2 Design Tools

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Project Management Meeting
The University of Manchester
Monday 7th April 2014

Scope of Theme

step 1	Step 2	Step 3
Online survey on: Missing electrical, thermal and mechanical links of today's Simulators **(Newcastle)**	Specific effects: •Prediction of convective heat transfer in electric machines **(City)** •Loss mechanism and heat removal in inductors for dc/dc converters **(Manchester)**	Development of new heat removal techniques: •Liquid cooler with locally changing thermal impedances **(Newcastle)** •High thermal conductivity potting compounds **(Sheffield)**

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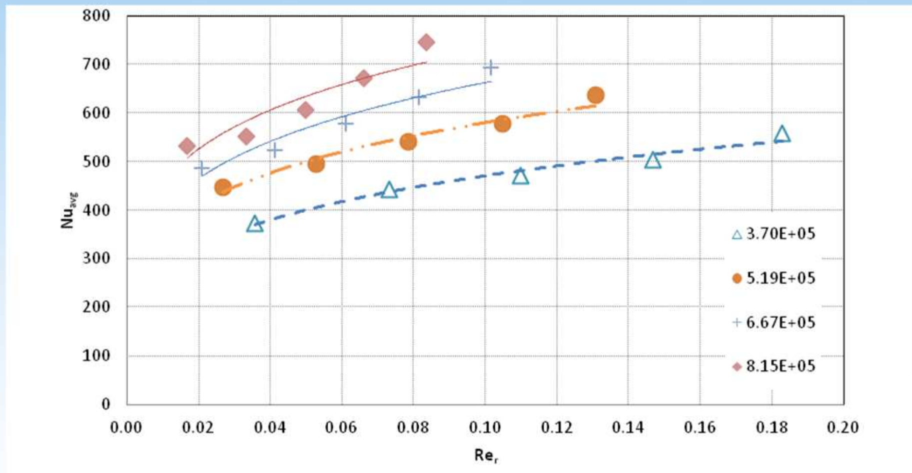
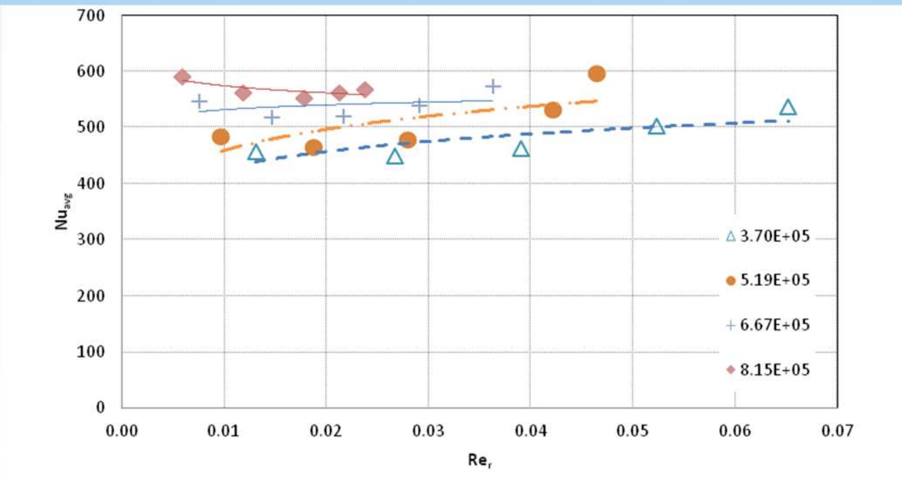
Current results

Correlation of experimental results to Re_r from Bayley (1971) – breaks down at large gap ratio



Average heat transfer against inlet and rotational Reynolds number ratio for forced radial out-flow and gap ratio 0.0106



Average heat transfer against inlet and rotational Reynolds number ratio for forced radial out-flow and gap ratio 0.0297

$$Re_r = \frac{C_w}{2\pi G Re_\omega}$$

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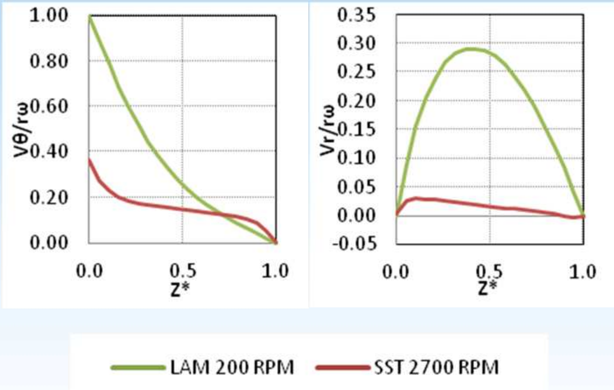
Current results

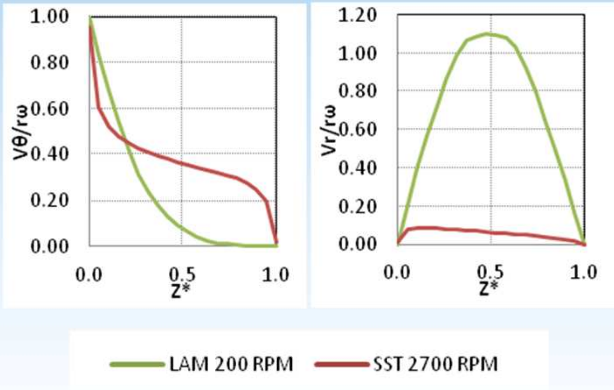
CFD results – 2D model

Forced flow dominates in laminar regime



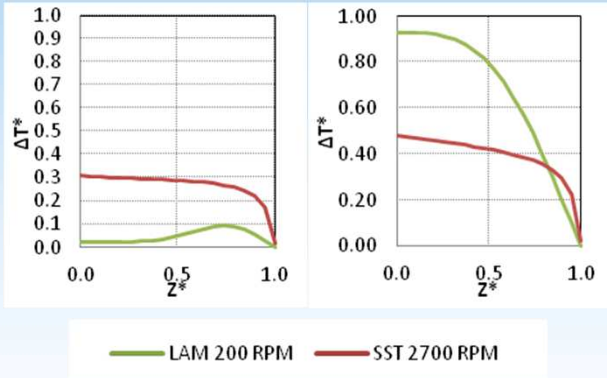
Velocity profiles at *r/R* = 0.99, *G* = 0.0106 and C_w = 9e2 for forced radial out-flow

Batchelor flow type (separate boundary layers)in turbulent regime for ALL forced outflow



Velocity profiles at *r/R* = 0.99, *G* = 0.0106 and C_w = 3.6e3 for forced radial out-flow

Ingress of ambient air at periphery causes drop in temperature, more pronounced in laminar regime



Comparison of temperature profiles, *r/R* = 0.99, *G* = 0.0106, left: no forced flow, right: C_w = 3.6e3 forced radial out-flow

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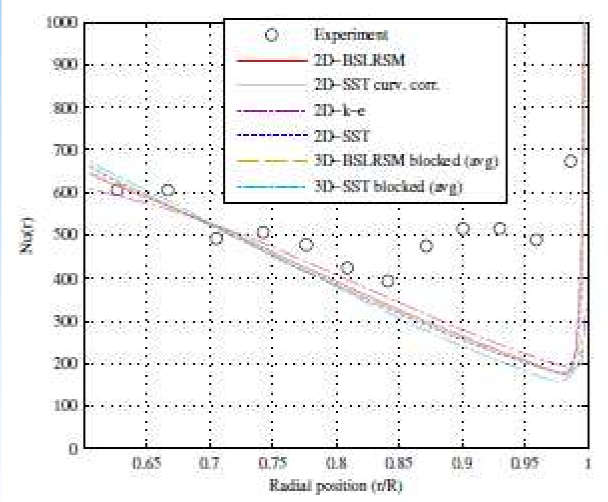
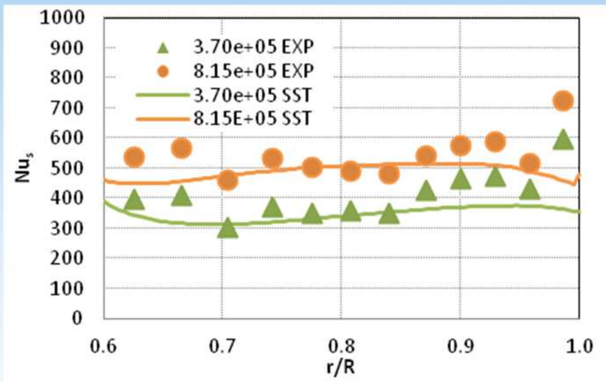
Current results

Comparison of CFD to experimental results

Forced outflow is better predicted by CFD - however - under prediction at the periphery still apparent and CFD model needs to be adapted

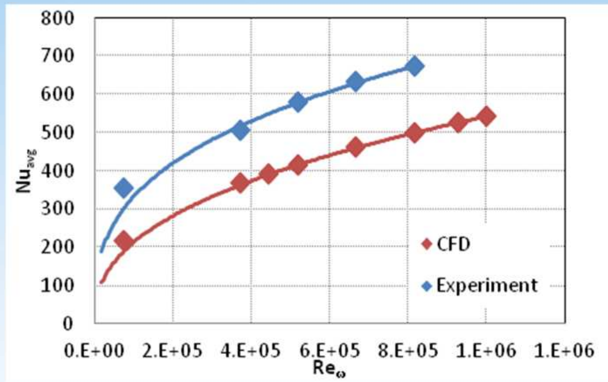


Comparison of CFD calculation and experimental measurement of radially resolved heat transfer against rotational speed for G = 0.0106 with no forced throughflow from Howey (2011)



Comparison of CFD calculation and experimental measurement of radially resolved heat transfer against rotational speed for G = 0.0106, C_W = 3.6e2 radial out-flow

Result is general under-prediction of average heat transfer results



Comparison of CFD calculation and experimental measurement of average heat transfer against rotational speed for G = 0.0106, C_W = 3.6e2 radial out-flow, turbulent correlations projected backward.

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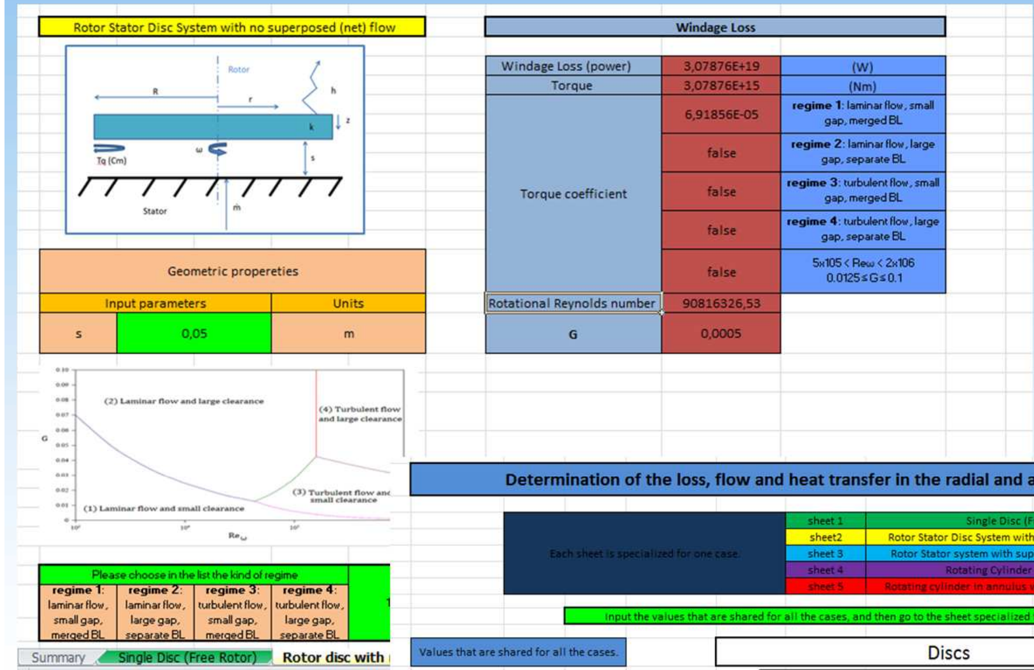
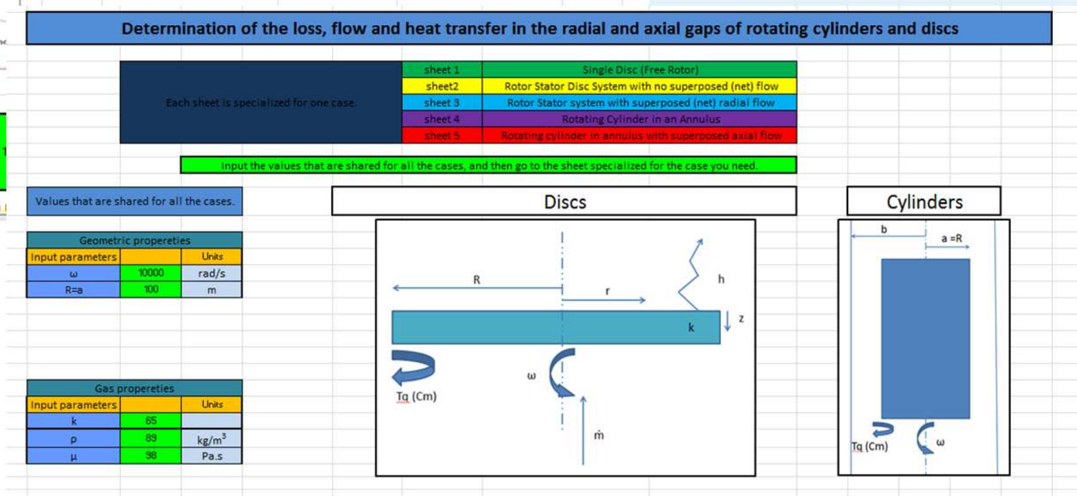
Progress and future work plan



- Transfer report completed
- Paper submitted to ICEM XXI International Conference on Electrical Machines 2014, Berlin, Germany
- Beginnings of a design tool that will bring together all correlations found in order to predict windage, pressure drops and heat transfer in electric machines



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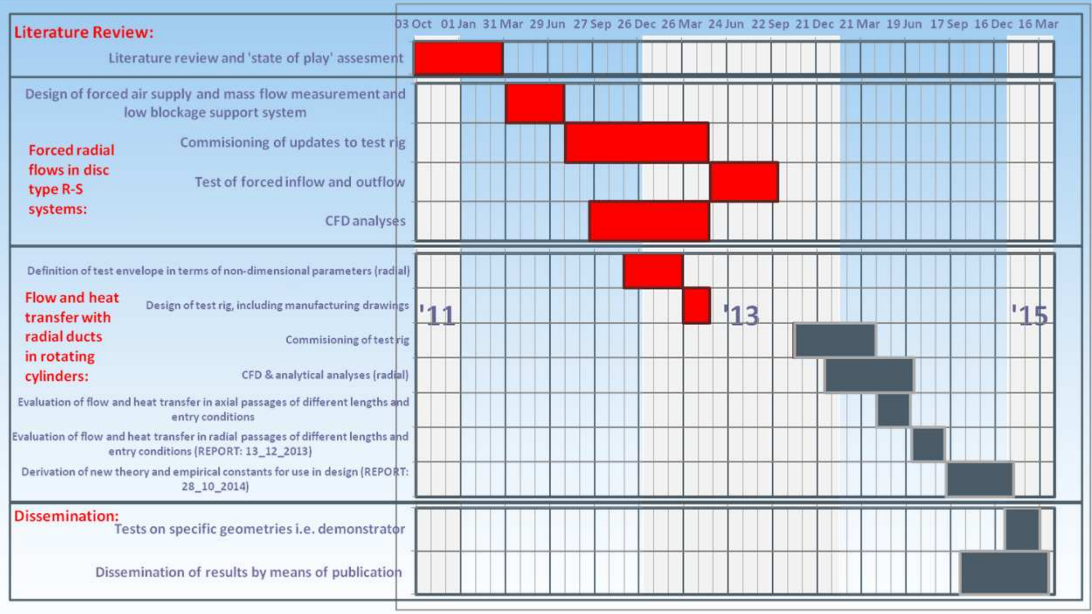
Progress and future work plan

Planned future work

- 3D CFD model and improvements
- Paper disseminating 3D results
- Drum-type test rig commissioned
- CFD analysis for drum type model
- Experiments on drum-type rig
- Paper disseminating drum-type rig results
- Final output of design tool for windage, pressure drops and heat transfer
- Final PhD report



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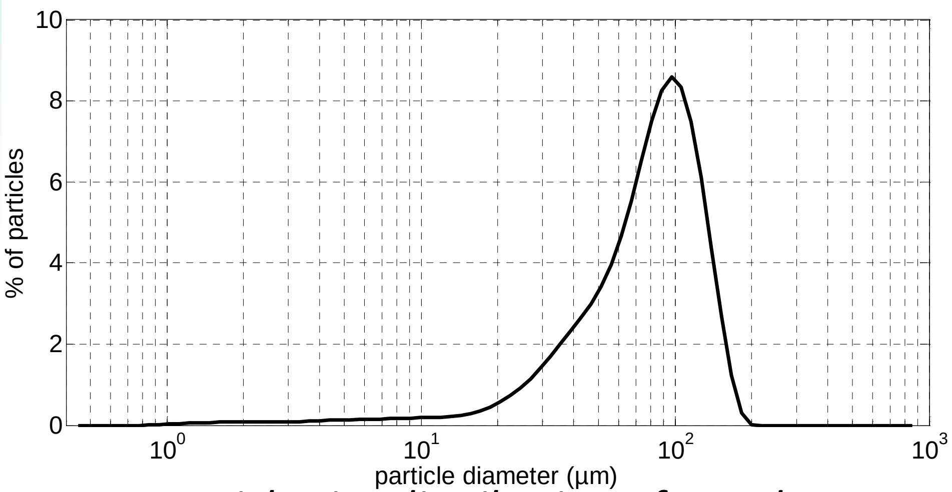
Introduction

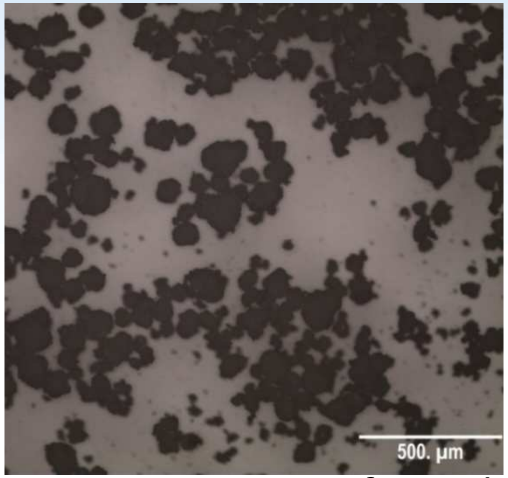
- Reasons for using encapsulants:
  - Enhance mechanical integrity of component
  - Seal component against environment
  - **Improve thermal performance of component by displacing trapped air within component**
    - This can be further enhanced by combining the encapsulant with a thermally conductive filler

Filler Properties

– The filler used in this work is aluminium oxide powder
  - Theoretical density = 3.97 g/cm^3
  - Thermal conductivity 30 W/m.K
– Poured Density = 0.84 g/cm^3 (21.2% of theoretical density)
– Tapped Density = 1.11 g/cm^3 (28.0% of theoretical density)
– Particles are approximately spherical



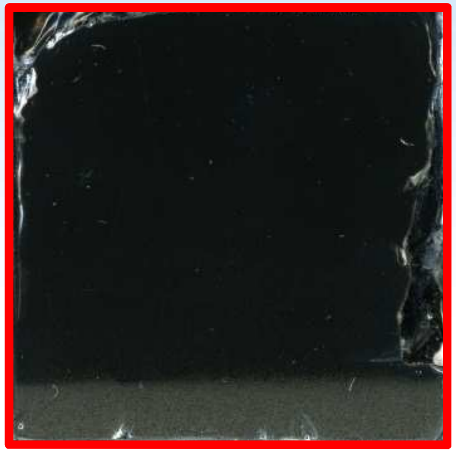
Particle size distribution of powder



Microscope image of powder

Sample production methods

- Different methods were used to produce the samples to allow differences in filler distribution to be considered

Mixed	Rotated	Settled
		

Blocks with a 5% filler concentration (by volume) produced using each method

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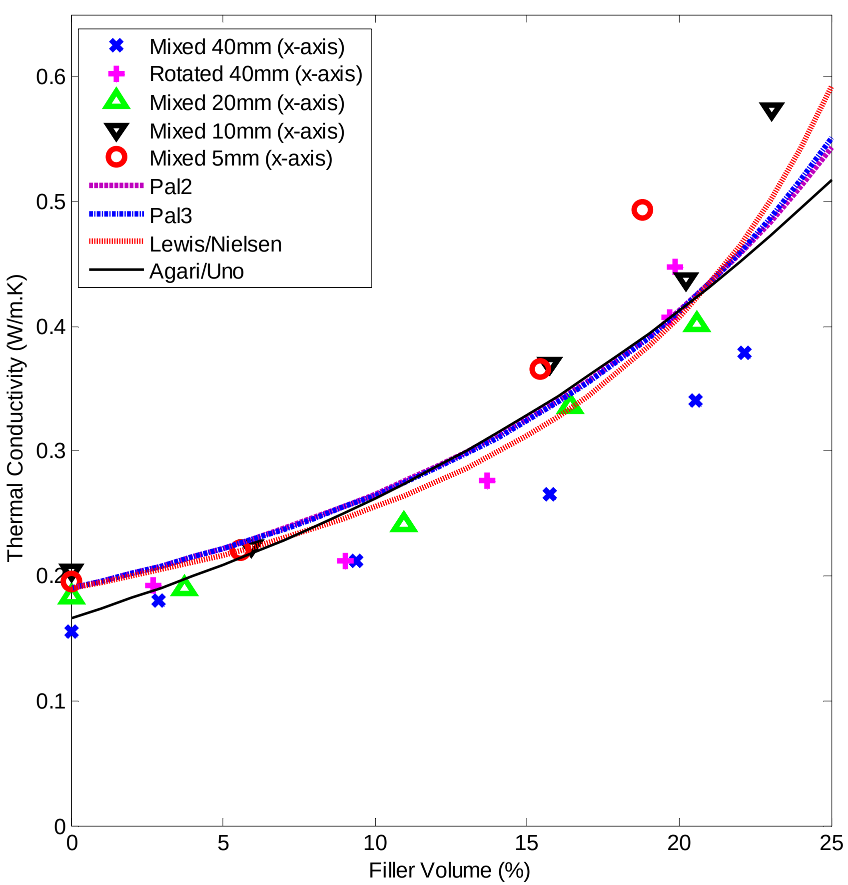
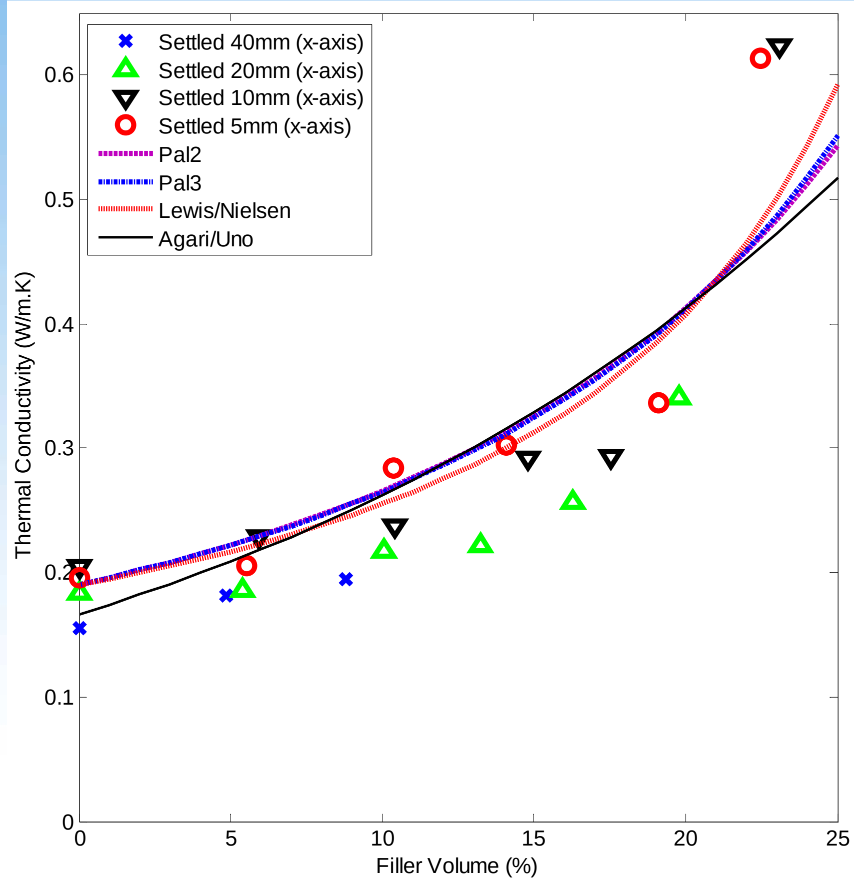
Sample production methods

- Mixed samples were produced to examine how the filler is distributed under normal conditions
- Rotated samples were produced in a manner which inhibits the settling of the filler particles
- Settled samples were produced to have a particularly uneven filler distribution (more so than the mixed samples)

Results – Empirical models



Mixed and Rotated block thermal conductivities (shown with empirical models)



Settled block thermal conductivities (shown with empirical models)

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Conclusions

- Dataset can be divided into three groups

Dilute (0% - 10%)	Intermediate (10% - 20%)	Full (20% +)
▪ Low filler loading level leads to only a small change in thermal conductivity ▪ Filler distribution not important	▪ Manufacturing technique influences filler distribution ▪ Effects of this can not be ignored when modelling composites ▪ More homogeneous samples exhibit higher bulk thermal conductivity	▪ Samples can be considered homogeneous as a full fill occurs regardless of manufacturing technique

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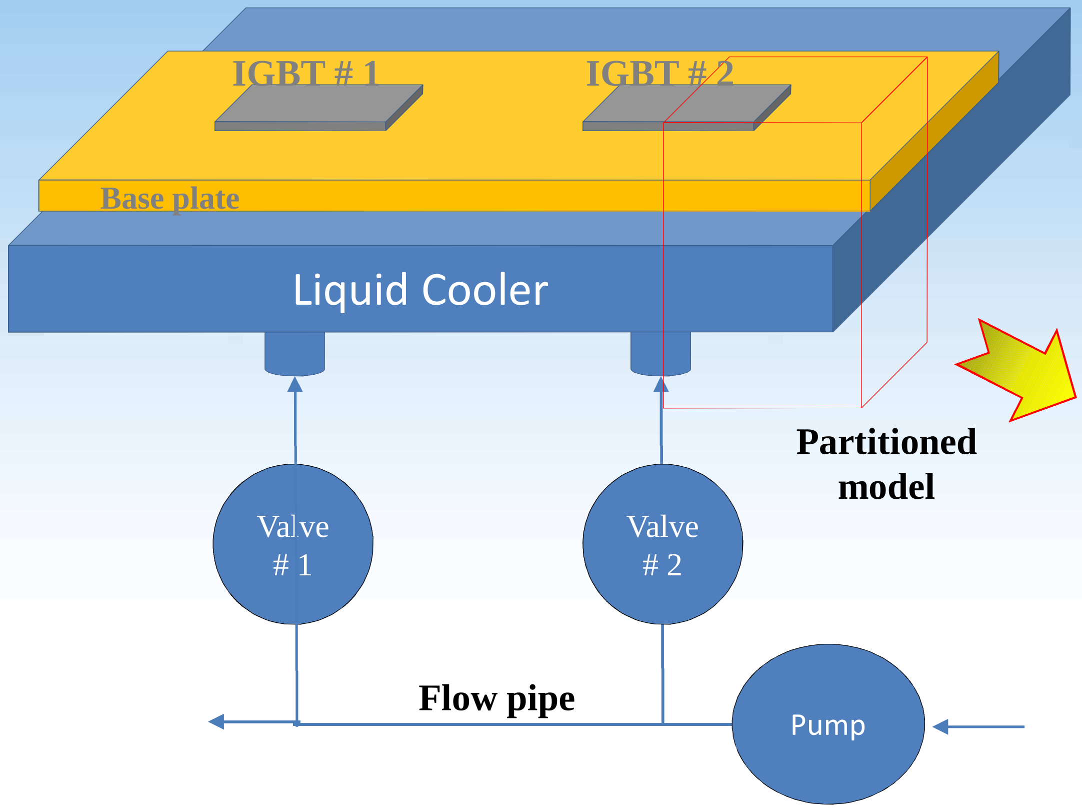
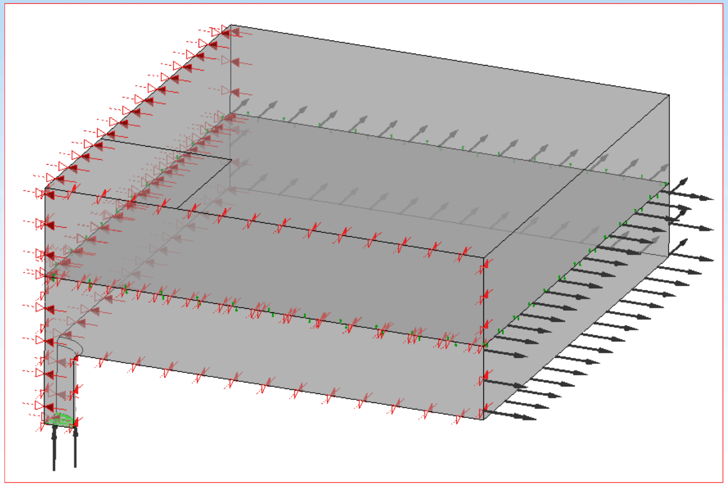
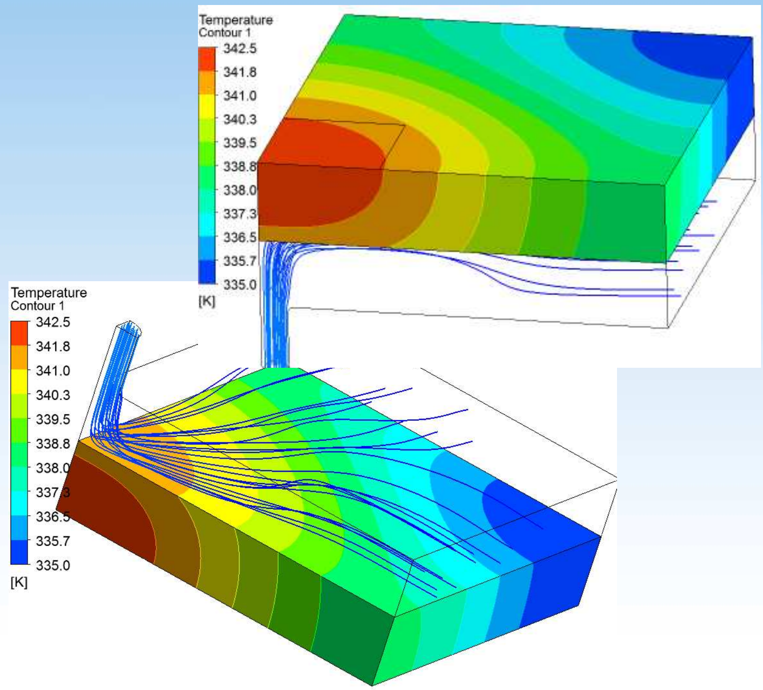
Cooling System Model



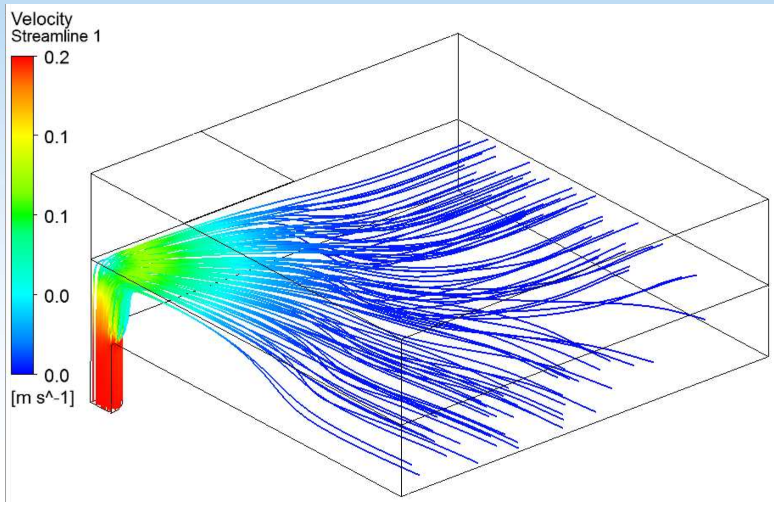


CFD model (ANSYS CFX 14.5)

CFD Analysis of the Liquid Cooler



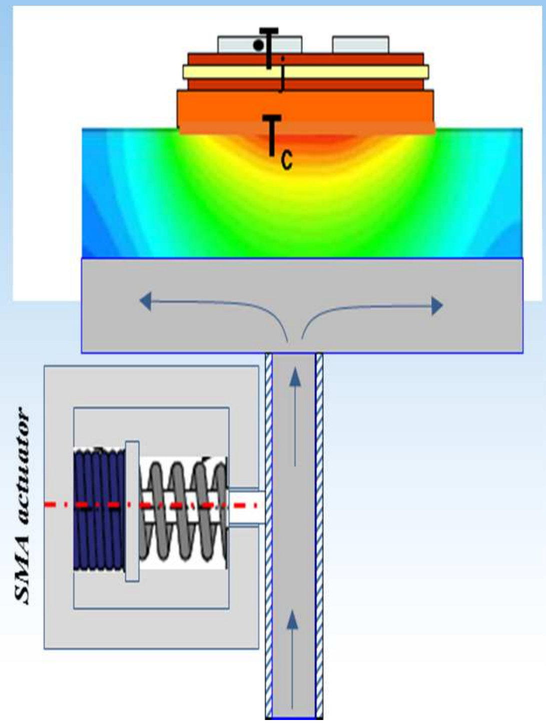
Temperature



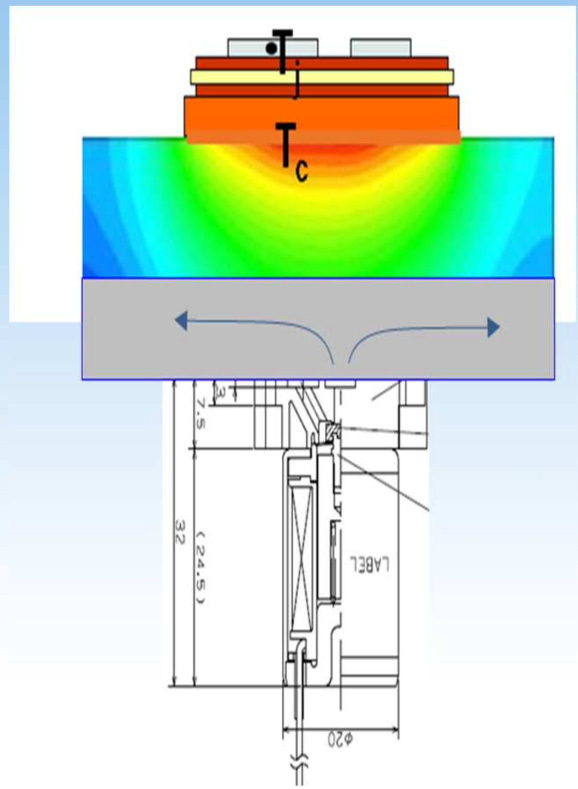
Liquid velocity

CFD results

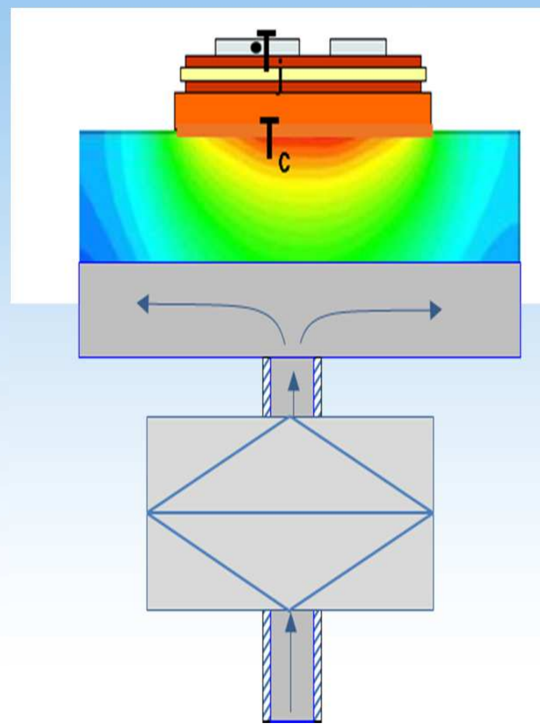
Comparison of valve techniques



SMA spring
(SAES Group, Italy)



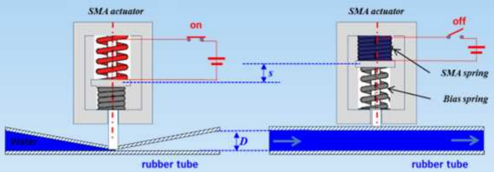
Solenoid valve
(Orion Valves Ltd, Japan)



Micro-valve
(Kemikro, Germany)

Dimensions

$20 \times 20 \times 25mm^3$

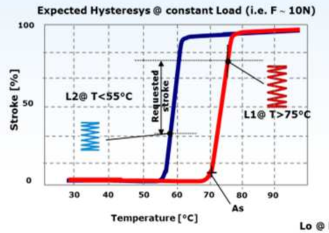


Note:
1. $s = D = 5mm$;
2. $P_{water} < 5000Pa$;
3. $f_{actuator} = 0.5Hz$;

Designed by NCL

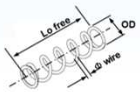
SMA Spring – Preliminary design

SMA Spring heated by Joule effect expands genetering the actuation force for the release of the pin lock. A typical hysteresis cycle for the SMA spring (fig. 1 below) shows how shape memory alloy starts the typical transformation over the As (autenite Temperature)

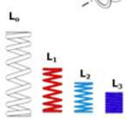


SMA Spring preliminary design

SMA Spring Details		
ϕ spring wire	1	[mm]
OD	10	[mm]
ID	5	[mm]
L spring free Lo	~25	[mm]
N° total coils	12	
N° active coils	10	
Stroke	> 5	[mm]

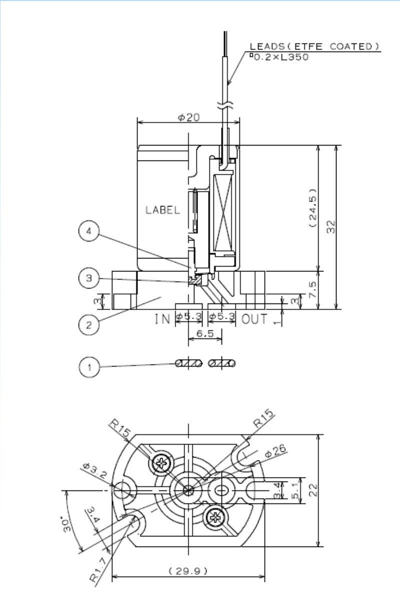


Lo @ RT no external force
L1 = 20 mm @T > 75°C
L2 = 15 mm @T < 50°C
L3 ~ 12 mm block length @RT



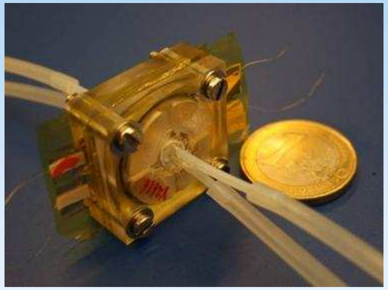
SMA spring
(SAES Group, Italy)

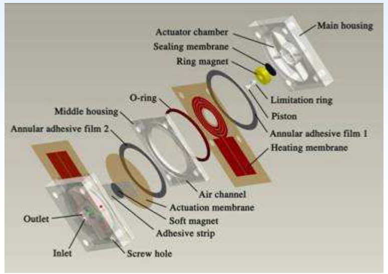
$22 \times 30 \times 32mm^3$



Solenoid valve
(Orion Valves Ltd, Japan)

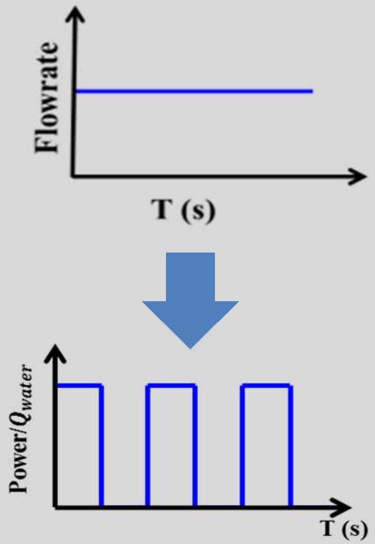
$26 \times 26 \times 11mm^3$



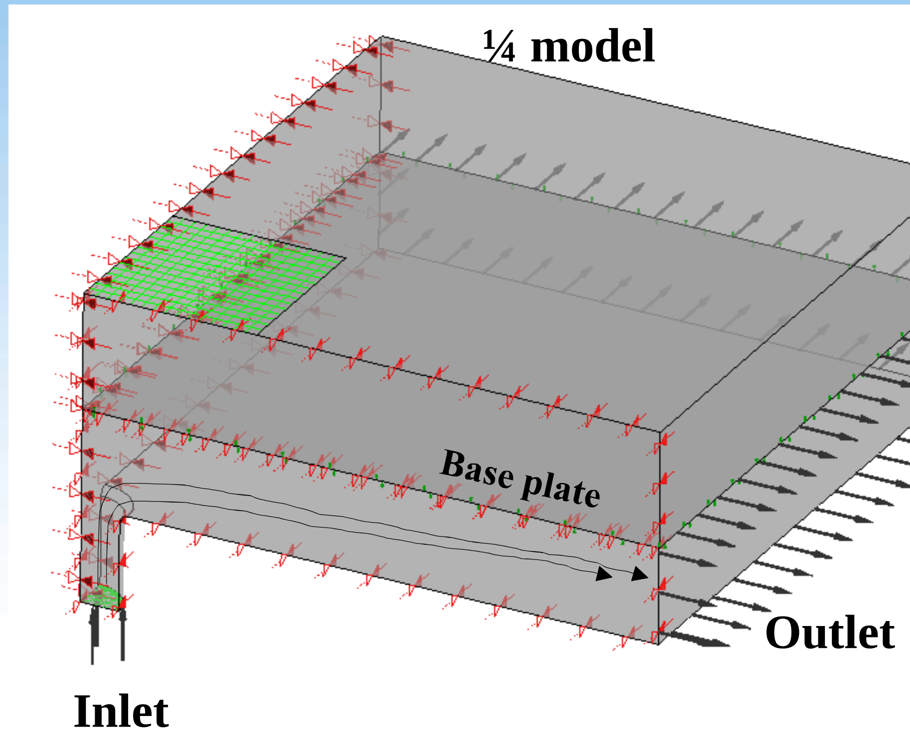


Micro-valve
(Kemikro, Germany)

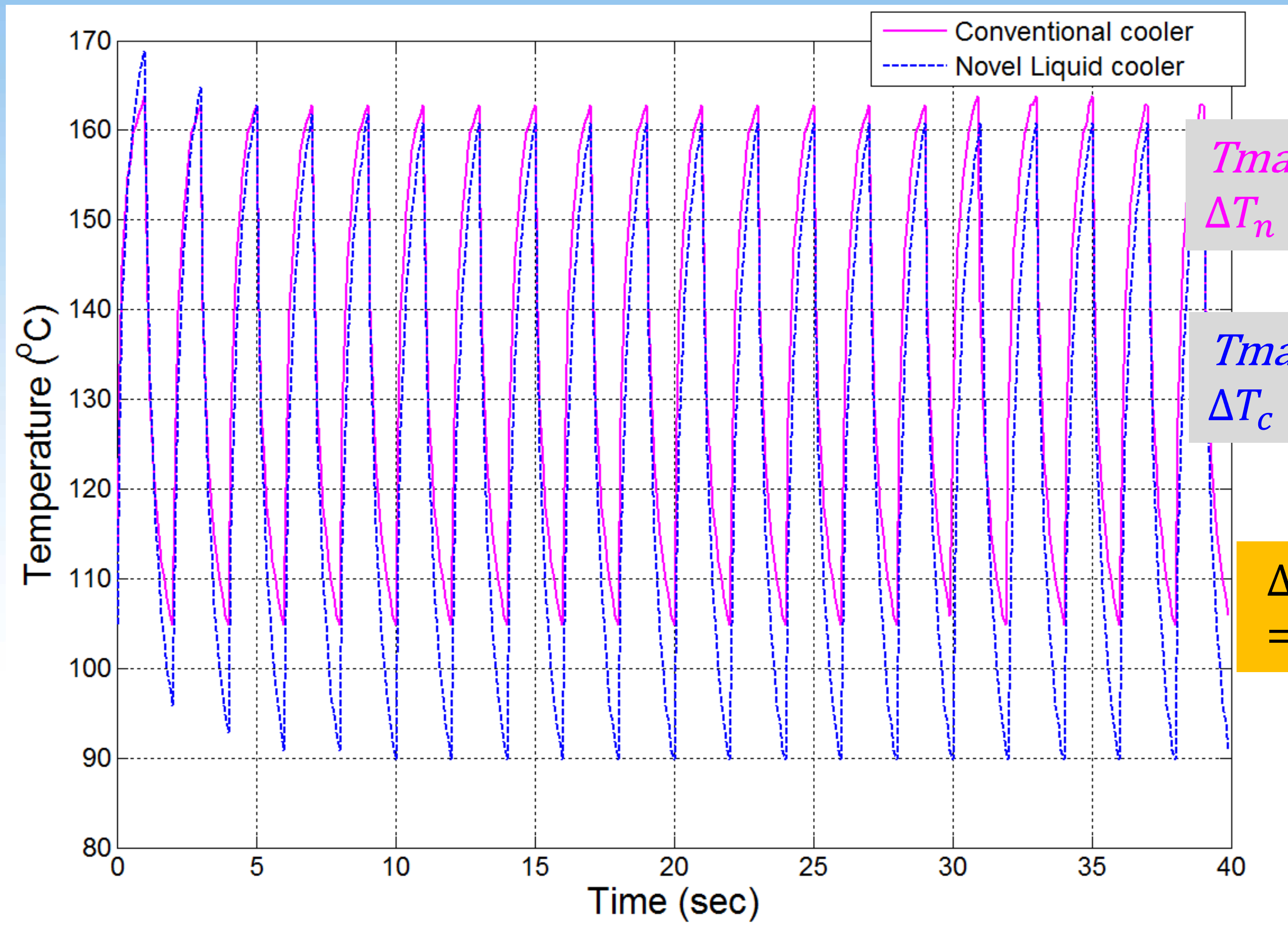
Benefit of using the flow rate actively



Dissimilar to conventional constant flow rate, a periodic flow rate is calculated based on the pressure vs flow rate curve of the system (pump pressure, pipe diameter and valve speed) .



CFD simulation results



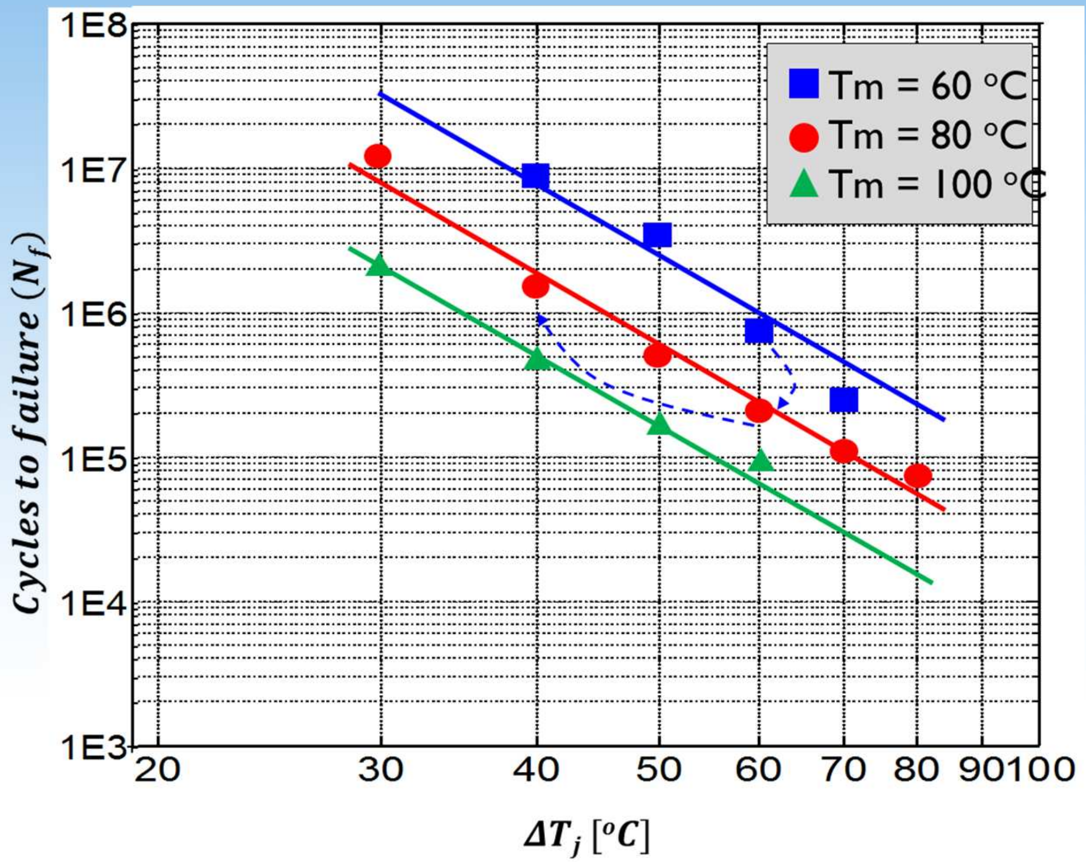
Temperature of IGBT

$Tmax \approx 162°C$
$\Delta T_n \approx 57°C$

$Tmax \approx 160°C$
$\Delta T_c \approx 70°C$

$\Delta T_n - \Delta T_c$
$= 13°C$

1. CFD Analysis of the Liquid Cooler



$\Delta T_n - \Delta T_c = 13°C$

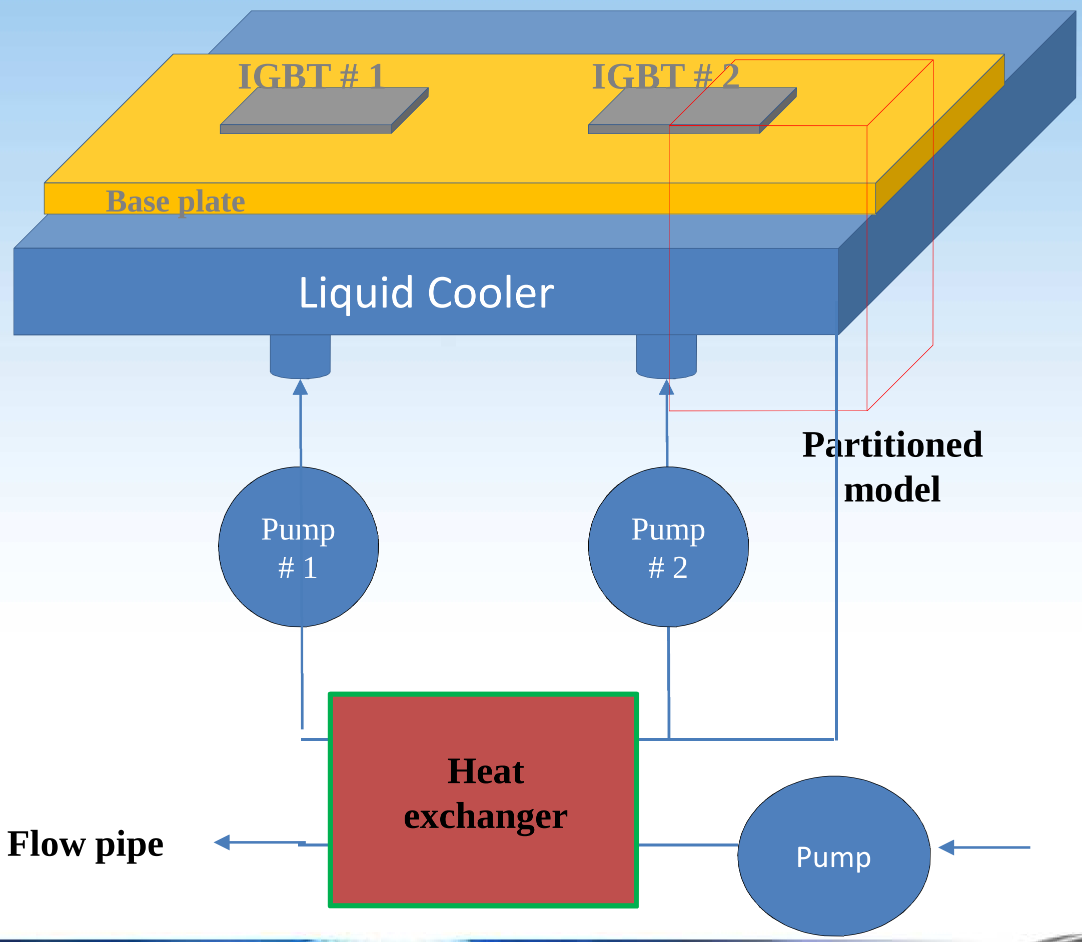
The lifetime of the IGBT module cooled by the new liquid cooler increases approximately by the factor of two compared to a conventional cooler.

Held, M., et al. "Fast power cycling test of IGBT modules in traction application." 1997 International Conference on. Vol. 1. IEEE, 1997.
Auerbach, F., and A. Lenniger. "Power-cycling-stability of IGBT-modules.“ Thirty-Second IAS Annual Meeting, IAS'97., Vol. 2. IEEE, 1997.

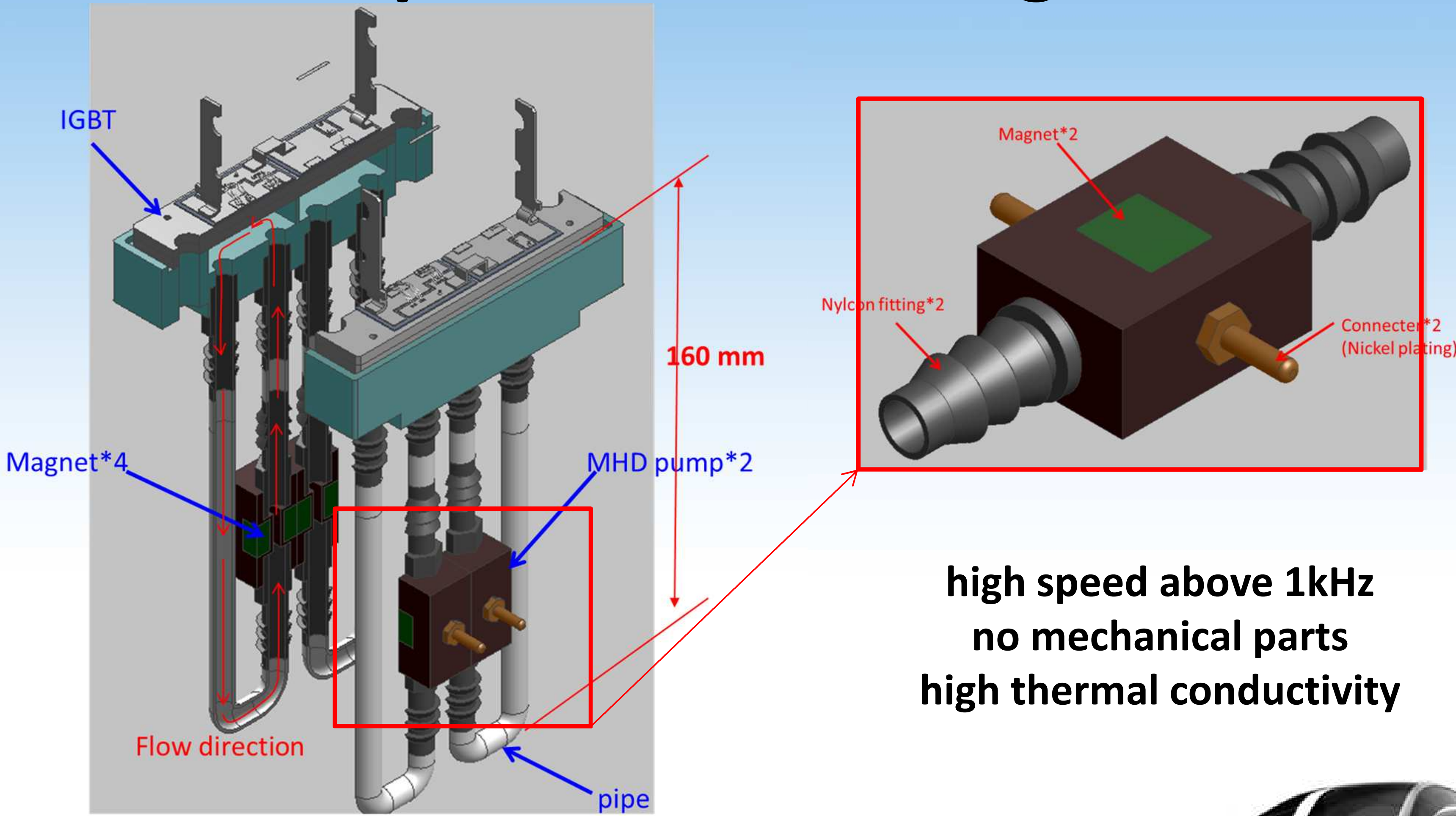
Lifetime of power modules increases but:

- Lifetime is now dependent on the reliability of the valves. It is predicted that the lifetime is low due to embedded mechanical parts.
- The frequency of the valves is low. Although the Orion valve can work up to 1kHz a faster operating valve would be preferable.
- The size of all valves are still too large.

New approach: use pumps rather valves

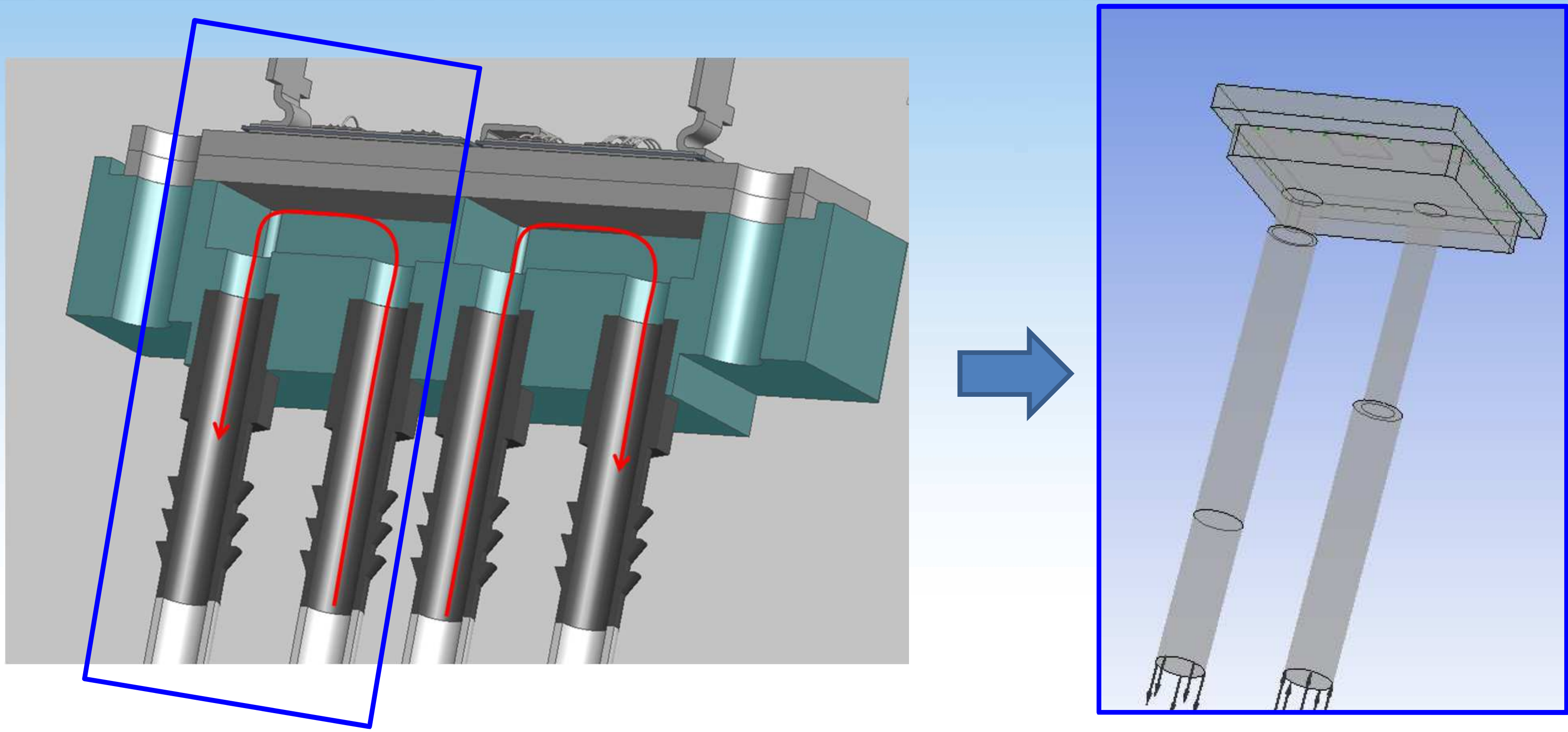


Magneto Hydro Dynamic (MHD) Pump with liquid metal cooling medium

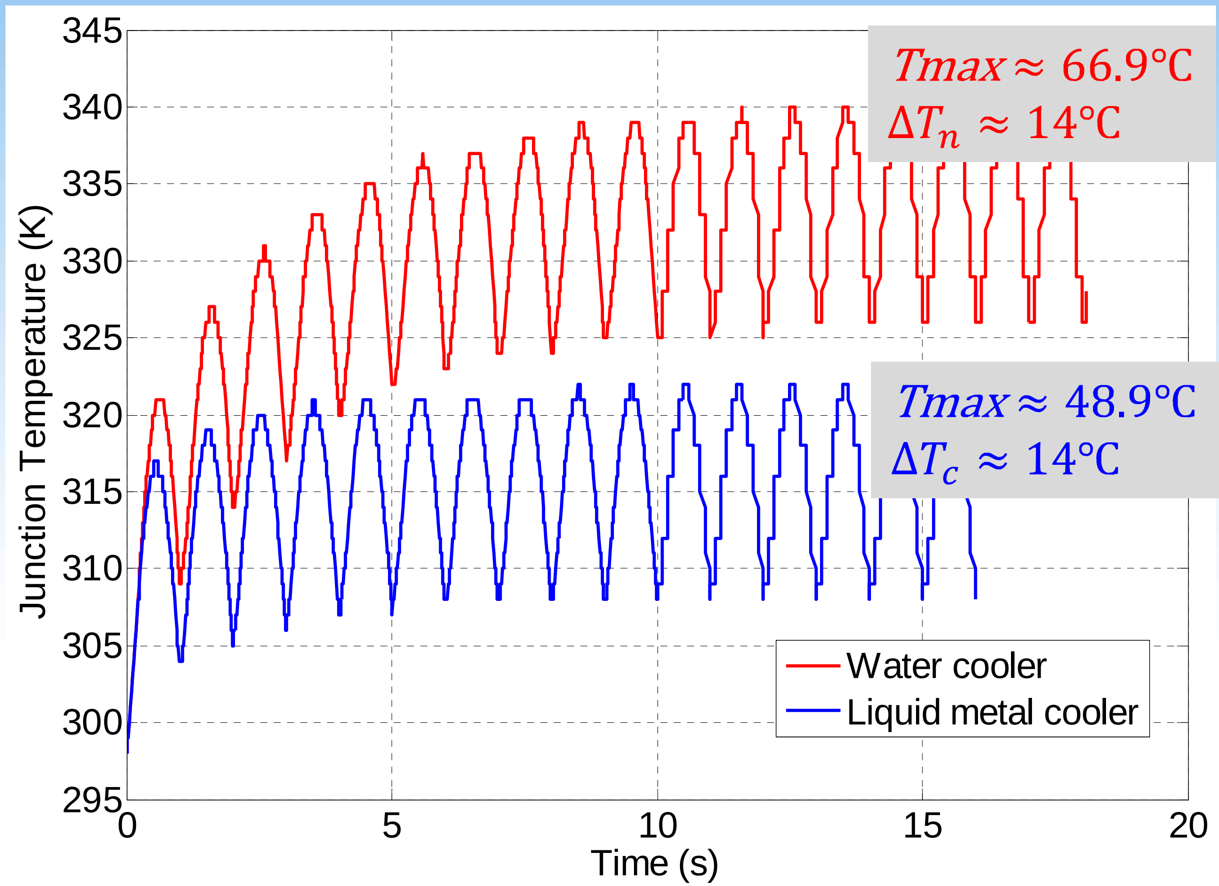


high speed above 1kHz
no mechanical parts
high thermal conductivity

Physical layout



Liquid metal vs. water



Conclusion

1. Liquid metal cooler has better thermal performance than water;
2. Liquid metal cooler has simpler structure than the proposed coolers with micro-valves;
3. MHD pump is more reliable and quieter compared to micro-valves have no moving components;
4. MHD pump is easy to control as the power is proportion to the given control current;
5. MHD pump can operate above 1kHz.

Next Steps

1. Simulation results at high frequency must be further investigated;

2. Construction is on its way.

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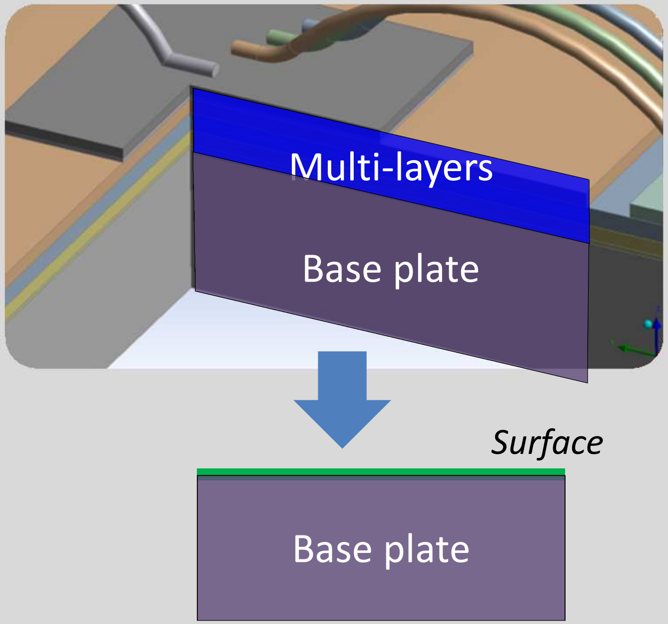
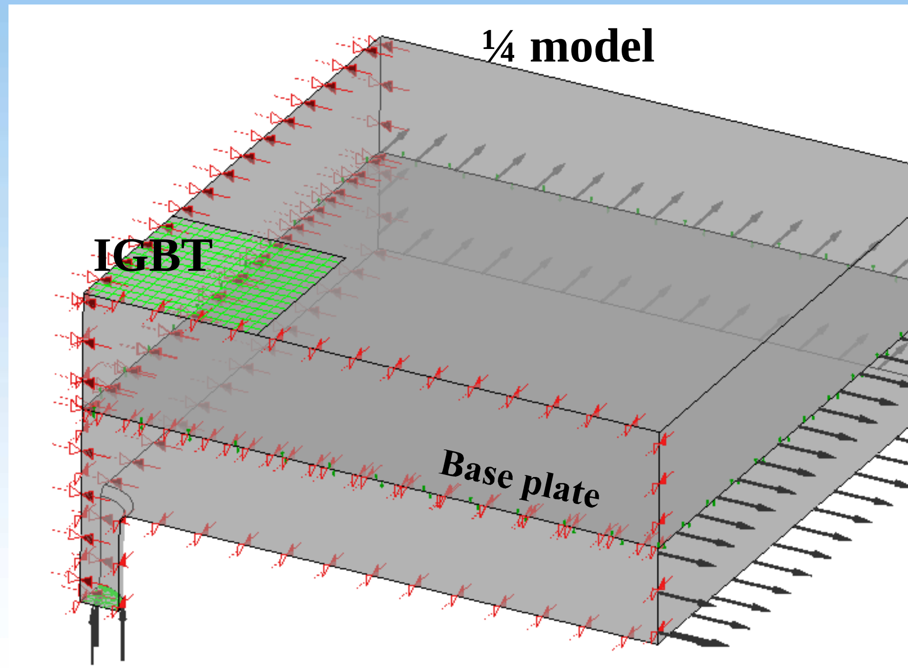
1. CFD Analysis of the Liquid Cooler

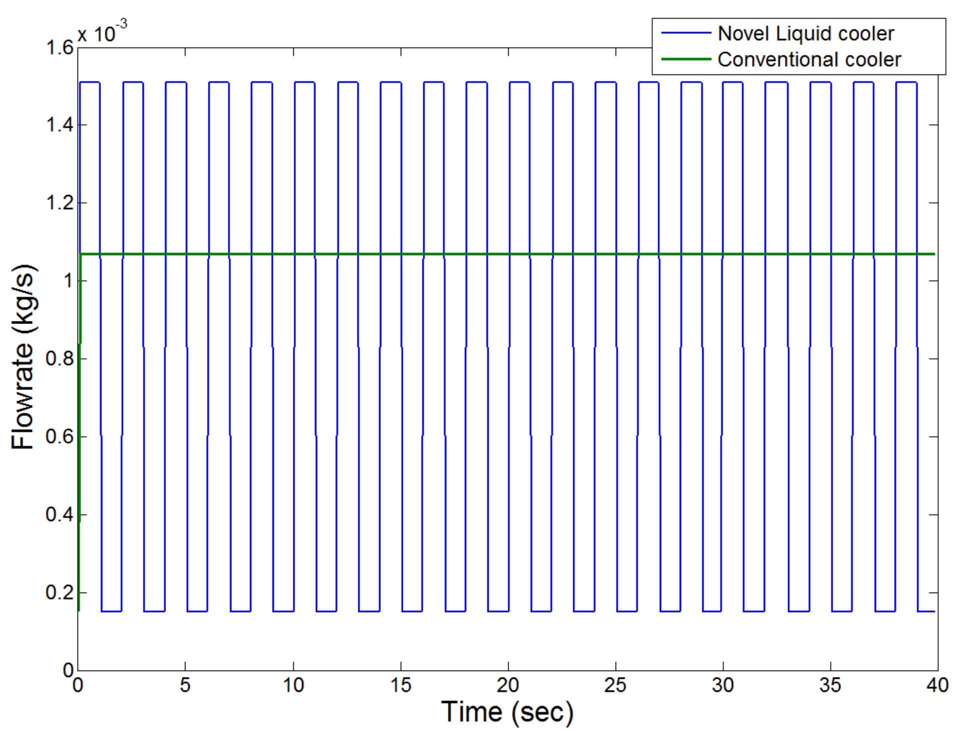


Multi-layered structure is simplified as one surface with equivalent R_{th} and C, as the base plate is the biggest contributor to the total thermal resistance and capacity.



Simplification of the multi-layered IGBT structure

1. CFD Analysis of the Liquid Cooler



Initial condition of the simulation:

1. On/off frequency of IGBT: 0.5

2. Flowrate of the conventional cooler is set as $Q = 1.07E3\ Kg/s$.

3. The max. flowrate of the liquid cooler is set as $\sqrt{2}Q = 1.51E3\ Kg/s$, which is conservative value (usually among $[\sqrt{2}Q, 2Q]$) based on the flow characteristics of the pump, valve and flow channels.