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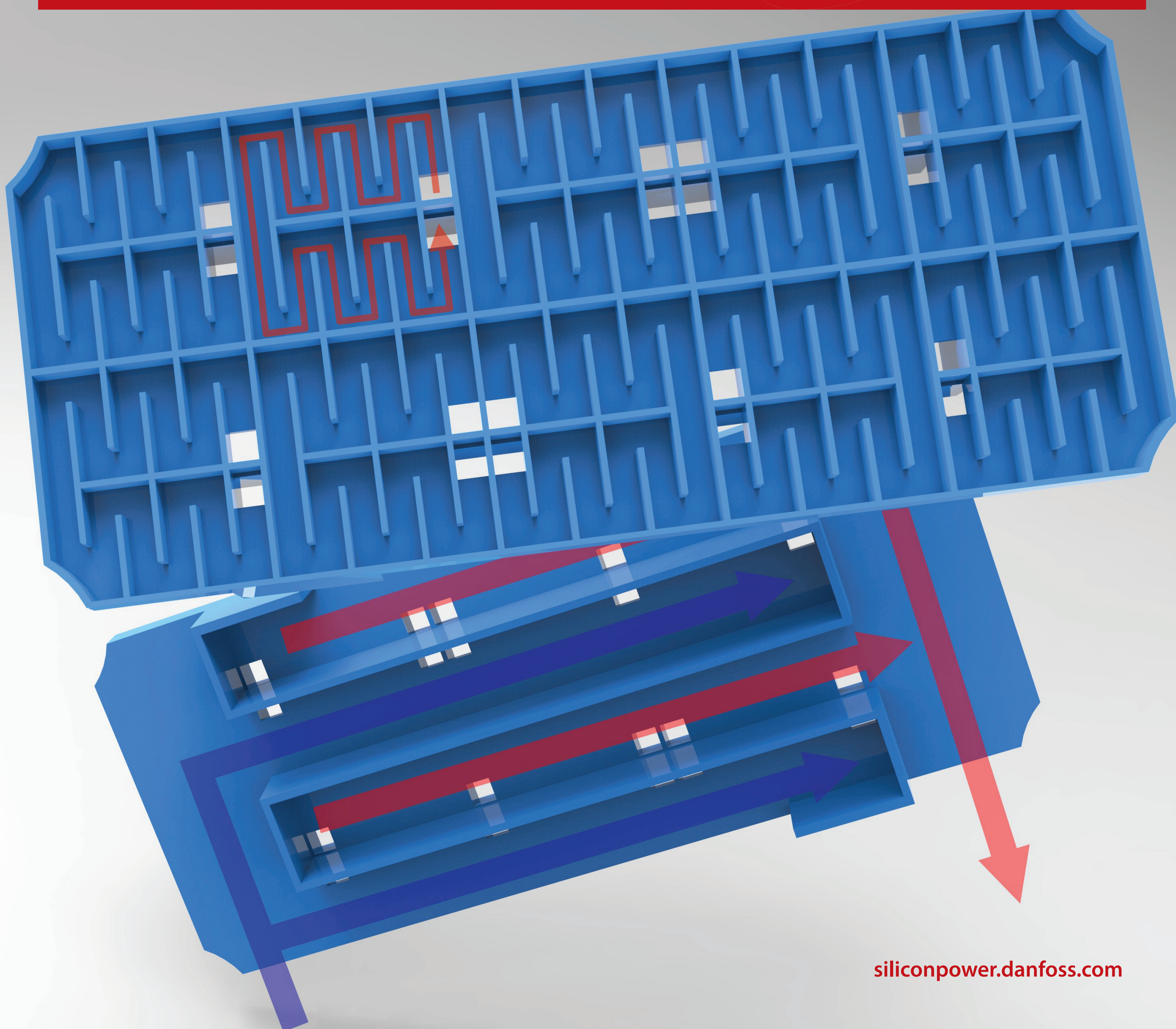
Application Note

ShowerPower®
cooling concept

This application note gives an introduction to liquid cooling of power modules, why cooling is needed, how it is done and a description of the Danfoss ShowerPower® cooling concept. Then follow sections on ShowerPower® thermal performance data, design guidelines, material choice recommendations and finally a description on how to perform thermal tests on a ShowerPower® cooler.



siliconpower.danfoss.com

Content and references

References

1. K. Olesen et al., "ShowerPower® New Cooling Concept", PCIM Conference Proceedings 2004, Nuremberg.

2. F. Osterwald et al., "Innovative Kühltechnologie für Leistungsmodule", '
   Bauelemente der Leistungselektronik und ihre Anwendungen, 10.-11. Oktober 2006, Bad Nauheim.

3. R. Bredtmann et al., ""Power under the hood" Increasing power density of inverters with a novel 3D-approach",
   APE, March 25-26 2009, Paris.

4. K. Olesen et al. "Designing for reliability, liquid cooled power stack for the wind industry",
   EWEC Conference Proceedings 2012.

5. COG "O-ring basics". http://www.cog.de/en/o-rings-products/o-ring-basics.html

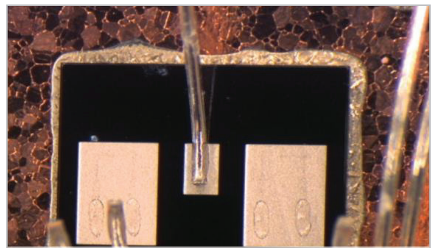
Cooling of Power Electronics

Why is cooling needed in Power Electronics?

Every electronic circuit generates heat during operation (excluding super-conductivity); this is due to conductive and switching losses in active devices as well as ohmic losses in conductor tracks. And since every new generation of power semiconductors becomes smaller than the predecessor and the market expects smaller and more compact solutions the demands to the thermal design engineer keeps growing. Sufficient cooling of Power Eectronics is crucial.

The dominant failure mechanisms in power semiconductor components are related not only to high absolute temperatures but to changes in temperature: temperature swings produce thermo-mechanical induced stresses and strains in the material-interfaces of the components (mismatches in coefficients of thermal expansion, CTE) which lead to fatigue failures.

The most important failure mechanism in power modules is the bond wire liftoff where the aluminum wire bonds (with a CTE of 24ppm/K) pop off the silicon chip surface (CTE of Si is 2-3pmm/K) .



Bond wire liftoff after power cycling

Why liquid cooling?

Liquid cooling of power electronics has been around for many years, primarily due to the ever increasing power densities and due to the availability of liquids in certain applications. Liquid cooling outperforms air cooling by having heat transfer coefficients several orders of magnitude higher thus enabling much higher power densities and more compact solutions.

The acceptance for liquid cooling varies from business segment to business segment. The automotive industry for example has used liquid cooling for cooling the combustion engines for more than a hundred years so the idea of cooling power electronics in an automotive application is not frightening for the design engineers. In other segments the idea of having fluids flowing through power electronic assemblies is most disturbing.

Liquid cooling – indirect vs. direct cooling

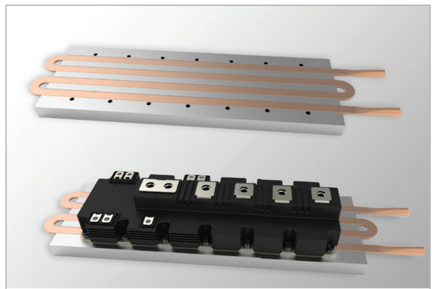
The large amount of liquid cooling solutions may be divided into two groups: indirect and direct liquid cooling.

Indirect cooling means that the power module is assembled on a closed cooler, e.g. a cold plate. Cold plates may be realised e.g. by gun drilling holes in aluminium plates or by pressed-in copper tubes in aluminium extrusions, an example of which is shown here.

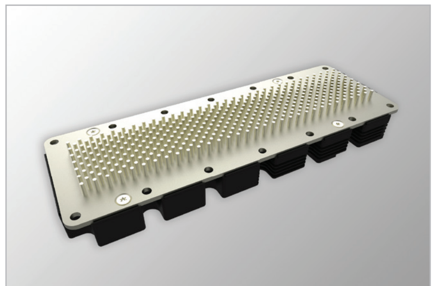
The first picture shows a P3 module being assembled onto a cold plate. When dealing with cold plates it is necessary to apply a layer of TIM between the power module and the cold plate.

Direct liquid cooling on the other hand means that the coolant is in direct contact with the surface to be cooled. Here the cooling efficiency is improved by increasing the surface area of the surface and this is commonly done by various pin fin designs. Below an example of how the P3 module would look if it was equipped with a baseplate with pin fins.

Direct liquid cooling eliminates the layer of TIM that is traditionally needed between the backside of the power module and the cold plate. Because the TIM layer accounts for 30%-50% of the Rth, junction-coolant, this TIM-elimination results in an improved thermal environment for the power module. Since the dominant failure mechanisms are temperature-driven, this will lead to higher reliability.



A cold plate for the P3 module.



A baseplate with pin fins for the P3 module may look like this

The ShowerPower® concept

ShowerPower® is a concept for direct liquid cooling developed by Danfoss. The main motivation for the concept was to solve the classical problem associated with liquid cooling of power modules namely:

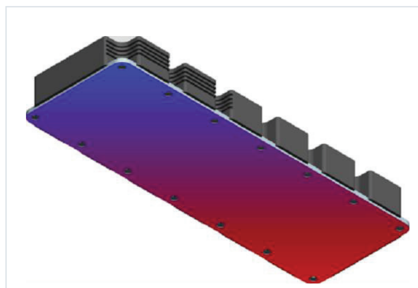
Classical problems with liquid cooling:

- Inhomogeneous cooling due to the calorimetric heating up of the coolant
- Thermal interface material (TIM) related quality issues like pump-out and dry-out effects
- High cost

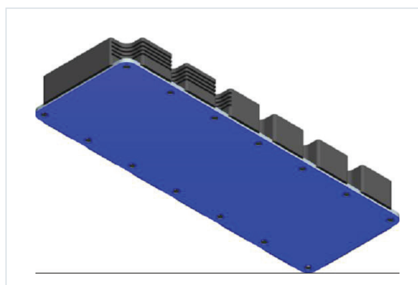
Key freatures are:

- Ability to homogeneously cool large flat baseplate power modules, and systems of modules, thereby eliminating temperature gradients thus improving live and facilitating paralleling of many power chips
- No TIM-related pump-out and dry-out effects
- Very low differential pressure drop
- Compact, low weight, high degree of design freedom enabling 3D designs
- Low cost: metal-to-plastic conversion into simple plastic parts.

The key element of the concept is the ShowerPower® turbolator that guides the coolant along the module baseplate in cells that are supplied with coolant in parallel thereby securing uniform module temperatures. Actually the term turbolator is misleading: under normal flow conditions the liquid flow in the flow channels is laminar; typical Reynolds numbers range around 500 and the transition into turbulence occurs at Reynolds numbers around 2400.



Temperature gradient in standard cooler.



No gradient as in ShowerPower®

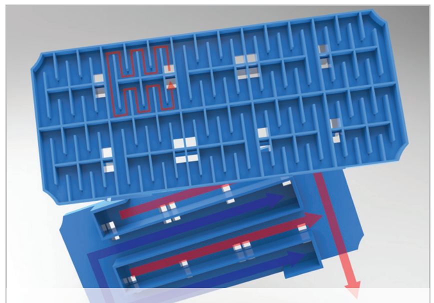
The ShowerPower® concept – continued

The general ShowerPower® plastic part having several cooling cells in the X and Y directions needs a manifold structure on the backside of the plastic part; this ensures that each cooling cell receives water with the same temperature.

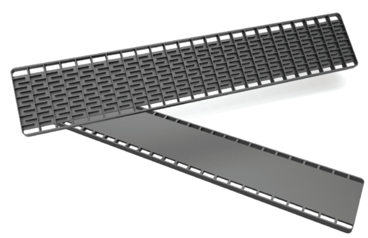
Since the P3 module is relative long and narrow only one cell is necessary across the module; this makes the plastic part much simpler since the manifold structure on the backside becomes obsolete.

Shown below is a ShowerPower® cooler assembly for a wind application featuring seven P3 IGBT modules, turbulators, sealings and manifold.

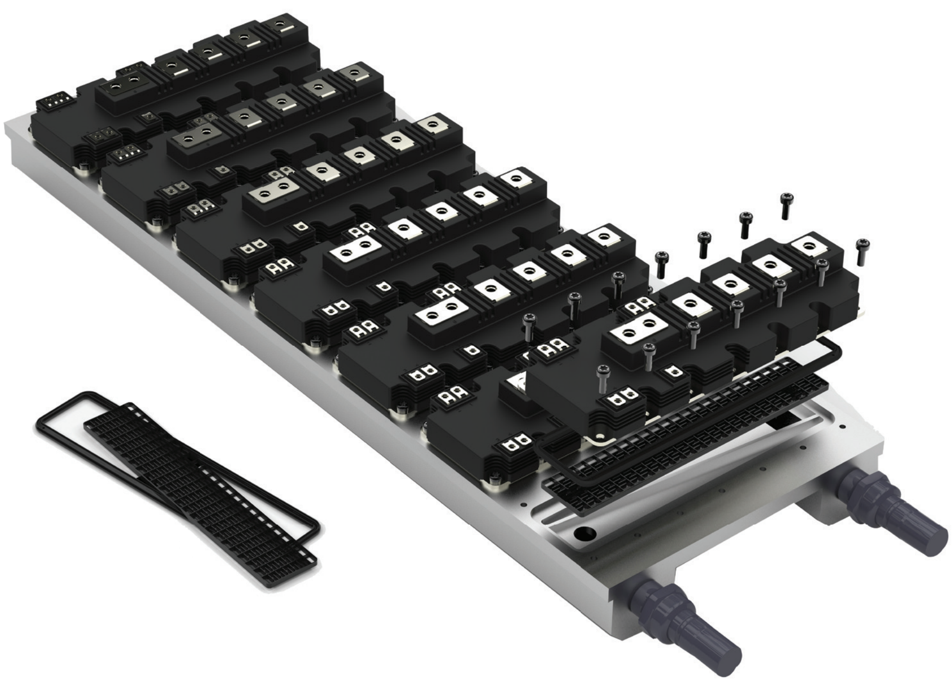
The design ensures that all chips in all modules are cooled equally well. The concept enables tailored cooling if hot spots need extra attention; this is simply done by designing the cooling channels individually. For further information on the principles of ShowerPower® please refer to 1, 2, 3, 4.



The general ShowerPower® turbolator

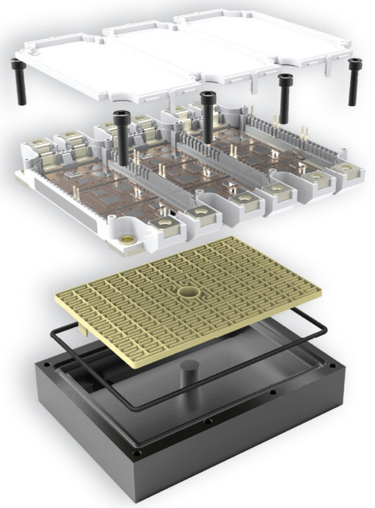


The ShowerPower® for the P3 module.

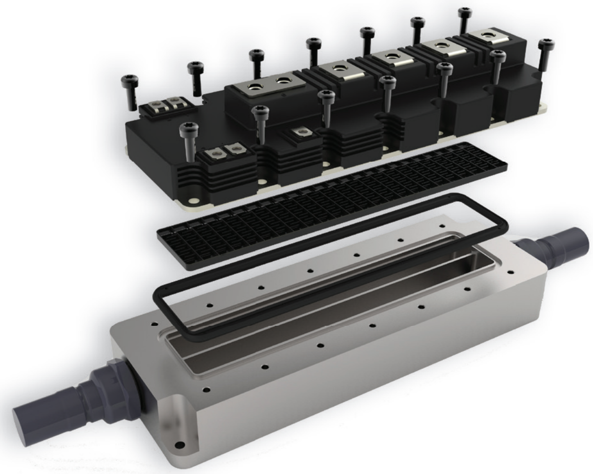


ShowerPower®
thermal performance

Numerous simulations and measurements have been done over the years on various ShowerPower® designs. The two most investigated power module coolers are the E+ and the P3 module-cooler combinations.



E+ module and cooler.



P3 module and cooler.

Simulations

Simulations, (thermal, fluid, mechanical, stress, vibrational etc.) are always important in any product development project; the obvious reason is to reduce the number of time-consuming and costly tests.

There are basically three approaches for doing simulations of fluid flow problems.

The best way to simulate a liquid cooling system is to use computational fluid dynamics, CFD. Here the fluid flow is solved numerically so that the correct heat transfer rates and pressure conditions are found and thus the relevant temperatures, e.g. semiconductor junction temperatures are found.

In some cases though, e.g. in complicated transient situations, it makes more sense to use finite element analysis, FEM. Here a heat transfer coefficient is applied as a boundary condition to the wetted surface of the power modules; this heat transfer coefficient is found either from measurements or from CFD analysis.

Typically a thermal step response analysis is being made and the resulting thermal impedance curve is curve-fitted to a sum of exponential functions from which thermal resistances and capacities can be extracted and forming the basis for a Foster network analysis. For analysing complicated mission profiles this is the only way; using a transient CFD analysis may take years of CPU time!

Thirdly simple calculations using e.g. Excel is often used to get a first glimpse of the thermal performance and pressure drop. An Excel model can also be used to analyse the thermal stack layer by layer and assess the thermal resistances and heat capacities of each layer which can then be used in a Cauer network for transient analysis.

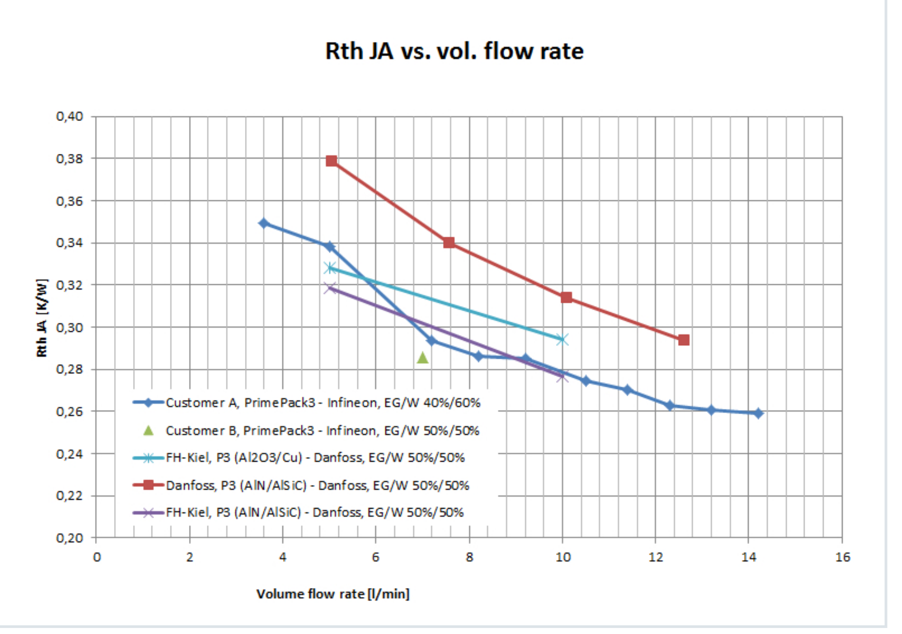
Measurements

Below a collection of measurements done on the P3 module is shown.

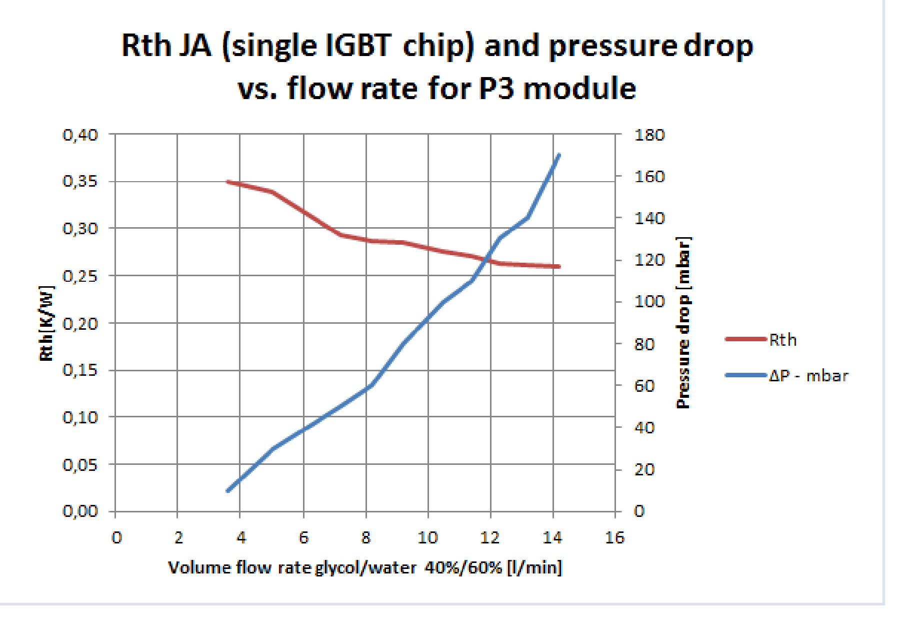
Note that there are two different module types represented: Al2O3 DCBs on copper baseplate and AlN DABs on AlSiC baseplate. All measurement sets but one are done with glycol/water 50%/50%; the other set was done using glycol/water 40%/60%. All the measurements were done by turning on the IGBTs only and using a DC current source for generating the heat loss. Temperature measurements were done using thermography.

Based on the measurements done on the P3 cooler for ShowerPower® two empirical expressions have been derived that predict the thermal resistance (junction-water) and the differential pressure drop as function of volume flow rate.

R_{thJA} is the thermal resistance (junction – coolant) for a single IGBT chip (SIGC186T170R3) and $\dot{V}$ is the volume flow rate [l/min] for the whole module.



Thermal resistance, junction-water, for one single IGBT chip in the P3 module.



The measurements from customer A.

Parameter	Value
R_{thJA} [K/W]	$0.48 \times \dot{V}^{-0.235}$
ΔP [mbar]	$1.07 \times \dot{V}^{2}$

Design considerations

When designing a liquid cooled system several issues have to be considered in order to ensure a reliable solution that is capable of delivering the performance needed over the required lifetime of the system.

When designing a liquid cooling system for a power electronics applications the issues in the table need to be considered.

Additionally it is very important to look into corrosion-, tightness-, sedimentation- (including bio-growth) and anti-freezing issues is discussed in the following sections.

It is recommended to apply a filter of 100µm before the ShowerPower® cooler.

It is also recommended to design a independent cooling loop for the ShowerPower® system for ensuring the best environment that will yield long life and high performance.

Parameter	Unit	Comment
Volume flow rate	l/min	What is the flow rate available
Coolant		Glycol/water mixture
Absolute pressure in the system	bar	High pressure may need special power modules (thicker baseplates) for avoiding excess mechanical deformation of power modules
Differential pressure drop allowed	mbar	From inlet to outlet, determines the size of the pump required
T_{in}	°C	Inlet coolant temperature; high temperatures may require special materials
Power losses	W	All heat that need to be transported away by the cooling system
T_{Jmax}	°C	Maximum allowed component temperatures
ΔT_{max}	K	Maximum allowed temperature variations over the power module assembly
Distribution of heat sources		The best is to have the physical layout of the power modules so the optimum cooling can be designed
Geometric and weight constraints		Size and form factor; is the system to fit into larger assemblies
Material compositions in the cooling system		Tubing, bathtub, power module baseplate; determine the chemistry of the coolant e.g. regarding the correct anti-corrosive additives
Particle sizes in coolant		Determines the minimum allowed geometries in the cooling system for avoiding clogging of narrow channels

Corrosion issues

Metals subjected to water are prone to corrode. Crevice and galvanic corrosion are the most important processes that need to be controlled.

Crevice corrosion is related to small gaps where the cooling liquid has limited flow- access, i.e. the water is moving very slowly. Therefore care should be taken when designing the groove for the sealing and for the ShowerPower® plastic insert.

Galvanic corrosion occurs when metals with different electrode potentials are immersed in an electrolyte, like water.

Typical metals in liquid cooled setups are aluminum, copper and nickel. If pure water is used as coolant galvanic corrosion will quickly corrode away the aluminum.

In order to avoid these corrosion issues anti-corrosive chemicals are added to the coolant. By far the most commonly used materials are ethylene-glycol mixtures with suitable anti-corrosives like the fluids used in every car in the world. Other substances used include ethylene-glycol and propylene-glycol.

The mixture needs to contain more than 30% glycol in order to avoid bio-growth: lower glycol concentrations may actually act as “food” for some microorganisms. Typical mixtures have 40-50% glycol and 60-50% water. This also acts to avoid freezing issues down to -35-40°C. The type of glycol depends on the material combination in the cooling system (for combustion engines the blue type is used for iron-cast motors and the red type for aluminum cast motors.

Water tightness

One of the biggest issues related to direct liquid cooling principles is how to design a reliable watertight solution that will remain watertight throughout the design life of the product. The correct sealing concept is key to success. Not only is a correct groove design important but the material choice and surface roughness also play important roles.

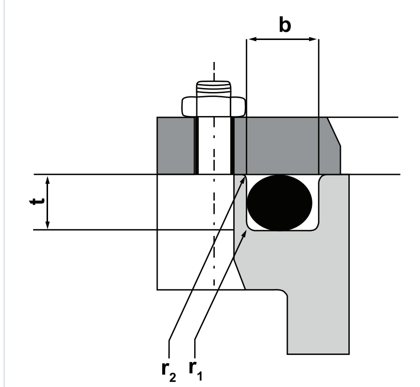
Sealing design
The design of a sealing concept involves the design of the sealing itself but also the groove into which the sealing is placed. Basically two types of sealing concepts are used:

- **Standard O-ring**
  The size of the O-ring depends on the geometry and size of the power module. For the P3 module Ø3-Ø4mm would be the best choice.

The recommended groove design for an O-ring is seen in the figure to the right.

- **Specific Gaskets**
  Danfoss can provide a specific gasket for the P3 modules. It is a rubber-plastic-compound component with a double sealing line and drainage holes in between the two lines. So if the inner sealing should leak the coolant can be drained outside the converter. The second sealing line will then take over. This gasket was successfully tested in an 8.000 hours test at 105°C with water glycol under operating conditions (assembled and with flow of coolant).

The surface quality of the gasket's contact surfaces (power module baseplate and gasket groove) needs to be specified as Rz6.3 / Rmax10.



d	b	t	r1	r2
2.00	2.85	1.45	0.3±0.1	0.2
2.50	3.55	1.90	0.3±0.1	0.2
2.65	3.80	2.00	0.3±0.1	0.2
3.00	4.20	2.30	0.6±0.2	0.2
3.55	5.00	2.75	0.6±0.2	0.2
3.70	5.15	2.90	0.6±0.2	0.2
4.00	5.55	3.20	0.6±0.2	0.2

Recommended groove geometry for different O-ring sizes, 5.

Material choices

Baseplate
The part of the power modules that is in contact with the coolant, most typically a copper baseplate, needs a surface treatment. The Danfoss base plate for Shower Power applications is plated with specific combinations of Ni layers to assure good robustness against corrosion.

Bathtub
The bathtub is most commonly made of aluminum. Depending on the manufacturing method there are different aluminum alloys having sufficient corrosion robustness:

- Extrusion, e.g. EN AW 6060
- Machining from casted block material, e.g. EN AW 5083
- Die Cast, e.g. EN AC 44300

Most often the bathtub neeeds to be machined at the sealing area in order to ensure a properly low surface roughness not exceeding Rz. 6.3.

Sealing
There are some vital parameters for selection of the right sealing material:

- Expected lifetime at maximum temperature level
- Temperature range (operation and storage)
- Coolant type
- Potential contaminations of the coolant
- Hardness of the material
- Material of contact surfaces (power module and bathtub)
- Surface roughness of the sealing area of Rz. 6.3.

The most commonly used material in glycol / water loops is EPDM (ethylene-propylene-diene-monomer) 70 shore A.

The application kit includes a double gasket comprising a plastic carrier upon which the EDPM rubber has been vulcanized.

It is generally recommended to clean O-rings or gaskets in isopropanol prior to assembly.

Coolant
Care must be taken choosing suitable coolant chemistry. The coolant must withstand the operating and storage temperatures (anti-freeze) and protect the materials included into the coolant loop. Danfoss recommends:

- Tyfocor® by Tyforop Chemie GmbH
- Antifrogen N® by Clariant

The double gasket for the P3 module featuring drainage holes for optional leakage detection.

Setting up the test

The application kit comprises the following:

- Power module, P3, not encapsulated and painted black[1] for optimum infrared imaging
- Bath tub
- ShowerPower® insert
- Double gasket
- Screws for assembling the module to the bathtub
- A copy of this application note

[1] Note that the black paint is only insulating up to 100V voltage levels; this is not an issue under normal thermal test conditions with DC-voltage levels of 3-4V.

Laboratory equipment needed

Necessary equipment for making measurements on a liquid cooling system:

- **Liquid cooling circuit**
  - **Closed loop system** incl. pump
  - **Heat exchanger for re-cooling the coolant**. With typical power dissipations of up to several kW in the power module it is recommended to connect a heat exchanger to the cooling circuit for re-cooling the water; otherwise the cooling water will heat up quickly making further testing impossible
  - **Pressure transmitters**, preferably as close as possible to the bathtub for getting the most precise assessment of differential pressure drop of the power module cooler
  - **Temperature transmitters**, preferably as close as possible to the bathtub for getting the most accurate measurements of the calorimetric heating up of the coolant.
  - **Flow meter**
  - **Air bleed**, if there is air entrapped into the cooling system this could lead to hot spots on the power module baseplates so the system must be degassed properly
- **Power supply** for generating the power losses in the power module
- **Voltage supply** for turning the gates of the IGBT chips on
- **Infrared camera** for measuring chip temperatures

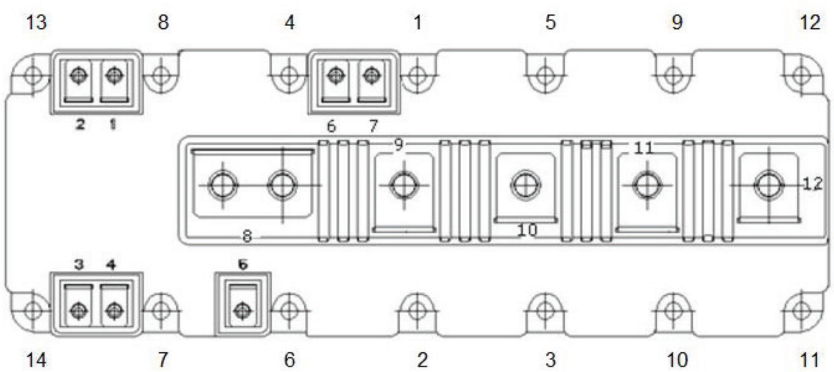
Connecting the bathtub to the coolant supply

If it is required to take out the bathtub leak free from the cooling circuit Danfoss recommends to use Stäubli SPT connectors made of aluminum. Please note that these connectors have a substantial inherent pressure drop. Every time the cooling loop has been opened the system needs degassing properly after reassembly.

Assembly of the power module on the bathtub

Assembling a power module on a heat sink, a cold plate or an open cooler must be done carefully otherwise the module may be damaged. The prescribed mounting sequence of the screws most be followed for minimizing the stresses inside the power module. The recommended mounting sequence for the P3 module is as follows.

The M5 bolts should be preset in a first step until the bolt heads touch the baseplate top side. In a second step the bolts must be torqued with 6 +/- 0,5Nm in the shown sequence. The bolt strength class needs to be 8.8 minimum; the use of impact wrenches is not permitted because of the ceramic components inside the power module. An electronic controlled screw driver with soft stop is the best choice in a series production.

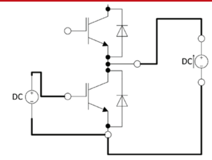
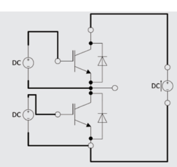
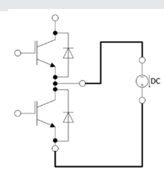
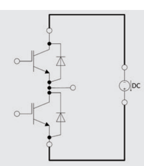
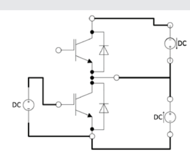


Recommended mounting sequence for the P3 module (Infineon/Danfoss).

Connecting the power module

When the IGBTs are turned on the voltage drop typically is 3V which means that the power supply must be capable to deliver currents up to several hundred Amperes. This also means that the cabling must be sufficiently dimensioned e.g. having cross sectional areas of 70-120mm2.

Testing on an IGBT module, like the P3 module supplied in the application kit, can be performed in a number of different modes; and because the P3 module is a half bridge module is can be decided whether the IGBTs and or diodes are active during the test.

Test mode	Connections	Comments
Active IGBTs, passive diodes		Low side IGBT is active and the diodes are active, the IGBT is turned on by a 15V gate voltage
Active IGBTs, passive diodes		High side and low side IGBTs are active, the IGBTs are connected to the power supply is in series and both IGBTs are turned on by a 15V gate voltage
Passive IGBTs, active low side diode		Only the low side diode is active; alternatively the high side diode can become active
Passive IGBTs, active high side and low side diodes		Both diodes are active by connecting them in series
Active IGBTs, active diodes		High side diode and low side IGBT are active; the IGBT needs to be turned on by a 15V gate voltage; alternatively the high side IGBT and low side diode can become active

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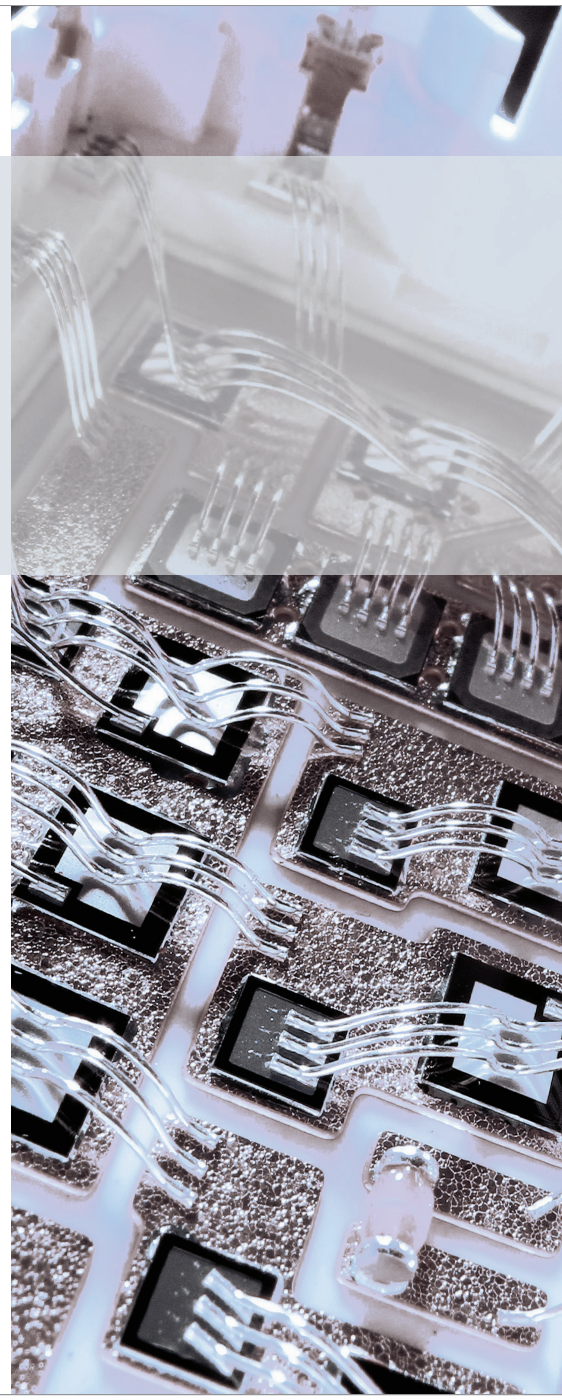
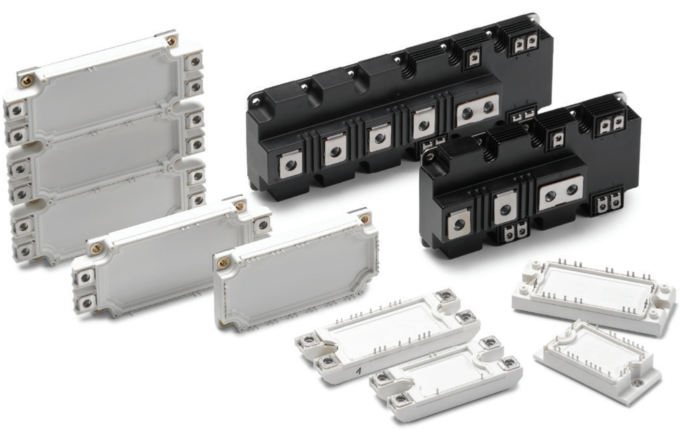
Based in Flensburg, Germany, Danfoss Silicon Power is a leading developer of customer specific IGBT and MOSFET modules and power stacks for power intensive applications.



Our power modules and power stacks are a preferred choice in demanding automotive and wind power applications and a wide variety of industrial applications.

Our 35,000 m^2 research, development and production facility is certified according ISO 9001, ISO/TS 16949, ISO 14001, ISO 50001 and OHSAS 18001. This enables us to quickly transfer development projects to high volume production that can be integrated seamlessly into our customers' supply chain with full focus on quality.

Danfoss Silicon Power is a subsidiary of the Danfoss Group, the largest industrial company in Denmark. Danfoss employs more than 24,000 people in 100 countries within development, production, sales and support.



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