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Using Liquid Cooling to minimize temperature impact in High Power Charging (HPC) Systems

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Summary

This whitepaper outlines ITT’s development approach to a liquid cooled HPC (High Powered Charging) system comprised of cable, connector and cooling package along CCS1/ CCS2 interfaces for up to 500A. The paper covers customer requirements, project management approach, theories and models used in the concept and development stage and temperature test results. The system is applicable to charging stations around the globe and is able to significantly decrease charging times for Electric Vehicles.

Keywords: Charger, charging, cooling, fast charge, thermal management

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1 Market Background

Greenhouse gases are the main root cause for man-made climate change [i]. To limit the impact of climate change, the 2015 United Nations Climate Change Conference, identified targets to keep global warming below 2 K [ii]. Based on EPA findings, 27% of all greenhouse gases are originated from burning fossil fuel for transportation [iii]. Electrification of powertrains has been identified as the most effective solution for CO_2 reduction [iv].

However, electric mobility is still missing its breakthrough for four major reasons:

Price

While upfront costs of Electric Vehicles (EV) are still significantly higher than for cars using conventional (ICE) propulsion, total costs of ownership are approaching cost levels of comparable class cars [v].

Range

While high weight / low power density of batteries caused electric vehicles to historically be limited in range , the next generation of EVs are approaching a range of 250 miles for Hatchbacks and up to 300 miles for sedans [vi] (see Figure 1).

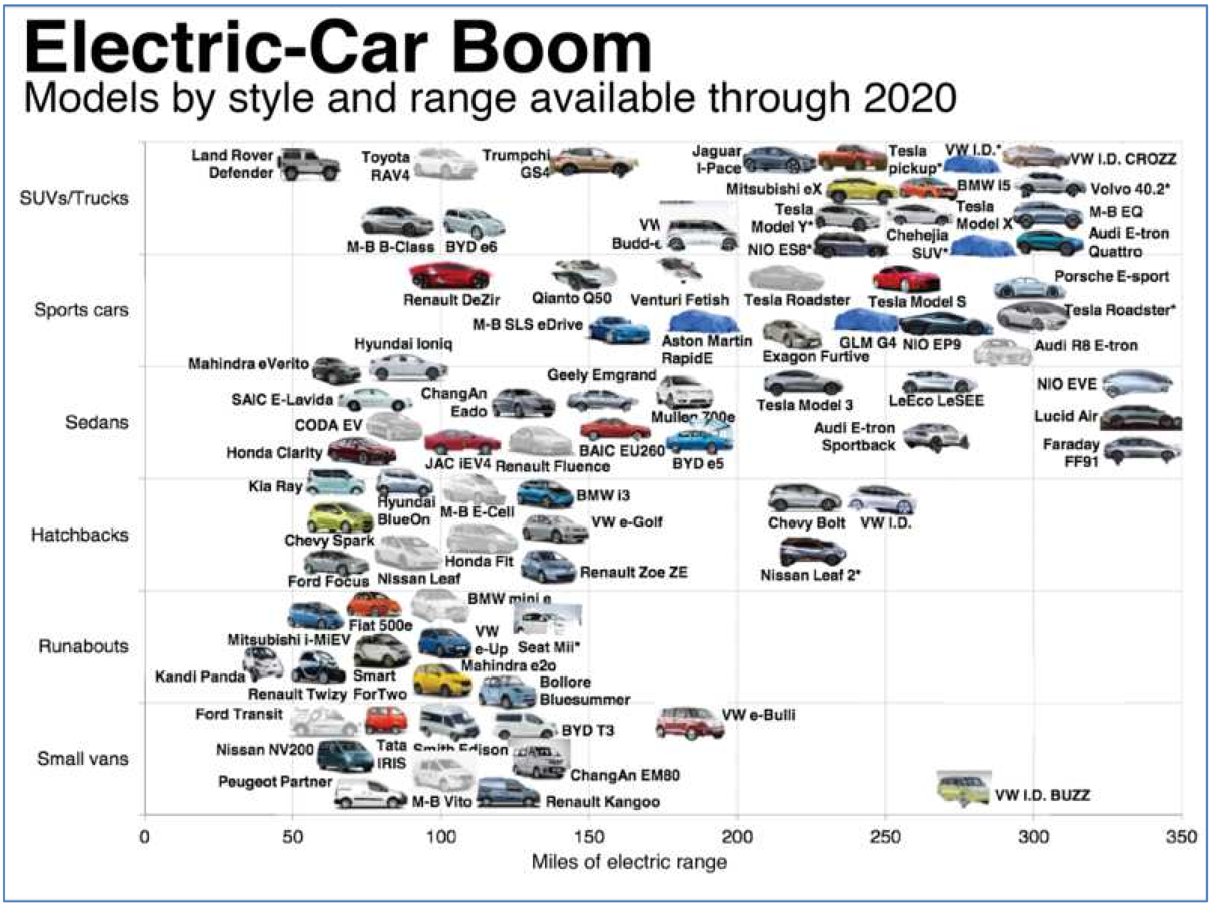

Figure 1: Range of EVs seeing their introduction between now and 2020

Availability of charging infrastructure

Although EVs are making inroads into the automotive fleet, the market for EVs cannot grow unless users can easily charge them. Accelerating infrastructure development is therefore crucial to support the transition to a decarbonized transport sector. Developing a network of charging stations facilitates market uptake. Several countries are therefore in the process of improving their network capacities to keep up with a growing EV market share. To facilitate the market uptake of electric mobility, the deployment of a minimum level of infrastructure for charging in both the public and private domain will be required. The European Commission, for example, has proposed that electric charging facilities should be built into new residential buildings with over ten parking spaces as of 2025. Also, the European Parliament called for an appropriate number of EV charging stations to be accessible to the public by 2020. Their number will depend on how many EVs are registered, with at least one charging point available for every 10 cars. [vii]

With e-mobility capable of addressing the three issues identified above, it is the time to recharge which is determining whether customer are accepting BEVs as an adequate alternative to ICE propelled conventional cars.

Time to recharge

Conventional AC charging, allowing for a maximum of 22 kW in NA or 43 kW in Europe (against existing standards), provides an adequate way to charge overnight. However, for long distance trips that require recharging on route, AC charging provides an inadequate charging solution due to the extended charging time required. DC charging to IEC 62196-3:2014 connector standards provides a capability to reduce charging hours significantly, but it is the latest High Power Charging (HPC) Combined Charging

Connectors (CCS) 1 / 2 with standards reaching up to 400 A / 1000 V that will enable charging of EVs to an additional range of 100 km (60 miles) within 3 to 5 min. OEMs that are first to offer HPC against an existing infrastructure will be those who solve the roadblock that still keeps EV from being a mass market product. The race for HPC is on.

2 The Starting Point for the HPC System Development

Based on various customer requests raised in 2015, ITT launched its high power connector development around the core demand identified (see Table 1). While underlying standards were precise in defining required interfaces, there was no guideline let alone standards to cover system approach for connectors of ≥ 400 A.

Table 1: Base specification HPC connector

Operating voltage	1000 V
Amperage	>400 A
Interface / core standards incl. subordinates	CCS 1: SAE J1772 / CCS2: IEC 62196
Temperature range	- 30°C to + 40°C
Standards	As they are introduced
Components offered	Connector, cable, cooling (optional)
Design	Core product
Cable length	Up to 8m

Based on close alignment to core players in the EV/EVSE industry, ITT anticipated an additional set of leading design principals to shape its HPC system development:

1. Safeguarding uncompromised product safety of service personal and end user
2. Find acceptance through all EV OEMs based on minimal impact beyond system barriers
3. Prime end user experience (light / flexible; comparable to DC standard solution)
4. Minimal life cycle costs to support EVSE manufacturers and operators
5. Easy installation and in field service capability

3 The Theory Behind Liquid Cooling HPC

To model heat input along the cable and connector, the system is considered as conductors set in series, (see Figure 2). Neglecting heat introduction through external heat radiation, heat dissipated along all resistors is determined by Jule’s law:

$$P = U * \dot{Q} = I^2 * R \qquad (1)$$

i.e. heat generation along a constant direct current is directly proportional to the resistance of the circuit and to the square of the current. To calculate power loss at a certain current for any element in series, resistance of corresponding element is to be raised as follows:

$$R = \rho(T) * \frac{l}{A} \qquad (2)$$

With l is the length and A the cross section area of resistor and ρ as specific resistance of underlying material, depends on absolute temperature T and thermal conductivity α:

$$\rho(T) = \rho(\mathrm{T_o}) * (1 + \alpha * (\mathrm{T} - \mathrm{T_o})) \qquad (3)$$

Beyond its copper conductor, there are further more resistances to be assessed, which are summarized by the diagram below (see Figure 2).

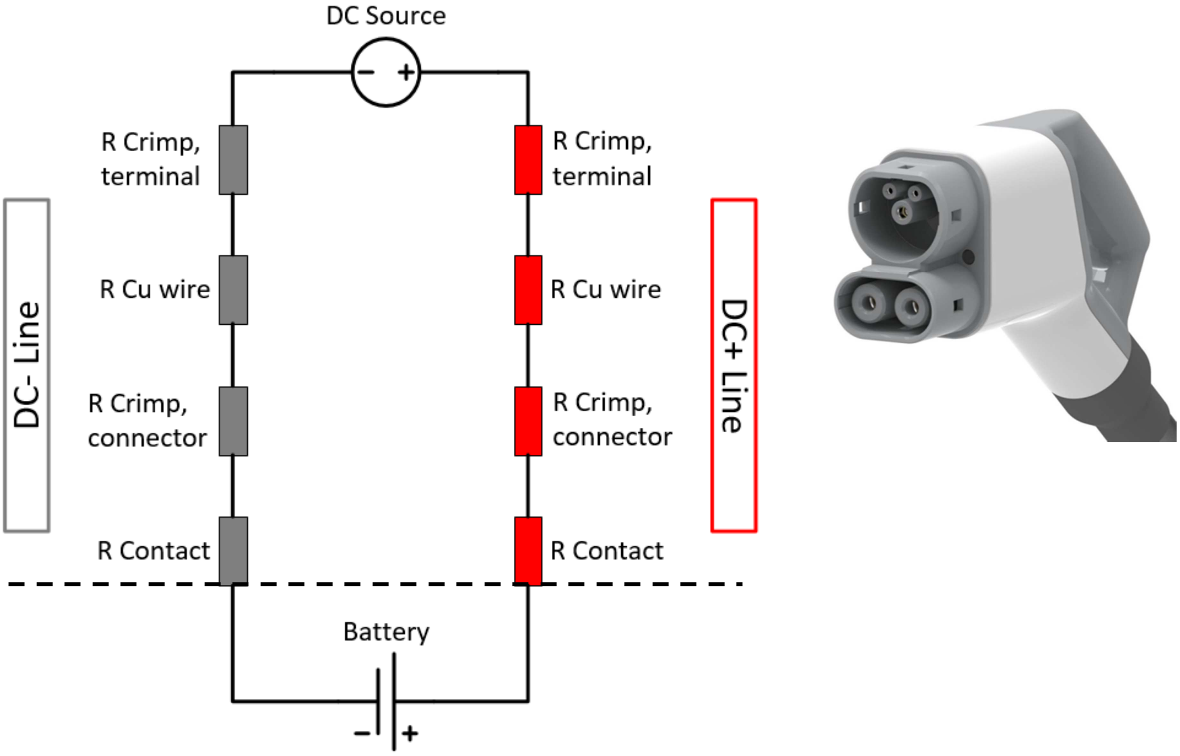

Figure 2: Major resistors considered for heat introduction

3.1 Contact Design

The heart of the contact design is the use of silver plated canted coil springs. While the material was chosen for optimal thermal transfer, the spring design was chosen to minimize mechanical impact and to secure longevity, (see Figure 3, right hand side).

Canted coil springs are outstanding in their characteristic of minimizing heat introduction through their 48 windings and thus multiple contact zones per spring. Based on the redundant spring system introduced, not only is the remaining active current reduced by 1/96 per contact area, but at the same time, Hertzian stress and residual mating force is also minimized due to faint translation force to widen spring.

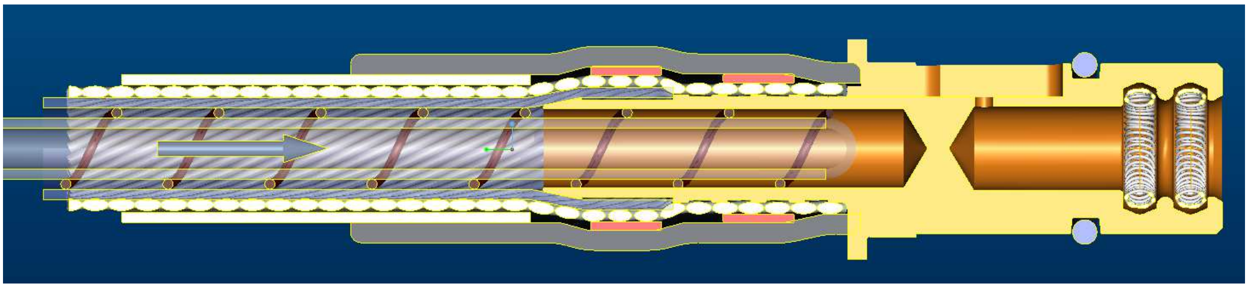

Figure 3: Cross section through cooled power line (left), cable crimp (central) and contact zone (right)

The target of residual design was to guarantee that heat impact through the contact carrier is negligible. Assessment of resistors along the contact R_{con} demonstrates:

$$R_{con} = R_{Crimp} + R_{Body} + R_{Spring}$$

R_{Crimp} residual resistor of crimp zone (17 µ Ω@ 400A continuous; measured)

R_{Body} residual resistor of contact body material ($R_{Body} << R_{Crimp}$; R_{Spring})

R_{Spring} residual resistor of contact spring (21 µ Ω; @ 400A continuous; measured)

with $R_{con} << R_{cable}$

heat dissipated through system is determined by

$$P(t) = I^{2}(t) * \rho(T) * l_{cable} / A_{cable} \qquad (4)$$

3.2 Contact Cooling

While various approaches for designing the cable were on trial, when checking them in concept phase against customer requirements, a liquid cooled cable was perceived as only viable solution to fulfill the ease of handling requirements identified. To keep the contact zone as effective cooled as possible and cable separated from the coolant medium, a tube in tube system was applied to allow the coolant to enter directly into the contact zone (see Figure3 left hand side).

3.3 System Cable

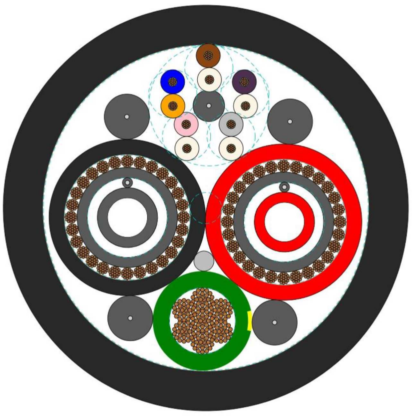

Figure 4: Cross section of cooled DC cable

Based on its optimized cooling design for both contact and cable, the cooling system can be run on 28 mm^2 copper cross section area only (see figure 4). Through optimization of filler and mantle material, easy handling is secured even for charging inlets difficult to access or at distance from EVSE. The cable is fitted by a 2 layer cooling system to ensure the medium is not able to exit its defined area of application. In case of vandalism or serious damage, the none-conductive medium is environmental friendly and will not damage users or ground soil. As applied to the contact design, redundancy to all major functional system components allows for maximum safety and reliability.

3.4 Integration Within EVSE

A plug and play end termination (see figure 5) allows for easy installation and cable exchanges in field within approx.+ 15 min dependent on final EVSE design. As such, the termination design allows for minimal service effort and allows for improved product availability along is life cycle.

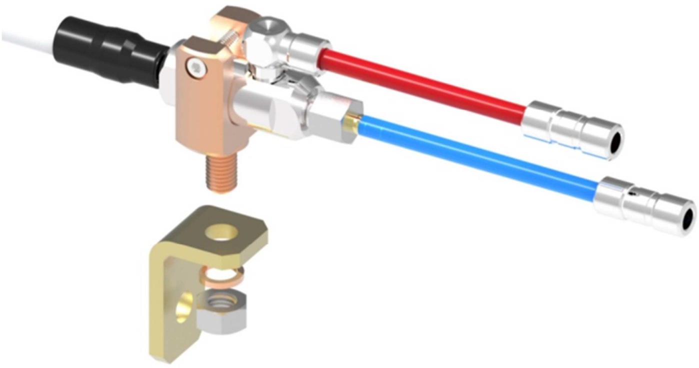

Figure 5: Termination to charging station

4 From Concept to Core Product

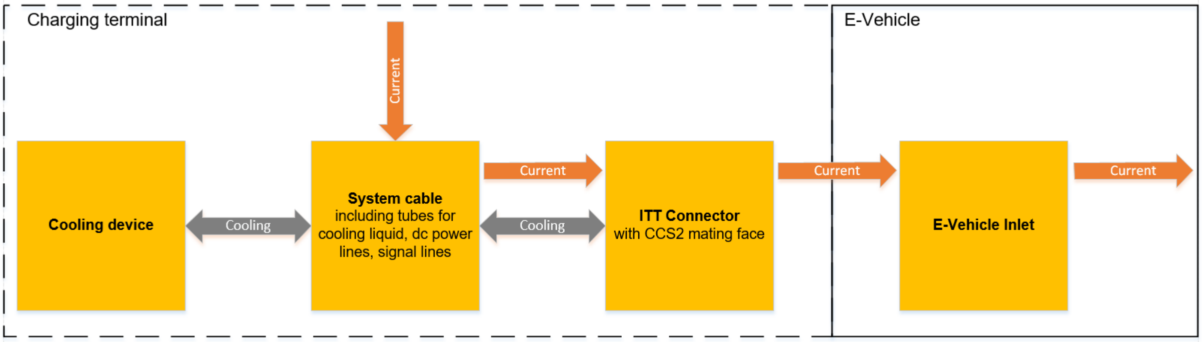

Figure 6: Block system applied to assess thermal conduction

For offering an all-in-one system that allows for reliable operation in all climate zones identified through table 1, ITT aligned with a cooling unit specialist. As a base solution, a modular standard unit was designed for continuous operation up to 500A. Considering EVSE design specific requirements, all unit components (see Figure 6) are easily rearranged to suit the most versatile compartment requirements posed for integration. Furthermore, cost effective approaches are also seen in passive cooling systems considering only extracts of base specification under consideration i.e. restrictions on cable length, load collective or ambient temperature below maximum base temperature stated. An effective and timely involvement of subcomponent manufactures introduced collective knowhow at early development stages and minimized revision efforts.

4.1 Modelling Heat Dissipation

Dependent on the conditions of operation, heat transfer along the cable is to be considered as steady or none-steady. Approaching the system as steady state during concept phase, heat development can be approximated by considering the cable as a carrier of n segments. For each segment i [1 .. n], according to Newton's law for heat transfer $\dot{Q}$ through wall surface A between media x and y of temperatures T_x and T_y and thermal conductivity $\alpha_{x,y}$:

$$\dot{Q} = \alpha_{x,y} A (T_x - T_y) \qquad (5)$$

and to be balanced with heat dissipation P(t) in (4), see figure 7:

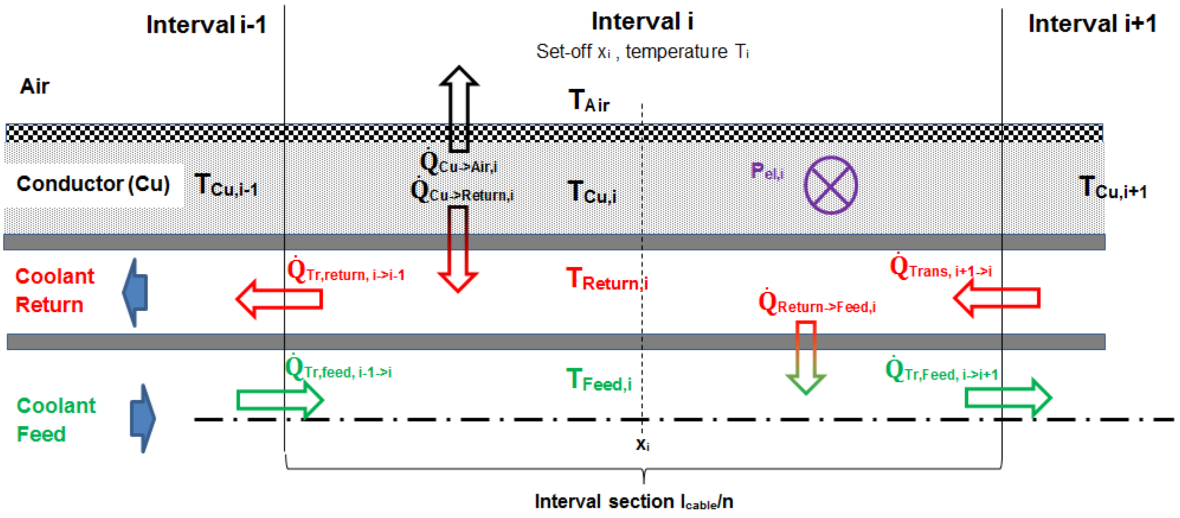

Figure 7: Heat flow along power line within one simulation interval i

When tested against heat development along steady state cable application in real unit, a correlation of absolute temperature values on a steady state current profile was confirmed (see Figure 8). During concept phase, the model primarily helped to quantify heat distribution along cable, crimp and contact zones. This approach secured the core functionality of the connector and lays the groundwork for the system's longevity by minimizing potential wear along weak areas along the assembly. At the same time, the model allowed the assessment the trade-off between securing low temperature range of touchable parts while allowing for a cable cross section design as flexible as possible.

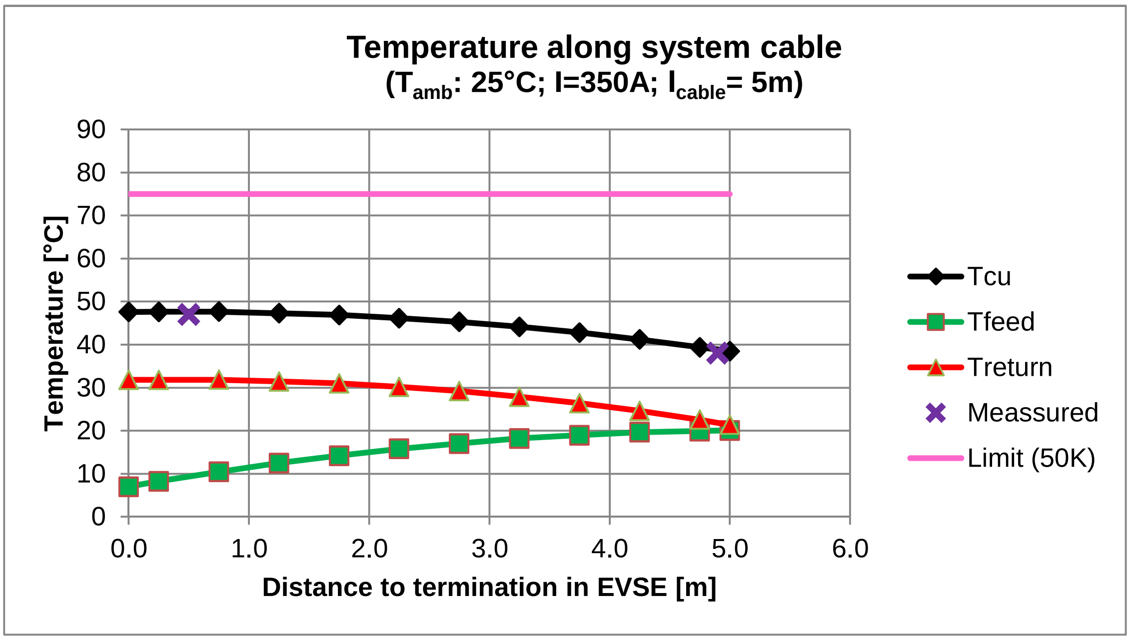

Figure 8: Model vs. measurements results on temperature along system cable

4.2 Test results on core product

Numerous test series were applied to iteratively assess design alternatives and gain quantitative results on the importance of various operation conditions. Various temperature sensors applied to critical positions allowed evaluation of the systems capability to dissipate heat as simulated (see Figure 9):

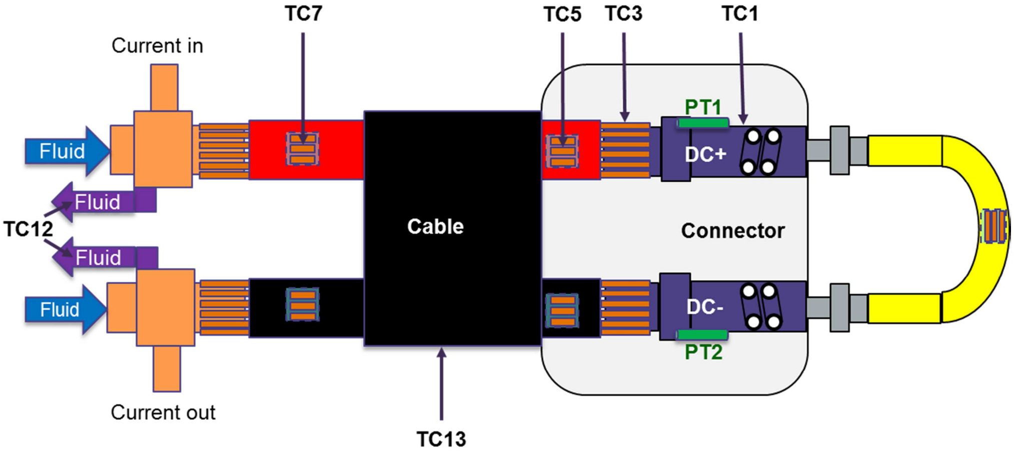

Figure 9: Thermocouples applied to validate connector system (as described in Table 2)

Table 2: Description of Thermocouples (TCs)

TC1: Element in contact zone	Element placed directly in contact zone
TC3: Element in crimp zone at connector	Element placed directly in crimp zone
TC5: Element in power wire (Connector)	Element 0.3 m away from crimp zone connector
TC7: Element in power wire (EVSE)	Element 0.3 m away from crimp zone termination
TC12:Fluid backflow within EVSE	Element 0.2 m away from termination
TC13:Jacket surface of cable (touchable part)	Element 1.5 m away from connector strain relief
PT1: PT1000 sensor of system	Positioned within HPC contact as requested by VDE-AR-E 2623-5-3

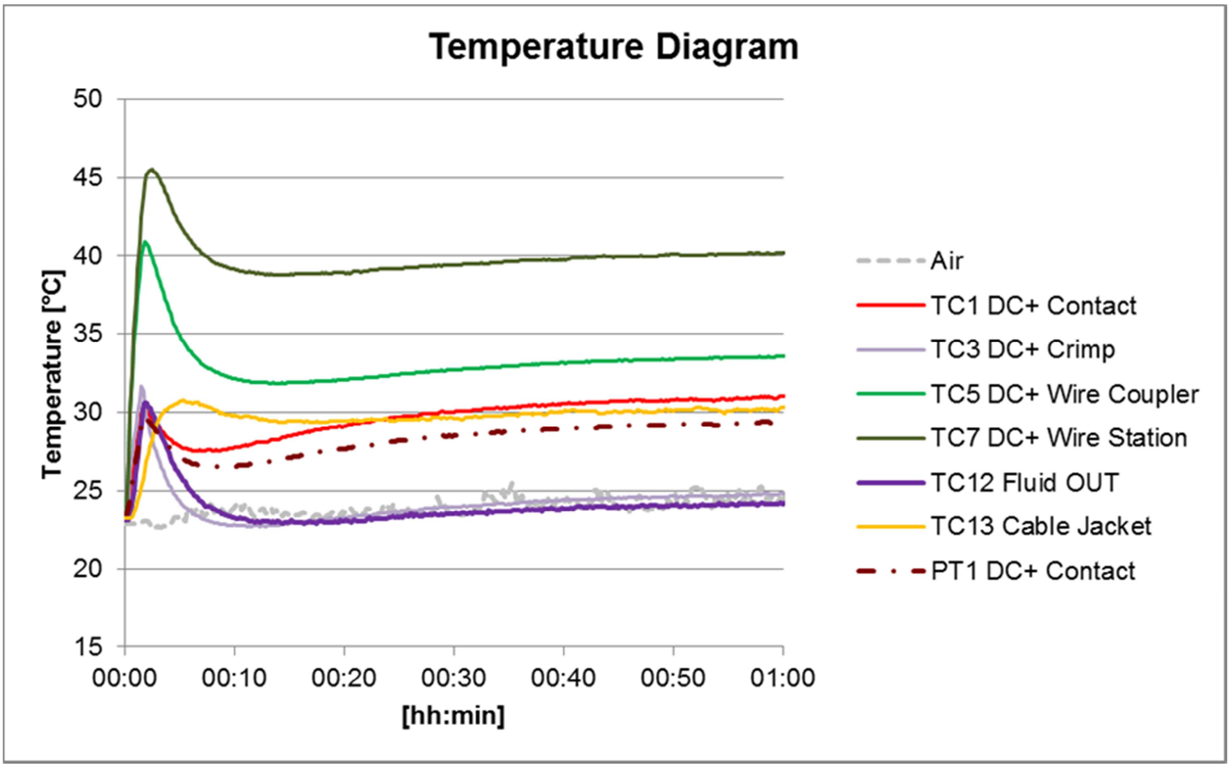

Figure 10: Temperature diagram at parameters illustrated in Table 3

Table 3: Parameters used for temperature test.

Current	350A
Flow rate	0,7 l/min
Cable length	5 m
Cooling	Continuous
Inlet configuration	pin contacts with 70 mm^2 wire

With current applied at full power and the cooling unit setting in (see Figure 10), the curves change from transient to steady state mode. While the contact zone is the most vulnerable of all connector systems, a ΔT of only 6K vs. ambient temperature at full load illustrates the superior design of the redundant canted coil spring system. With a crimp zone temperature ingress of ΔT=0K at the connector side, the system is proved to be ideally balanced for full performance heat dissipation. While TC5 and TC7 within the power wire reflect the temperature profile identified in 4.1., the temperature increase in TC13 of only ΔT=5K vs. ambient temperature on touchable parts demonstrates the capability to stand significantly higher current and/or ambient temperatures. Finally, the PT1000 element to monitor contact temperature follows both dynamical and accurately within a range of ΔT=2K vs. contact zone temperature.

Concluding on the above test results compared against VDE-AR-E 2623-5-3 [viii] confirmed the theoretical approach which resulted in minimal thermal and mechanical stress along the contact, thus securing the connector's core function. The system's limitation is in the cooling unit allowing for sufficient heat dissipation. All other components are far from their limitations and designed to fulfill further enhanced performance demands, i.e. on current rating or individual customization. Validation tests based on EVSE hardware in field allowed for positive interoperability results. A core product was developed based on the building blocks of connector, cable and cooling unit that allow for a fully certified system upon core specifications. Experience has been secured for both CCS 1 and CCS 2 development.

5 From Core Product to End Product

Key in developing a HPC solution is the trade-off between safeguarding product longevity against the needs for modification and the requirement of minimal time to market. While the core product will still need necessary amendments as final standards are introduced, any system changes that modify form, fit or function may cause significant impact on in bearing current, mating cycles and impact load (e.g. drop). With the connector being one of the few components an end user is directly interacting with during the charging process, it is there where haptics and design are significant drivers for differentiation. With a growing number of EVSE manufacturers requesting specific customizations, an efficient approach is required to validate individual needs.

In consequence, the project management approach was changed from sequential to iterative to become as agile as possible. Besides, new functions were introduced for further speeding up of process. Considering thermodynamics, high definition (HD) simulation (Figure 11) of all connector, cable and cooling system along the assembly was introduced to reduce time for development on both core product and customizations. The non-steady state model considers temperature distribution at heat transmission factor a upon Fourie's law on temperature transfer:

$$\frac{\partial T}{\partial t} = a\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right) \quad (6)$$

along with current density and dissipation losses on the system [ix].

The simulation enables the assessment of the impact of modifying operating conditions, e.g. altered current functions vs. cooling media inertia and comparing various cross sections. It also safeguards components safety on thermal and mechanical impact as identified through its load model, thus reducing significantly test cycles along the cooled connector system development. Reducing incremental elements assessed with the simulation allows for an ever closer approximation of individual temperatures shown in figure 9, however adding significant calculation effort to determine results. Thus, in an effort to minimize time, it was then to decide on a minimal solution required to allow for meaningful conclusions.

In summary, both core product adjustments to meet final standards as well as an iterative approach to project management supplemented by simulation for individual customer requests offers significantly reduced turnaround times on new projects and thus time to market.

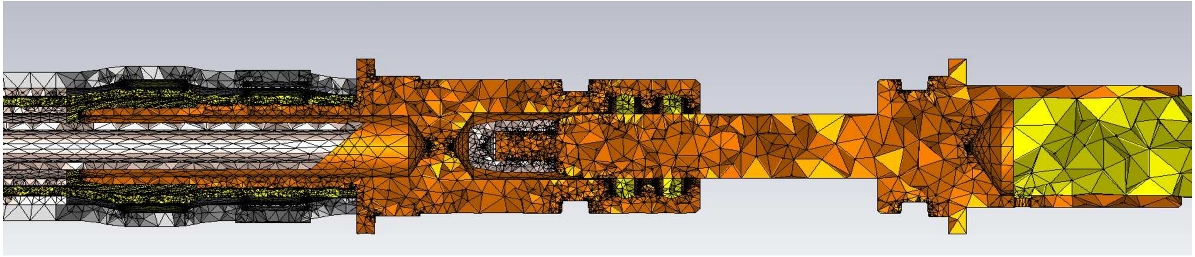

Figure 11: mashed contact cross-section as fraction of heat dissipation system used for modelling simulation

6 Summary of HPC System

A self-sustaining but modular cooled HPC system was developed against base specifications that can be easily adjusted to specific application needs, (see Table 4). System certifications are being raised against preliminary standards available today. To minimize time to market for standards still under modification and customizations of the end product, the iterative project approach was supplemented by HD simulation of heat flow. As infrastructure demands EVSE manufacturers to offer AC, DC standard and DC HPC connectors in parallel, the entire product portfolio was tooled up to allow for single sourcing of connector solutions.

Table 4: Features, benefits and values of HPC system

Feature	**Benefit**	**Value**
• contact / cable are cooled from inside	• Minimized copper diameter (28 mm^2) • Balanced heat distribution along cable	• System ampacity (>500 A) • Weight reduction
• Redundant canted-coil spring contact	• Minimized wear and current impact	• Extended lifetime and product availability
• Plug and play end terminal integration	• Cable exchange w/in < 15 min	• Minimal service effort • Improved product availability
• None-conductive and environmental friendly coolant medium • 2-layer sealing design	• Redundant safety system	• Best possible safety for life and environment
• Autarkic modular system	• wide range of features already at hand	• availability • Economies of Scope
• Customization beyond existing modularity • Support by HD simulation	• Differentiator • Minimal time for implementation	• USP of end system • Minimal time to market

7 Author

Ralf Glocker held various senior positions in business development and product management in both the automotive and Off-Highway industry. He became global product manager for electric vehicle connectors with ITT in 2014. Ralf Glocker holds a Dipl.-Ing. in design engineering from BW Cooperative State University (Stuttgart) and an MBA from Open University Business School (London).

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