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Prepared by:	Marion Kind
Approved by:	Prof. Dr. Uwe Scheuermann

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Estimation of Liquid Cooled Heat Sink Performance at Different Operation Conditions

1. Introduction

The aim of this Application Note is the estimation of the thermal impedance $Z_{th(s-a)}$ (heat sink performance) as a function of flow rate, glycol concentration and fluid temperature for water glycol mixtures.

Power semiconductors produce heat in operation. For high power density forced cooling is necessary. Depending on the application requirements forced air cooling or forced fluid cooling can be applied. While air cooling will be engaged especially for lower cooling request applications and where no external cooling system is available, the advantage of fluid cooled system is the high thermal performance of a heat sink. More heat and therefore more dissipated losses can be extracted by a fluid cooled system.
This Application Note describes the impact of different flow rates, glycol concentrations and fluid temperatures on the thermal impedance $Z_{th(s-a)}$ (s: heat sink, a: ambient). First the definition of $Z_{th(s-a)}$ will be summarized and the Semikron method for $Z_{th(s-a)}$ evaluation will be exemplified. Furthermore, this Application Note will explain how to calculate different cooling conditions using data sheet values. The Semikron standard data sheet values for $Z_{th(s-a)}$ are based on a defined flow rate, a defined glycol concentration and a defined fluid temperature. The Semikron standard coolant liquid is a mixture of 50% water and 50% glycol (Glysantin G48 by BASF). The fluid temperature and the flow rate depend on the type of product.

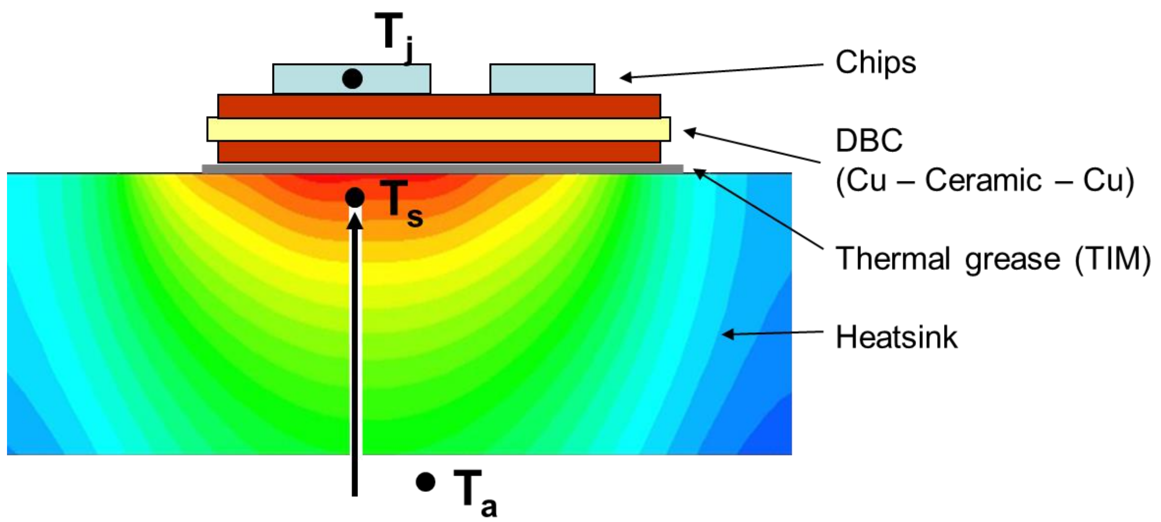
2. Thermal Impedance

The thermal impedance Z_{th} is defined as the ratio of the accomplished difference between the internal virtual temperature and the temperature of a specified external reference point at the end of a defined time period on the one hand, and the step-functional change in power loss occurring at the beginning of this time period (which causes this temperature change) on the other. Directly before this step-functional change, the temperature distribution must have been stationary.
The thermal resistance R_{th} is the stationary value of the thermal impedance. This specification is necessary for the thermal design of the customers system. The power semiconductors are limited by a maximal chip temperature T_{j_max} (j: junction). The time-dependent junction temperature can be calculated for any power dissipation profile by the thermal impedance.

2.1 Definition of $Z_{th(s-a)}$

The $Z_{th(x-y)}$ is defined as a difference of the reference point x temperature (T_x) and the reference point y temperature (T_y) as a function of time divided by the magnitude of a step functional change in power dissipation. For modules without base plate, the $R_{th(j-s)}$ and the $Z_{th(j-s)}$ are defined as typical values in the data sheets for Semikron modules. For modules with base plate, the $R_{th(j-c)}$ and $Z_{th(j-c)}$ are specified as maximum values and the $R_{th(c-s)}$ is specified as typical value in Semikron data sheets. For a complete system (heat sink included), the $R_{th(s-a)}$ for different flow rates and the $Z_{th(s-a)}$ of a specific flow rate are part of the data sheets also (for one specific glycol concentration and one specific fluid temperature only).
For this Application Note, the focus is set on a fluid cooled system without base plate. The location of the reference points for measuring T_j, T_s and T_a can be seen in figure 1. The junction temperature is defined as the area related average surface temperature of a chip or as the area related average temperature of multiple parallel chips. The junction temperature is not a temperature of a fixed reference point in general. T_s is measured below the center of each chip of the measured switch in a blind hole ending 2mm below the heat sink surface [2]. T_a is the ambient temperature, in case of a fluid cooled heat sink it is the fluid temperature at the heat sink inlet. The $R_{th(j-s)}$ is defined as the stationary temperature difference of the area related average temperature of all chips of the hottest switch and the average heat sink temperature below each chip of the hottest switch divided by the stationary power dissipation of this switch (see AN14004). [3]

Figure 1: Cross section of a module without base plate and reference temperature points



2.2 Measurement / calculation

The Semikron standard measurement method of T_j is the V_{CE}-(T) method. The V_{CE}-(T) method is an sensorless method using the physical relation between forward voltage and temperature in pn-junctions. There is a linear correlation between the forward voltage at small current and chip temperature. To measure the calibration curve, the device is heated up externally to different temperatures until the

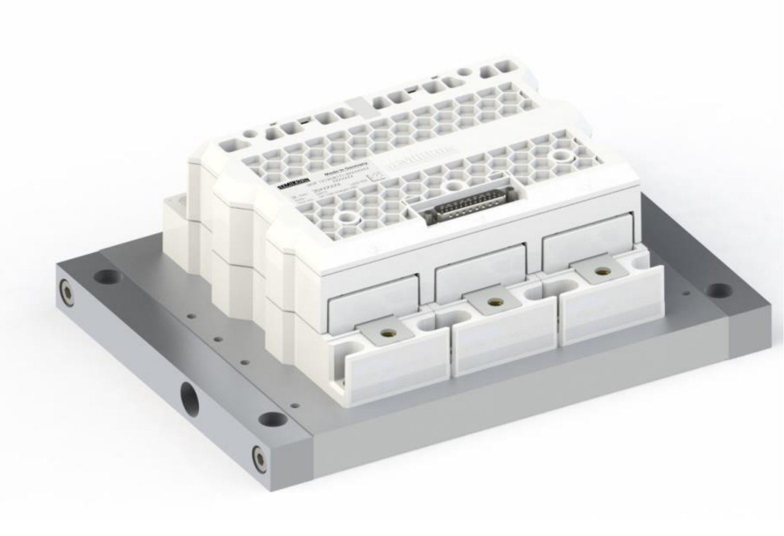
thermal stability is reached. Then the temperature and the corresponding forward voltage can be measured for a defined small sense current. Using the calibration curve, the measured voltage drop during R_{th}/Z_{th}-measurement is convertible into the junction temperature. For the R_{th}/Z_{th} measurement, a load current is applied to the device. The load current heats up the device until thermal equilibrium is reached and after turning off the load current as fast as possible, the voltage drop can recorded for the sense current (cooling curve). It is only possible to measure IGBT or Diode chips with this method. For IGBT measurement a V_{GE} of typically 15V is applied.
Unfortunately it is difficult to measure the $Z_{th(s-a)}$ directly. The stationary heat sink temperature T_s is measured using a thermocouple. It is not possible to measure the transient heat sink temperature with adequate accuracy because of the delay of the thermocouple response. The $Z_{th(s-a)}$ can be calculated by the difference of the measurable $Z_{th(j-a)}$ and the not directly measureable $Z_{th(j-s)}$ (see formula below). To measure the $Z_{th(j-a)}$ the V_{CE}-(T) method is used. The established Semikron determination of $Z_{th(j-s)}$ consists in measuring the $R_{th(j-s)}$ and to create the transient curve using FEM simulation or an approximation as described in the last section of this analysis. By means of $R_{th(j-s)}$ and $Z_{th(j-a)}$ measurement results, a FEM simulation model can be validated and used afterwards for a $Z_{th(j-s)}$ simulation. The approximation method for evaluation of $Z_{th(j-s)}$ is based on the time response of the measured $Z_{th(j-a)}$ and adapts the curve of $Z_{th(j-a)}$ to fit the value of $R_{th(j-s)}$. Now the $Z_{th(s-a)}$ can be calculated by means of the measured $Z_{th(j-a)}$ for one or more cooling conditions and the simulated or calculated cooling-independent $Z_{th(j-s)}$ (see formula below).

$$Z_{th(s-a)}(V,G,T_a) = Z_{th(j-a)}(V,G,T_a) - Z_{th(j-s)}$$

3. Measurement and Calculation Results for Different Cooling Conditions

For this investigation a SKiiP1814GB17E4 (mounted on the fluid cooler NHC, figure 2) is measured for different cooling conditions. This product has been selected because it is a Semikron standard system including a fluid cooled heat sink. The device consists of three half bridges. Each half bridge consists of a Top and a Bot switch. Each switch is internally realized by a parallel connection of eight chips. For the test all six switches are connected in series to impress the same current in all switches. It is necessary to remove the original driver electronic. A load current source supplies a constant DC current to the series connection of all six switches. Only the voltage drop of the hottest switch will be measured, that means the measured T_j is the area related average temperature of eight parallel chip. The heat sink temperature is measured under all these eight chips of the hottest switch. For the $R_{th(j-s)}/Z_{th(j-s)}$ calculation, an average heat sink temperature T_s of the measured switch is used.

Figure 2: SKiiP1814GB17E4, fluid cooled (NHC)



The following table summarizes the different cooling conditions investigated by measurement.

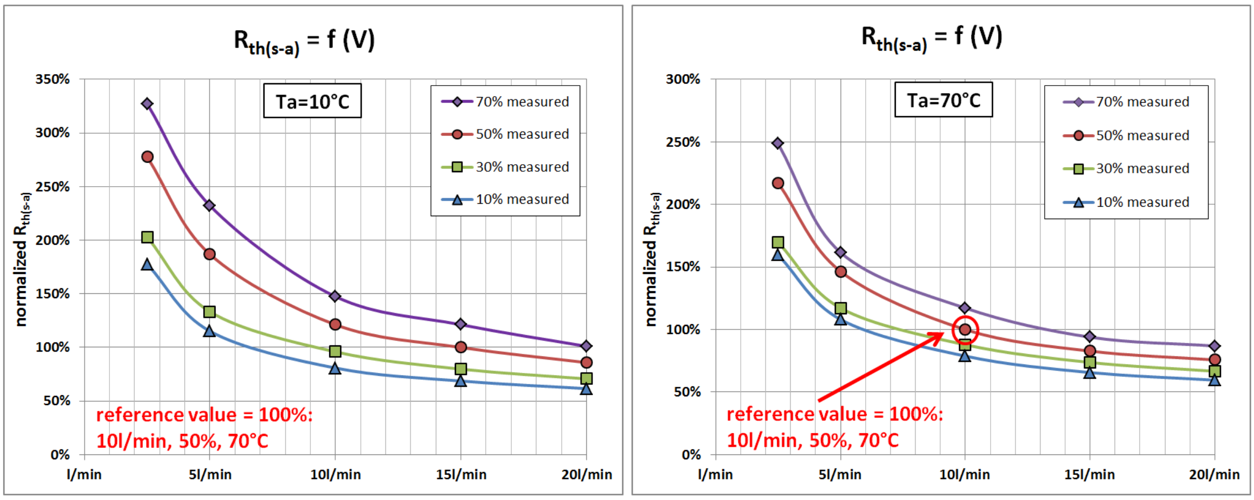
Table 1: Measured cooling conditions

Flow Rate V	Glycol Concentration G	Fluid Temperature T_a
2.5l/min	10%	10°C
5l/min	30%	70°C
10l/min	50%	
15l/min	70%	
20l/min		

3.1 $R_{th(s-a)}$ as a function of flow rate V

The flow rate is usually the simplest cooling parameter to increase, if a better thermal performance of the heat sink is needed. An increased flow rate leads to a higher velocity and possibly to an enlarged turbulent flow or a change from laminar to turbulent flow. The following figure shows the $R_{th(s-a)}$ as a function of the flow rate for different glycol concentrations and different fluid temperatures. The curve corresponds to a hyperbolic function, thus the greater the flow rate the lower and better the $R_{th(s-a)}$. For very high flow rates the improvement in thermal resistance becomes smaller and smaller as shown in Figure 3.

Figure 3: Normalized $R_{th(s-a)}$ as a function of flow rate

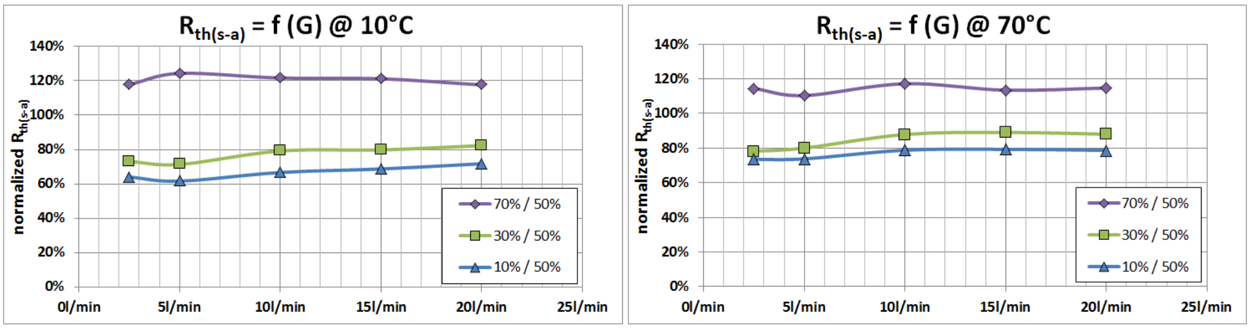


3.2 $R_{th(s-a)}$ as a function of glycol concentration G

First of all, it is not possible in most application to run the heat sink with pure water because of frost and corrosion risk. The optimal glycol concentration is depending on the application. To avoid corrosion, corresponding inhibitors are necessary, which are included in specific glycol products. The main cause of glycol concentration is the frost protection. For determining the glycol concentration the minimum temperature of the coolant liquid in the chiller is essential. The coolant liquid is heated up by the electronic components during operating time und must be cooled by the chiller. To keep the fluid temperature at the chiller's outlet (=inlet of the heat sink) constant, the liquid temperature in the chiller can be lower than the defined fluid temperature T_a. This must be considered when determining the glycol concentration. From a thermal point of view, a glycol content as small as possible leads to the best thermal performance of the heat sink because the glycol reduces the cooling capability of the liquid. The dynamic viscosity is higher for glycol than for water. The dynamic viscosity is inversely proportional to the Reynolds number, which is a characteristic parameter for turbulent flow (large Re number = large turbulence = large heat transfer

coefficient). Furthermore, the thermal conductivity, which is directly proportional to the heat transfer coefficient and also the specific heat capacity, which is directly proportional to the Prandtl number and therefore to the heat transfer coefficient, is worse for glycol than for water.
The following figure 4 shows the impact of different glycol concentrations on the $R_{th(s\text{-}a)}$ in relation to 50% glycol concentration. It can be seen that the impact of glycol concentration is almost constant and therefore independent of flow rate and fluid temperature.

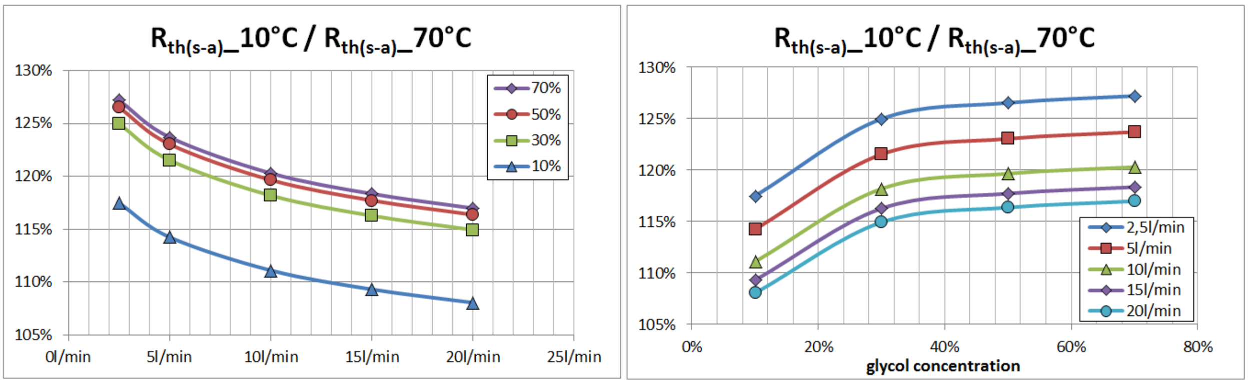
Figure 4: Normalized $R_{th(s\text{-}a)}$ as a function of glycol concentration



3.3 $R_{th(s\text{-}a)}$ as a function of fluid temperature T_a

The fluid temperature impact on the cooling and therefore on the $R_{th(s\text{-}a)}$ is explained by the temperature depending material properties of the fluid. The thermal conductivity of water increases for higher temperature, the thermal conductivity of glycol decreases for higher temperature (based on temperature range between 0°C and 100°C). A mixture of 40% glycol and 60% water has a nearly temperature independent thermal conductivity (0°C-100°C). The specific heat capacity for pure water is nearly constant, a 50% water/glycol mixture features an increasing specific heat capacity with increasing temperature, but stays always lower than the value of pure water. Another important material property for cooling is the dynamic viscosity. The dynamic viscosity is smaller for pure water than for glycol. Furthermore, the dynamic viscosity is dependent on temperature. For higher temperature the viscosity decreases, which leads to a higher Reynolds number, which is improving the heat transfer coefficient.
The following figure shows two charts. The $R_{th(s\text{-}a)}$-correlation is shown in the chart on the left side for different fluid temperatures (10°C/70°C) and flow rates. The ratio between a fluid temperature of 10°C and 70°C decreases with higher flow rate, thus the greater the flow rate, the lower the impact of the fluid temperatures. It means, that the $R_{th(s\text{-}a)}$-ratio between the fluid temperature of 10°C and 70°C is smaller for higher flow rates. The chart on the right side explains the relation between 10°C and 70°C fluid temperature and glycol concentration. By increasing the glycol concentration, the influence of $R_{th(s\text{-}a)}$ between the fluid temperature of 10°C and 70°C increases also.

Figure 5: Normalized $R_{th(s\text{-}a)}$ as a function of fluid temperature



4. Combination of all Impact Factors

The impact of the each individual cooling parameter on the $R_{th(s\text{-}a)}$ was described before. Now we will combine all influences in a general formula, that allows to estimate the thermal resistance $R_{th(s\text{-}a)}$ for a set of parameters in relation to a specified value for a different set of parameters.

4.1 Calculation of $R_{th(s\text{-}a)}$

As per description, the $R_{th(s\text{-}a)}$ is dependent on the flow rate, glycol concentration and fluid temperature. Furthermore, the flow rate is also dependent on the glycol concentration and the fluid temperature. On the other hand, the glycol concentration is constant related to the flow rate and the fluid temperature. Additionally, the fluid temperature is influenced by the flow rate and the glycol concentration. The following description summarizes the correlation of all impact factors:

Table 2: Impacts of V, G and T_a on $R_{th(s\text{-}a)}$

	Flow Rate V	Glycol Concentration G	Fluid Temperature T_a
V	/	++	++
G	0	/	0
Ta	+	++	/

In the "Application Manual Power Semiconductors" [2] from Semikron, the following formula was given to calculate the $R_{th(s\text{-}a)}$ for different flow rates:

$$R_{th(s\text{-}a)\_V2} = R_{th(s\text{-}a)\_V1} \cdot \left(\frac{V_1}{V_2}\right)^K \qquad ; K=0.3...0.5\ [2]$$

This is a simple approximation to estimate the $R_{th(s\text{-}a)}$ for different flow rates. The specified range of the coefficient K leads to a significant variation of R_{th} depending on the selected value (0.3…0.5). The target for this investigation is to improve this approximation to obtain a better estimation in relation to flow rate, and include the impact of glycol concentration and fluid temperature. The following figure (Fig.6) shows the normalized $R_{th(s\text{-}a)}$ in comparison to the measured and calculated values using the Semikron Application Manual formula (see formula above, K=0.4). The measurement values of 10l/min for each glycol concentration and each fluid temperature are used as reference flow rate. The comparison shows that the calculated curves for different flow rates do not always fit the measured points, especially for small flow rates. Furthermore, the impact of different glycol concentrations or fluid temperatures is not included. In Figure 7 the calculated values based on the new formula presented here related to flow rate, glycol concentration and also fluid temperature in comparison with the measured values are shown. By means of this new formula, only one measured value (10l/min, 50%, 70°C) is needed to produce all the diagramed curves.

Figure 6: Normalized $R_{th(s-a)}$ = f(V); measurement vs. calculation (old formula, K=0.4)

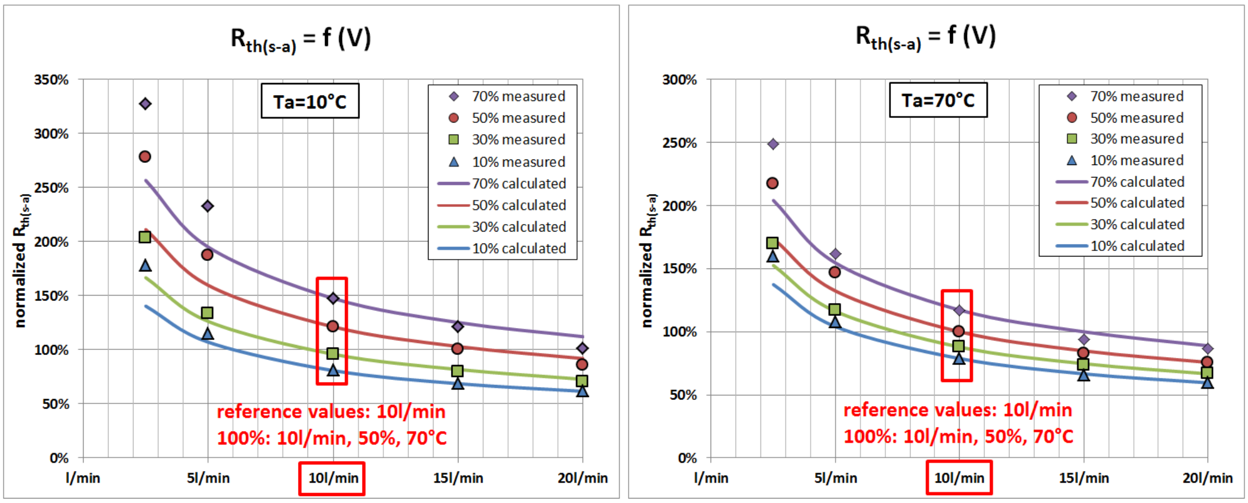
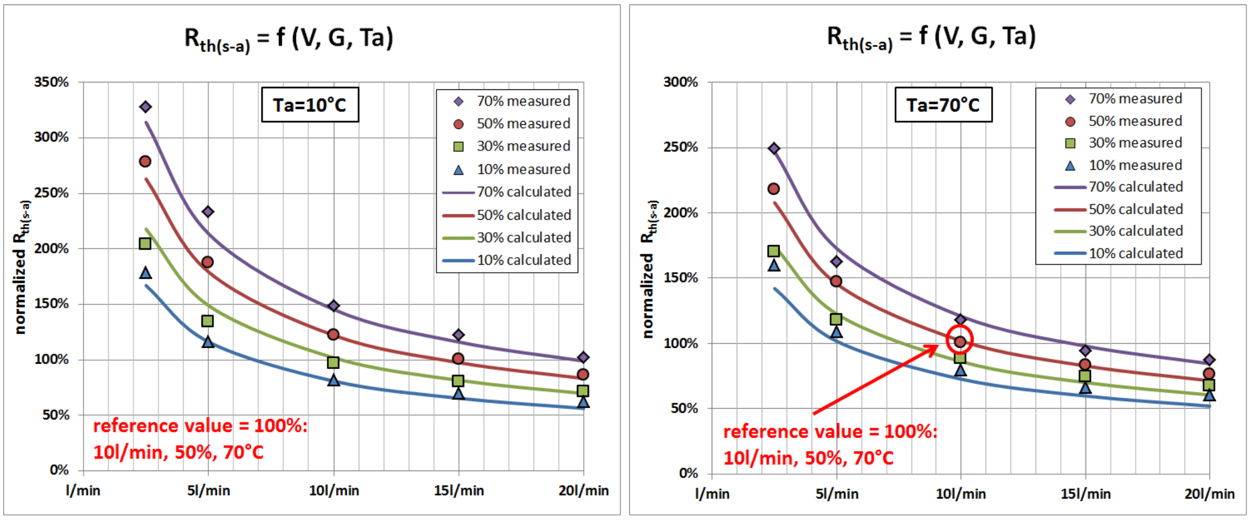


Figure 7: Normalized $R_{th(s-a)}$ = f(V, G, T_a); measurement vs. calculation (new formula)



The new formula related to flow rate, glycol concentration and fluid temperature to calculate $R_{th(s-a)}$ for different cooling conditions is presented below. The scope of this formula is limited as follows:

Table 3: Limitation of the new formula

Flow Rate V	Glycol Concentration G	Fluid Temperature T_a
2l/min … 30l/min	10% … 90%	10°C … 90°C

$$R_{th(s-a)}(V,\,G,\,T_a)=SF\cdot R_{th(s-a)}(V_{ref},\,G_{ref},\,T_{a_{ref}})\cdot\left(\frac{V_{ref}}{V}\right)^{Exp_{(V)}}\cdot 0.92^{\frac{G_{ref}[\%]-G[\%]}{10\%}}\cdot\left(\frac{T_{a_{ref}}}{T_a}\right)^{Exp_{(T)}}$$

SF=1…1.1 (safety factor)

$$Exp_{(V)}=0.51+0.0085\cdot\left(1-\frac{G_{ref}[\%]}{G[\%]}\right)-0.0067\cdot\left(1-\frac{T_{a_{ref}}}{T_a}\right)$$

$$Exp_{(T)}=0.092+0.0085\cdot\left(1-\frac{G_{ref}[\%]}{G[\%]}\right)$$

The safety factor SF (first factor of the formula) is introduced to account for a safety margin. If the referenced point $R_{th(s-a)}$ is far away from the required operating point, a safety factor of 1.1 improves the approximation. The $R_{th(s-a)}(V_{ref},G_{ref},T_{a\_ref})$ (second part of the formula) is the measured reference value of the Semikron data sheet. The third factor of the formula describes the impact of the flow rate. This element of the formula can be compared with the old formula of the Semikron Application Manual. The exponent is not a constant value of 0.3…0.5 anymore, but a function of glycol concentration and fluid temperature. The fourth factor of the formula shows the glycol concentration impact. The last element of the formula describes the fluid temperature influence on the $R_{th(s-a)}$. The exponent of this factor is a function of the glycol concentration. The influence of the flow rate is negligible in the temperature exponent.
In case that one cooling parameter (V, G, T_a) is not changed with respect to the reference point, the corresponding part of the formula has no influence on the calculated $R_{th(s-a)}$.

4.2 Calculation of $Z_{th(s-a)}$

The thermal transient behavior is usually described by a Foster model in Semikron data sheets (detailed explanation can be found in the "Application Manual Power Semiconductors" from Semikron [2]). The Foster model is a mathematical approach and can be calculated as follows:

$$Z_{th(x\text{-}y)}=R_{th_1}\cdot\left(1\text{-}e^{\frac{-t}{\tau_{th1}}}\right)+R_{th_2}\cdot\left(1\text{-}e^{\frac{-t}{\tau_{th2}}}\right)+\ldots=\sum_{i=1}^{n}R_{th_i}\cdot\left(1\text{-}e^{\frac{-t}{\tau_{thi}}}\right)$$

τ_{th} = time constant [s]

n = number of R_{th}/τ_{th} pairs

In Semikron data sheets the $Z_{th(s-a)}$ is defined as several pairs of R_{thi} and τ_{thi} for one specific cooling condition. These are the reference values $R_{th\_ref\_i}$ and $\tau_{th\_ref\_i}$ for the following calculation. It is necessary to change the values of both parameters, R_{thi} and τ_{thi}, to determine the $Z_{th(s-a)}$ for different cooling conditions. A modification of cooling parameters leads to a change of the stationary value of the thermal impedance ($R_{th(s-a)}$), but also to a change of the time response.
The following formulas explain the calculation of the $Z_{th(s-a)}$ parameters R_{thi} and τ_{thi} for different cooling conditions.
The $R_{th\_ref\_i}$ and $\tau_{th\_ref\_i}$ pairs must be sorted for increasing time constants ($\tau_{th\_ref\_i} < \tau_{th\_ref\_(i+1)}$, i=1…n).

$$R_{th(s-a)}(V,\,G,\,T_a)=SF\cdot R_{th(s-a)}(V_{ref},\,G_{ref},\,T_{a_{ref}})\cdot\left(\frac{V_{ref}}{V}\right)^{Exp_{(V)}}\cdot 0.92^{\frac{G_{ref}[\%]-G[\%]}{10\%}}\cdot\left(\frac{T_{a_{ref}}}{T_a}\right)^{Exp_{(T)}}\quad\text{(see chapter 4.1)}$$

$$R_{th_1}=R_{th_{ref\_1}}\qquad ;\ \text{if}\ \ R_{th_{ref\_1}}\cdot\frac{R_{th(s-a)}}{R_{th(s-a)_{ref}}}<0.5\cdot R_{th(s-a)}$$

$$R_{th_i}=R_{th_{ref\_i}}\qquad ;\ \text{if}\ \ \sum_{1}^{i}R_{th_i}=\sum_{1}^{i}R_{th_{ref\_i}}\cdot\frac{R_{th(s-a)}-\sum_1^{i-1}R_{th_i}}{R_{th(s-a)_{ref}}-\sum_1^{i-1}R_{th_{ref\_i}}}<0.5\cdot R_{th(s-a)}\quad ;\ i>1$$

$$R_{th_1}=R_{th_{ref\_1}}\cdot\frac{R_{th(s-a)}}{R_{th(s-a)_{ref}}}\qquad ;\ R_{th_1}\neq R_{th_{ref\_1}}$$

$$R_{th_i}=R_{th_{ref\_i}}\cdot\frac{R_{th(s-a)}-\sum_1^{i-1}R_{th_i}}{R_{th(s-a)_{ref}}-\sum_1^{i-1}R_{th_{ref\_i}}}\qquad ;\ R_{th_i}\neq R_{th_{ref\_i}}\quad ;\ i>1$$

$$R_{th(s-a)}=\sum_{i=1}^{n}R_{th_i}$$

The change of the R_{thi} parameters depends on the weighting of the single pairs. Only when the half of the $R_{th(s-a)}$ value is achieved, the individual pairs are adapted to the new $R_{th(s-a)}$. The τ_{thi} values will accordingly adjusted, if the R_{thi} values are changed.

$$\tau_{th_i} = \tau_{th_{ref\_i}} \quad ; \text{ if } R_{th_i} = R_{th_{ref\_i}}$$

$$\tau_{th_i} = \tau_{th_{ref\_i}} \cdot \left(\frac{V_{ref}}{V}\right)^{0.7} \cdot 0.92^{\frac{G_{ref}[\%]-G[\%]}{10\%}} \cdot \left(\frac{T_{a_{ref}}}{T_a}\right)^{0.2} \quad ; \text{ if } R_{th_i} \neq R_{th_{ref\_i}}$$

5. Calculation Example

To illustrate the application of the presented formulas, an example is given below. As reference point, the data sheet values of SKiiP1814GB17E4-3DUW (Rev.0 – 31.10.2013) are selected.
The following tables show the data sheet values of $R_{th(s-a)}$ and $Z_{th(s-a)}$ and also the parameters of the referenced and the required cooling condition.

Table 4: Referenced and required parameters of cooling condition and $R_{th(s-a)}$

	V	G	T_a	$R_{th(s-a)}$
referenced	15l/min	50%	40°C	0.0087K/W
required	5l/min	30%	70°C	?

Table 5: $Z_{th(s-a)}$: data sheet values of referenced cooling condition (Foster elements)

i*	$R_{th\_ref\_i}$	$\tau_{th\_ref\_i}$
1	0.0065K/W	5.27s
2	0.0022K/W	17.9s

* $\tau_{th_{ref\_i}} < \tau_{th_{ref\_(i+1)}}$

It must be noted, that the data sheet values of $R_{th\_ref\_i}$ and $\tau_{th\_ref\_i}$ related to i are often sorted differently.

5.1 Calculation of $R_{th(s-a)}$

Definition: SF=1

$$R_{th(s-a)}(5l/min,\ 30\%,\ 70°C) = 1 \cdot 0.0087K/W \cdot \left(\frac{15l/min}{5l/min}\right)^{0.501} \cdot 0.92^{\frac{50\%-30\%}{10\%}} \cdot \left(\frac{40°C}{70°C}\right)^{0.086} = 0.0122K/W$$

$$Exp_{(V)} = 0.51 + 0.0085 \cdot \left(1 - \frac{50\%}{30\%}\right) - 0.0067 \cdot \left(1 - \frac{40°C}{70°C}\right) = 0.501$$

$$Exp_{(T)} = 0.092 + 0.0085 \cdot \left(1 - \frac{50\%}{30\%}\right) = 0.086$$

5.2 Calculation of $Z_{th(s-a)}$

$$R_{th_1} = 0.0065K/W \cdot \frac{0.0122K/W}{0.0087K/W} = 0.00911K/W \qquad (> 0.5 \cdot 0.0122K/W = 0.0061K/W)$$

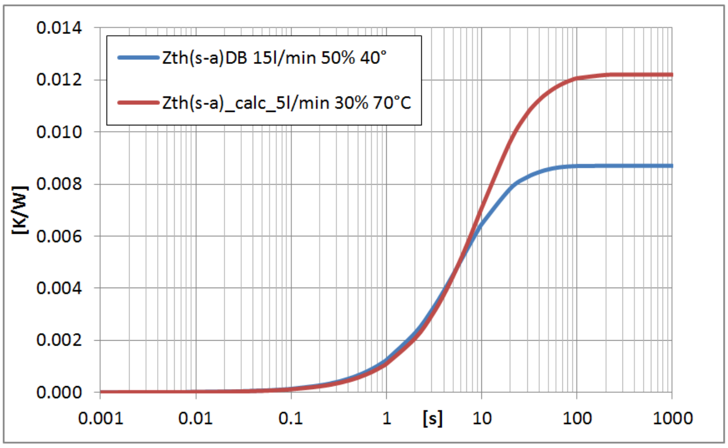
$$R_{th_2} = 0.0022K/W \cdot \frac{0.0122K/W - 0.00911K/W}{0.0087K/W - 0.0065K/W} = 0.0031K/W$$

$$\tau_{th_1} = 5.27s \cdot \left(\frac{15l/min}{5l/min}\right)^{0.7} \cdot 0.92^{\frac{50\%-30\%}{10\%}} \cdot \left(\frac{40°C}{70°C}\right)^{0.2} = 8.6$$

$$\tau_{th_2} = 17.9s \cdot \left(\frac{15l/min}{5l/min}\right)^{0.7} \cdot 0.92^{\frac{50\%-30\%}{10\%}} \cdot \left(\frac{40°C}{70°C}\right)^{0.2} = 32$$

Table 6: Calculation example: $Z_{th(s-a)}$ of required cooling condition		
i	R_{thi}	τ_{thi}
1	0.0091K/W	8.6s
2	0.0031K/W	32s

Figure 8: Zth(s-a): referenced and calculated



6. Conclusion

The presented formulas for the estimation of $R_{th(s-a)}$ and $Z_{th(s-a)}$ allow to calculate the impact of different cooling parameters (flow rate, glycol concentration and fluid temperature) with reference to a specified cooling condition. It will be implemented in the Semikron simulation tool Semisel to reflect the different cooling conditions, which is not possible with the current version. A validation of this approximation for different fluid cooled heat sink designs is planned for the future.
It should be emphasized, that the presented formula is an approximation to estimate the impact of different cooling conditions on the stationary and transient thermal characteristics of the cooling system. It allows to estimate the cooling capability of a system in the design phase, i.e. before a prototype is available for measurement. However, it is mandatory to validate these estimations by thermal measurements on the first available hardware systems.

Symbols and Terms

Letter Symbol	Term
DBC	Direct bonded copper (ceramic substrate)
G	Glycol concentration [%]
NHC	Semikron standard heat sink profile for liquid cooling
$R_{th(x-y)}$	Thermal resistance between reference points x and y [K/W]
R_{th_i}	Partial thermal resistance of Foster network pair i [K/W]
SF	Safety factor
τ	Time constant [s]
T_a	Ambient temperature = fluid temperature [°C]
T_j	Virtual junction temperature [°C]
T_s	Heat sink temperature [°C]
τ_{th_i}	Time constant of Foster network pair i [s]
V	Flow rate [l/min]
V_{CE}	Collector-Emitter-Forward voltage, exemplary used here for the forward voltage of a semiconductor with pn-junction
V_{GE}	Gate-Emitter Voltage
$Z_{th(x-y)}$	Thermal impedance between reference points x and y [K/W]

A detailed explanation of the terms and symbols can be found in the "Application Manual Power Semiconductors" [2]

References

[1] www.SEMIKRON.com

[2] A. Wintrich, U. Nicolai, W. Tursky, T. Reimann, "Application Manual Power Semiconductors", ISLE Verlag 2011, ISBN 978-3-938843-666

[3] A. Wintrich: "AN1404: Thermal resistance of IGBT Modules – specification and modelling", www.SEMIKRON.com

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SEMIKRON INTERNATIONAL GmbH
P.O. Box 820251 • 90253 Nuremberg • Germany
Tel: +49 911-65 59-234 • Fax: +49 911-65 59-262
sales.skd@semikron.com • www.semikron.com