Thermal Simulation Models

ZVEI - German Electrical and Electronic Manufacturers' Association

ZVEI:

Die Elektroindustrie

Contents

1. Introduction

1.1 Background

The heat generation and derating curves specified by manufacturers in cylindrical cable and contact system data sheets are still frequently used in modern wiring harness design. This is why the 3D data required for an FEM or CFD simulation is not yet available in the concept phase. And even in subsequent development phases, the effort required to simulate the thermal system of an automotive wiring harness using the above methods is usually disproportionately high.

The standard characteristic curves in data sheets are only valid for the steady state and it is not possible to adequately assess how the wiring conducts heat using data sheets. Consequently, optimisation potential resulting from the thermal inertia of the wiring harness and heat reduction effects due to axial thermal conduction often remains untapped.

HV wiring harnesses are especially ideal for thermal simulation, because
- they have a simple structure and usually consist of point-to-point connections between individual cables,
- even changing the nominal cross-section by just one step can have a significant impact on costs, weight and installation space,
- it is easy to calculate electric currents in the wiring, because they are only defined by one or very few parameters.

When designing a wiring harness, an inaccuracy of the simulation in the order of a few Kelvin (K) is perfectly acceptable. This is why it is unnecessary to use highly complex and thus time-consuming FEM models. Taking the rotational symmetry into account makes it possible to simplify simulation models even further.

The "thermal networks" simulation method, on which all other representations are based, has proven itself as extremely efficient and surprisingly precise for HV wiring harnesses. Simulation times for the dynamic behaviour of a wiring harness are typically less than one minute. Reference measurements prove the accuracy in the range of measurement tolerance.

1.2 Guideline objective

Thermal networks may have relatively simple structures, but developing them and outlining their parameters is far from trivial. So it should come as no surprise that thermal networks for wires and connectors should be developed and used collaboratively.

There are many different simulation tools for thermal networks, which are usually subfunctions of larger program packages. The decision for such a development environment is usually made as part of a longer-term approach, so it would neither be possible nor sensible to agree on a single development tool for the joint development of thermal networks.

Unfortunately, no standard format exists for the tool-independent exchange of thermal networks. Nevertheless, the parties compiling this guideline had the overarching objective of making it possible to share models across different organisations. To this end, modules – i.e. generic submodels – required for modelling connectors and wires were compiled and their parameter sets defined in this guideline.

Now it is sufficient for development partners to reference the respective modules provided in this guideline and specify the associated parameter sets in order to exchange thermal models. Each development partner can store the modules they use in a library in their preferred tool.

This guideline not only includes a catalogue of simulation modules along with their "compact" parameters; it also features instructions on how to determine these compact parameters from the "basic parameters", i.e. the physical properties of the materials and components used.

To determine the parameters for connector models, measurements or simulations are required. This guideline also provides instructions on these measurements, thereby ensuring that the thermal simulations based on the models in this guideline lead to comparable results.

1.3 Scope

1.3.1 Application scenarios
The models created using this guideline can be employed to correctly design an HV wiring harness for the respective field of work.

This simulation model is valid within the ambient temperature range (-40 °C to 125 °C) customary in the automotive industry and up to the limiting temperature of the materials used (up to 180 °C).

When designing this guideline, bulk goods and connector manufacturers defined the basic structure and the compact parameters of the components in such a way that the data provided to the user would be sufficiently accurate within the defined temperature ranges and for standard operating current curves.

Irreversible processes, such as relaxation or corrosion due to impermissible excess temperatures and short circuit effects such as levitation or arc formation are not mapped by the models and must be considered separately.

In the case of two-pin HV connectors, the same amount of current flows through both contacts. In the models, the same resistance is assumed for both contacts. Since both contacts thus exhibit the same thermal behaviour and no heat flows between the contacts, the thermal path between the contacts was not modelled.

Contact ageing was considered using different contact resistances for new and aged parts.

Both highly simplified models that are easy to parameterise and more detailed, precise models are available to calculate convection on the surface of cables and connectors. However, details of these models are beyond the scope of this document.

1.3.2 Accuracy
The models are mainly used to design wiring harnesses as is done during the concept phase of automotive development. In this phase, CAD data is generally not yet available and ambient temperatures can only be estimated.

The accuracy of the available models is much higher than necessary given the inaccuracy that inevitably results from the unclear framework conditions.

Simulation accuracy within the measurement tolerance can be achieved when the models are used in subsequent development phases. The design premise for these models was a simulation error of just a few Kelvin.

The thermal networks method allows the wiring harness models to be supplemented with application-specific elements, which go beyond the scope of this guideline.

2 Common denominators

2.1 Description of the equivalent circuit diagram

2.1.1 Colour-coding

Since at least two different physical sub-areas are generally implemented in a thermal equivalent circuit diagram, it is advisable to introduce a colour distinction between the physical domains:

Table 1: Domains of the equivalent circuit diagram

Physical domain	Colourcoding	Example
Electrodynamics	Blue	Power source:
Thermodynamics	Red	Convection:

2.2 General symbols

It is also often necessary to use non-physical, purely mathematical constructs, for example, to use a data output (e.g. temperature pick-up) or to transfer constants, such as defining the ambient temperature or setting the amperage. These mathematical values are featured in black in the equivalent circuit diagram.

Table 2: Constants

Name	Symbol	Interfaces
Constant	C	Output

2.2.1 Orientation of the equivalent circuit diagram

Circuit diagrams are read from left to right along the main current paths (electrical and thermal load paths) on which the primary transport mechanisms take place. The heat transfer paths for heat exchange with the environment are drawn vertically to the load paths in the equivalent circuit diagram.

2.2.1.1 Horizontal alignment

The electrical load path reflects the current flow along the conductors; the primary heat transfer path reflects the temperature flow along the conductors. Both mechanisms can interact with each other (e.g. via joule heating). Secondary heat transfer involves the orthogonal transfer of heat from one conductor to another conductor, to plastic components or to the environment and is drawn vertically.

Figure 1: Heat transfer path

Source: ZVEI

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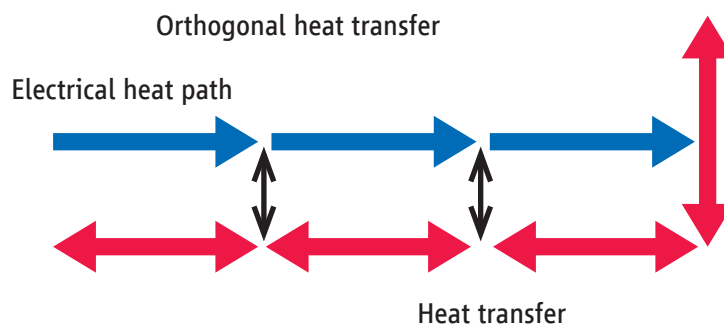
2.2.1.2 Arrangement in the equivalent circuit diagram

Details regarding the general arrangement should also be defined alongside the read/write direction for primary heat transfer along the load path.

Figure 2: Arrangement of heat transfer
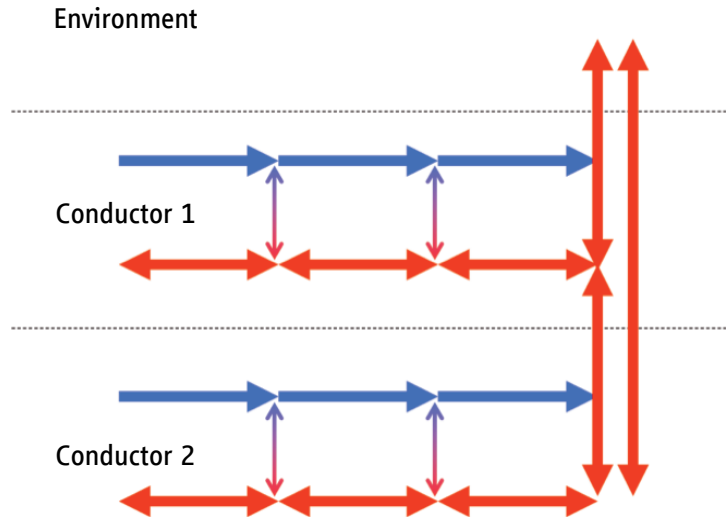
Source: ZVEI

In general, the vertical thermal paths that interact with the environment (e.g. convection, radiation and thermal conduction to other components) should be arranged in the upper part of the equivalent circuit diagram. The equivalent circuit diagram components for the load paths should be mapped below the environmental conditions and spatially separated.

2.2.1.3 Geometric interpretation and representation in the equivalent circuit diagram

In order to map thermal properties of complex components in the simulation, it is necessary and expedient to simplify them first. One such simplification is the return to simple geometric shapes.

Figure 3: Simplification of components

Inner conductor, wire bundle, contact pin → cylinder

Source: Gebauer & Griller
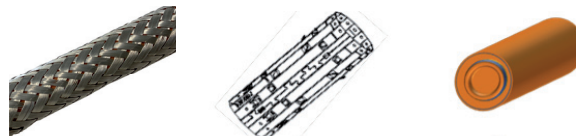
Shield widing, insulation, screen grid → hollow cylinder

Source: ZVEI
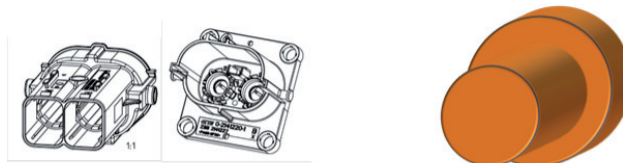
Pin header & connector housing → cylinder

Source: TE

To correctly map the heat transfer mechanisms in the equivalent circuit diagram, it is important to consider the connection of sources and sinks. There are two approaches that are identical, but have an impact on the connection of sources and sinks:

The first approach is based on a T or Y structure, the second on an arrangement of the components in a Pi-shaped structure:

Figure 4: Arrangement of components in a T and Y structure
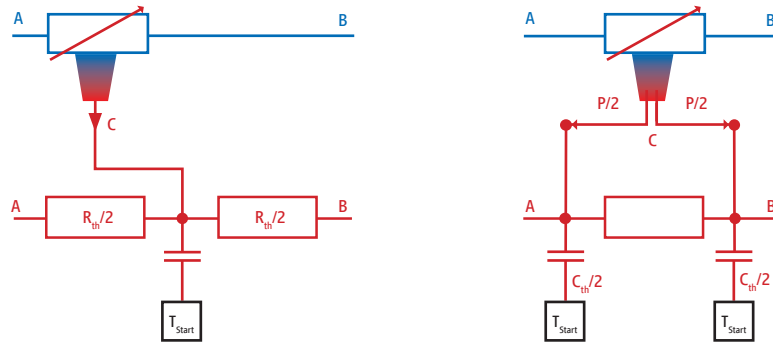
Source: ZVEI

The equivalent circuit shown here is a representation of an electrical conductor without external heat dissipation. This means that the only heat transfer paths can be found along the conductor. Since it is necessary and practical to also consider radial thermal conduction for many components, it is advisable to rely on the model in the Y structure. It can be extended as follows:

Figure 5: Arrangement of components in a Y structure

Model with vertical thermal path

Model with two vertical thermal paths, e.g. conductor and braided shield
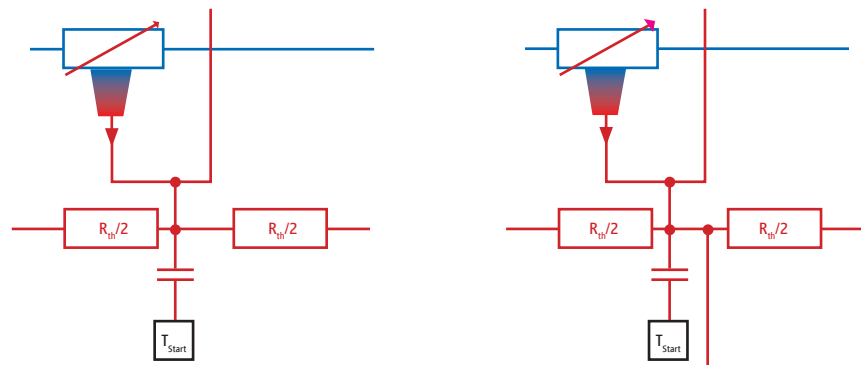
Source: ZVEI

In the equivalent circuit diagram on the left, the outward radial thermal conduction is taken into account, for example from a conductor to an insulation source. The equivalent circuit diagram on the right is an extension that now also considers "downward" thermal conduction. For instance, this equivalent circuit diagram represents a shield that interacts with the conductor via internal insulation and with the environment via external insulation (sheath).

Put in more general terms, the right equivalent circuit diagram can be used for every component, whereby the vertical thermal paths might not be connected, depending on the application.

Since several such modules are interconnected in the thermal equivalent circuit diagram, the individual components can also be combined (e.g. series connection of resistors) to simplify the complete equivalent circuit. For visualisation purposes, it is advisable to map a uniform circuit layout in blocks, which can then be combined in a clearly arranged block diagram. The corresponding parameters for the individual components and the starting conditions must be transferred accordingly.

The Y structure is shown as follows:

Figure 6: Block diagram of the Y structure
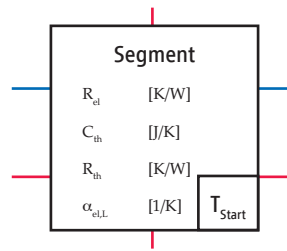
Source: ZVEI

The horizontal inputs and outputs mirror the electrical and thermal path of the current and thermal conduction from and to the next segment. The vertical outlets are connections to thermal elements located further inside and outside (e.g. insulation and housing elements).

2.3 Electrical components

This section describes the electrical components of the equivalent circuit diagram.

2.3.1 Joule heat source

The equivalent circuit diagram features an interface between thermodynamics and electrodynamics in the form of joule heating. Electric current is converted into heat output at this heat source.

The corresponding element in the thermal equivalent circuit diagram thus has three interfaces. Interfaces A and B are interfaces in the electrodynamic domain. They correspond to the inputs and outputs for the electrical current. Interface C is in the thermodynamic domain and impresses a heat flow into the equivalent circuit diagram.

Table 3: Equivalent circuit diagram for joule heating

Name	Symbol	Interfaces
Joule heating		A: Current input B: Current output C: Heat flow/ power output

2.3.1.1 Mathematical description

Joule heating can be described using formula (1)

$$\dot{Q} = I^2 \cdot R_{\text{el}} \text{ oder } P = I^2 \cdot R_{\text{el}} \qquad (1)$$

where $\dot{Q}$ or P describes the heat flow or the electrical power loss and I the electrical current. The parameter R represents the electrical resistance and depends on various factors such as the dimensions, material and temperature of the solid. The inclusion of the resistor's temperature dependence is first approximated using the linear temperature coefficient α_{el}.

$$R_{\text{el}}(T) = R_{\text{el},0} \cdot \left(1 + \alpha_{\text{el}} \cdot (T - T_0)\right) \quad (2)$$

In equation (2), $R_{el,0}$ indicates the electrical resistance at the reference temperature $T = T_0$. This temperature is usually $T_0 = 20\,°C$, but temperatures of $T_0 = 0\,°C$ or $T_0 = 25\,°C$ can also be used. When no other data have been specified, the reference temperature of $T_0 = 20\,°C$ applies.

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The component supplies the heat flow in the unit Watt [W].

2.4   Thermal components

This section describes the thermal components of the equivalent circuit diagram.

2.4.1   Thermal resistance

The thermal resistance of a solid body is defined as being reciprocal to the thermal conductivity and indicates the temperature difference that arises at the body when a heat flow is impressed. Thermal resistance has two interfaces in the thermal equivalent circuit diagram: the thermal inputs and outputs.

Table 4: Equivalent circuit diagram for thermal resistance

Name	Symbol	Interfaces
Thermal conductive resistance		A: Thermal port B: Thermal port

2.4.1.1   Mathematical description

The heat flow $\dot{Q}$, coupled via the interfaces in the thermal network with the power P, is the quotient of the temperature difference ΔT and the thermal resistance R_{th}, cf. formula (3).

$$\dot{Q} = P = \Delta T / R_{th} \qquad (3)$$

The thermal conductive resistance R_{th} can depend on the temperature, comparable to the electrical resistance, and a linear thermal coefficient $\alpha_{R_{th}}$ can be taken into account in the calculation.

$$R_{th}(T) = R_{th,0} \cdot \left(1 + \alpha_{Rth} \cdot (T - T_0)\right) \quad (4)$$

In equation (4), $R_{th,0}$ indicates the thermal conductive resistance at the reference temperature $T = T_0$ (typically 20 °C). To calculate $R_{th}(T)$ in the volume of the body using formula (4), the average of the temperatures at interfaces A and B is used for T for simplification purposes:

$$T = (T_A + T_B)/2 \qquad (5)$$

For some representations, it is advantageous to use the conductance Y_{th} instead of the resistance in the calculation. In these cases, the following relationship applies:

$$R_{th} = \frac{1}{Y_{th}} \qquad (6)$$

2.4.1.2   Physical unit

The conductive resistance of the component is described using the unit Kelvin/Watt [K/W]. The conductance is thus indicated using the unit Watt/Kelvin [W/K].

2.4.2   Thermal mass/thermal capacity

The thermal mass or thermal capacity reflects the amount of heat that a body can absorb when the temperature changes. Thus, the thermal capacity – analogous to its electrical counterpart – is responsible for representing chronological system behaviour. In physical terms, thermal capacity reflects the volume of the body along with its material properties. Consequently, a thermal interface represents the input from which the inflow or outflow of heat takes place, while the other interface is linked to the temperature at the start of the measurement – this will be the ambient temperature if the simulation begins in equilibrium.

Table 5: Equivalent circuit diagram for thermal capacity

Name	Symbol	Interfaces
Thermal capacity		A: Thermal port The second port is connected to the initial condition, never to any other components!

2.4.2.1 Mathematical description

The heat flow $\dot{Q}$, coupled via the interfaces in the thermal network with the power P, is the product of the thermal capacity C_{th} and the chronological change in temperature $\frac{dT}{dt}$, cf. formula (7).

$$\dot{Q} = P = C_{th} \cdot \frac{dT}{dt} \qquad (7)$$

The thermal capacity is derived from the mass of the body m and the specific heat capacity c of the material. The volume V and the specific density ρ can be used as an alternative to mass.

$$C_{th} = m \cdot c \Leftrightarrow C_{th} = V \cdot \rho \cdot c \qquad (8)$$

It is also possible to define a linear temperature coefficient α_{Cth} for thermal capacities, analogous to the linear temperature coefficient for electrical and thermal resistance.
Taking this coefficient into account, the following applies to the capacity:

$$C_{th}(T) = C_{th,0=T_0} \cdot \left(1 + \alpha_{Cth} \cdot (T - T_0)\right) \qquad (9)$$

2.4.2.2 Physical unit

The capacity of the component is described using the unit Joule/Kelvin [J/K] or Watt second/Kelvin [Ws/K].

2.4.3 Convection resistance

Convection is the transfer of heat from a solid body to a fluid medium and is affected by many medium-related factors. For the body, on whose surface thermal convection takes place, the surface and, in extreme cases, geometric factors are involved that influence the flow and can cause vortexing and turbulence, for instance. Therefore, the convection resistance reciprocally describes the size of the transfer of heat via convection.

Table 6: Equivalent circuit diagram for convection resistance

Name	Symbol	Interfaces
Convection resistance		A: Thermal port B: Thermal port

2.4.3.1 Mathematical description

The heat flow that is exchanged via the interfaces can be described by the temperature difference $\Delta T = T_A - T_B$, where T_A and T_B reflect the temperatures of the partners involved in the exchange of heat.

$$\dot{Q} = P = \alpha_{Conv} \cdot A \cdot \Delta T \qquad (10)$$

Here A represents the surface of the body for heat exchange and α_{Conv} the heat transfer coefficient.

The convection conductance $Y_{th,Conv}$ is defined as follows:

$$Y_{th,Conv} = \alpha_{Conv} \cdot A \qquad (11)$$

Parameters such as fluid thermal conductivity, characteristic length, flow velocity, density, viscosity and specific heat capacity must be used to calculate the heat transfer coefficient. Its value is dependent on the temperature due to the different influencing variables. Specifying a table of plausible values or just using the values from the VDI Heat Atlas is recommended.

Convection resistance $R_{th,Conv}$ is the reciprocal of convection conductance $Y_{th,Conv}$.

$$R_{th,Conv} = \frac{1}{Y_{th,Conv}} \qquad (12)$$

$$\dot{Q} = P = \frac{\Delta T}{R_{th,Conv}} \qquad (13)$$

2.4.3.2 Physical unit
The thermal convection resistance $R_{th,Conv}$ is specified using the unit Kelvin/Watt [K/W].

2.4.4 Radiation resistance
Heat radiation describes the heat exchange between two bodies or the heat transfer from one body to an environment. In this case, the environment can be seen as a body with the temperature T_B.

Table 7: Equivalent circuit diagram of the radiation resistance

Name	Symbol	Interfaces
Radiation resistance		A: Thermal port
		B: Thermal port

2.4.4.1 Mathematical description
The heat flow that is exchanged via the interfaces can be described using Stefan Boltzmann's Law of Radiation on the temperature difference between a surface and its environment, where T_A and T_B reflect the temperatures of the entities involved in the exchange of heat. For heat that radiates to the surrounding environment, T_A is equal to the surface and T_B is equal to the ambient temperature.

$$\dot{Q} = P = \varepsilon \cdot \sigma \cdot A \cdot \left(T_A{}^4 - T_B{}^4\right) \qquad (14)$$

In this context the parameter ε indicates the emissivity of the radiating solid and A its surface. σ is the Stefan Boltzmann constant.

$$\sigma = 5{,}67 \cdot 10^{-8} \frac{W}{m^2 \cdot K^4} \qquad (15)$$

The emissivity ε is a dimensionless number between 0 (perfect whitebody) and 1 (perfect blackbody). The following formula defines the heat transfer coefficient for radiation α_{Rad}.

$$\alpha_{Rad} = \varepsilon \cdot \sigma \cdot \frac{T_A{}^4 - T_B{}^4}{T_A - T_B} = \varepsilon \cdot \sigma \cdot (T_A + T_B) \cdot (T_A^2 + T_B^2) \qquad (16)$$

If, using α_{Rad}, the transferred power refers to the temperature difference, the result is the formula for the thermal radiation conductance.

$$Y_{th,Rad} = \frac{P}{T_A - T_B} = \alpha_{Rad} \cdot A \qquad (17)$$

2.4.4.2 Physical unit of radiation conductance
The radiation conductance is indicated using the unit Watt/Kelvin [W/K].

2.4.4.3 Sample values for emissivity ε
Emissivity values to be taken into account vary greatly depending on the substrate and temperature dependencies (see Reference list [1], [2]):

Table 8: Sample values for the emission coefficients of various relevant materials

Material	Emissivity ε		Note
	For T = 293 to 300 K	For T= 600 K	
Aluminium (polished)	0.04	0.05	(h)
Aluminium (anodised)	0.82		(h)
Copper (polished)	0.03	0.04	(h)
Silver (polished)	0.02	0.03	(h)
Black paint	0.98		(h)
Rubber	0.92		(n)

The letters listed in the Note column indicate the type of emission coefficient – here a distinction is made between the total radiation (hemispherical = h) and the radiation normal to the surface (normal = n).

2.4.4.4 Physical unit of radiation resistance
The radiation resistance is specified using the unit Kelvin/Watt [K/W].

2.5 Information on the cable slices

The parameters of the cable slices describe a cable section with a unit length of $L_c = 1$ m at a temperature of 20 °C. The temperature coefficients for resistances, thermal and electrical conductivity as well as the specific heat capacity also refer to the base values at 20 °C.

Simulating the temperature drop of a component cable requires simulating multiple cable slices arranged in series in lengths smaller than one metre.

It is simplified as followed: Only heat flows in metallic structural components (conductors, shields) in the axial direction are considered between the individual cable slices; heat flows in the axial direction in the insulation and sheath are not considered.

The thermal resistances of multiple cable slices in the axial direction $R_{th,ax}$ are arranged in series and are therefore added together. The thermal resistances of multiple cable slices in the radial direction $R_{th,rd}$ are arranged in parallel. Thus, the thermal resistances are not added together; their thermal conductances $Y_{th,rd}$ are added together instead.

Radiation and convection are also radial thermal resistances, which must therefore also be treated as thermal conductances.
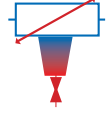
When converting length-based cable parameters from one metre to the actual length required for the simulation, it is important to consider whether the parameter is an axial (series circuit), radial (parallel circuit) or a non-directional unit (thermal capacitance, temperature coefficient).

Figure 7: Cable components

Source: Coroplast

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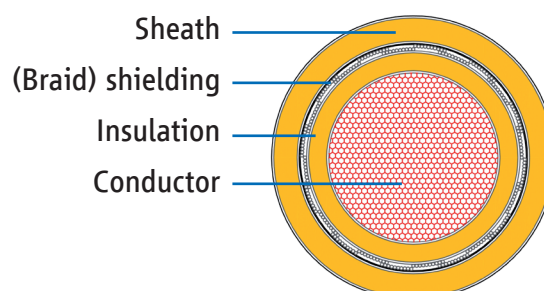
Table 9: Converting cable parameters to cable slices

Description	Formula symbol	Phys. unit	Symbol	Conversion
Thermal resistance in axial direction	$R_{th,ax}$	K/W		$R_{th,ax,LS} = R_{th,ax,1m} \cdot L \text{ [m]}$
Thermal resistance in radial direction	$R_{th,rd}$	K/W		$R_{th,rd} = \dfrac{R_{th,rd,1m}}{L \text{ [m]}}$
Thermal capacity, thermal mass	C_{th}	W·s/K		$C_{th,LS} = C_{th,1m} \cdot L \text{ [m]}$
Electrical resistance	R_{el}	Ω		$R_{el,LS} = R_{el,1m} \cdot L \text{ [m]}$
Linear temperature coefficient of thermal resistance	α_{Rth}	1/K	–	No conversion required
Linear temperature coefficient of thermal conductance	α_{Yth}	1/K	–	No conversion required
Linear temperature coefficient of electrical resistance	$\alpha_{R_{el}}$	1/K	–	No conversion required
Linear temperature coefficient of thermal capacity	α_{Cth}	1/K	–	No conversion required

The ambient temperature T_a is also the temperature of the cable components at the beginning of the simulation T_{Start}.

The physical unit of the temperatures is specified by the simulation program and is either °C or K.

2.6 Determining values

The process for determining the values for each component is an essential aspect.

2.6.1 Electrical resistance

Multiple approaches can be used to determine the electrical resistance:
For simple solid bodies, the electrical resistance can be determined using

$$R_{el} = \rho \cdot \frac{l}{A} \qquad (18)$$

where l describes the length of the solid and A the cross-sectional area. ρ is the electrical resistivity.

Unlike simple ohmic resistances, additional resistances are also present in reality and are dominant in a plugged in connector. These are the contact resistance between the mated contacts of the connector on the one hand and the resistance present in the transition area from the plug to the line/busbar on the other. Resistances occur here for bolted connections, crimp resistances or welding resistances that can be dominant to the conductive resistances for high-power connectors.

Although it is sometimes possible to determine theses resistances mathematically, measuring them is definitely more effective. To this end, the connector must be supplied with current and the voltage drop must be determined at various points. Under ideal circumstances, measurements would be taken at four different measuring points in order to provide the level of detail needed for the thermal model. If the resistivity (Rho) and exact geometry are known, a 3D simulation can also provide an accurate result.

For known current strengths I, the ohmic resistance R can then be calculated using the voltage drop U:

$$R_{el} = \frac{U}{I} \qquad (19)$$

2.6.2 Thermal resistance

Similar to electrical resistance, there are several ways of determining thermal resistance. For simple components, a computer-based approach makes sense:

$$R_{th,cond} = \frac{l}{\lambda \cdot A} \qquad (20)$$

For example, (20) can be used to determine the thermal conductive resistance for simple geometries, where l indicates the length of the body, A the cross-sectional area and λ the thermal conductivity. FEM models offer more advantages for complex geometries. A defined heat flow $\dot{Q}$ or P is impressed across the component and the temperature difference $\Delta T = T_1 - T_2$ between two measurement points can be used to determine the thermal resistance with equation (21).

Figure 8: Thermal resistance in FEM models
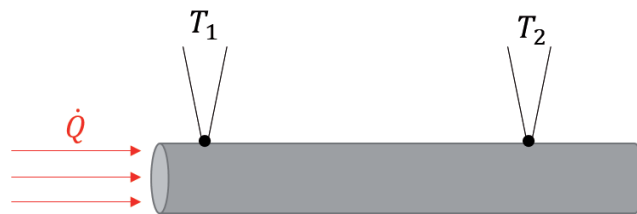
Source: ZVEI

$$R_{th,cond} = \frac{\Delta T}{P} \qquad (21)$$

2.6.3 Thermal mass

CAD data can be used for thermal mass in the first step. The volumes V and density ρ of the materials used for the affected components are determined for this purpose. The specific heat capacity c can be used to estimate the thermal mass C_{th}, as shown in equation (7).

FEM can also be used to determine thermal capacities. The model is divided into volume elements and the thermal energy of the elements that is fed in is measured along with the associated heating.

Figure 9: Thermal capacity in FEM models
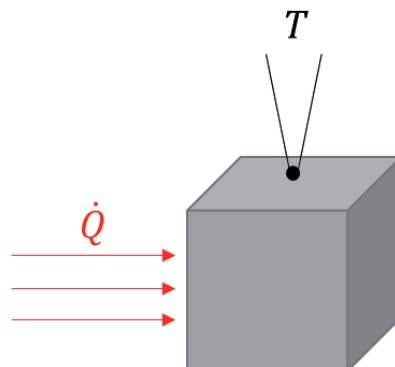
Source: ZVEI

Then (7) can be used for the thermal capacity to:

$$C_{th} = \frac{dQ}{dT} \qquad (22)$$

where Q indicates the thermal energy that is impressed across the volume element:

$$Q = \int_{\tau=0}^{t} \dot{Q}(\tau) \ d\tau \qquad (23)$$

3 Specifities/subsystems

3.1 Special wiring harness cases

3.1.1 Joule heat source for the conductor element

The conductor has an electrical resistance, two elements for axial heat conduction along the conductor, and a thermal capacity that represents the thermal mass of the cable.

Table 10: Equivalent circuit diagram for a conductor

Name	Symbol	Block representation
Conductor		

*) The linear temperature coefficient for the specific thermal conductivity, $\alpha_{R^{th}}$, and the linear temperature coefficient for the specific heat capacity, α_{Cth}, of the metals and polymers are optional. They are set to 0 if they are not used and refer to the base values at 20 °C.

When creating the program libraries, care must be taken to reference the module shown here as conductive element. In this case, an instance of the module is created when using it as conductor, contact spring, female terminal or plug.

3.1.2 Thermal conduction via insulation

For length-based components such as bulk cables, thermal resistances are lower the longer the cable slice is. Therefore, the radial thermal resistances referring to one metre of cable must be divided by the actual length of the cable slice in metres.

Table 11: Equivalent circuit diagram for conductor insulation

Name	Symbol	Block representation
Insulation Sheath		

*) The linear temperature coefficient for the specific thermal conductivity, $\alpha_{R\text{th}}$, and the linear temperature coefficient for the specific heat capacity, $\alpha_{C\text{th}}$, of the metals and polymers are optional. They are set to 0 if they are not used and refer to the base values at 20 °C.

3.1.3 Cooling via radiation and convection

The conductor element releases heat to the environment via convection and radiation. For length-based components such as bulk cables, thermal resistances are lower the longer the cable slice is. Therefore, the radial thermal resistances referring to one metre of cable must be divided by the actual length of the cable slice in metres.

Table 12: Equivalent circuit diagram for cooling conductor

Name	Symbol	Block representation
Cooling of cable via insulation surface		

3.2 Special connector system cases: Female terminal

3.2.1 Joule heat source for the contact element

Heating via the contact resistance is a special case. This resistance should be included in the circuit diagram for the female terminal.

Since electrical contact usually takes place via several spring elements, it is also necessary to map the contact resistance and thermal conduction via resistances and the thermal capacities.

Table 13: Equivalent circuit diagram for contact springs

Name	Symbol	Block representation
Multiple contact spring	$2R_{el,K}+R_{el,L}$ $R_{th,K}+R_{th,L}/2$ $R_{th,K}+R_{th,L}/2$ T_{Start}	**Contact spring** $R_{el,K}$ [Ω] $R_{ek,L}$ [Ω] C_{th} [J/K] $R_{th,K}$ [K/W] $R_{th,L}$ [K/W] $\alpha_{el,L}$ [1/K] $\alpha_{th,L}$ [1/K] T_{Start} **Contact spring** $R_{el,K,einzel}$ [Ω] $R_{ek,L,einzel}$ [Ω] $C_{th,einzel}$ [J/K] $R_{th,K,einzel}$ [K/W] $R_{th,L,einzel}$ [K/W] N [#] $\alpha_{el,L}$ [1/K] $\alpha_{th,L}$ [1/K] T_{Start}
Simple contact resistance	$R_{th}/2$ $R_{th}/2$	**Crimp** **Contact resistance** R_e [Ω] R_{th} [K/W] α_{el} [1/K] α_{th} [1/K] T_{Start}

Simple contact resistances without thermal capacities can be used in the load paths for clamped electrical connections such as crimp transitions and bolted connections. Failure to analyse the temperature at this point could result in serious errors.

3.2.1.1 Mathematical description

The element of joule heating comprises multiple individual components. For contact via a spring with two contact points, one at the female terminal and one in the female terminal, the total electrical resistance of the contact system is

$$R_{el} = 2 \cdot R_{el,K} + R_{el,L} \qquad (24)$$

The contact resistance $R_{el,K,einzel}$ of the individual spring elements is divided by the number of contact elements $N_{Kontakt}$ on the side to be contacted, meaning that contact resistance on one side results in:

$$R_{el,K} = R_{el,K,einzel}/N_{Kontakt} \qquad (25)$$

The conductive resistance of the contact springs, or the bulk resistance, is considered according to the spring elements in a parallel circuit:

$$R_{el,L} = R_{el,L,einzel}/N_{Kontakt} \qquad (26)$$

Similar to the electrical resistance, the thermal capacity C_{th} is also calculated so that the low thermal masses of the individual contacts $C_{th,einzel}$ are addressed,

$$C_{th} = C_{th,einzel} \cdot N_{Kontakt} \qquad (27)$$

The thermal conductive resistances are adapted in the same way, resulting in:

$$R_{th,L} = R_{th,L,einzel}/N_{Kontakt} \qquad (28)$$
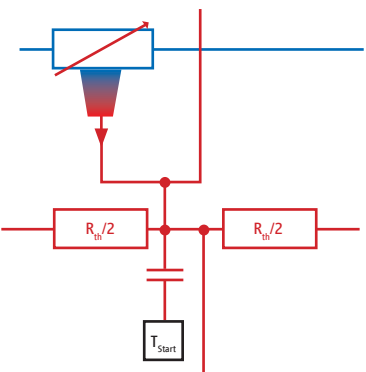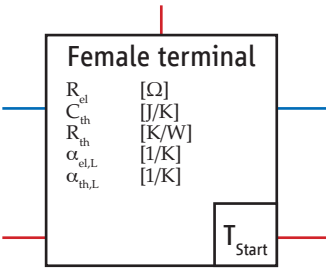
The thermal contact resistances on each side are the result of the single thermal resistances of the individual contacts:

$$R_{th,K} = R_{th,K,einzel}/N_{Kontakt} \qquad (29)$$

3.2.2 Joule heat source for the line resistance for the female terminal

Alongside the contact resistance, the contact pairs (in this case the female terminal) also have a thermal mass and a thermal resistance, which is determined by the geometry and the material of the solid.
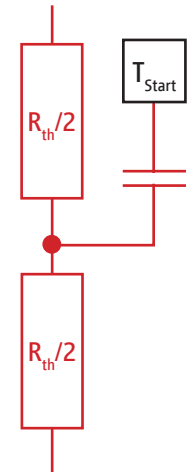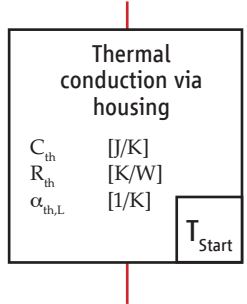
Table 14: Equivalent circuit diagram female terminal

Name	Symbol	Block representation
Female terminal		

3.2.3 Thermal conduction from contact path to housing

The thermal conduction via non-metallic components is described by a simple Y model, in which the total thermal resistance of the component is divided and the capacity is connected between the two partial resistances to its start temperature.
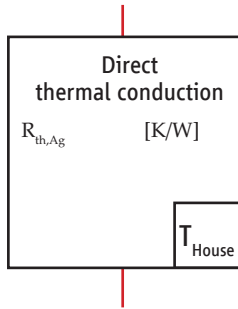
Table 15: Equivalent circuit diagram for housing

Name	Symbol	Block representation
Thermal conduction via housing		

3.2.4 Thermal conduction from the contact path to pin header housing surface inside the component

The basic principle is that the pin header can be connected to the component via some type of mounting, such as a bolted connection. In this case, the pin header is connected to the component temperature T_{House} via a thermal resistance $R_{th,Ag}$, which is influenced by the type of connection and quality.
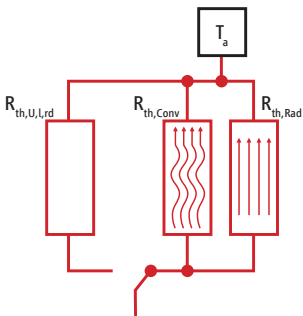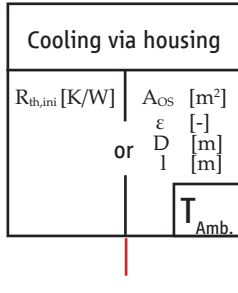
Table 16: Equivalent circuit diagram for thermal conduction pin header – component housing

Name	Symbol	Block representation
Direct thermal conduction via pin header to component housing	T_{Start} $R_{th,Ag}$	Direct thermal conduction $R_{th,Ag}$ [K/W] T_{House}

3.2.5 Cooling via the female terminal housing to the environment

Both the female terminal housing and the pin header interact with the respective environment via radiation and convection. In the case of the component, this interaction always impacts the component temperature T_{Aggr} inside the component. This interaction affects the ambient temperature T_{Amb} around the female terminal itself. To simplify things, complex transfer mechanisms via convection and radiation can switch to simple heat transfer using thermal resistance.

Table 17: Equivalent circuit diagram for the cooling of the female terminal housing

Name	Symbol	Block representation
Cooling via female terminal housing environment	T_a $R_{th,U,l,rd}$ $R_{th,Conv}$ $R_{th,Rad}$	Cooling via housing $R_{th,ini}$ [K/W] | A_{OS} [m²] ε [-] or D [m] l [m] $T_{Amb.}$

3.2.5.1 Mathematical description

For a simplified representation of thermal resistance $R_{th,ini}$, it should be noted that this approach only applies for an approximate description of the cooling process and only for the equilibrium situation, because the thermal resistance for the transfer of radiation should be described using a fourth-order polynomial.

If the description of convection and radiation is applied, the free surfaces of the components A_O are used for the pin header and A_{OS} of the female terminal housing. The parameter ε indicates the emission coefficient for the radiation and is a material parameter.

When the female terminal housing cools, it is assumed that its shape can be approximated with a cylinder. In this case, the following relationship results for the calculation of the convective heat transfer coefficient α_K:

$$\alpha_K = \frac{Nu \cdot \lambda}{\tilde{L}} \tag{30}$$

With the Nusselt number Nu and the characteristic length L, λ indicates the thermal conductivity of the environment (air). $\lambda_{20°C} = 0.02587 \; \frac{W}{m \cdot K}$ can be used initially as literature value (see Reference list [2]). Depending on the type, the Nusselt number can be determined using the Grashof or Rayleigh number, the Prandtl number and the Reynolds number, all of which are dependent on the flow velocity v. In addition to material properties and natural constants, only the flow velocity v of the air (for forced convection) and the characteristic length L remain influencing factors in the equation. For a cylinder with a length of l and a diameter of D the following applies:

$$\tilde{L} = \frac{l \cdot \pi \cdot D^2}{4 \cdot A_{OS}} \qquad (31)$$

3.3 Special connector system cases: Pin header

3.3.1 Joule heat source for the pin

The conduction path represents a simple current/thermal conduction, consisting of an element that describes the joule heat, the thermal resistances and thermal capacity.

Table 18: Equivalent circuit diagram for thermal resistance and capacity of the pin

Name	Symbol	Block representation
Simple contact resistance		Crimp Contact resistance R_e $[\Omega]$ R_{th} $[K/W]$ α_{el} $[1/K]$ α_{th} $[1/K]$ T_{Start}
Conductive resistance connector		Connector R_{el} $[\Omega]$ C_{th} $[J/K]$ R_{th} $[K/W]$ $\alpha_{el,L}$ $[1/K]$ $\alpha_{th,L}$ $[1/K]$ T_{Start}

3.3.2 Pin header cooling to inside of the component

Parallel to the simple thermal conduction to the component, interaction also takes place between the pin header and the environment inside the component. In this case, in addition to the thermal conduction to the component, heat is also conducted to the surface of the pin header. This thermal path is connected to an element for cooling by convection, radiation or a simplified heat exchange.

Table 19: Equivalent circuit diagram for thermal conduction pin header – component interior

Name	Symbol	Block representation
Thermal conduction via pin header to component		

3.3.3   Cooling via pin header to inside of component

The pin header also interacts with the environment via radiation and convection. In the case of the component, this interaction always impacts the component temperature T_{Aggr} inside the component. To simplify things, complex transfer mechanisms via convection and radiation can switch to simple heat transfer using thermal resistance.

Table 20: Equivalent circuit diagram for cooling inside component via pin header

Name	Symbol	Block representation
Cooling inside component via pin header		

3.4 Exchange of parameters

In addition to the description of the individual modules for the simulation on the basis of thermal equivalent circuit diagrams and the underlying physics, a suggestion on how to exchange parameters should also be included.

To avoid errors caused by large text documents and confusion in the nomenclature, it makes sense to rely on a structure that also represents the equivalent circuit diagram layout. A table is proposed for this purpose. Its rows present the conduction along the primary current path and its columns present the heat flow to the environment.

Table 21: Exchange table for cable parameter set

Parameter set Shielded cablex	Cable segment
Heat exchange with environment	
Sheath	
Shield	
Insulation	
Conductor	

Table 22: Exchange table for connector parameter set

Connector parameter set		Component Terminal	Pin	Contact resistance	Female terminal	Cable Terminal
Heat exchange with environment						
Contact 1	External insulation					
	Shield					
	Internal insulation					
	Primary conductor					
Contact 2	External insulation					
	Shield					
	Internal insulation					
	Primary conductor					

3.5 Verification of the transferred model

As we see it, when transferring parameters, the parties involved are responsible for verifying the models in their own simulation environment. It is recommended to check the parameters entered into the user's simulation environment by comparing them with the results provided by the original data. This comparison assumes that the ambient conditions and excitation are the same. Consequently, both should be defined as simply as possible to enable "manual" transfer.

Connecting a sufficiently long cable (1.5 m recommended) to the pin and female terminal side is one option to create a simulation model for verification. Obviously, the cable model should also be aligned; however, it can be assumed that over time, mutually tested models of standard cable types will be available. If these conditions are fulfilled, the cooling of the connector via the cables is also captured and a practical answer provided.

The comparison with derating is simple and requires no further explanation. To obtain information about the dynamic behaviour, it is recommended to simulate a short-term load exposure. It is also possible to use the values of a timing chart for short-time exposure if available.

For a compact pulse shape, both types of load exposure can be combined. The following pulse shape form consisting of short-long-short pulses is a good example: - 2.5 x nominal current, until 160 °C is reached (1 min) - 0.8 x nominal current for 1 h - 2.5 x nominal current up to 160 °C (10 x) cooling up to 5000 s

The times mentioned above are reference values. They should be selected to ensure that a sufficient increase in temperature is achieved within the defined range. The result can be made available as a diagram or screenshot in conjunction with the temperature values after the three phases. In addition, a history table can be created.

It is important that identical measuring points are defined in addition to the boundary conditions. As a precaution, the temperature of an interference-free cable should also be transferred.

Driving profiles are less suitable for verifying the transferred parameters, as the irregular curves may make troubleshooting more difficult, and deviations in small peaks may be the result of numeric effects.

To eliminate errors caused by the periphery, it is also possible to simulate the connector without any cable attached to it. However, this makes it difficult to detect errors in the series thermal resistance of the conductors. Due to the lack of cooling via the cables, the relevant continuous current must be determined separately; it can be up to 25 percent lower than determined using this method. The higher thermal resistance also results in a significantly greater time constant, which results in lower temperatures during pulse loading and shifts the heating from short to long pulse loading.

It should be noted that the test pulse described here should only be used to verify the correct transfer of the parameter set. The simulation conditions for the verification should be agreed directly between the parties involved, since the procedure and the boundary conditions can vary depending on the application. The test pulse described here is not recommended for comparing the real connector with the simulation.

3.6 Safety tolerances for connectors
For connectors it is common to specify a safety factor in derating curves that compensates for the effects of environmental influences and thus guarantees reliability over the guaranteed application lifetime.

Figure 10: Contact heating due to current flow
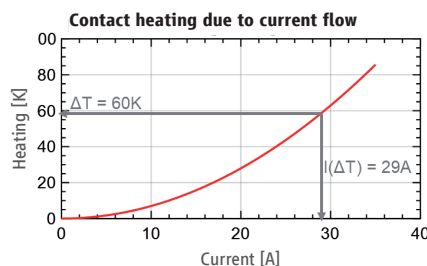
Source: ZVEI

Figure 11: Derating curve connector
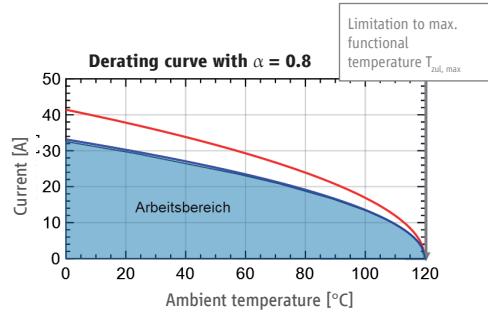
Source: ZVEI

Contact heating follows Joule's First Law:

$$\Delta T = k \cdot I_{\text{Qual}}{}^2 \qquad (32)$$

Where k is a coefficient derived from the heat generation curve. Considering a maximum permissible contact temperature $T_{\max}$, a formulation results that accounts for the ambient temperature T_{Amb} and a permissible temperature increase ΔT_{zul} resulting from it.

$$T_{\text{Amb}} + \Delta T_{\text{zul}} \leq T_{\max} \qquad (33)$$

The current-carrying capacity is calculated taking into account the two formulas above

$$I_{\text{zul,max}} \leq \sqrt{\frac{T_{\max} - T_{\text{Amb}}}{k}} \qquad (34)$$

A safety factor α_{SF} is introduced in this formalism:

$$I_{\text{zul,max}} \leq \alpha_{\text{SF}} \cdot \sqrt{\frac{T_{\max} - T_{\text{Amb}}}{k}} \qquad (35)$$

This safety factor or correction factor is set to a value of $\alpha_{\text{SF}} = 0.8$ according to LV214 or to a value of $\alpha_{\text{SF}} = 0.9$ for USCAR. The procedure introduced below is propagated in order to store a corresponding safety factor for the electrical resistances in the system using the approach presented here:

Joule heating occurs after (1) and taking into account $\alpha_{\text{SF}} = \dfrac{I_{\text{zul}}}{I_{\text{Qual}}}$.
However, this heating must not exceed the permissible heating by $T_{\max}$.

$$P_{\text{V,Qual}} = R_0 \cdot I_{\text{Qual}}^2 \qquad (36)$$

$$P_{\text{V,zul}} = R_{\text{zul}} \cdot \alpha_{\text{SF}}{}^2 \cdot I_{\text{Qual}}^2 \qquad (37)$$

By equating $P_{\text{V,Qual}} = P_{\text{V,zul}}$ and converting

$$R_0 = R_{\text{zul}} \cdot \alpha_{\text{SF}}{}^2 \qquad (38)$$

The resistance comprises the conductive resistances of the female terminal and the pin, the conductive resistance of the contact spring, the contact resistance/the contact resistances and the connection resistances (bolted connection, welded connection, crimp connection). Only the connection resistances are expected to degrade over time, the consequence of which is

$$R(t) = \sum R_{\text{L}} + \sum R_{\text{K,Anschluss}}(t) \qquad (39)$$

26

Because the total permissible resistance in the system depends on α_{SF} but is not directly scaled to the value, a new scaling factor ξ is defined for the resistances:

$$R_{\text{zul}} = \sum R_{\text{L}} + \xi \sum R_{\text{K,Anschluss}} \tag{40}$$

It follows with $R_{\text{const}} = \sum R_{\text{L}}$

$$R_0 = R_{\text{const}} + \sum R_{\text{K,Anschluss}} = \alpha_{\text{SF}}{}^2 \cdot \left(R_{\text{const}} + \xi \sum R_{\text{K,Anschluss}} \right) \tag{41}$$

$$\Leftrightarrow \xi = \frac{R_{\text{const}} \cdot (1 - \alpha_{\text{SF}}{}^2) + \sum R_{\text{K,Anschluss}}}{\sum R_{\text{K,Anschluss}} \cdot \alpha_{\text{SF}}{}^2} \tag{42}$$

From the above formula, a value for ξ can be derived for known resistances, taking into account α_{SF}. In a connector, different connections are subject to different ageing mechanisms w.l.o.g., so that a different ageing factor ξ_i must be taken into account for each contact resistance.

$$\xi \cdot \sum R_{\text{K,Anschluss}} = \sum_i \xi_i \cdot R_{\text{K,Anschluss},i} \tag{43}$$

Since the individual ξ_i are dependent on each other and on the total value ξ, the values must be carefully chosen and the equation (43) must be observed. It should be noted that constant resistances in the overall system also play a role in the calculation of ξ. The method presented here assumes a punctiform, adiabatic curve model, so no components outside the connector are considered.

The factors ξ_i in the model are not taken into account in the screens, but are taken into account when entering the individual electrical resistances in the model ($R_{\text{el},K}$, $R_{\text{el,Anschluss},i}$...):

$$R_{\text{el,K,SF},i} = \xi_i \cdot R_{\text{el,K},i}$$

$$R_{\text{el,Anschluss,SF},i} = \xi_i \cdot R_{\text{el,Anschluss},i} \tag{44}$$

4 Cables

Parameters for one metre cable

Figure 12: Equivalent circuit diagram for one metre unshielded cable
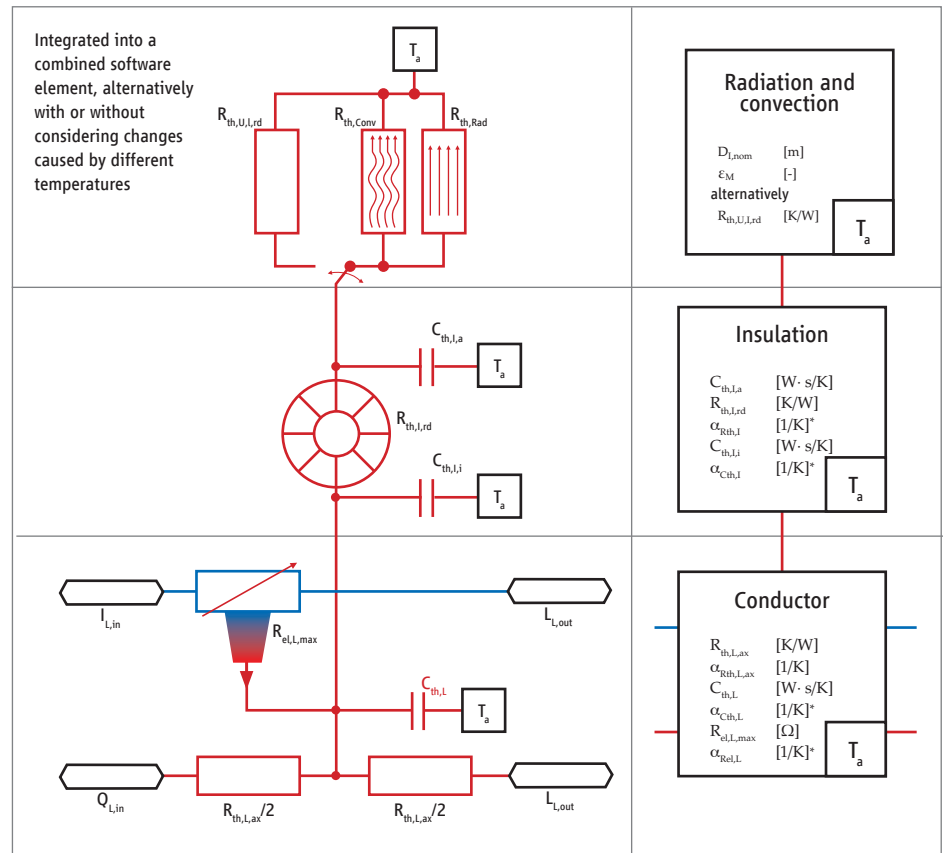
*) The linear temperature coefficient for the specific thermal conductivity, $\alpha_{R\text{th}}$, and the linear temperature coefficient for the specific heat capacity, $\alpha_{C\text{th}}$, of the metals and polymers are optional. They are set to 0 if they are not used and refer to the base values at 20 °C.

Source: Gebauer and Griller

Figure 13: Equivalent circuit diagram for shielded cable
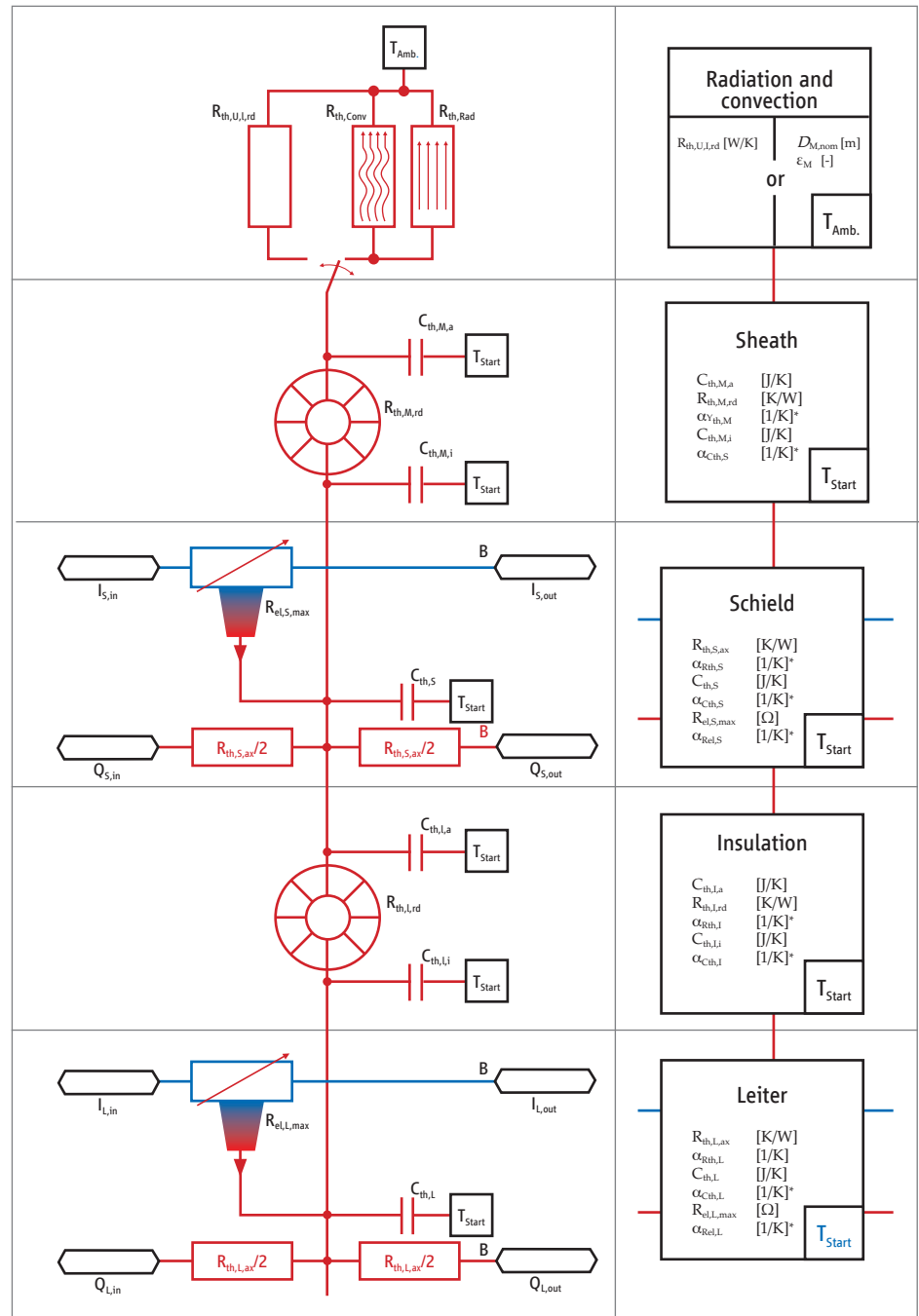
*) The linear temperature coefficient for the specific thermal conductivity, $\alpha_{R^{th}}$, and the linear temperature coefficient for the specific heat capacity, $\alpha_{C^{th}}$, of the metals and polymers are optional. They are set to 0 if they are not used and refer to the base values at 20 °C.

Source: Gebauer and Griller

Based on this, the following parameter set can be determined for the example of an unshielded cable:

Table 23: Parameter set for an unshielded cable

Parameter set Unshielded cable	Cable segment	
Heat exchange with environment	$D_{I,nom}$ ε_M alternatively $R_{th,U,I,rd}$	[m] [-] [K/W]
Insulation	$C_{th,I,a}$ $R_{th,I,rd}$ $\alpha_{Yth,I}$ $C_{th,I,i}$ $\alpha_{Cth,I}$	[W·s /K] [K/W] [1/K]*) [W·s /K] [1/K]*)
Conductor	$R_{th,L,ax}$ $\alpha_{Rth,L}$ $C_{th,L}$ $\alpha_{Cth,L}$ $R_{el,L,max}$ $\alpha_{Rel,L}$	[K/W] [1/K]*) [W·s /K] [1/K]*) [Ω] [1/K]

*) The linear temperature coefficient for the specific thermal conductivity, α_{Rth}, and the linear temperature coefficient for the specific heat capacity, α_{Cth}, of the metals and polymers are optional. They are set to 0 if they are not used and refer to the base values at 20 °C.

Thus the following representation results for the parameter set for a shielded cable:

Table 24: Parameter set for a shielded cable

Parameter set Shielded cable	Cable segment	
Heat exchange with environment	$D_{M,nom}$ ε_M alternatively $R_{th,U,M,rd}$	[m] [-] [K/W]
Sheath	$C_{th,I,a}$ $R_{th,I,rd}$ $\alpha_{Yth,I}$ $C_{th,I,i}$ $\alpha_{Cth,I}$	[W·s /K] [K/W] [1/K] *) [W·s /K] [1/K]*)
Shield	$R_{th,L,ax}$ $\alpha_{Rth,L}$ $C_{th,L}$ $\alpha_{Cth,L}$ $R_{el,L,max}$ $\alpha_{Rel,L}$	[K/W] [1/K]*) [W·s /K] [1/K]*) [Ω] [1/K]
Insulation	$C_{th,I,a}$ $R_{th,I,rd}$ $\alpha_{Yth,I}$ $C_{th,I,i}$ $\alpha_{Cth,I}$	[W·s /K] [K/W] [1/K]*) [W·s /K] [1/K]*)
Conductor	$R_{th,L,ax}$ $\alpha_{Rth,L}$ $C_{th,L}$ $\alpha_{Cth,L}$ $R_{el,L,max}$ $\alpha_{Rel,L}$	[K/W] [1/K] *) [W·s /K] [1/K]*) [Ω] [1/K]

*) The linear temperature coefficient for the specific thermal conductivity, α_{Rth}, and the linear temperature coefficient for the specific heat capacity, α_{Cth}, of the metals and polymers are optional. They are set to 0 if they are not used and refer to the base values at 20 °C.

5 Connector

5.1 Application example

A simple, unshielded contact female terminal with multiple contact springs is the simplest application example. There are three sources of heat: From left to right, these are the contact spring connection resistance, the contact female terminal resistance, and the crimp resistance to the cable. The current and thermal conduction along the current path is shown here. Heat conduction via the housing to the outside has not yet been included.

Figure 14: Application example connector
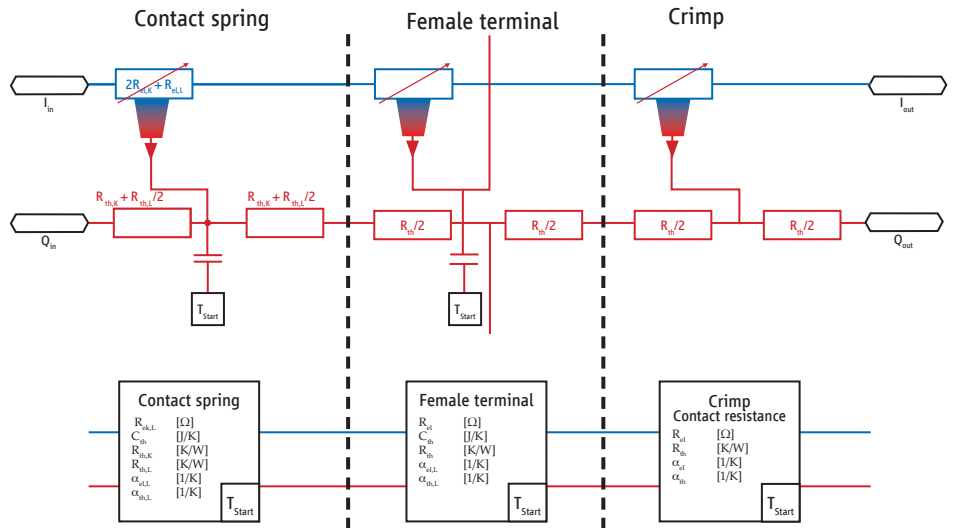
Source: ZVEI

5.1.1 Single-pin unshielded connector

An illustration also follows featuring a complete contact path via connector and female terminal with additional cooling via the housing to the outside. There are multiple interfaces here: The starting temperature, which is usually the same as the ambient temperature at the start of the simulation, serves as a reference for the thermal capacities or masses. The housing temperature interface is primarily determined by convection inside the component (control unit). The temperature interface to the module describes the heat transfer to a model of a component housing to which the connector is attached. The temperature interface to the outside is connected to the environment (ambience) via convection and radiation.

Figure 15: Equivalent circuit diagram for an unshielded single-pin connector

Source: ZVEI

31
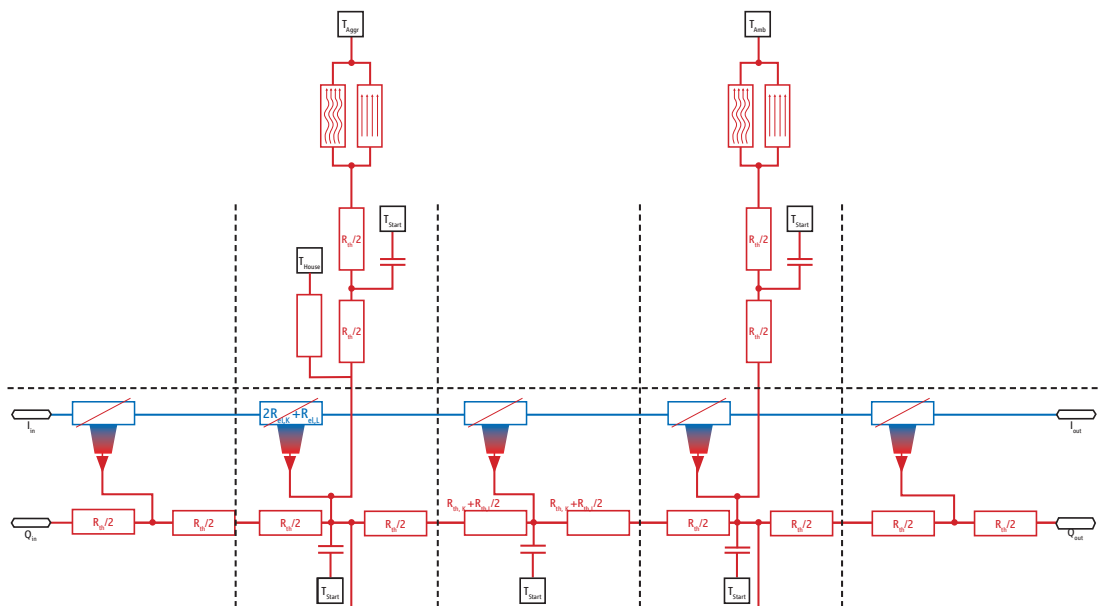
Figure 16: Simplified equivalent circuit diagram for an unshielded single-pin connector
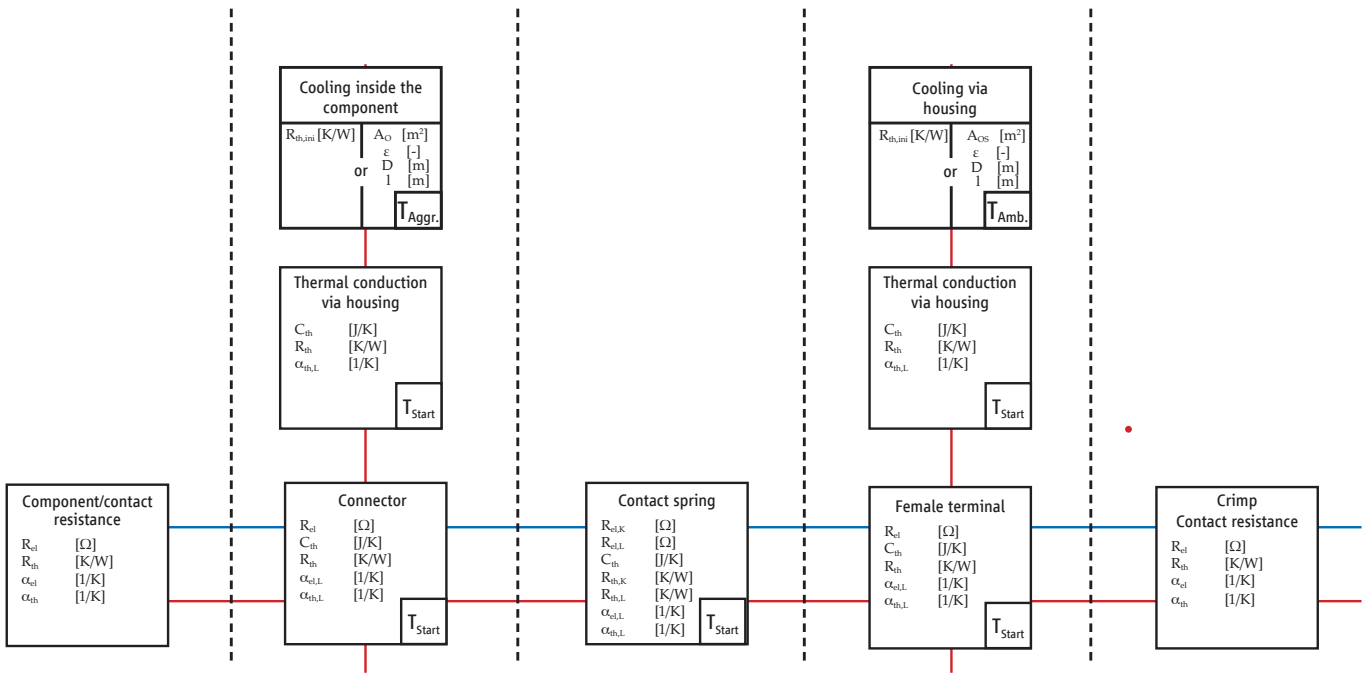
Source: ZVEI

5.1.2 Two-pin unshielded female terminal connectors with heat exchange via housing

Figure 17: Equivalent circuit diagram for a two-pin unshielded female terminal connector with heat exchange via housing
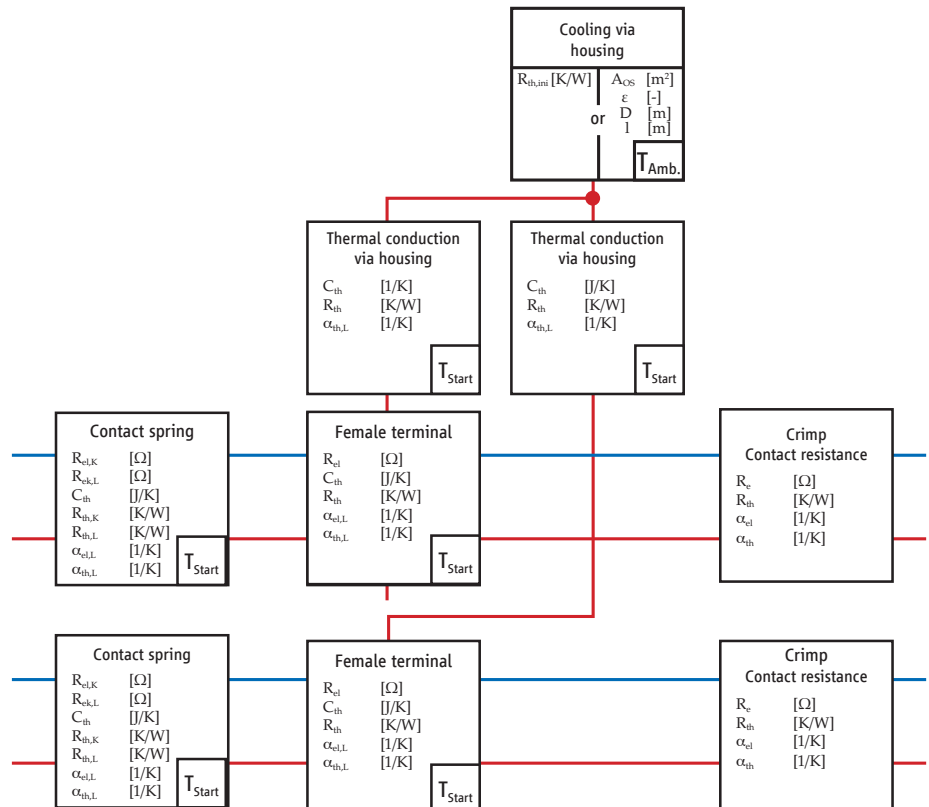
Source: ZVEI

5.1.3 Two-pin unshielded pin header with heat exchange via component

Figure 18: Equivalent circuit diagram for a two-pin unshielded pin header with heat exchange via component
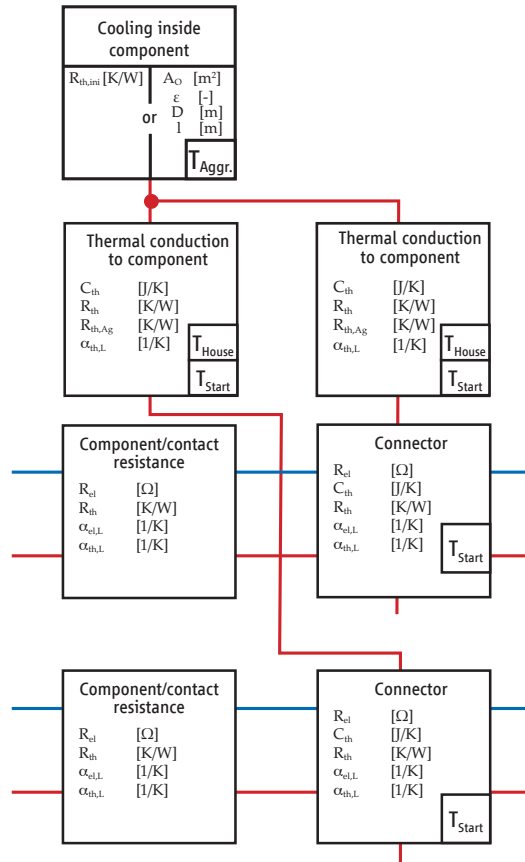
Source: ZVEI

5.1.4 Single-pin shielded connector

Figure 19: Equivalent circuit diagram for a single-pin shielded connector
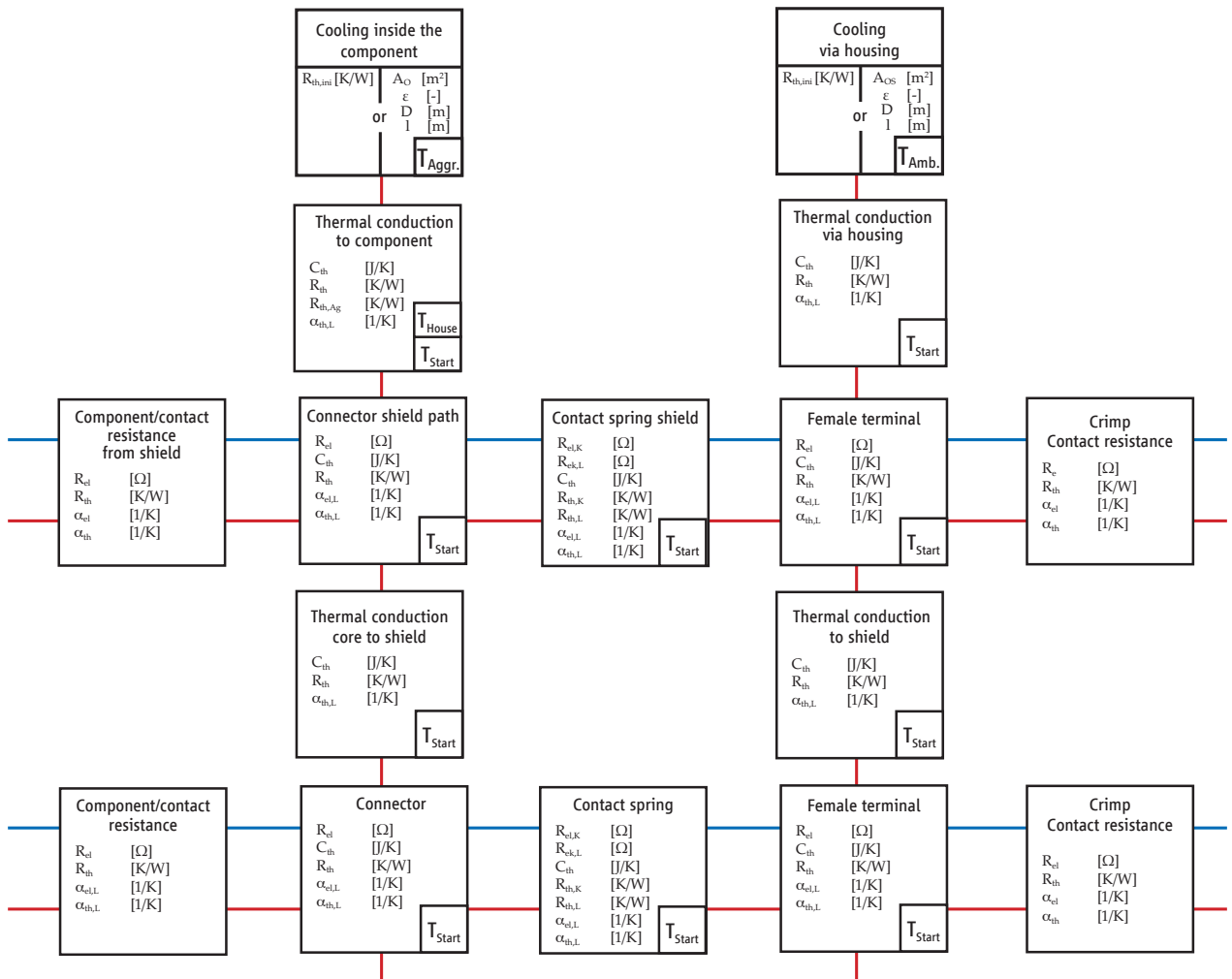
Based on this, the following parameter set can be determined for the example of an unshielded connector:

Table 25: Parameter set for unshielded connector

Parameter set Two-pin unshielded connector		Component Terminal	Pin	Contact resistance	Female terminal	Cable Terminal
Heat exchange with environment			$R_{th,ini}$ A_O ε D l		$R_{th,ini}$ A_{OS} ε D l	
Contact 1	External insulation		C_{th} R_{th} $R_{th,Ag}$ α_{th}		C_{th} R_{th} α_{th}	
	Primary conductor	R_{el} α_{el} R_{th} α_{th} ξ_{el}	R_{el} α_{el} C_{th} R_{th} α_{th}	$R_{el,K}$ $R_{el,L}$ α_{el} C_{th} $R_{th,K}$ $R_{th,L}^{*}$ α_{th} N^{*} $\xi_{el,K}$	R_{el} α_{el} C_{th} R_{th} α_{th}	R_{el} α_{el} R_{th} α_{th} ξ_{el}
Contact 2	External insulation		C_{th} R_{th} $R_{th,Ag}$ α_{th}		C_{th} R_{th} α_{th}	
	Primary conductor	R_{el} α_{el} R_{th} α_{th} ξ_{el}	R_{el} α_{el} C_{th} R_{th} α_{th}	$R_{el,K}$ $R_{el,L}$ α_{el} C_{th} $R_{th,K}$ $R_{th,L}^{*}$ α_{th} N^{*} $\xi_{el,K}$	R_{el} α_{el} C_{th} R_{th} α_{th}	R_{el} α_{el} R_{th} α_{th} ξ_{el}

*) The parameters marked with an asterisk are optional and are only required for some of the equivalent circuit diagrams.

For shielded connectors, the following applies analogously:

Table 26: Parameter set for two-pin shielded connector – contact 1

Parameter set Two-pin shielded connector		Component Terminal	Pin	Contact resistance	Female terminal	Cable Terminal
Heat exchange with environment			$R_{th,ini}$ A_O ε D l		$R_{th,ini}$ A_{OS} ε D l	
Contact 1	External insulation		C_{th} R_{th} $R_{th,Ag}$ α_{th}		C_{th} R_{th} α_{th}	
	Shield path	R_{el} α_{el} R_{th} α_{th} ξ_{el}	R_{el} α_{el} C_{th} R_{th} α_{th}	$R_{el,K}$ $R_{el,L}$ α_{el} C_{th} $R_{th,K}$ $R_{th,L}^*$ α_{th} N^* $\xi_{el,K}$	R_{el} α_{el} C_{th} R_{th} α_{th}	R_{el} α_{el} R_{th} α_{th} ξ_{el}
	Internal insulation		C_{th} R_{th} α_{th}		C_{th} R_{th} α_{th}	
	Primary conductor	R_{el} α_{el} R_{th} α_{th} ξ_{el}	R_{el} α_{el} C_{th} R_{th} α_{th}	$R_{el,K}$ $R_{el,L}$ α_{el} C_{th} $R_{th,K}$ $R_{th,L}^*$ α_{th} N^* $\xi_{el,K}$	R_{el} α_{el} C_{th} R_{th} α_{th}	R_{el} α_{el} R_{th} α_{th} ξ_{el}

*) The parameters marked with an asterisk are optional and are only required for some of the equivalent circuit diagrams.

Table 27: Parameter set for a two-pin shielded connector – contact 2

Parameter set Two-pin shielded connector		Component Terminal	Pin	Contact resistance	Female terminal	Cable Terminal
Contact 2	External insulation		C_{th} R_{th} $R_{th,Ag}$ α_{th}		C_{th} R_{th} α_{th}	
	Shield path	R_{el} α_{el} R_{th} α_{th} ξ_{el}	R_{el} α_{el} C_{th} R_{th} α_{th}	$R_{el,K}$ $R_{el,L}$ α_{el} C_{th} $R_{th,K}$ $R_{th,L}{}^{*}$ α_{th} N^{*} $\xi_{el,K}$	R_{el} α_{el} C_{th} R_{th} α_{th}	R_{el} α_{el} R_{th} α_{th} ξ_{el}
	Internal insulation		C_{th} R_{th} α_{th}		C_{th} R_{th} α_{th}	
	Primary conductor	R_{el} α_{el} R_{th} α_{th} ξ_{el}	R_{el} α_{el} C_{th} R_{th} α_{th}	$R_{el,K}$ $R_{el,L}$ α_{el} C_{th} $R_{th,K}$ $R_{th,L}{}^{*}$ α_{th} N^{*} $\xi_{el,K}$	R_{el} α_{el} C_{th} R_{th} α_{th}	R_{el} α_{el} R_{th} α_{th} ξ_{el}

*) The parameters marked with an asterisk are optional and are only required for some of the equivalent circuit diagrams.

5.2 Validation

Validation cannot be performed at the component level because the solid bodies interact with each other, meaning that every element to be simulated has sources and sinks. Validation must thus be performed at a level that enables the entire system to be mapped. One limitation is that some components that are not included in the scope of supply are still required – such as a cable to attach a connector. Therefore, the validation must be designed to minimise the influence of these components (e.g. short cables) and ensure that there are defined, known boundary conditions that are also stored in the simulation.

These boundary conditions include:
- A thermal coupling to a known "infinite" sink – for example, a cooling point with a defined temperature.
- A known ambient temperature and a known/controlled air flow to simulate heat radiation and convection.
- Optional: Convection can be greatly reduced by wrapping the device under test (DUT). This can be accounted for in the model using a low convection coefficient $\alpha \approx 0$.
- It is important to note that the DUT is free-floating and that contact surfaces are kept to a minimum in order to avoid heat conduction to the environment.
- Air circulation (forced convection) should be avoided; otherwise, this must be taken into account in the convection coefficient.
- Measurements and simulation should be performed at different current strengths to represent temperature-dependent variables, such as the linear temperature coefficients for electrical resistance and thermal resistance.

5.3 Ambient conditions

Validation of the method described in the document is subject to the following ambient conditions:
- Horizontal and non-bundled cylindrical cables
- Cable and connector with free convection

The limitations mentioned above are based on the logic that high-current cables have large cross-sections and are thus are usually routed in single or parallel and operated symmetrically. This means that supply and return conductors are identically supplied with power and thus heat up evenly in the first approximation. Consequently, cables installed in parallel do not form heat sinks and are not engaged in any thermal interaction. These cables are cooled via convection and radiation, which represents a worst-case scenario in a draught-free environment. Forced convection can be introduced via the convection interfaces of the model.

This applies equally to the contacts of the connector system. However, the connectors can have a thermal connection to a cable on the one hand and to a component on the other. As a result, the connecting conductor at the transition point (PCB, busbar, etc.) must be defined via the operating temperature and the heat flow. Further models that provide thermal and electrical descriptions of the compoennt side are not included in this application rule.

See also Section 1.3 Scope of this document.

6 Determining the parameter sets

6.1 Cables

A standard data format is crucial to ensure comparability of the results of thermal simulations of electrical components between different users. This document proposes a standardised format for input data for electrical cables. The minimum number of input parameters is taken into account; i.e. only the input parameters that are indispensable for thermal simulation of electrical cables are used.

The parameters required to describe bulk goods are based on the notation introduced in [3] and [4] (see Reference list). In contrast to the description of a load case in an assembled wiring harness with contacts, fewer parameters are required for describing bulk goods. The exchange format used to describe bulk goods can be reduced to these parameters. First, unshielded single cables are documented.

6.1.1 Basic parameters for unshielded single cables

Table 28: Basic parameters for unshielded single cables

Structural component	Parameter	Unit	Description
Insulation	$D_{I,nom}$	m	Nominal outer diameter of the insulation
Insulation	λ_I	W/(K·m)	Thermal conductivity of the insulation material
Insulation	γ_I	J/(K·m³)	Volumetric heat capacity of the insulation material
Insulation	ε	-	Emissivity of insulation
Conductor	$D_{L,nom}$	m	Nominal diameter of the conductor
Conductor	$R'_{L,max}$	Ω/m	Maximum electrical conductor resistance per m at 20 °C
Conductor	α_L	1/K	Linear temperature coefficient of $R_{el,L,max}$
Conductor	κ_L	S/m	Electrical conductivity at 20 °C
Conductor	λ_L	W/(K·m)	Thermal conductivity of the conductor material
Conductor	γ_L	J/(K·m³)	Volumetric heat capacity of the conductor material

Comments:
- To ensure a clear and unique form of base units, it is recommended to work with SI units.
- The basic parameters are for internal use only and are usually not transferred.
- The parameters that provide worst-case results in thermal simulation are transferred, such as the maximum electrical resistance at 20 °C.
- Instead of specifying the conductor cross-section, it is sufficient to specify the electrical conductivity of the conductor material and the conductor resistance per metre at 20 °C.
- The electrical conductivity of the conductor material is not a compact parameter and thus not transferred.
- However, the maximum conductor resistance is transferred as compact parameter.

6.1.2 Compact parameters for unshielded single cables

The compact parameters define the actual exchange format of input data for the calculation of thermal networks. They comprise the basic parameters using the formulas mentioned in Section 5. The number of compact parameters is kept to a minimum, i.e. only parameters relevant to the simulation are used. The compact parameters alter the original material parameters as far as possible, thus making it possible to exchange parameters that are relevant to the simulation without revealing any cable structure details.

Table 29: Compact parameters for unshielded single cables

Structural component	Parameter	Unit	Description
Insulation	$D_{I,nom}$	m	Nominal outer diameter of the insulation*)
Insulation	ε	-	Emissivity of insulation*)
Environment	$R_{th,U,I,rd}$	K/W	alternative to*): combined radial thermal resistance of radiation and convection (for insulation)
Insulation	$C_{th,I,s}$	J/K	Outer part of the heat capacity of the insulation
Insulation	$R_{th,I,rd}$	K/W	Radial thermal resistance of the insulation
Insulation	$C_{th,I,i}$	J/K	Inner part of the heat capacity of the insulation
Conductor	$R_{el,L,max}$	Ω	Maximum electrical conductor resistance at 20 °C
Conductor	$\alpha_{el,L}$	1/K	Linear temperature coefficient of $R_{el,L,max}$
Conductor	$R_{th,L,ax}$	K/W	Axial thermal resistance of the conductor
Conductor	$C_{th,L}$	J/K	Heat capacity of the conductor
-	X	m	Length constant of the unshielded cable

Comments:

- In order to detect the heat output generated in the conductor *independently of the load case*, the values $R_{el,L,max}$ and $\alpha_{el,L}$ are also required for the compact parameters.

6.1.3 Basic parameters for shielded single cables

The following variables are required for shielded cables in addition to the basic parameters for unshielded cables:

Table 30: Basic parameters for shielded single cables

Structural component	Parameter	Unit	Description
Sheath	$D_{M,nom}$	m	Nominal outer diameter of the sheath
Sheath	λ_M	W/(K·m)	Thermal conductivity of the sheath material
Sheath	γ_M	J/(K·m³)	Volumetric heat capacity of the sheath material
Sheath	ε_M	-	Emissivity of the sheath
Shield	$D_{S,nom}$	m	Nominal diameter of the shield
Shield	$R'_{el,S,max}$	Ω/m	Maximum electrical shield resistance per m at 20 °C.
Shield	α_S	1/K	Linear temperature coefficient of $R'_{el,S,max}$
Shield	K_S	S/m	Electrical conductivity at 20 °C
Shield	λ_S	W/(K·m)	Thermal conductivity of the shield material
Shield	λ_S	J/(K·m³)	Volumetric heat capacity of the shield material

The basic parameter ε (emissivity of the insulation) is not required for shielded single cables.

6.1.4 Compact parameters for shielded single cables

The following variables are required for shielded cables in addition to the compact parameters for unshielded cables:

Table 31: Additional compact parameters for shielded single cables

Structural component	Parameter	Unit	Description
Sheath	$D_{M,nom}$	m	Nominal outer diameter of the sheath*)
Sheath	ε_M	-	Emissivity of the sheath*)
Environment	$R_{th,U,M,rd}$	K/W	alternative to*): combined radial thermal resistance of radiation and convection (for the sheath)
Sheath	$C_{th,M,a}$	J/K	Outer part of the heat capacity of the sheath
Sheath	$R_{th,M,rd}$	K/W	Radial thermal resistance of the sheath
Sheath	$C_{th,M,i}$	J/K	Inner part of the heat capacity of the sheath
Shield	$R_{el,S,max}$	Ω	Maximum electrical shield resistance at 20 °C
Shield	$\alpha_{el,S}$	1/K	Linear temperature coefficient of $R_{el,S,max}$
Shield	$R_{th,S,ax}$	K/W	Axial thermal resistance of the shield
Shield	$C_{th,S}$	J/K	Heat capacity of the shield
-	X	m	Length constant of the shielded cable

For shielded single cables, the compact parameter $R_{th,U,I,rd}$ (combined radial thermal resistance of the insulation surface) is *not* required.

6.1.5 Formulas for determining the compact parameters

The calculation paths for determining the compact parameters are specified below. The compact parameters are highlighted in **bold.**

6.1.5.1 Electrical resistances of shields and conductors

As basic parameters, the electrical resistances for bulk goods data are typically specified independently of the length. If the cable length L is specified, the required compact parameters are obtained as absolute values of the shield and conductor resistance [Ω]:

$$\boldsymbol{R_{el,S,max}} = R'_{el,S,max} \cdot L \qquad (45)$$

$$\boldsymbol{R_{el,L,max}} = R'_{el,L,max} \cdot L$$

Comments
- The cable length L for determining the conductor resistance is standardised to one metre.
- The temperature dependence of the shield and conductor resistance is determined by the formula

$$R_{el,max}(T) = R_{el,max} \cdot \left(1 + \alpha_{el} \cdot (T - T_0)\right) \qquad (46)$$

T indicates the conductor and/or shield temperature and T_0 the reference temperature of $R_{el,max}$. This is typically 20 °C.

6.1.5.2 Radial thermal resistance of plastics

The thermal resistance per metre of length is first determined:
Radial thermal resistance of the sheath per m, [(K·m)/W]:

$$R'_{th,M,rd} = \frac{ln\left(\frac{D_{M,nom}}{D_{S,nom}}\right)}{2 \cdot \pi \cdot \lambda_M} \qquad (47)$$

Radial thermal resistance of the insulation per m, [(K·m)/W]:

$$R_{th,I,rd} = \frac{ln\left(\frac{D_{I,nom}}{D_{L,nom}}\right)}{2 \cdot \pi \cdot \lambda_I} \tag{48}$$

Radial thermal resistance $R_{th,rd}$ in [K/W] of the sheath and insulation at a given cable length L:

$$R_{th,M,rd} = \frac{R'_{th,M,rd}}{L} = \frac{ln\left(\frac{D_{M,nom}}{D_{S,nom}}\right)}{2 \cdot \pi \cdot \lambda_M \cdot L} \tag{49}$$

$$R_{th,I,rd} = \frac{R'_{th,I,rd}}{L} = \frac{ln\left(\frac{D_{I,nom}}{D_{L,nom}}\right)}{2 \cdot \pi \cdot \lambda_I \cdot L}$$

Comments
- The cable length L for determining the thermal resistance is standardised to one metre.
- The temperature dependence of thermal resistances of plastics can be controlled via a temperature coefficient, analogous to the electrical resistance. It is usually set to 0; i.e. we usually consider constant thermal resistances.

6.1.5.3 Radial heat resistance of radiation and convection for round cables
The thermal conductivities per metre of length are first determined:
Thermal conductivity sheath surface, [W/(K·m)]:

$$Y'_{th,U,M,rd} = \pi \cdot D_{M,nom} \cdot \alpha_M \tag{50}$$

Combined thermal conductivity insulation surface, [W/(K·m)]:

$$Y'_{th,U,I,rd} = \pi \cdot D_{I,nom} \cdot \alpha_I \tag{51}$$

Combined thermal conductivity $Y_{th,U,rd}$ in [W/K] of the sheath and insulation surface at a given cable length L:

$$\mathbf{Y_{th,U,M,rd}} = Y'_{th,U,M,rd} \cdot L = \pi \cdot D_{M,nom} \cdot \alpha_M \cdot L \tag{52}$$

$$\mathbf{Y_{th,U,I,rd}} = Y'_{th,U,I,rd} \cdot L = \pi \cdot D_{I,nom} \cdot \alpha_I \cdot L$$

Comment
- The cable length L for determining the thermal conductivity is standardised to one metre.
- In many software applications that simulate thermal networks, *thermal resistances* are mandatory input values. They can be calculated directly using the reciprocal of the conductances.

Combined radial thermal resistance $R_{th,U,rd}$ in [K/W] of sheath and insulation:

$$R_{th,U,M,rd} = 1/Y_{th,U,M,rd} \tag{53}$$

$$R_{th,U,I,rd} = 1/Y_{th,U,I,rd}$$

6.1.5.4 Radiation
The radiation and convection heat transfer coefficients $\alpha_{M,I} = \alpha_{konv} + \alpha_{str}$ depend on the dimensions of the heat-emitting surface and surface temperature. When dealing with bulk goods for shielded and unshielded cables, the cylindrical surfaces are considered. The following formula applies to the radiation term for cylindrical surfaces:

$$\alpha_{str} = \varepsilon_{M,I} \cdot \sigma \cdot \left(T_U + T_{M,I}\right) \cdot (T_U^2 + T_{M,I}^2) \tag{54}$$

The elements contained in the formula: Stefan Boltzmann Constant $\sigma = 5.671 \cdot 10^{-8} \ W/(m^2 K^4)$, ambient temperature T_U, surface temperature of the sheath or insulation $T_{M,I}$ the emissivity of the sheath or insulation $\varepsilon_{M,I}$. T_U and $T_{M,I}$ are indicated in Kelvin.

6.1.5.5 Convection

The convection term α_{konv} can be determined for defined temperature ranges Δ_T and cable dimensions with an outer diameter D. α_{konv} describes the heat dissipation for round cables with *free* convection.

α_{konv} for varying temperature differences and diameters

Table 32: Convection of cables

	D = 1 mm	D = 5 mm	D = 20 mm
$\Delta T = 10$ K	$\alpha_{\text{konv}} = 22 \ W/(K \ m^2)$	$\alpha_{\text{konv}} = 9 \ W/(K \ m^2)$	$\alpha_{\text{konv}} = 5 \ W/(K \ m^2)$
$\Delta T = 50$ K	$\alpha_{\text{konv}} = 27 \ W/(K \ m^2)$	$\alpha_{\text{konv}} = 12 \ W/(K \ m^2)$	$\alpha_{\text{konv}} = 7 \ W/(K \ m^2)$
$\Delta T = 150$ K	$\alpha_{\text{konv}} = 32 \ W/(K \ m^2)$	$\alpha_{\text{konv}} = 15 \ W/(K \ m^2)$	$\alpha_{\text{konv}} = 10 \ W/(K \ m^2)$

ΔT describes the temperature difference between the surface and the environment. In contrast to the radiation term, the convection term is virtually independent of the actual value of the ambient temperature. The line highlighted in blue contains the values for the convection term with a temperature difference of 50 K. These convection term values can be used in the calculation for constants that are characteristic of the cable – such as the length constant.

6.1.5.6 Thermal resistance of metals, axial

In the event the values for the thermal conductivities of metals are known, the thermal resistances per metre of length are determined first:

Axial thermal resistance shield [K/(W·m)]:

$$R'_{th,S,ax} = \frac{1}{A_S \cdot \lambda_S} \tag{55}$$

Axial thermal resistance conductor [K/(W·m)]:

$$R'_{th,L,ax} = \frac{1}{A_L \cdot \lambda_L} \tag{56}$$

If the thermal conductivity of the metals is unknown, the application of the Wiedemann-Franz Law can provide a reliable approximate value for 20 °C. This law relates the electrical and thermal conductivity of a metal and reads:

$$\frac{\lambda}{\kappa} = T \cdot Lr = cLr$$

with $\quad \lambda \ldots$ thermal conductivity in W/(k · m)

$\kappa \ldots$ electrical conductivity in 1/(Ω · m)

$T \ldots$ absolute Temperature in K

$Lr \approx 2.3 \cdot 10\text{-}8 \ldots$ Lorenz number in V²/K

$cLr \ldots$ temperature-dependent Lorenz number in V²/K

At 20 °C, the temperature-dependent Lorenz number reads cLr≈6.74·10-6 V2/K.

Combined with the conductor cross-sections $A_S = \dfrac{1}{\kappa_S \cdot R'_{el,S,max}}$, $A_L = \dfrac{1}{\kappa_L \cdot R'_{el,L,max}}$ of the shield

and/or of the conductor, the following relationships can be established:

Axial thermal resistance shield [K/(W·m)]:

$$R'_{th,S,ax} = \frac{1}{A_S \cdot \lambda_S} = \frac{\kappa_S \cdot R'_{el,S,max}}{\lambda_S} = \frac{R'_{el,S,max}}{c_{Lr}} \qquad (55a)$$

Axial thermal resistance conductor [K/(W·m)]:

$$R'_{th,S,ax} = \frac{1}{A_S \cdot \lambda_S} = \frac{\kappa_S \cdot R'_{el,S,max}}{\lambda_S} = \frac{R'_{el,S,max}}{c_{Lr}} \qquad (56a)$$

The thermal conductivities λ_S and λ_L already shown in grey in the tables for basic parameters are *not* required in this case.

Axial thermal resistance $R_{th,ax}$ in [K/W] of the shield and conductor at a given cable length L:

$$\mathbf{R_{th,S,ax}} = R'_{th,S,ax} \cdot L = \frac{R_{el,S,max}}{c_{Lr}} \cdot L \qquad (57)$$

$$\mathbf{R_{th,L,ax}} = R'_{th,L,ax} \cdot L = \frac{R_{el,L,max}}{c_{Lr}} \cdot L$$

Comment
The cable length for determining the thermal resistance is standardised to one metre.

6.1.5.7 Heat capacities of plastics
The heat capacities per metre of length are first determined:
Van Wormer coefficient sheath, dimensionless:

$$p = \frac{1}{2 \cdot \ln\left(\frac{D_{M,nom}}{D_{S,nom}}\right)} - \frac{1}{\left(\frac{D_{M,nom}}{D_{S,nom}}\right)^2 - 1} \qquad (58)$$

Interior heat capacity sheath [J/(K·m)]:

$$C'_{th,M,a} = (1-p) \cdot \gamma_M \cdot \frac{\pi}{4} \cdot \left(D^2_{M,nom} - D^2_{S,nom}\right) \qquad (59)$$

Exterior heat capacity sheath [J/(K·m)]:

$$C'_{th,M,i} = (1-p) \cdot \gamma_M \cdot \frac{\pi}{4} \cdot \left(D^2_{M,nom} - D^2_{S,nom}\right) \qquad (60)$$

Van Wormer coefficient insulation, dimensionless:

$$p = \frac{1}{2 \cdot \ln\left(\frac{D_{I,nom}}{D_{L,nom}}\right)} - \frac{1}{\left(\frac{D_{I,nom}}{D_{L,nom}}\right)^2 - 1} \qquad (61)$$

Interior heat capacity insulation [J/(K·m)]:

$$C'_{th,I,i} = p \cdot \gamma_I \cdot \frac{\pi}{4} \cdot \left(D^2_{I,nom} - D^2_{L,nom}\right) \qquad (62)$$

Exterior heat capacity insulation [J/(K·m)]:

$$C'_{th,I,a} = (1-p) \cdot \gamma_I \cdot \frac{\pi}{4} \cdot \left(D^2_{I,nom} - D^2_{L,nom}\right) \qquad (63)$$

In the next step, the heat capacities C_{th} in [J/K] of the plastics with the specified cable length L are calculated:

$$C_{th,M,i} = C'_{th,M,i} \cdot L \tag{64}$$

$$C_{th,M,a} = C'_{th,I,i} \cdot L$$

$$C_{th,I,i} = C'_{th,M,i} \cdot L$$

$$C_{th,I,a} = C'_{th,I,i} \cdot L$$

Comments:
- The cable length L for determining the heat capacity is standardised to one metre.
- The temperature dependence of the specific heat capacities of plastics can be controlled via a temperature coefficient, similar to the electrical resistance. Since it is normally set to 0, constant heat capacities are usually considered.

6.1.5.8 Heat capacities of metals
Heat capacity shield [J/(K·m)]:

$$C'_{th,S} = A_S \cdot c_S \tag{65}$$

Heat capacity conductor [J/(K·m)]:

$$C'_{th,L} = A_L \cdot c_L \tag{66}$$

With the conductor cross-sections $A_S = \dfrac{1}{\kappa_S \cdot R_{el,S,max}}$, $A_L = \dfrac{1}{\kappa_L \cdot R_{el,L,max}}$ to the shield or to the conductor.

The heat capacity C_{th} in [J/K] of the metals with the specified cable length L is calculated:

$$C_{th,S} = C'_{th,S} \cdot L = A_S \cdot c_S \cdot L \tag{67}$$

$$C_{th,L} = C'_{th,L} \cdot L = A_L \cdot c_L \cdot L$$

Comment
The cable length L for determining the heat capacity is standardised to one metre.

6.1.5.9 Length constant
The length constant χ describes the axial transient response of the cable temperature. A lower limit can be determined directly from the axial and radial thermal resistances of shielded or unshielded cables. The following applies:

χ of an unshielded cable [m]:

$$\chi = \sqrt{\frac{R'_{th,I,rd} + R'_{th,U,I,rd}}{R'_{th,L,ax}}} \tag{68}$$

χ of a shielded cable [m]:

$$\chi = \sqrt{\frac{R'_{th,I,rd} + R'_{th,M,rd} + R'_{th,U,M,rd}}{R'_{th,L,ax} + R'_{th,S,ax}}} \tag{69}$$

To determine the thermal resistance to the environment (combined radial thermal resistance $R'_{th,U,M,rd}$ and/or $R'_{th,U,I,rd}$), a surface temperature of 110 °C and an ambient temperature of 60 °C is assumed.

This constant can be used as a *standard length* when selecting the length L of a cable slice. For more details, please refer to [5] (see Reference list).

6.2 Connector

### 6.2.1 Proposed test design for determining the thermal properties of HV connectors

The aim is to define a measuring setup that makes it possible to test the connector to be examined independently of other influencing factors in terms of its thermal behaviour and determine the parameters for the thermal equivalent circuit diagram. To characterise the heat generation behaviour, power must be supplied to the connector via the cable and it must be possible for thermal energy to dissipate via convection, radiation and contact heat with the environment. While the derating measurement is sufficient for characterising comparatively small connectors with low currents, higher currents mean that cable supply lines and convection have a greater impact on the overall system. Another essential point is that system cooling measures (active or passive) are not taken into account.

To counteract this, the measurement should be set up to meet the following requirements:
- Flexibility: can be adapted for different connectors, cable cross-sections and can be used for shielded and unshielded systems.
- Minimal environmental influences: the supply lines must be kept as short as possible to minimise the influence of the cable. The heat output from convection and radiation from the housing must be controlled as effectively as possible.
- High voltage: it should also be possible to test the connector beyond current requirements to account for cooling measures in the system. A good way to do this is to integrate cooling mechanisms and defined heat sinks in the test design.
- Control: the boundary conditions of the test design must be known. This means that, in addition to the design parameters (cable cross-section, cable length, ambient temperature…), the cooling capacity and/or temperature at the cooling points must also be known/measurable. Redundant measurements should be carried out to verify the parameters and detect possible measurement errors. For example, the temperature should be checked via the voltage drop in the system to ensure the accuracy of the temperature measurements by means of a plausibility check.

These requirements can be implemented as follows: the cables at the connector are limited to a length of 15 cm for connection to the heat sinks, both to define how the cables self-heat and to minimise heat dissipation via the surface. The cables are terminated after these 15 cm with cable lugs. To generate the most effective cooling possible, an established procedure is to attach a copper plate with the cross-section of the cable to each of the four cable lugs (Figure 20).

Figure 20: Copper plate with cooler

Copper plate

CPU cooler
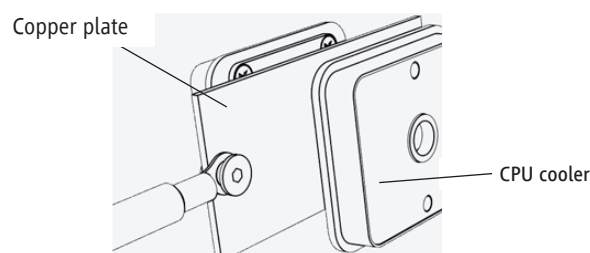
Source: TE

The length and width of the copper plates must be selected so that they can be mounted between two heat sinks. Cooling should ideally take place via a water circuit with known flow rates along with inlet and return temperatures, which can be used to determine the corresponding cooling capacity. The cross-section of the copper plate used must be greater than or equal to the cable cross-section in order to avoid creating an additional thermal source. Following the copper plates, the measurement setup is then connected to a controllable power source via back-wiring as a short circuit loop (Figure 21).

Figure 21: Proposed measurement setup for determining the thermal properties of HV connectors

CPU cooler

Connection to power source

Short circuit loop
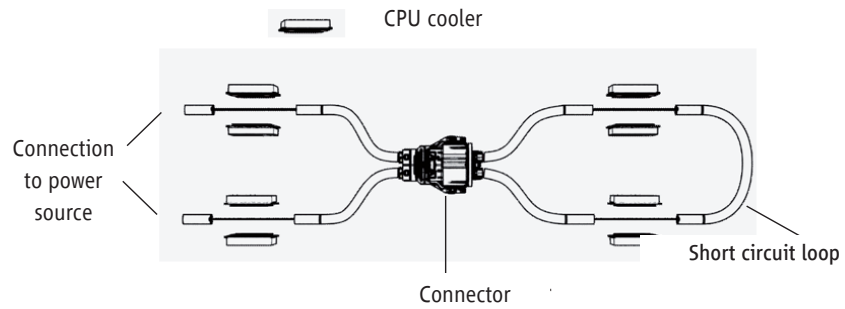
Connector

The cooling plates can be connected in series to a water cooling system that regulates to a constant inlet temperature. Since the cooling capacity decreases over the length of the cooling circuit and the thermal connection of the heat sinks to the copper plates is subject to statistical fluctuation, at least one temperature sensor should be attached to the copper plates to determine the material temperature at the cooling point. This value is used as a boundary condition in thermal simulation.

6.2.2 Derivation of model parameters

Various parameters are required to model the connector in the equivalent circuit diagram. These parameters can be inferred from geometric considerations, material data, FEM simulations and even measurements. These individual parameters are outlined in the following:

Determining thermal conductive resistance

Thermal conductive resistance can be determined in several ways. The preferred method is determined based on the geometry and accessibility of the component to be characterised. The Wiedemann-Franz Law can be used to determine the thermal resistance along the cable path:

$$\frac{\lambda}{\sigma} = L \cdot T \qquad (70)$$

λ describes the thermal conductivity of the metal, σ the electrical conductivity, T the temperature and L is the Lorenz number. The thermal resistance of a metallic body with a length l and cross-section A results in $R_{\text{th}} = \frac{l}{\lambda \cdot A}$. Similarly, the electrical resistance is calculated with $R_{el} = \frac{l}{\sigma \cdot A}$. Conversion and insertion can be used to calculate the thermal resistance:

$$R_{\text{th}} = \frac{R_{\text{el}}}{L \cdot T} \qquad (71)$$

It should be noted here that the linear temperature coefficient is not taken into account in the absence of any values specified in the literature. Furthermore, the respective data sheets should be used to determine the Lorenz number for the different alloys.

In contrast to thermal resistance, it is easy to accurately determine the electrical resistance by the voltage drop U between the measuring points: $R_{\text{el}} = \frac{U}{I}$. In this instance, the electrical current I is sufficiently known – either by adjusting the power source or measuring it via a shunt. The basic prerequisite for this method is the ability to access the components via which the voltage drop/electrical resistance should be measured. In addition, the application is limited to metallic basic solids.

FEM simulations can also be used as an alternative. This methodology offers the most advantages in determining the thermal resistance of non-metallic bodies when conducting heat to different spatial directions. It involves feeding a thermal stimulus in the form of a heat flux P into a surface (Figure 22) and determining the temperature difference $\triangle T$ between the contact surfaces. It is then possible to determine the thermal resistance $R_{\text{th}} = \frac{\triangle T}{P}$. This method can reach its limits in complex components due to the computational effort required and when there are interfaces between the components.

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Figure 22: FEM method for calculating thermal resistances
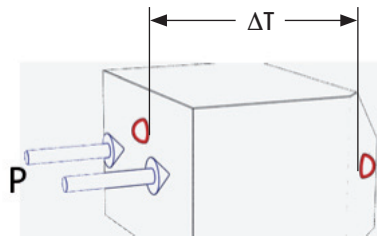
Source: TE

A third method can be used to bridge these gaps: temperature measurement. Temperature measurement makes it possible to validate the approaches outlined and to quantify complex components and assemblies in terms of their thermal resistance. Similar to FEM simulations, a heat flow is impressed into the system at one point and the temperature difference to the relevant points is determined. It is important to suppress convection to the greatest extent possible. The heat flow can be impressed using a cartridge heater with a defined heating capacity (see also Figure 23).

Figure 23: Defined heat input using cartridge heaters
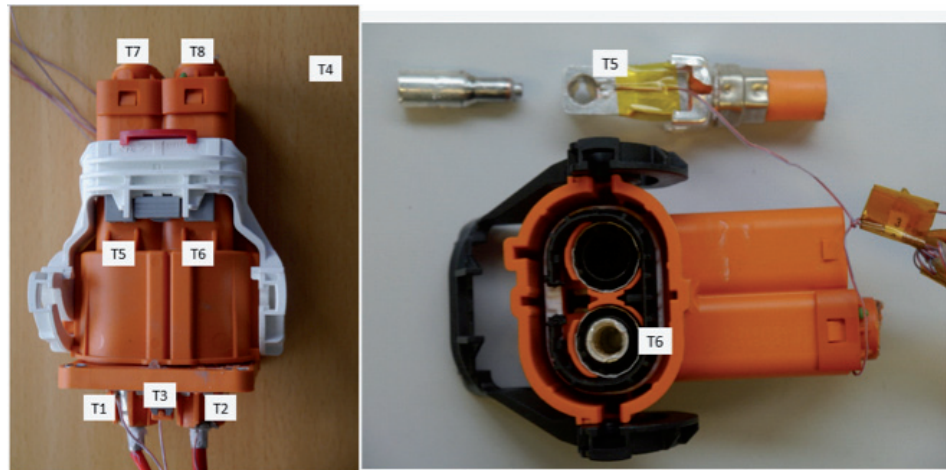
Source: TE

Determination of thermal capacities/heat capacities

Determining the heat capacity is much more difficult. The established process is to calculate the volumes V of the bodies using geometric data and to determine the thermal mass or capacity C via the density ρ_b and specific heat capacity c: $C = c \cdot V \cdot \rho_b$. An empirical determination of the thermal mass using a calorimeter, for instance, is not very effective, since in a thermal equivalent circuit diagram only parts of components or multiple components are combined to form a single thermal mass. For simple geometries, it is possible to use the same test setup as the one used to determine resistance. Here, a heat flow P (electrical heat output) is impressed into the system using a resistance wire or a heater cartridge and the temperature increase is measured. This temporal analysis can be used to determine the thermal capacity as long as the heating behaviour is largely linear over time:

$$C = \frac{\int_{t=0}^{\tau} P \, dt}{T(t = \tau) - T(t = 0)} \qquad (72)$$

The methods described here offer a basis of data that can be selected as the starting point for the thermal equivalent circuit diagram.

Determination of convection and radiation resistances

Convection and heat radiation both play a role in the measuring setup, but will differ significantly in the final system and are therefore not part of the connector model – nevertheless, they still must be considered in model design.

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Initially, the geometry of surface A can be used. Empirical values are used for the convection parameter α. These two parameters can be used to describe convection using $P = \alpha \cdot A \cdot \Delta T$, where ΔT indicates the temperature difference between the body and the environment.

For heat radiation, $P = \varepsilon \cdot \sigma \cdot A \cdot (T_A^4 - T_B^4)$ applies, where σ is the Stefan Boltzmann constant, T_A and T_B specify the temperatures of the partners involved in the heat exchange and ε is the emissivity, a material constant for the surface of the radiating solid.

The first approximate value for a rough rated resistance can be derived from the power loss related to the connector and the temperature increase in the case of static heating.

Optimisation of model parameters

In order to achieve final model parameters, the basic model (i.e. the complete measuring setup) must be compared with the measured values. This can be done either using special software or "manually". The capacities must be adjusted so that the transient response can adapt. With suppressed convection and radiation, electrical resistances ultimately determine the temperature of the stationary case.

Logic for naming the parameters

A) Table 33: The reference to thermal or electrical physical quantity is written in subscript

th	thermal quantity	el	electrical quantity

B) Table 34: Description of the physical quantities in the circuit model

Symbol	Physical quantity	Unit	Note
$P, \dot{Q}$	Heat flow or ohmic power loss	W	Generally referred to as $\dot{Q}$
I	Electrical current	A	
C_{th}	Heat capacity	J/K	Also referred to as thermal mass. Must always be connected against the "start temperature".
T	Temperature	°C; K	The absolute temperature must be considered for radiation
R_{el}	Electrical resistance	Ω	The power loss is generated from the electrical path as heat flow according to $R \cdot I^2$
$R_{el, K}$	Electrical contact resistance	Ω	Contact resistance
R_{th}	Thermal resistance	K/W	The model distinguishes between three types of thermal resistances: conduction resistances, convection resistances and radiation resistances.
b	Width	m	
l	Length	m	
h	Height	m	
D	Diameter	m	
A	Area	mm²	Surface of various components, e.g.: A_O as surface for the pin connector and A_{OS} as surface for the female terminal housing
α_{el}	Linear temperature coefficient – electrical		Parameter for changing the electrical resistance via the temperature
α_{th}	Linear temperature coefficient – thermal		Parameter for changing the thermal resistance via the temperature
α_K	Convection factor	W/(m² K)	Depends on many parameters – convection model (heat atlas)
ε	Emission factor		For plastics in the range of 0.5-0.9
t	Time	sec	

Index	Definition	Index	Definition
Amb	Ambiance, environment	Start, t = 0	Time t = 0
L	Conductor	V	Stranding
S	Shield	Z	Filler
I	Insulation	M	Sheath
G	Housing	rd	radial
P	Pin contact	min	minimum
B	Contact path for multi-contact elements	max	maximum
K	Contact	nom	nominal
F	Spring	l	left
C	Crimp	r	right
T	Termination	i	inner
A	Outer surface	a	outer
Aggr , Ag	Refers to the inside of the component/control unit	ax	axial
House	Refers to the component housing	cond	conduct
0	Output variable	single	Single contact element
A, B	Left/right interface		

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6.3 Geometry preparation

To analyse the system simulation parameters, the first step is to split the CAD model into the individual system simulation blocks. To do this, the geometry must be analysed and the system/clipping boundaries must be defined. To correctly determine the separation, the equivalent circuit diagram for the system simulation (Figure 24) should be set up in the first step.

Figure 24: Block diagram for single-pin shielded connectors
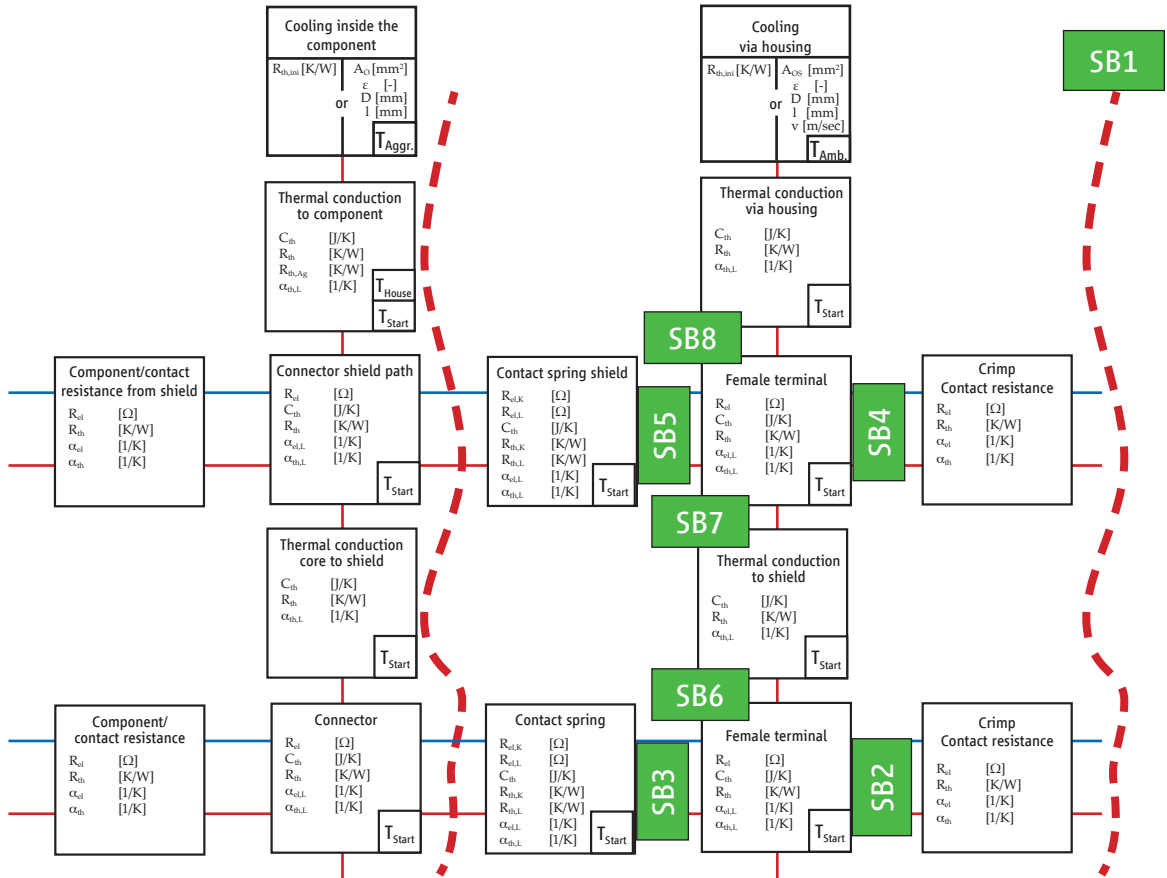
Source: ZVEI

For geometry analysis, the pin and female terminal contact parameters can be viewed separately when performing the simulated extraction, because the wiring connection to the mating connector in the simulation does not rely on any existing geometry. The coupler shown the coupler shown in Figure 25 is used to present the general procedure.

Figure 25: Example of CAD geometry
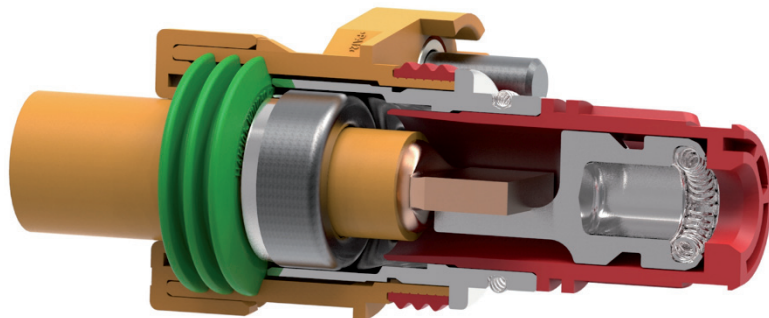
Source: Rosenberger

6.4 Definition of clipping boundaries

6.4.1 System boundary to cable

The system boundary of the cable to the connector at the electrical transition is defined in the block diagram. A secondary boundary condition is that the cable at the system boundary must remain undisturbed in its electrical or thermal properties. For the connector shown in Figure 26, the flat plastic housing surface represents the system boundary to the cable (system boundary 1 in Figure 26).

Figure 26: System boundaries for cables and inner conductors

System boundary 1:
cable/connector

System boundary 2:
contact resistance and
inner conductor
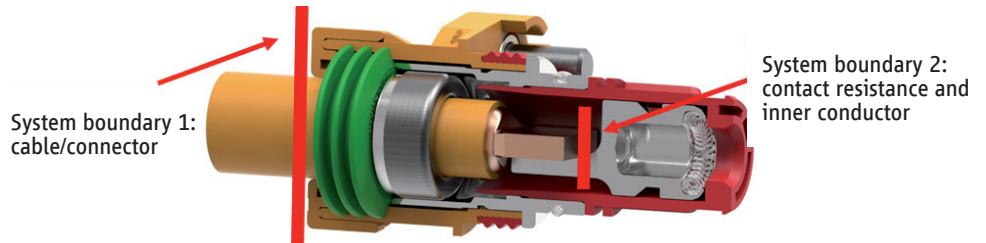
Source: Rosenberger

6.4.2 Contact resistance cable inner conductor

In the sense of the block diagram shown in Figure 24, the contact resistance from cable to inner conductor is modelled without thermal properties. For coaxial structures, modelling and measurement are both rather difficult, because from the system boundary SB 1 (cable/connector) there is still a portion of the cable present with axial and radial expansion properties. To ensure a standardised definition of the value, the contact resistance from system boundary 1 (SB 1) to system boundary 2 (SB 2, cable/inner conductor) should be defined, although here, several resistors are connected in series with varying temperature coefficients.

Alternatively, the cable/inner conductor contact resistance can be specified separately. In this case, the portion of cable must be assigned thermally and electrically to the inner conductor.

Both variants are possible for system simulation. The parameter set of these two variants differs considerably, but the system response will not differ significantly.

6.4.3 Inner conductor female terminal

The "inner conductor female terminal" block is determined by the electrical and thermal properties of the inner conductor between SB 2 and SB 3. Depending on which cable components were considered for the inner conductor contact resistance (Section 3.2.1), the corresponding pin and cable line portions that have not been considered will be assigned to this block.

Figure 27: Inner conductor system boundaries

System boundary 2:
Female terminal/cable

System boundary 3:
contact element
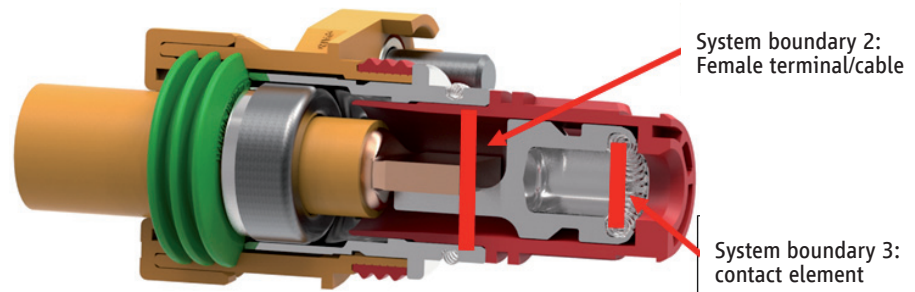
Source: Rosenberger

6.4.4 Heat flow from core to shield

To calculate the radial heat resistance R_{th}, all of the components of the inner conductor (cable + female terminal inner conductor) are combined. The components of the outer conductor, which contribute to the cooling of the inner conductor, are also combined.

6.4.5 Crimp/shield transition

To calculate the shield resistance at the cable transition, the transition point itself and the portion of the cable from the system boundary to the shield transition must be taken into account. The metal portion of the connector outer conductor between SB 1 and SB 4 is assigned to the crimp/shield transition block.

Figure 28: System boundaries for cable shield

System boundary 1: Cable/connector

System boundary 4: contact resistance inner conductor
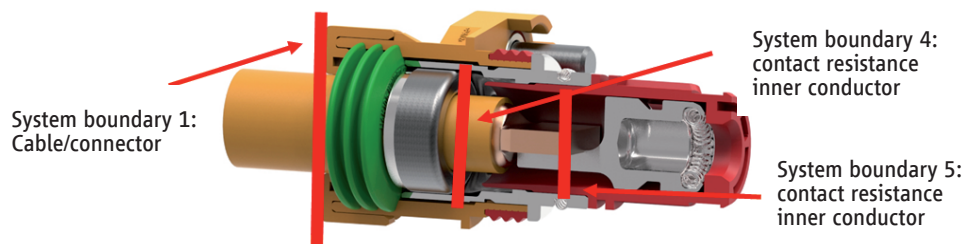
System boundary 5: contact resistance inner conductor

As with the inner conductor, the cable portion can also be assigned to the "female terminal shield" block. Depending on the variants, the portion of the cable that is not considered must be included in the heat flow via shield conductor" block.

6.4.6 Heat flow via shield conductor

The heat flow via the shield conductor corresponds to the metal portion between SB 4 and SB 4 (see Figure 28). The axial thermal resistance from the female terminal housing to the connector housing in this block must also be taken into account, as no axial heat conduction is possible in the "thermal conduction via housing" block. For plastic components, this portion is very small and can usually be ignored.

6.4.7 Thermal conduction via housing

The radial conduction of the shield through the housing takes into account all heat-conducting components that surround the shield conductor outwards. In the example in Figure 28, these are the outer plastic housing and the sealing element. The heat transfer from the housing to the environment via convection and radiation is taken into account in a separate block, to make it easier to calculate variations in these portions later on.

6.4.8 Cooling via housing

This block takes into account the convection and radiation of the plastic housing surrounding the connector. The heat transfer coefficients are determined using the calculation principles of the technical guideline. Note that the heat transfer related to the surface of the housing must be standardised to its basic form. The approaches outlined in the VDI Heat Atlas can be used as an alternative.

6.5 Contact definition

The contact zones must be modelled with a contact formulation that reflects the real electrical and thermal contact resistance. Note that the thermal and electrical contact properties do not have to be calculated. Instead, they should be determined by performing measurements on real components. The influence of the air gap in the contact area must also be taken into account.

6.6 Boundary conditions and analysis

The objective of the FE simulation is to determine the power loss and the resulting heating of current-carrying (live) components as precisely as possible. In addition, the thermal resistance should be determined in conductor expansion (axial) and transversely to this (radial). A coupled thermal-electric simulation is proposed for this purpose. Alternatively, electrical and thermal excitations can be considered separately.

To correctly calculate the characteristic values, all parts and components must be modelled with the correct geometric dimensions and mounting positions. Deviations from reality result in deviations in the characteristic values. In addition, all components must be assigned the correct material models in order to achieve accurate results. Note that the material properties can change with the temperature. It is therefore essential for these effects to be stored correctly in the material map.

Unlike measurements performed on real components, the individual components cannot be precisely separated when calculating the parameters. For this reason, the parameter set will always differ between calculated and measured values.

## 6.7 Electrical power loss and axial thermal resistance

6.7.1 Axial heat flow by impression

The electrical power loss is calculated by impressing a freely selectable test current. To this end, the current on one side and the voltage on the other side of the conductor must be defined. The resulting voltage difference can be obtained when solving the model calculation. Ohm's Law can then be used to calculate the electrical line resistance for the system simulation.

The thermal line resistance is also calculated in the direction of the cable. The temperature is defined on one side and the heat flow is impressed on the other side. This causes the temperature to rise. Analogous to Ohm's Law, the thermal line resistance can also be calculated here with the temperature difference and the impressed heat flow.

Alternatively, the heat flow can be determined by specifying a temperature difference.

## Figure 29: Boundary condition for determining electrical and thermal line resistance
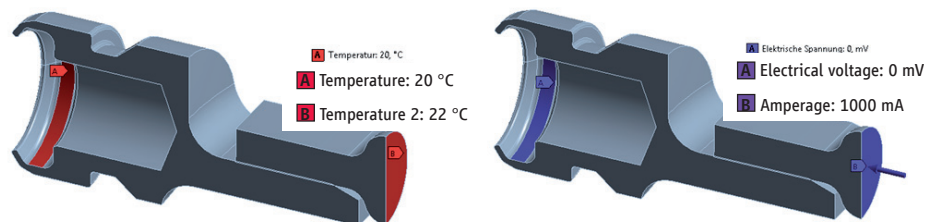
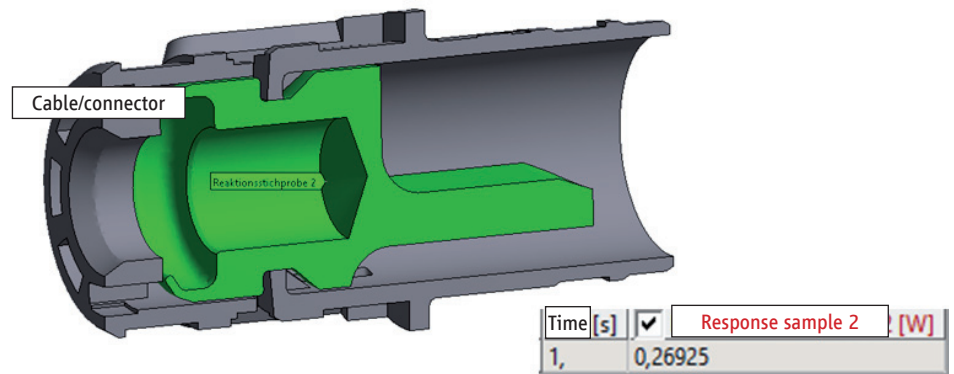
Source: Rosenberger

6.7.2 Radial heat flow

Radial heat flow is calculated in a manner similar to that of the axial heat flow. As one option for the boundary condition, a thermal boundary condition can be defined for the inner conductor side. To force the heat flow, a thermal boundary condition is also defined for the shield conductor side (see Figure 30). However, the two boundary conditions have a temperature difference that can be freely selected. The temperature gradient initiates a heat flow in the calculation, which can then be output (see Figure 31). The thermal resistance for the system simulation can be calculated using the equation (74).

Figure 30: Thermal boundary condition for determining the radial heat flow

Temperature 2: 25 °C   Temperature: 20 °C
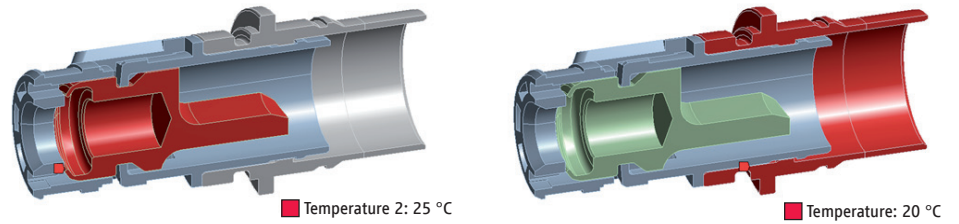
Source: Rosenberger

Figure 31: Thermal response to set temperature gradients

Cable/connector

| Time [s] | ☑ | Response sample 2 | [W] |
| 1, | | 0,26925 | |

Source: Rosenberger

6.8 Evaluation and transfer of parameters for system simulation

The existing 3D CAD geometry is abstracted to the respective ground point for the system simulation. The following possible content results for the respective module:

Electrical resistance	R_{el}	[Ω]
Linear electrical temperature coefficient	α_{el}	$[\frac{1}{K}]$ –
Thermal resistance	R_{th}	[K/W]
Thermal capacity	C_{th}	[J/K]
Linear thermal temperature coefficient	α_{th}	$[\frac{1}{K}]$ –

This section offers a general description of how to determine the parameters for the system simulation. Equivalent calculation approaches are described for a single component and referenced to this method for similar cases.

When they are not listed in this technical guideline, the substance values required to calculate characteristic values are taken from material data sheets or the VDI Heat Atlas.

6.9 Necessary equations

Electrical resistance:

$$R_{el} = \frac{\Delta U}{I} \qquad (73)$$

Thermal resistance:

$$R_{th} = \frac{\Delta T}{\dot{Q}_V} \qquad (74)$$

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6.10 Crimp/contact resistance (IL)

The real crimp resistance cannot be determined on the basis of the CAD model. Even with complex conversion simulations, this parameter is difficult to determine. Therefore, this parameter should be measured universally for each transition. To determine the correct line resistances, the distances between the test terminals must be known, as this portion of the cable must be offset when determining the remaining line resistance.

6.11 Female terminal

The electrical and thermal resistance of the female terminal is determined from the calculated voltage drop or temperature difference in the simulation. The conductor resistance of the female terminal can be determined with the current impressed, which has been defined as the boundary condition, and Ohm's Law (equation (73)).

Female terminal heating is calculated from the electrical power loss. The temperature difference defined by the impressed heat source and heat sink is divided by the electrical power loss for this purpose.

6.12 Contact spring

To calculate the electrical resistance of the contact spring, the contact resistance of the individual contact point must be added to the line resistance of the contact spring. The line resistance is determined based on the principle outlined in Section 6.10. The line resistance percentage can be calculated based on the geometry (Section 6.7). The contact resistance must be determined by measuring it.

For parallel current paths, the resistance of a single current path must be divided by the number of parallel paths (considering the parallel connection).

6.13 Thermal conduction core to shield

To determine the radial thermal resistance, the heat source and heat sink are defined with freely selectable temperatures at the inner conductor and the insulation. The resulting heat flow can be determined by calculating the system. The thermal resistance is then determined using equation (74).

6.14 Crimp/contact resistance shielding between female terminal-shield, contact spring shield and thermal conduction via housing

The procedure for determining the contact resistance of the shielding is analogous to Section 6.10.

6.15 Cooling via housing

The cooling of the housing must be modelled according to the actual circumstances. Convection and radiation are generally used for plastic housings. These parameters can be determined with a good approximation using the equations from this guideline or the substance values from the VDI Heat Atlas (Section Fa1 in the Heat Atlas). In the case of metal housings, the heat flow via attachment or contact to a component must be considered.

Convection

Convection is calculated according to the procedure outlined in this guideline. Alternatively, the VDI Heat Atlas can be used.

Radiation

The radiation coefficient can be found in the material data sheet.

7 Reference list

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