–high	★ Poor: anticipate Nu errors of 25–100%	★★ Fair: may have incorrect location or magnitude
Shear stress transport (SST), hybrid method	★★★ Low–moderate	★★★ Good: typical Nu errors of 20–40%	★★ Fair
$v^2 f$	★★★ Moderate	★★★★ Excellent: anticipate Nu errors of 2–30%	★★★★ Excellent
DNS/LES time-variant models	★ Extremely high (DNS available for low Re only)	★★★★ Good–Excellent	★★★★ Good–Excellent

★: undesirable model characteristics
★★★★: excellent model characteristics

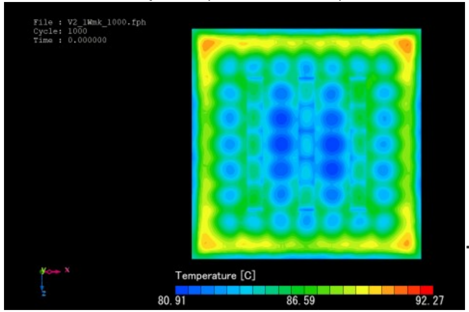
Y+ in line with K-w SST model

Final cooler design results



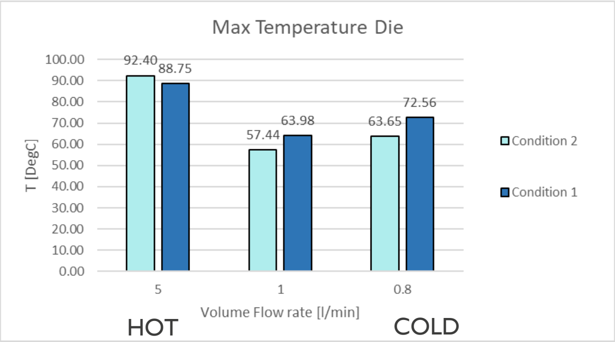
Top & bottom die (condition n.1)

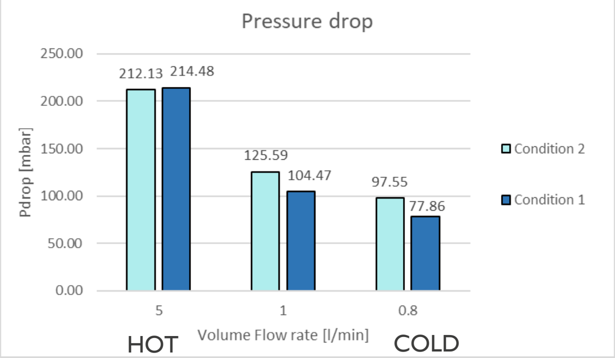
Top die (condition n.2)



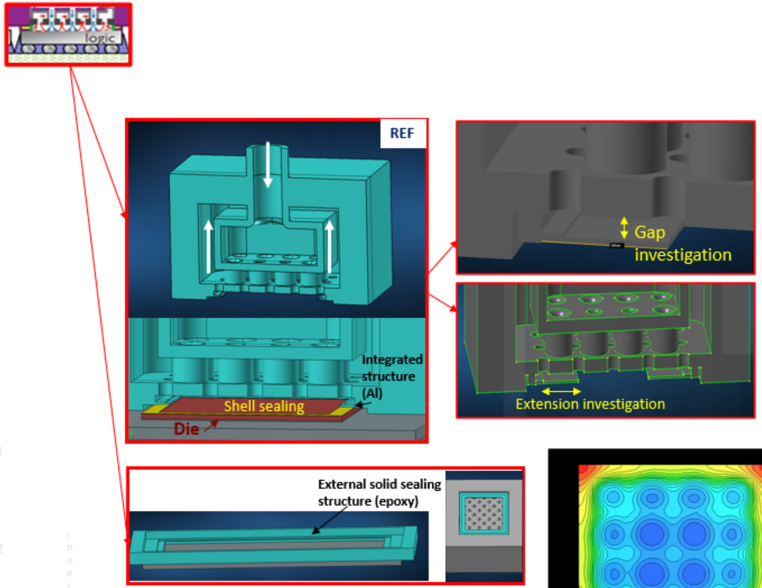
Resume table equivalent HTC [W/m^2-K]			
Condition (BC)	**Surface Die**	**Temperature considered**	**HTC calculated**
n.1	Top surface (20x20)	Tavg* Die	3.76E+04
		Tavg* @TopSurfDie	5.25E+04
		Tmax** Die	3.16E+04
	All	Tavg* Die	1.79E+04
		Tavg* @TopSurfDie	2.50E+04
		Tmax** Die	1.50E+04
n.2	Top surface (20x20)	Tavg* Die	3.45E+04
		Tavg* @TopSurfDie	3.72E+04
		Tmax** Die	2.74E+04
	All	Tavg* Die	1.64E+04
		Tavg* @TopSurfDie	1.77E+04
		Tmax** Die	1.30E+04

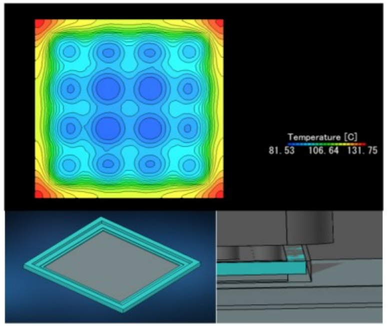
The normalized thermal resistance is equal to:
R^* =0.076 $K*cm^2$ /W (condition n.1)
R^* =0.088 $K*cm^2$ /W (condition n.2)

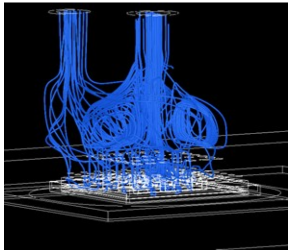




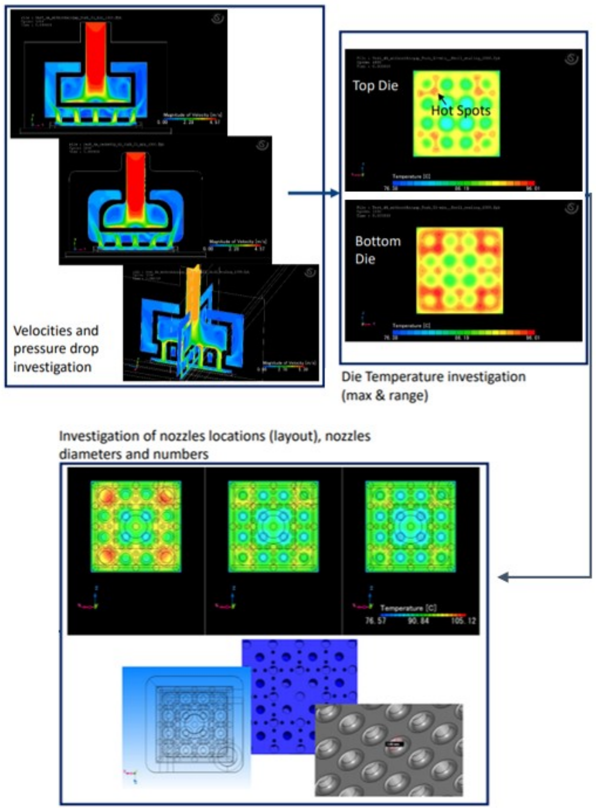
Areas of improvements investigated with CFD





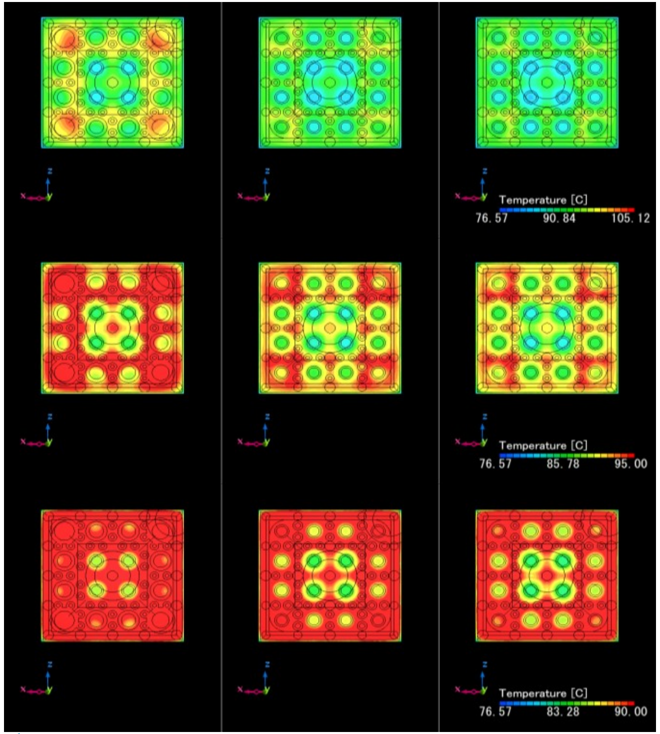


2 vortexes (inflow chamber)



Areas of improvements investigated with CFD: zoom in “Nozzles”

Originally higher heat extraction in the middle (momentum)



Enlarging nozzles on the external sides/corners guiding more fluid peripherally generates secondary drawbacks

Different nozzles configurations simulated showed (contrasting needs and behaviors):

- Need to guide fluid on the external sides
- Need to compensate higher vertical momentum in the center vs external areas
- Need to have locally energetic fluid (high momentum, thus high velocity and small diameters)
- Need to not trap locally the fluid (outflow vs inflow ratio)
- Need to have limited vena contracta at nozzles entrance (relative orientation)
- Need to limit pressure drop (better less nozzles with bigger diameters)

Local ratio between outlet and inlet nozzles cross section area is a key factor

Application based:

Globally AR~1. 56
(outflow/inflow)

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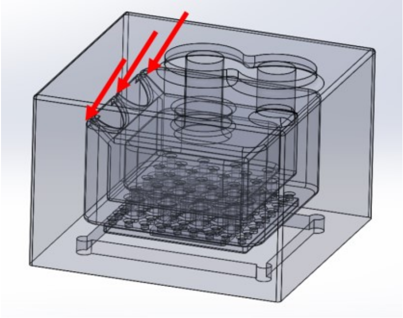
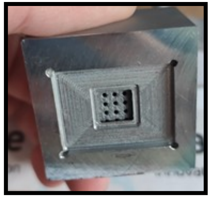
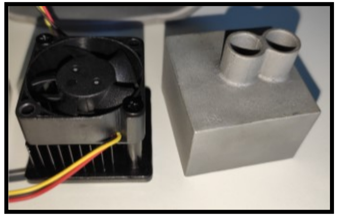
imec

Prototyped Metal 3d printed cooler

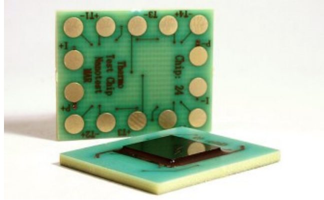


- Scaled basic version (no optimal features)
- Supports generated
- Housing Nanotest chip



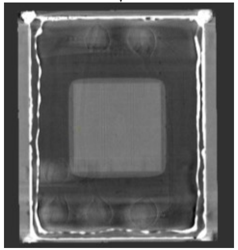


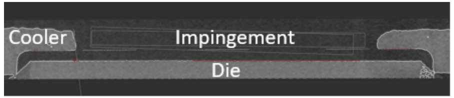
Metal Prototyped cooler

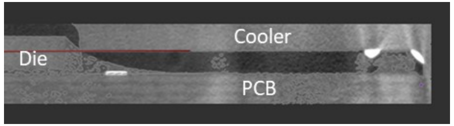


Nanotest thermovehicle chip (9.8*9.8 mm die)

Amicon C990 one component epoxy



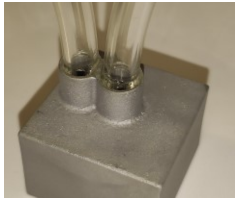




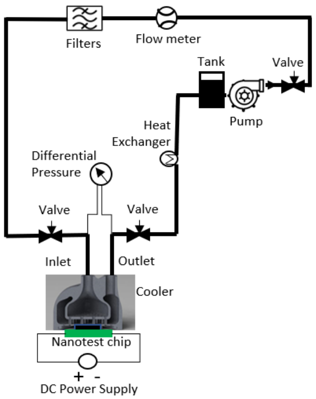
Ad-hoc simulation

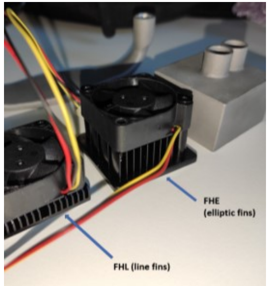
Testing

- Water
- T_amb: 22 ± 1°C
- T_inlet: 20 °C
- VFR: 3l/min & 2.55 l/min (80% max)



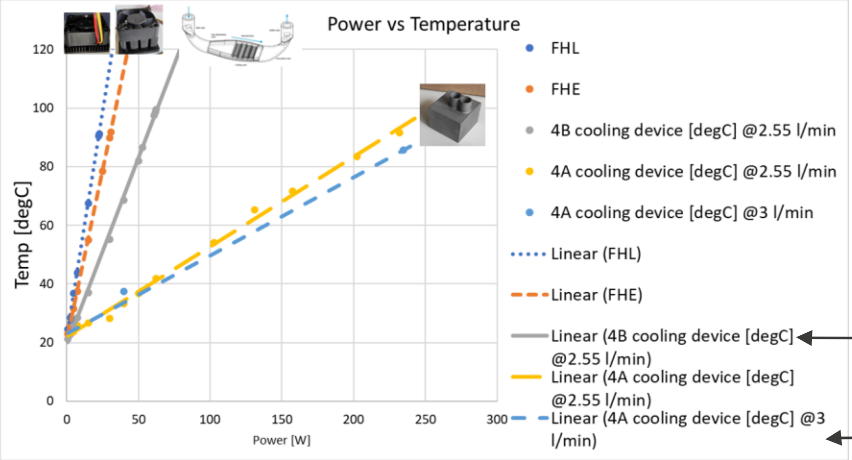
Prototyped Metal 3d printed cooler: performances



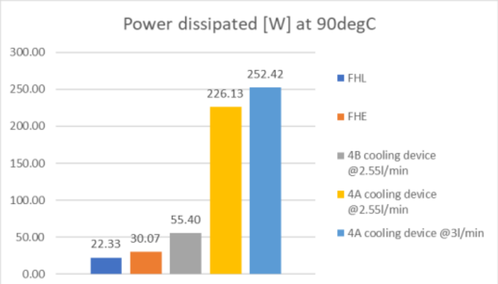


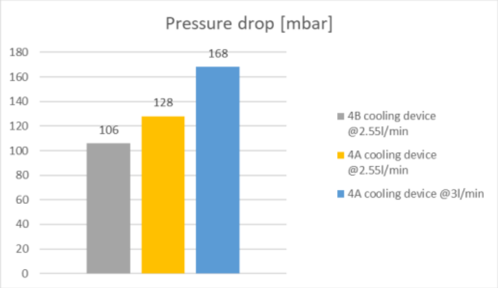
Further details in appendix (1) (2)

- 232W dissipated with prototyped cooler @**2.55l/min** (sensor temperature 91.64°C)
- Surface Power density [W/cm2] of 241.62
- Normalized Thermal resistance [K*cm2/W] of 0.29
- Pressure drop of 128mbar

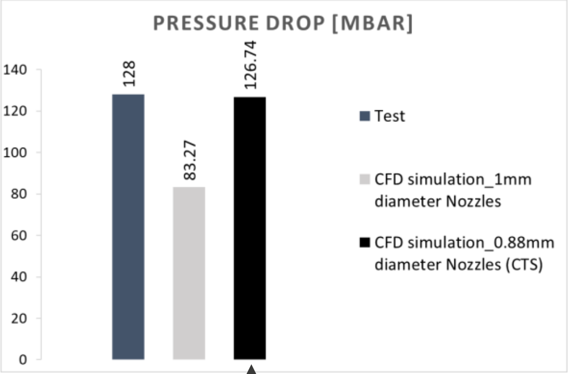


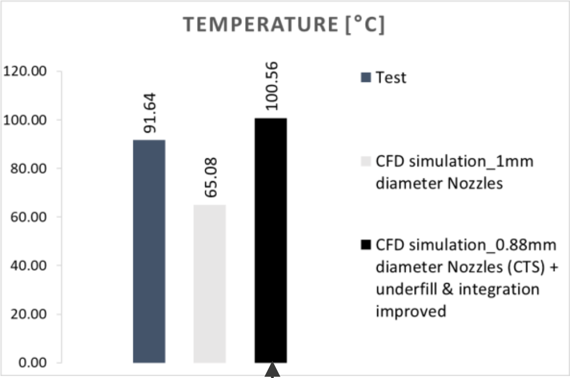
- 266W dissipated with prototyped cooler @**3 l/min** (sensor temperature 93.34°C)
- Surface Power density [W/cm^2] of 276.97
- Normalized Thermal Resistance [K*cm^2/W] of 0.26
- Pressure drop of 168mbar

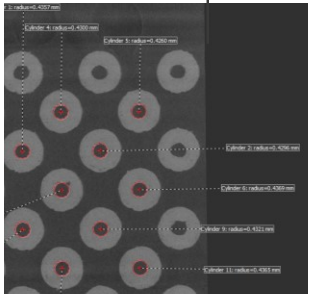




CFD simulations results vs testing







CTS Nozzles Diameters

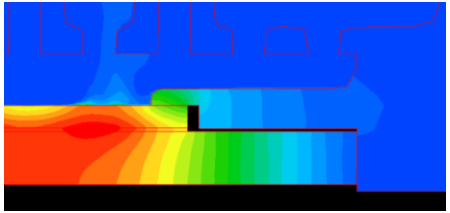
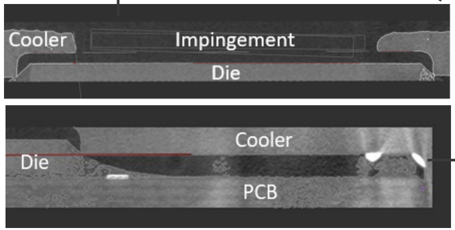


Figure 1 Detail: previously no gap between top die surface and cooler surface



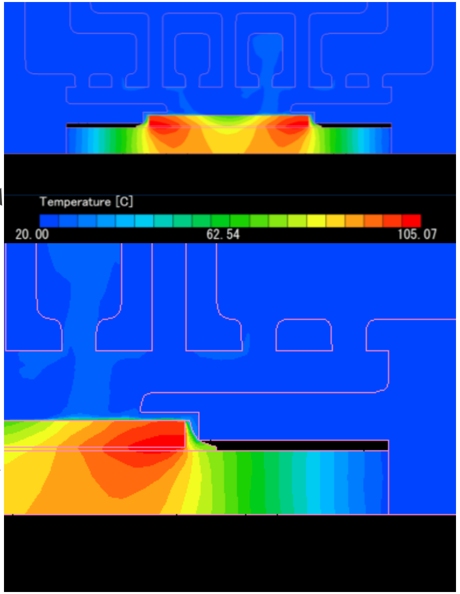


Figure 1: Section view middle plane & zoom on detail (underfill + gap)

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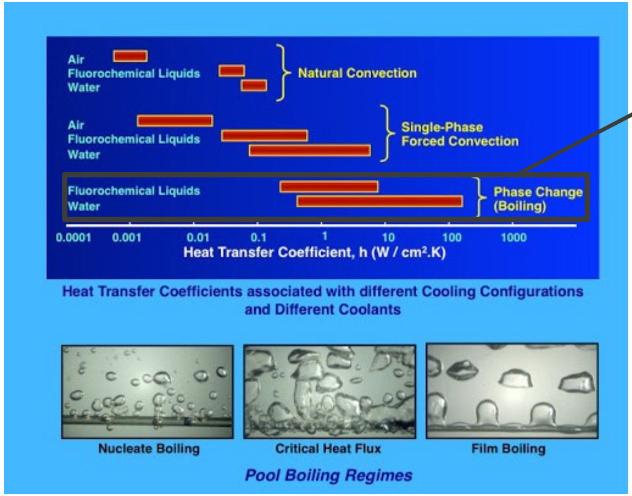
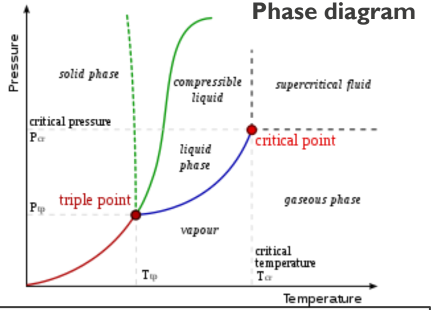
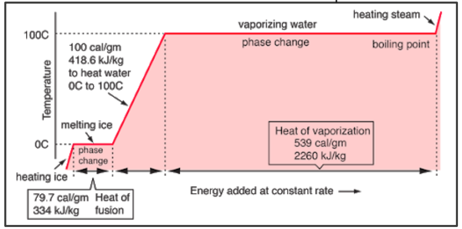
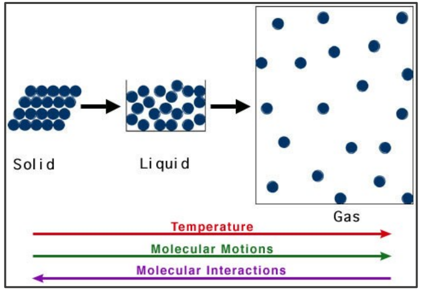
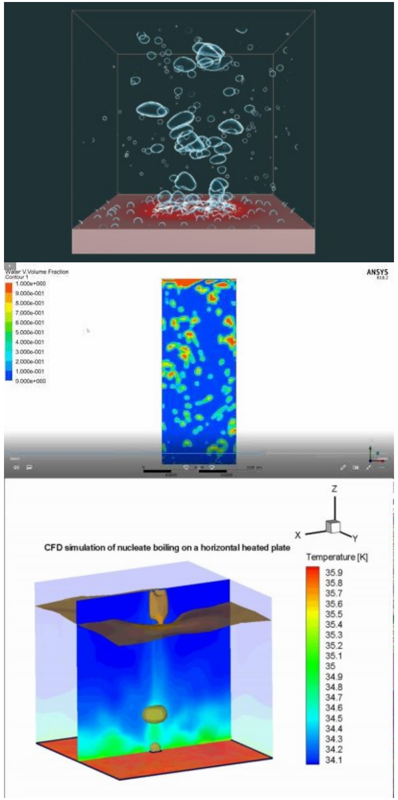
Future trend: boiling/phase change cooling





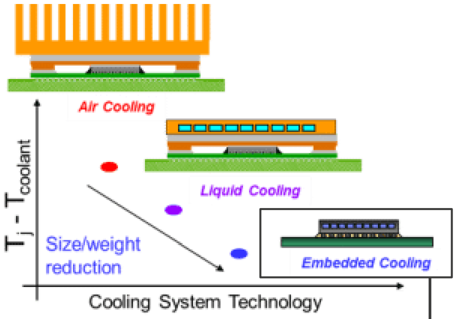


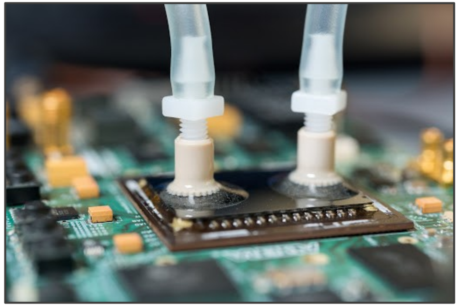


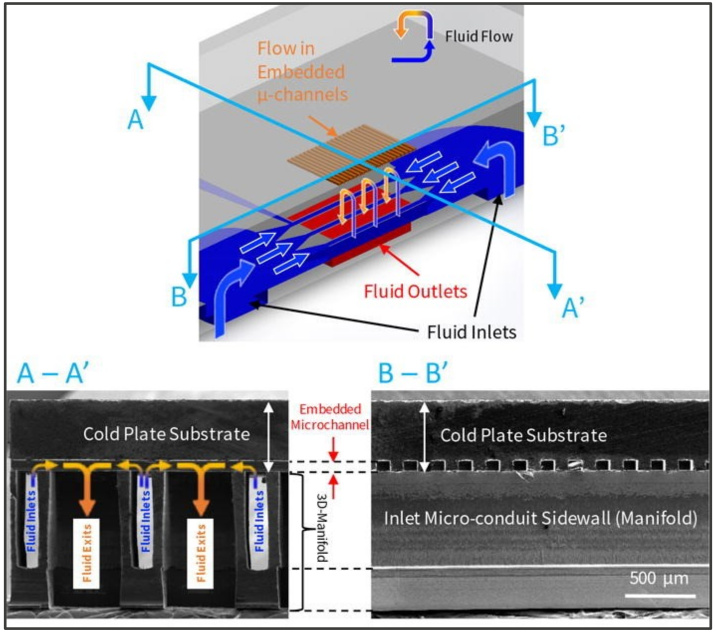


Sample CFD pictures

Future trend: embedded cooling (µChannels)







- Embedded cooling µChannels Fabricated in Device
- Reduction of Volume/external encumbrance and weight
- Really suitable in power electronics applications

Enabler:
Manufacturing technology and cost

Reference pictures

imec

embracing a better life

Table of content

1. Introduction (TIM, jet-impingement)

2. Concept design (CFD)
3. Final design (CFD)
   - Design overview
   - Simulation setting
   - Final results
   - Areas of improvements investigated

Case Study 1: based on 20x20mm die

4. Prototyped metal 3D printed cooler
5. Experiments vs CFD model

Case Study 2: based on 9.8x9.8mm die

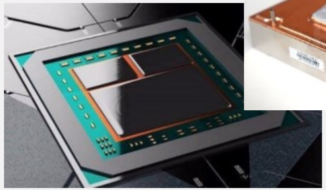
6. Conclusions: future trends

7. Appendix

Appendix: AD vehicle computer thermal requirements

High Power vehicle computer:

Today: Desktop



Air cooling

AMD Vega 10 GPU features two HBM2 dies, featuring up to 8 GB VRAM and a massive interposer.

Automotive

Liquid cooling

GPU today: Nvidia GP100, **P_{GPU} = 300 W**

Drive: 2 GPU in Nvidia PX Pegasus (shown)

Challenges:

Power dissipation
- 2 GPUs
  - ***1st full power 100 % = 300 W***
  - ***2nd (redundant at 80%) = 240 W***
- RAM = 50 W
- CPUs = 10 W
- VRM = 20 W
- PCB wiring losses (25 %) = 125 W

Total system power = 750..800 W min

Low thermal budget

Liquid BC:

T = 85 °C (poor)

T = 65 °C (very good)

T = 55 °C (best possible)

Reliability
- Harsh environment, heat, gradients
- Sensitive hardware: large die
- Fixations, warpage, th-mech stresses
- Functional safety requirements (100% availability, always)

→ Liquid system cooling (dissipating 300W) with enhanced heat path

~

Approx. x9 times TDP commercial entry level CPU (Core i3-10305T: 35W)

Appendix: overall CFD setting

Turbulence model: *K-w SST (ref. paper)*
Turbulence BC: *preliminary analytical calculations*

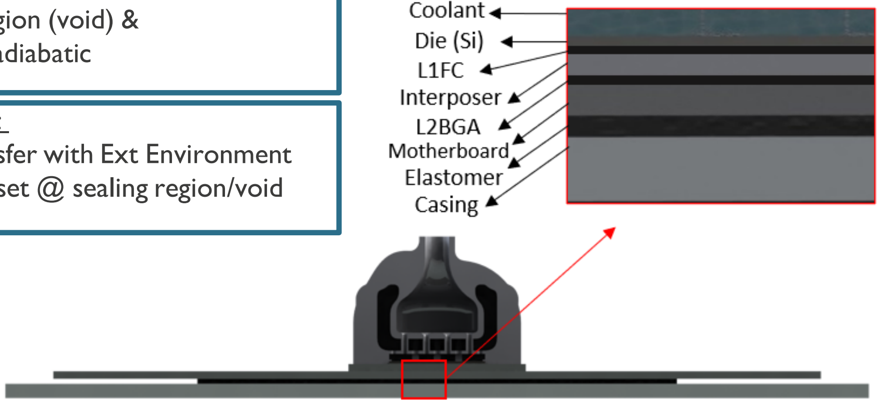
- *Intensity*
- *Length scale*

Liquid: *Glycol-water (58%) → Temp. dependent properties*
Power: *300W (bottom die)*
VFR, Tfluid & Tamb: *Based on "Hot Condition" (previous slide)*

Condition n.1:
- Sealing region (void) & ext walls adiabatic

Condition n.2:
- Heat transfer with Ext Environment
- 1 W/m-k set @ sealing region/void

Solid Material Properties Assigned



Turbulence model	Computational cost (time required)	Impingement jet transfer coefficient prediction	Ability to predict secondary peak
k-ε	★★★★ Low cost	★ Poor: Nu error of 15–60%	★ Poor
k-ω	★★★★ Low–moderate	★★ Poor–fair: anticipate Nu errors of at least 10–30%	★★ Fair: may have incorrect location or magnitude
Realizable k-ε and other k-ε variations	★★★★ Low	★★ Poor–fair: expect Nu errors of at least 15–30%	★★ Poor–fair: may have incorrect location or magnitude
Algebraic stress model	★★★★ Low	★★ Poor–fair: anticipate Nu errors of at least 10–30%	★ Poor
Reynolds stress model (full SMC)	★★ Moderate–high	★ Poor: anticipate Nu errors of 25–100%	★★ Fair: may have incorrect location or magnitude
Shear stress transport (SST), hybrid method	★★★ Low–moderate	★★★ Good: typical Nu errors of 20–40%	★★ Fair
$v^2 f$	★★★ Moderate	★★★★ Excellent: anticipate Nu errors of 2–30%	★★★★ Excellent
DNS/LES time-variant models	★ Extremely high (DNS available for low Re only)	★★★★ Good–Excellent	★★★★ Good–Excellent

★: undesirable model characteristics
★★★★: excellent model characteristics

Y+ in line with K-w SST model

Areas of improvements investigated with CFD: zoom in "Grid array"

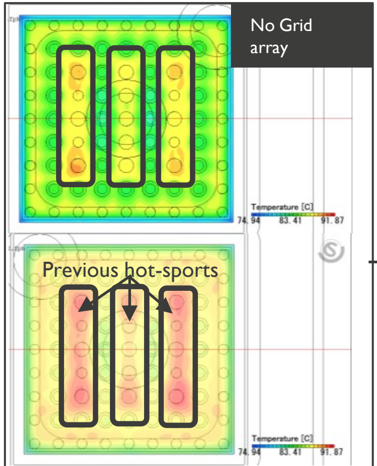
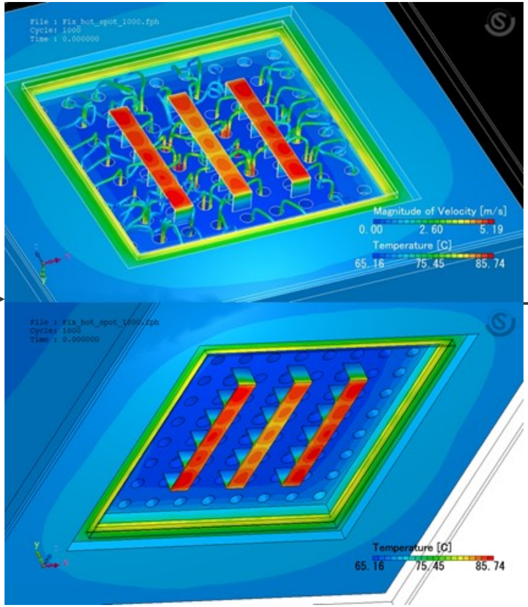


Figure 1: Temperature distribution on the top (above) and bottom (below) surfaces of the die without grid array

- Grid array (below some outflow nozzles)



- Enhanced heat transfer surface
- Tidy guided flow (less stagnation & recirculation)
- Better temperature distribution (hot spots reduction)

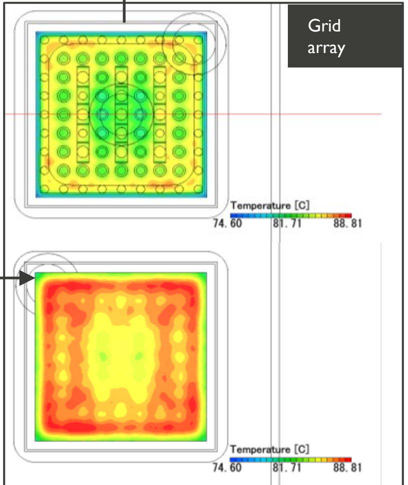
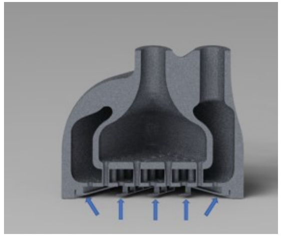


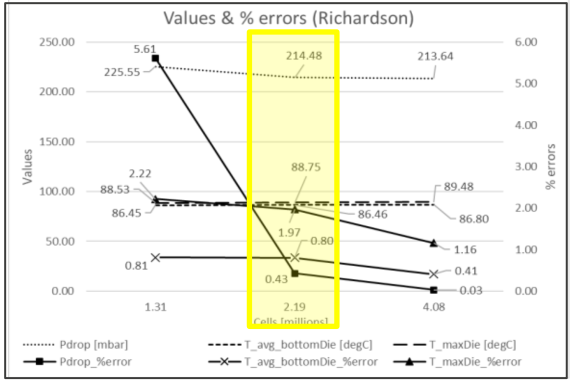
Figure 1: Temperature distributions on top (above) and bottom (below) die surfaces



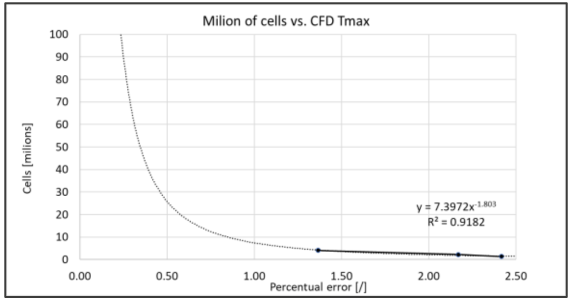
Appendix: Final cooler design CFD sensitivity analysis

Mesh Setting:

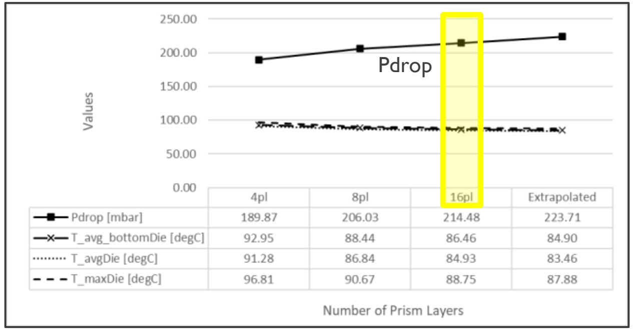
- 2.19 M elements (400K Octrees)
- 16 Prism Layers→ 2.8% error Pdrop



Mesh size sensitivity analysis (Richardson)

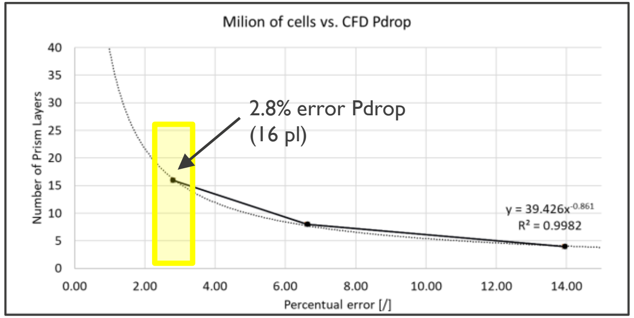


Mesh size sensitivity analysis (Temperature Max)

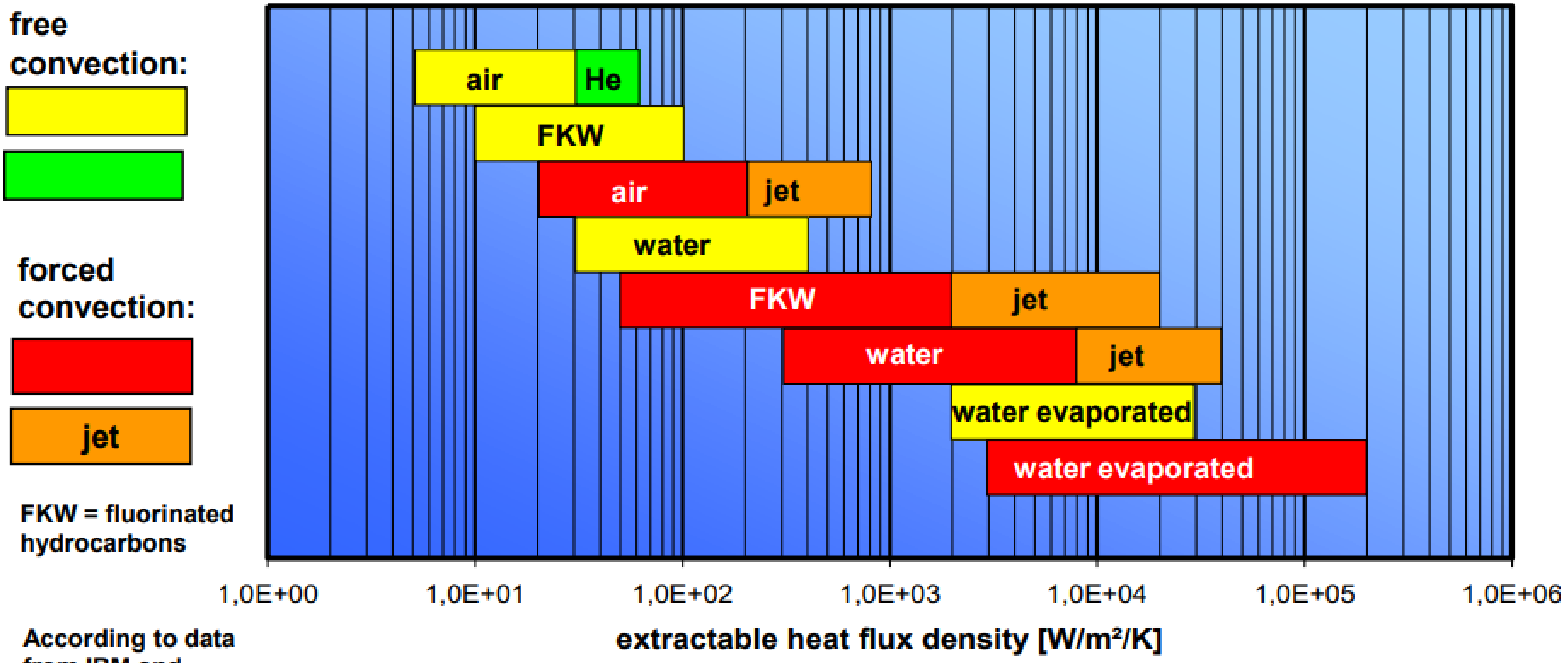


	4pl	8pl	16pl	Extrapolated
Pdrop [mbar]	189.87	206.03	214.48	223.71
T_avg_bottomDie [degC]	92.95	88.44	86.46	84.90
T_avgDie [degC]	91.28	86.84	84.93	83.46
T_maxDie [degC]	96.81	90.67	88.75	87.88

Prism Layers sensitivity analysis (Richardson)



Prism Layers sensitivity analysis (Pressure Drop)



According to data from IBM and Philips Research