Innovative Cooling Concept for Power Modules

High thermal performance gives high reliability solutions

ShowerPower, a newly developed cooling concept, solves the key problems related to liquid cooling namely the high cost and the inhomogeneous cooling. The challenges for future liquid cooled power module assemblies, especially in hybrid electrical vehicle traction applications, can be met by the ShowerPower cooling principle.

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Requirements for liquid cooling systems

In order to increase thermal performance and lifetime the manufactures of power electronic assemblies request:

High cooling performance, which saves silicon and ensures long life.
Homogenous cooling, which enables paralleling of several power semiconductors.
And all this at a low cost of course.

Present cooling technologies can not meet these requirements; performance and cost follow each other in state of the cooling technology. Even the step from coldplate technology to open pin fin coolers, that eliminates the need to use thermal interface materials between power module and cooler, does not solve the problems. However at Danfoss Silicon Power we have developed a cooling principle which is highly efficient (better than pin fin coolers), offers homogenous cooling across even large surfaces (temperature gradients are fractions of a °C), and at a low cost since the key part of the concept is a simple plastic part.

In a traditional liquid cooled system the heating up of the coolant causes a temperature gradient in the power module, see the left part of Figure 1.

ShowerPower™, the basic idea

The fundamental idea is to turn the direction of the coolant flow by 90° and to introduce coolant having the same temperature all over the surface to be cooled, which can be perfectly flat having no structuring, see the right part of Figure 1 below. The name of the concept originates from the conceptual resemblance to using a common shower-head from a daily life bathroom. But as opposed to other jet impingement coolers the trick here is to get rid of the coolant before large temperature gradients are generated.

Metal-to-plastic conversion

Parallel injection of coolant perpendicular to the surface to be cooled is obtained by a simple plastic part manufactured by e.g. injection moulded, the cost typically a fraction of one EURO. This metal-to-plastic conversion offers a very large cost reduction potential since the costly processes involved in standard coldplate- as well as pin fin manufacturing have been transferred to a simple low cost plastic part.

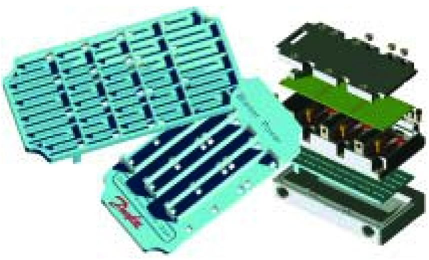

Figure 2. A simple plastic part acts as a guide for the coolant. Front and back of the plastic part are shown.

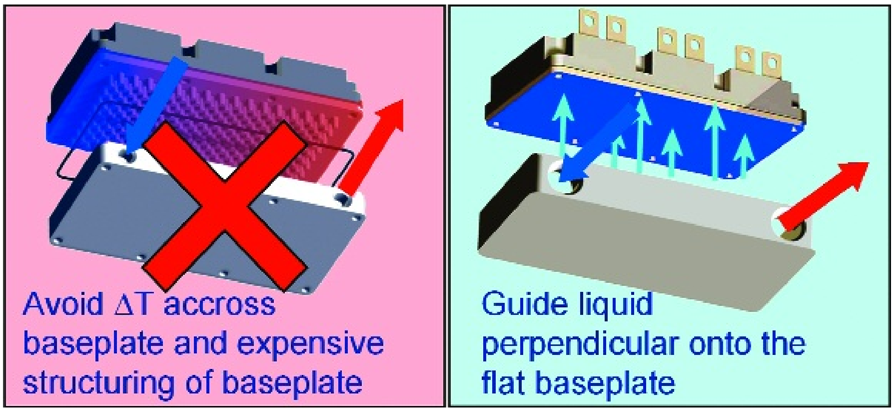

Figure 1. Turning the flow direction by 90° eliminate temperature gradients.

Several cooling cells on the top side of the plastic part guide the coolant to the baseplate surface; the meandering structure of the cooling channels ensures high heat transfer.

Homogenous cooling

To obtain homogeneous cooling the cooling cells are supplied with coolant that have the same inlet temperature; this is accomplished by the manifold structure on the backside of the plastic part.

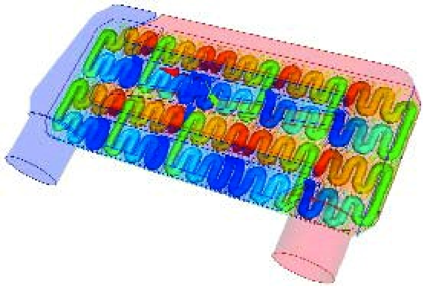

Figure 3. The fluid flow inside the cooler. The flow in the main manifolds is shown dimmed.

Figure 3 illustrates the principle: the pressure distribution in each meandering cell are identical and the inlet manifold feed (dimmed red) the channels whereas the outlet manifold (dimmed blue) guide the coolant away from the cooling cells.

Thus the concept offers true homogenous cooling with the ability to remove temperature gradients over arbitrarily large areas.

Tailored cooling

The concept can be used to solve specific thermal problems, e.g. if a particular hot spot in a power module needs special attention, the cooling channels of the cooler are simply adjusted locally. In other words the concept offers total design freedom to tailor the temperature gradients across the surfaces to be cooled.

Typical performance

Numerous tests have been conducted, in-house as well as externally at customers and research institutions. Typical performance parameters are heat transfer coefficients in the excess of 10.000W/(m2K) with pressure drops of a few hundred mbar's using ethylene-glycol/water 50%/50% as coolant. The chart below shows the thermal comparison between a pin fin cooler and a ShowerPower™ cooler, measured by Ernst Schimanek, Fraunhofer IISb- Erlangen. It shows the thermal resistance, junction to coolant, and pressure drop vs. the volume flow rate through the coolers.

It is seen that especially at lower flow rates that the ShowerPower™ performs better than the pin fin cooler.

ShowerPower™ offers:

- Uniform cooling of the power module, the temperature gradients are gone; alternatively tailored cooling is possible
- High thermal performance yielding more reliable cooling solutions
- Metal-to-plastic conversion drives down the cost significantly
- The direct cooling eliminates the need for a thermal interface material.

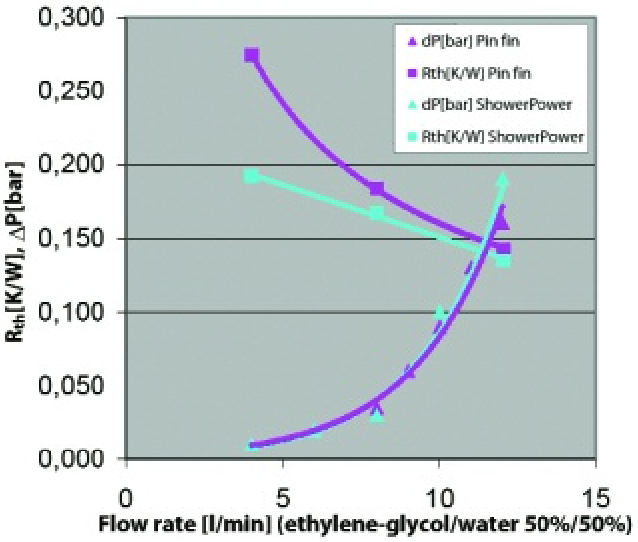

Figure 4. The thermal performance of a pin fin cooler compared with a ShowerPower cooler.

Applications for liquid cooling
The potential applications for liquid cooling and thus ShowerPower™ are numerous especially where high power densities represent a thermal challenge, and where liquid coolant is available. A dozen potential customers are performing or have done tests on ShowerPower™ coolers ranging from automotive applications to CPU coolers. Some examples:

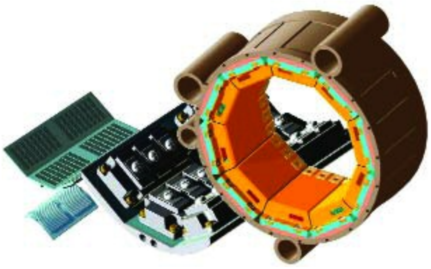

Figure 5. Assembly for a hybrid electric vehicle traction converter module, the shape of the ShowerPower coolers are adapted to needed application, e.g. a cylindrically shaped motor.

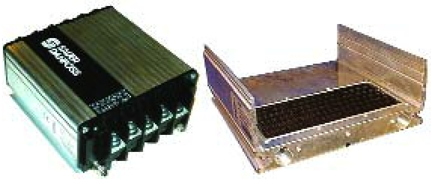

Figure 6. Battery driven inverter, BPI (Sauer-Danfoss); the Al baseplate (right) having integrated the ShowerPower cooler; intended mainly for forklift truck applications.

Figure 7. CPU cooler with a one-part ShowerPower cooler, (to the right the front and backside of the cooler is shown).

Designing a cooling system
When designing a cooling system it is necessary to understand the physics of the problem.

Characterising the system: hydrothermal performance
The requirements for a cooling system of course vary greatly from application to application. Nevertheless two main parameters are needed for characterising the hydrothermal performance of a cooling system namely the heat transfer coefficient (also called the convection coefficient) and the pressure drop. The latter is directly linked to the system cost since a high pressure drop requires a strong=expensive pump. Most often the maximum allowed pressure drop is specified along with the required thermal performance for a specific application and the task then is to design the cooling system accordingly.

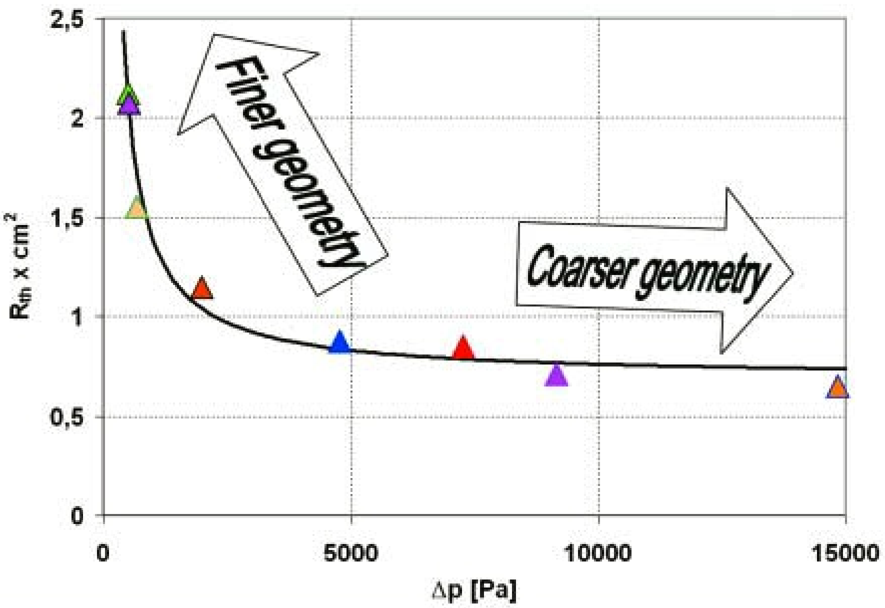

Figure 8. Varying the channel geometry influences the hydrothermal performance.

When comparing the performance of different coolers, or when optimising a specific cooler, it is necessary to consider both parameters: the heat transfer coefficient and the pressure drop since the hydrothermal performance is always a trade-off between the two: a higher thermal performance most often means a higher pressure drop and vice versa. It is also much more convenient to consider the heat transfer coefficient than e.g. temperature since temperature depends on a number of additional boundary conditions related to the thermal stack (materials and geometries) that makes the comparison complicated.

Trade-off between thermal performance and pressure drop
As discussed in the previous section the hydrothermal performance is a trade-off between thermal performance and pressure drop. The chart below plots the pressure drop vs. the thermal performance for a large variety of meander channel geometries where channel width and length have been varied. It turns out that the results basically follow the same hyperbolic curve. Note that the thermal performance here is given as normalised thermal resistance, which basically is the reciprocal of the heat transfer coefficient.

It is seen that coarser channel geometry results in lower pressure drop but also a higher thermal resistance and vice versa.

Optimising the performance
Improving the hydrothermal performance of a cooling system is a challenge: how to improve the ability to remove heat without sacrificing the pressure drop. This is equivalent to find other hyperbolic curves in the same way as in Figure 8 that features lower pressure drops at lower normalised thermal resistances.

In many cases simple empirical formulas applying dimensionless parameters like the Reynolds-, Prandtl- and Nusselt-numbers can be used to get a first assessment of the hydrothermal properties, but for more thorough investigations CFD (computational fluid dynamics) is a must.

Simulation strategy
The ShowerPower^{TM} is unique in that sense that it is based on identical cooling channels supplied with coolant in parallel, this means that it is only necessary to consider the cooler on single-cell level which makes simulations and optimisations much simpler.

Optimisation example
As an example of how the hydrothermal per-

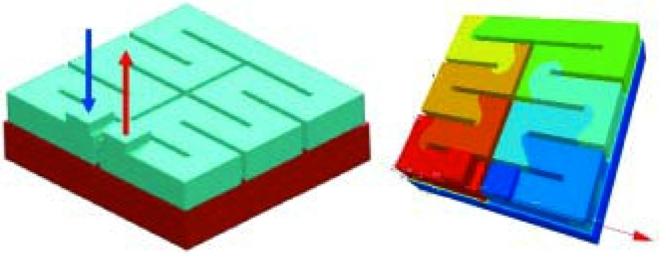

Figure 9. A unit meander cell, the liquid (blue) is placed on a piece of baseplate. To the right the pressure distribution is shown, found from a CFD simulation.

formance of the ShowerPower™ cooler can be optimised, the introduction of small bypass flows is presented.

Small gaps between the plastic part and the power module baseplate allow fluid flow over the top of the walls separating the “legs” of the meander channels. The sketch below illustrates the idea.

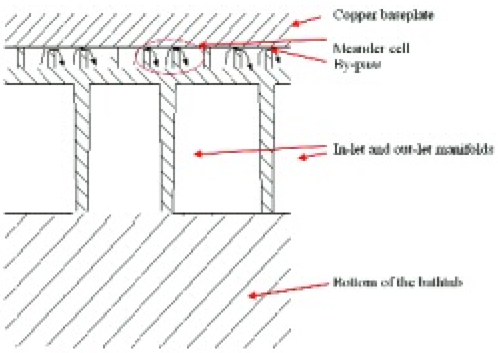

Figure 10. A gap between the walls of the channels and the baseplate allows a bypass flow.

The CFD simulation result below shows the fluid velocity distribution in a meander channel having gaps between wall and baseplate of 0,25mm. It is seen that the fluid velocity is quite high in the bypass area.

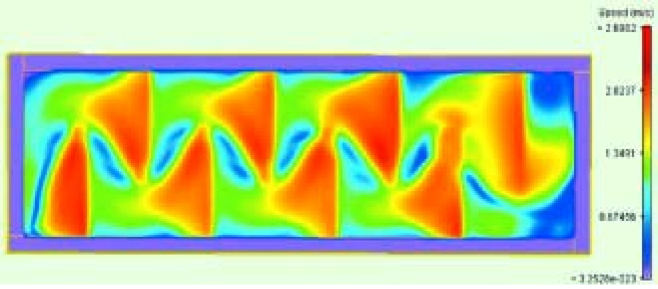

Figure 11.
The fluid flow velocity in a meander cell having a bypass flow.

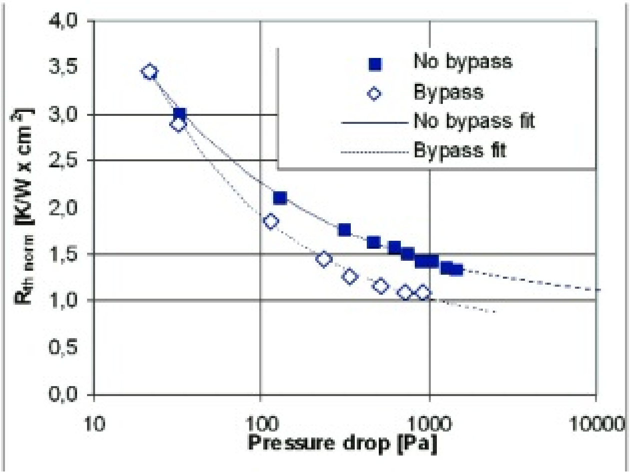

Figure 12. Normalised thermal resistance vs. pressure drop for meander channels with- and without the bypass flow. CFD simulations and fit curves.

Varying the channel geometry of the meander channel, i.e. channel width, height and length, with- and without the bypass gap and plotting the normalised thermal resistance vs. the pressure drop yields two hyperbolic like curves as seen in figure 12.

The two curves represent the CFD results for meander channels having meander-channel lengths from 0 to 9,5mm, with and without a bypass of 0,25mm. The upper left point represents the straight channel having no bends, therefore the two sets start at the same point (a straight channel can not have any bypass). As soon as the bend length increases the thermal resistance decreases but at the cost of increased pressure drop, but the meander cells having a bypass drops faster meaning that the overall performance is better for this cell type.

Also shown in the chart are two curves that represent the best fit to the individual CFD results, the fit-function being a power function.

The conclusion is that by introducing a bypass flow gives a better hydrothermal performance: lower thermal resistance at lower pressure drops.

Summary

It has been demonstrated how the shortcomings of conventional liquid coolers such as inhomogeneous cooling and high cost have been overcome by a metal-to-plastic conversion of costly mechanical features in the metal parts of power modules and liquid coolers into simple plastic parts. This metal-to-plastic conversion offered by ShowerPower™ has even brought along further features that are not available in conventional coolers: the ability to tailor the cooling thereby giving true design freedom. Additionally the high thermal performance gives high reliability solutions, which are especially important in the hybrid traction vehicle area.

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