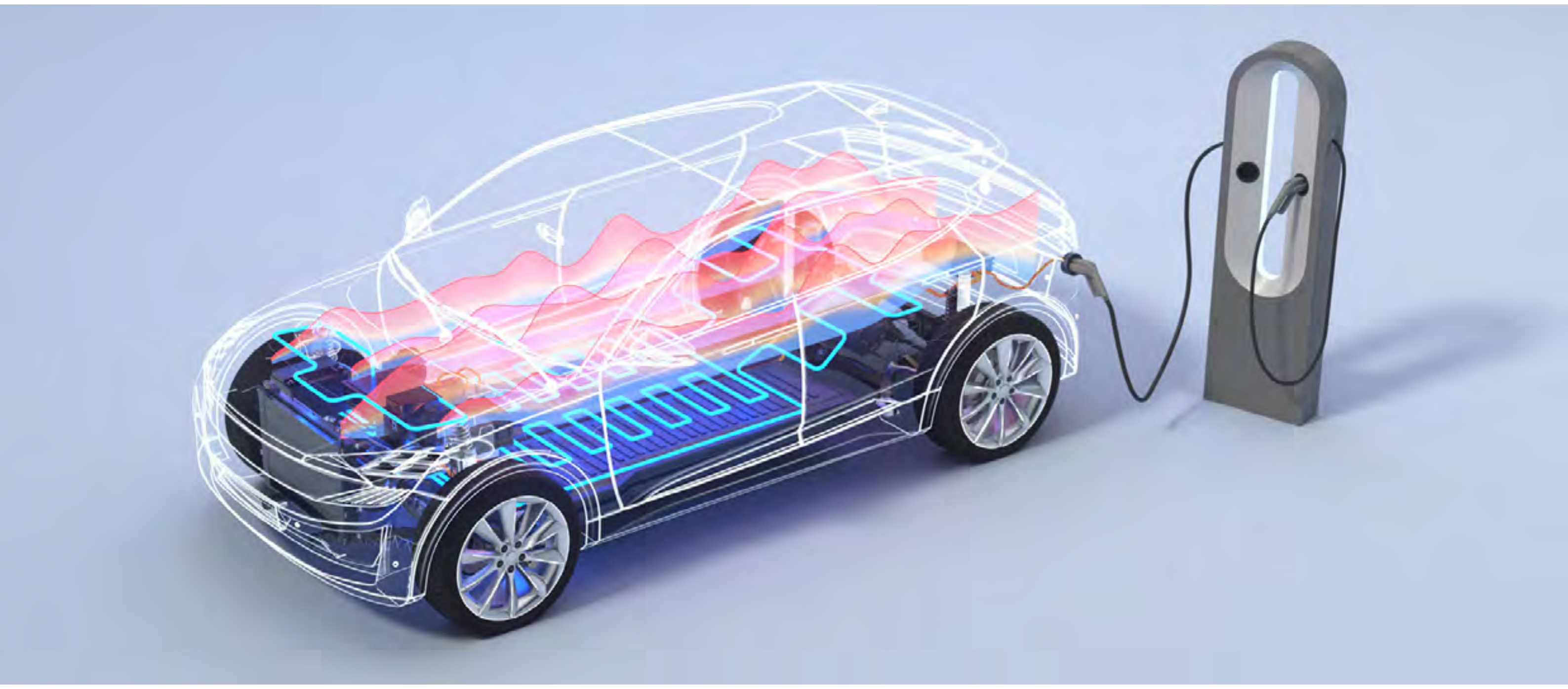
WHITEPAPER



Thermal management for BEVs with TDK sensor solutions optimized by computer-aided modeling

Abstract

One of the main challenges with developing BEVs (Battery Electric Vehicles) is ensuring all systems can operate efficiently from a single power source. Without an internal combustion engine, all of the electronic systems rely on the BEV's battery for their power. Managing that single source of energy requires complex and sophisticated battery, power and thermal management systems. Close attention must be paid to the response behavior of temperature sensors in all relevant measuring positions.

The safe and efficient operation of a BEV powertrain relies on temperature control. Therefore, many of the systems in BEVs need active cooling using pressurized refrigerants. With the response and accuracy of pressure sensor measurements dependent on temperature, the close connection between pressure and temperature has given rise to fully integrated pT sensors. These sensors combine both pressure and temperature measurement at effectively the same point. This allows correlation between the two parameters, as well as the ability to use the temperature to compensate for variations in the pressure signal.

The response of pressure and temperature sensors depends on absolute parameters, such as the design and construction of the sensor. Its performance is also highly influenced by the application, such as where and how the sensor is mounted. This White Paper explores the thermal behavior of surface-mounted temperature sensors for thermal battery management systems and bus bar systems, as well as combined pT sensors for cooling fluids. The importance of sensor design and material selection is shown. The features contribute to the Thermal Contact Conductance in simulation as well as in the real world (TCC). A comparison between simulation and measurement results illustrates the benefits of evaluation simulation of the thermal behavior for specific sensor designs.

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1 Executive Summary

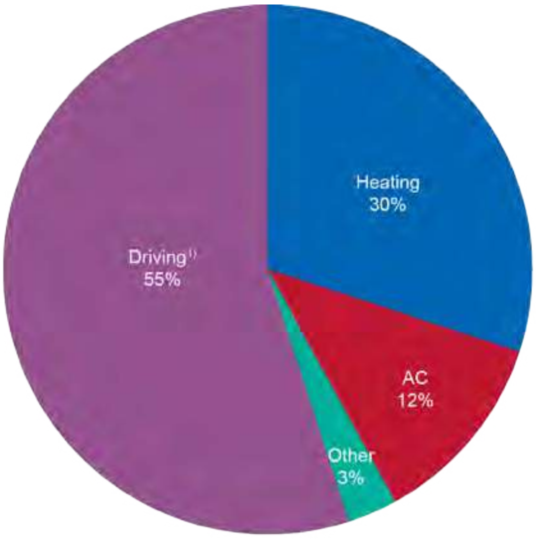
1.1 Why is energy efficiency so important in BEVs?

The battery in BEVs the only available source of power for both driving and passenger comfort. The range of a battery electric vehicle is highly influenced by environmental conditions and driving style. BEVs use complex thermal management systems to connect the subsidiary systems in a very efficient way in order to provide the best possible user experience.

Most BEVs currently use Lithium-Ion (Li-Ion) battery technology. While this offers many benefits in terms of an established supply chain and manufacturing solutions, it also presents challenges. One of those challenges is the thermal management of the Li-Ion battery during charging and discharge cycles. The driving style will determine how much energy is drawn from the battery at any given time. During discharge, Li-Ion batteries generate heat, which needs to be monitored and managed. During charging, Li-Ion batteries need to be maintained at an optimal temperature in order to get the highest level of charging efficiency and, therefore, the shortest charge times.

The power density of Li-Ion battery is as much as 100 times lower than fossil-based fuels. This means for the same given size, space and weight, a Li-Ion battery can deliver 100 times less energy than gas or diesel fuel. This alone is all the motivation needed by the automotive industry to maximize overall efficiency.

In a typical system, motive energy may account for just 50 % of the energy stored in the battery. The climate control or HVAC system can consume more than 40 % of the stored energy, see Figure 1. Accurate sensing of physical parameters, such as temperature and pressure, improves the efficient control of these systems, so drivers and passengers can enjoy greater range and comfort from the BEV.



1) 30 kWh battery capacity; 15 kWh per 100 km with speed of 100 km/h;
Source: http://schaufenster-elektromobilitaet.org

Figure 1: Percentage of the energy consumption of a BEV

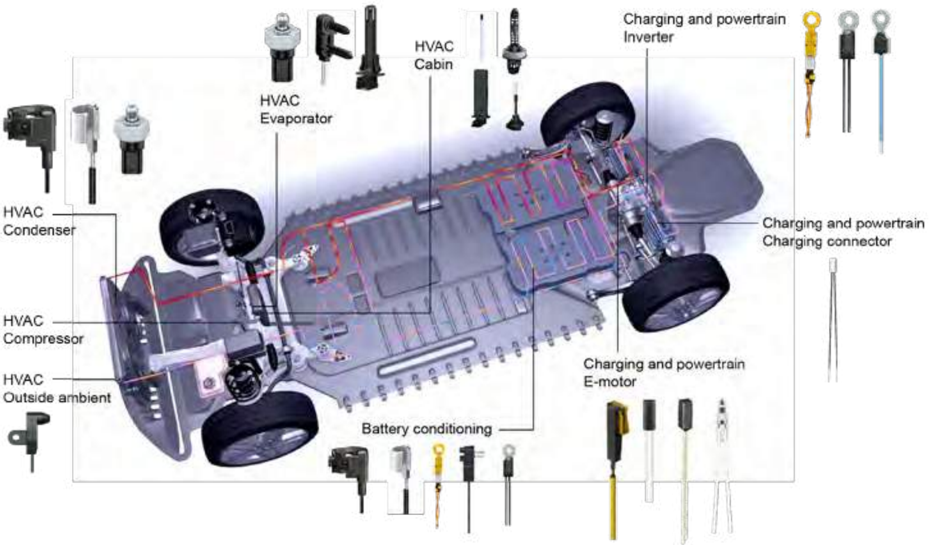


Figure 2: Pressure and temperature sensor systems for battery electric vehicle

Efficiency, coupled with the safe operating conditions needed for Li-Ion battery technology, mean temperature sensing is now a key requirement in BEVs' design. This requires the use of the most appropriate sensor technologies, but it also demands a close examination of how the sensors are used. Careful integration of the sensors is a priority. It requires an optimized thermal bond between the application surface and the sensor. Besides the importance of sensing system selection, careful sensor housing design is essential in order to achieve good response levels and accurate measurements.

Temperature data are required from multiple points in BEVs. This includes the battery management system, the OBC (on-board charger), the inverter, the traction motor and the cooling systems. Inside the cabin, the climate control system also requires accurate temperature measurement, as do other occupant comfort systems such as heated seating or steering wheels, see Figure 2.

TDK has developed a different sensor solutions for each of the above tasks by optimizing design, housing materials and thermal response behavior to the unique mounting positions of the different use cases.

1.2 Finding the balance between power, performance and lifetime

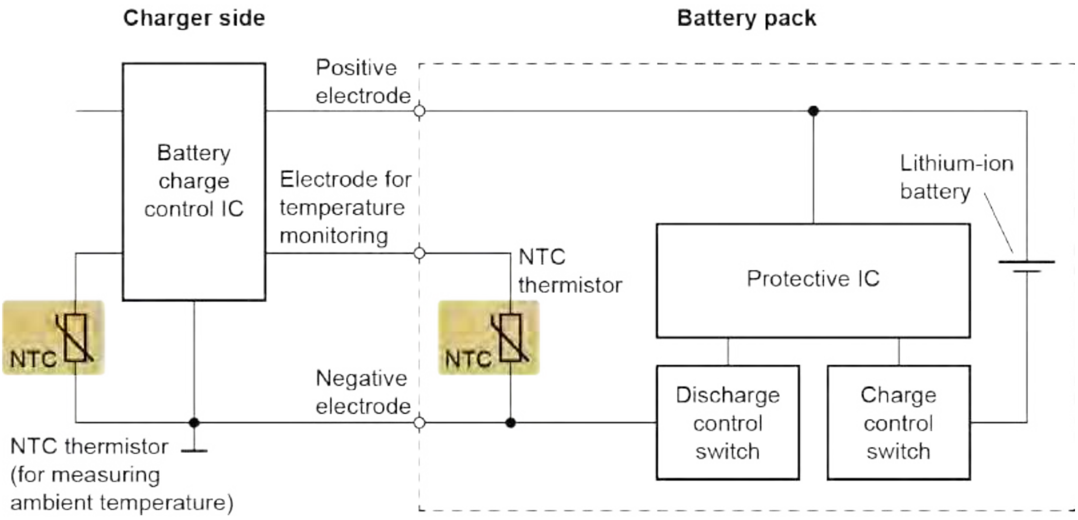


Figure 3: Battery pack charging control unit with NTC thermistors

Li-Ion battery cycles

The charge/discharge cycle of battery cells is fundamental to the performance of any vehicle that relies even partly on stored electrical energy. This is true for mild hybrids as well as full electric BEVs. To ensure optimal operation of the battery, the operating temperature must be monitored at multiple positions in the sealed casing.

The aggregate temperature, along with point-temperatures, will be used by the BMS to control the charge and discharge functionality of the battery, see Figure 3.

On-Board chargers

While DC charging provides the best user experience and shortest charge times, the availability of off-board DC charge points is still limited. The majority of plug-in vehicles will rely at least partially on taking an AC source as an input and converting this into DC in order to charge the battery. This means the need for an on-board (OBC) and/or off-board charger is unavoidable.

The amount of power through both AC and DC charge points is considerable, often in excess of 100 kW. This amount of power passing through cables and semiconductors will inevitably generate heat as a by-product. If left uncontrolled, the level of heat generated can become a potential safety hazard. For this reason, temperature sensing is even more important at all critical points in the power supply chain.

The charging sub-system includes the power inlet to the vehicle. The plugs used may vary by manufacturer, but the International Electrotechnical Commission has determined that they must include a temperature sensor to ensure safe operation. The sensors used need to comply with the standard IEC TS 62196-3 1 DIN as a minimum requirement. Sensors for this application have to be mounted inside the connector, typically directly to the AC or DC pin. The response time of these temperature sensors must be in the region of less than 2 s and provide an operating temperature of between -40 °C and +155 °C, with short-term capacity for temperatures as high as 180 °C.

e-Motor operation

The operating temperature of the motor's stator winding and insulation also need to be monitored. Derating the motor may be necessary if temperatures reach high levels. Temperature sensors in and around the motor need to respond quickly, be physically small and operate at temperatures around 200 °C.

In terms of measuring surface temperature of battery or motor bus bars, new solutions have been developed that allow the sensor to be screwed directly to the material. These sensors are packaged to protect them from moisture while allowing good contact with the material being monitored.

Active battery cooling

At about 40° C, Li-Ion batteries start to show accelerated aging. Therefore, the battery management systems use active cooling to regulate the temperature of the battery cells. The heat flow of battery and coolant must be closely monitored in order to optimize efficient operation and lifetime. In modern BEVs, the battery cooling cycle is linked to the HVAC sub-system of the car. This requires temperature sensors and pressure-temperature sensors mounted in various positions, along with pressure sensors for the refrigerant fluid. Multiple valves are used to direct the heating and cooling efforts, which means the HVAC system in an EV now plays a vital role in a complex thermal management solution.

Hose-mounted surface temperature sensors can accurately monitor the temperature of the coolant fluid. These 'clip-on sensors' are mounted directly on the inlet and outlet pipe of the coolant system. An integrated pressure-temperature sensor needs direct fluid contact but provides a full measurement of the thermodynamical state of the refrigerant, with the added benefit of being able to apply temperature-related corrections to pressure measurements at the source. Typical working conditions depend on the refrigerant and reach from up to 40 bars and 80 °C for R1234, to 170 bar and 165 °C for R744.

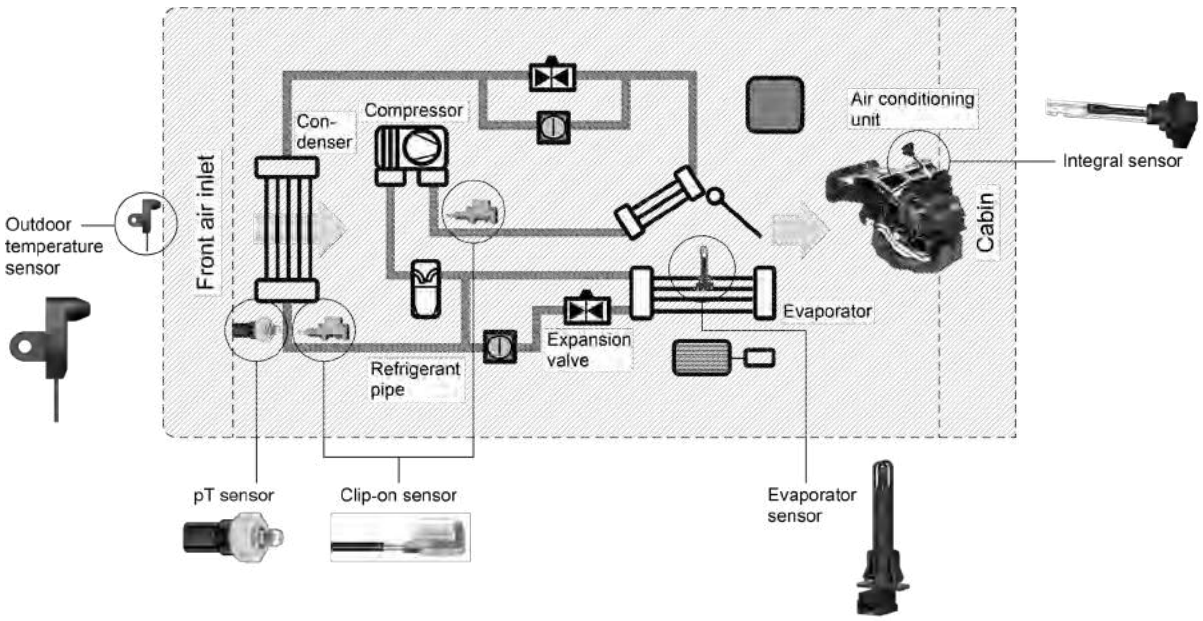


Figure 4: HVAC System of BEVs with heat pump function

HVAC system for passenger comfort

To also ensure the passengers' comfort in BEVs, multiple HVAC sensor systems are used (Figure 4). They check the cabin air temperature by air duct sensors and monitor evaporator temperature by airflow evaporator sensors behind the evaporator.

The pipes of the refrigerant cycle are equipped with 'clip-on sensors', as described in the previous section. They enable the measurement of the fluid temperature, which is also important for the thermal control of heat pump cycles. Especially located before and after the HVAC compressor, a pressure temperature sensor monitors the physical parameters of the refrigerant. This ensures the electric driven compressor is always running in the most efficient way, depending on the cooling or heating requirements.

The wide portfolio of NTC temperature sensors available from TDK includes screw-on and spring-load types, compatible with copper and aluminum pipes and able to operate in high voltage and high humidity environments. Clip-on sensors manufactured in both plastic and metal can fit various pipe sizes for coolant fluid or refrigerant pipes while combined pT sensors for direct fluid contact can measure the thermodynamical state of the fluid. New additions to the sensor range include a mini ceramic series designed to attach to the AC/DC pins in charging plugs, which offer high voltage tolerance up to 4 kV AC. The soft-case series produced by TDK has been designed for mounting inside the stator windings of electric motors, providing simpler manufacturing and assembly without compromising on performance.

Selecting the best sensor solution for each measuring application ensures the efficiency and the longevity of the sub-systems in the car are maximized.

2 Temperature and Pressure Sensor Accuracy – an Introduction

The repeated accuracy of an NTC sensor may vary, based on the material and the way it is used. Managing this variation requires an understanding of the way the material changes in response to temperature.

2.1 NTC temperature sensors

NTC (Negative Temperature Coefficient) thermistors are thermally sensitive semiconductor resistors that show a decrease in resistance as temperature increases. With a typical sensitivity of $\alpha = -4\%/K$, the negative temperature coefficients of resistance are about ten times greater than those of metals and about five times greater than those of silicon temperature sensors.

α is the relative sensitivity defined by the relative change of resistance per temperature interval:

$$\alpha = \frac{1}{R_{NTC}} \frac{\partial R_{NTC}}{\partial T}$$

The dependence of the NTC resistance on temperature is usually approximated by the following exponential equation. Note that all temperatures need to be converted to absolute Kelvin scale for calculation:

$$R_T = R_R \cdot e^{B \cdot \left(\frac{1}{T} - \frac{1}{T_R}\right)}$$

With a high basic rated resistance of typically 10 to 100 k Ohm at 25 °C and high sensitivity, NTC is an excellent choice for remote temperature sensing in exposed positions.

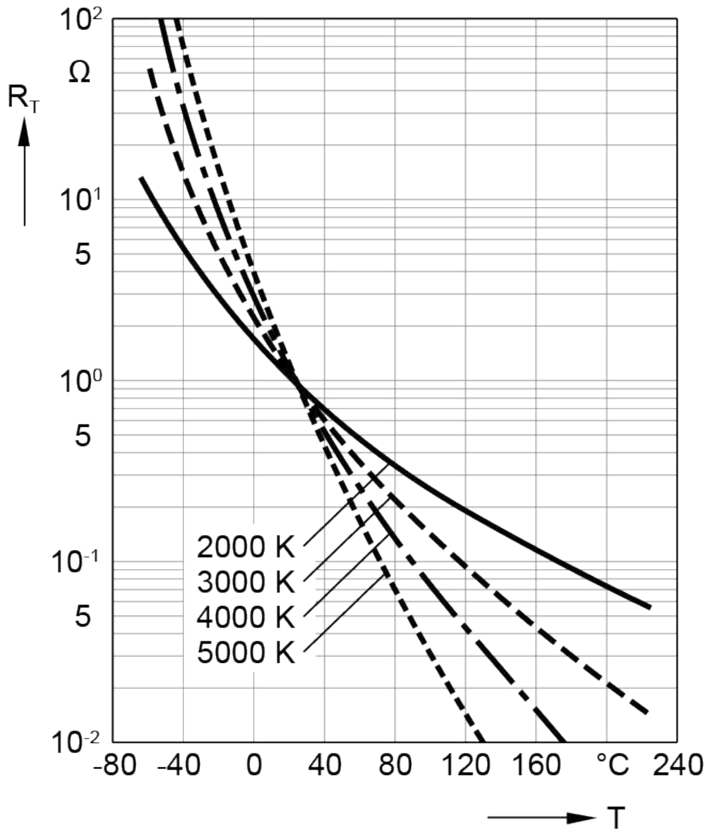


Figure 5: NTC R/T curve

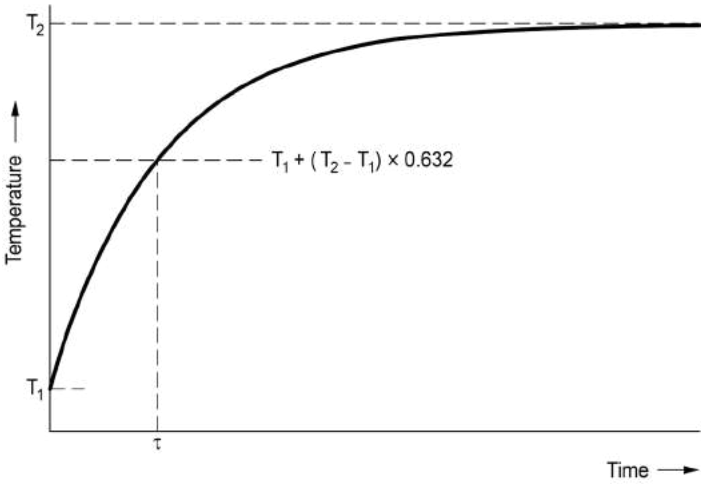


Figure 6: Temperature increase from T_1 to T_2 of a sensor modeled with an exponential law

Sensor manufacturers like TDK can design NTC temperature sensors to be optimized for a specific rated temperature and range, according to the application's requirements.

The thermal time constant, τ_a, can be a crucial parameter when selecting a temperature sensor to match an application. The thermal time constant (thermal response time) of a temperature sensor is mainly influenced by:

- Its design (including sensor element, material used to assemble the sensor element in the sensor case, connection technology and housing)
- Its mounting configuration (for example immersed, surface-mounted)
- The environment will be exposed to (such as airflow, inactive air, fluid)

When a temperature sensor with temperature T_1 is immersed in a medium (air, water) with temperature T_2, the change in temperature of the sensor as a function of time follows to a first approximation an exponential law:

$$T(t) = T_2 + (T_1 - T_2) \cdot e^{-t/\tau_a}$$

After the thermal time constant, τ_a, the temperature change of the sensor is $1 - 1/e = 63.2\%$ of the temperature difference $T_1 - T_2$, this means $T(\tau_a) = T_1 + (T_2 - T_1) \cdot (1-1/e)$, see Figure 6.

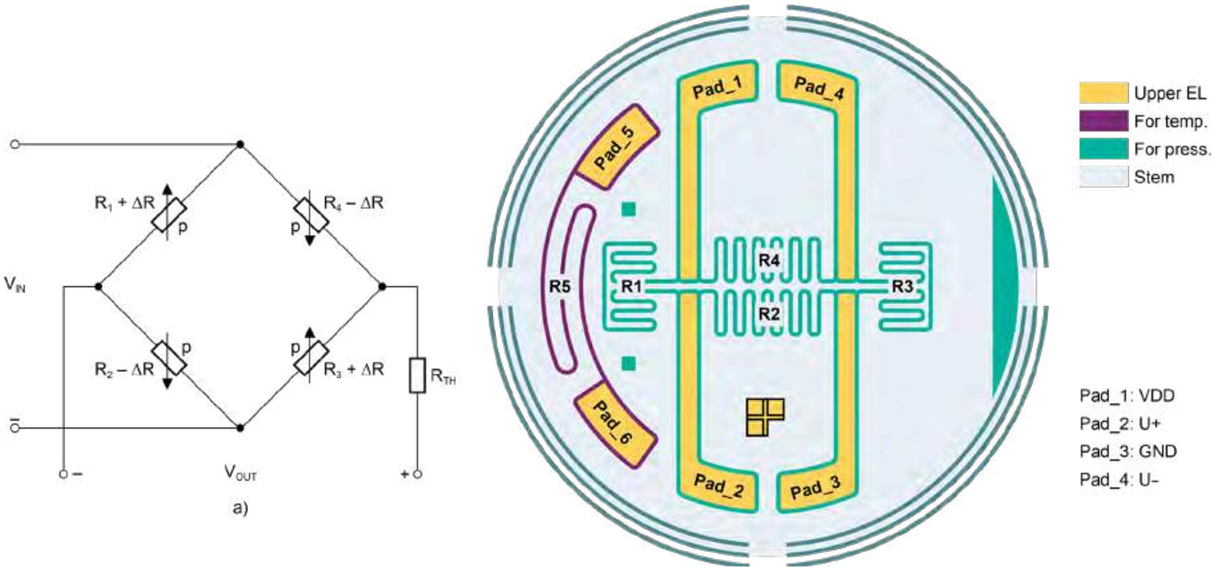


Figure 7: RTD resistor and piezoresistor full bridge configuration on a single metal stem of a combined pT sensor

2.2 Pressure-temperature sensors

The electrical resistance of every conductor and semiconductor changes under mechanical stress. This is known as the piezo-resistive effect and it is exploited to create sensors. In order to be useful in sensors, the cause of the stress must be intentional and comes typically from an external force, such as fluid or liquid pressure, torque, deflection or angle of rotation, for example. The sensor's design needs to take the nature of the source into account. The so-called K-factor characterizes the magnitude of the effect:

$$\frac{\Delta R}{R} = K \cdot \varepsilon$$

Where delta R denotes the change in resistance caused by the stress applied, represented by epsilon.

By integrating multiple piezo-resistive sensing elements together on a single substrate they can be arranged to form a Wheatstone bridge. This level of integration can be used to create effective pressure sensors. The sensing elements are protected by a thin membrane, or diaphragm, which is exposed to the fluid being measured. The pressure of the fluid causes the diaphragm to exert that pressure on the sensing elements, which are typically manufactured on a thin-film substrate.

This effect can be used with a thin diaphragm made from silicon or metal, using resistors in a Wheatstone configuration at the diaphragm rim. The amount of deflection of the membrane under the influence of pressure can be measured with high accuracy. Figure 7 shows a typical resistor arrangement (indicated as meanders) on a steel membrane.

In case of mechanical stress by applied pressure, the resistivity of the longitudinal stressed resistors is rising, while the resistance of the transverse stressed resistors decreases. The Wheatstone bridge gets imbalanced and provides a voltage deviation at the output. The readout of such an uncompensated device is defined by:

$$V_{out} = V_{DD} \cdot \upsilon_0 + p \cdot s \cdot V_{DD} + O(p^2)$$

With: V_{out}: Output Voltage
V_{DD}: Input Voltage
υ_0: Offset voltage (as ratio of VDD)
p: Pressure
s: Sensitivity
$O(p^2)$: The quadratic contribution in pressure refers to the nonlinearity error of the reading, which is typically in the range of 0.3% full-scale output.

The offset voltage V_0 is part of this equation as ratiometric contribution of the driving voltage: $V_0 = V_{DD} \cdot \upsilon_0$. In case of an offset-compensated device, one may consider $\upsilon_0 = 0$.

Due to the given tolerances of the offset, the sensitivity and the bridge resistance, the readout of a device deviates from the nominal values. The reduction of the offset and sensitivity variation by external circuits is subject to section 2.1. The accuracy of a compensated device is then only limited by the nonlinearity and drift, if not for the fact that important parameters of equation 1 significantly change with temperature. In fact, all piezo-resistive pressure sensors show the following inherent characteristics:

A decrease in sensitivity with increasing temperature, which is referred to as the negative temperature coefficients of span TCS.

$$s(T) = s_N \cdot \left(1 + \alpha_s(T - T_N) + \beta_s(T - T_N)^2\right)$$

An increase with bridge resistance with temperature range. To overcome this, temperature-based compensation can be applied. By measuring the temperature alongside the pressure, in the same sensor, the compensation can be calculated and applied more accurately.

$$R_s(T) = R_{SN} \cdot \left(1 + \alpha_{Rs}(T - T_N) + \beta_{Rs}(T - T_N)^2\right)$$

With T_N being the nominal temperature (typically 25 °C), s_N and R_{SN} the sensitivity and bridge resistance at T_N and α_s, β_s, α_{Rs} and β_{Rs} are the coefficients for the first and second order of the quadratic approximations.

The temperature dependence of the offset voltage is introduced by the thermo-mechanical stress put onto the device. This stress is mainly introduced by the method used for assembly and is therefore not referred to as an intrinsic temperature dependency.

The change of the output voltage with temperature is given by:

$$\frac{\partial V_{out}}{\partial T} = \frac{\partial V_{DD}}{\partial T} \cdot (\upsilon_0 + p \cdot s) + V_{DD} \cdot \left(\frac{\partial \upsilon_0}{\partial T} + p \cdot \frac{\partial s}{\partial T}\right)$$

The purpose of temperature compensation is to eliminate this dependency by applying a mathematical model. The data fusion in a pressure sensor follows the same principle as the temperature impact control of electric motors or climate systems: The quality of the compensation or control system depends strongly on the availability of an accurate and responsive temperature signal. Mounting the temperature sensor close to the relevant control spots, using excellent thermal coupling, is essential for good temperature control (see Figure 8).

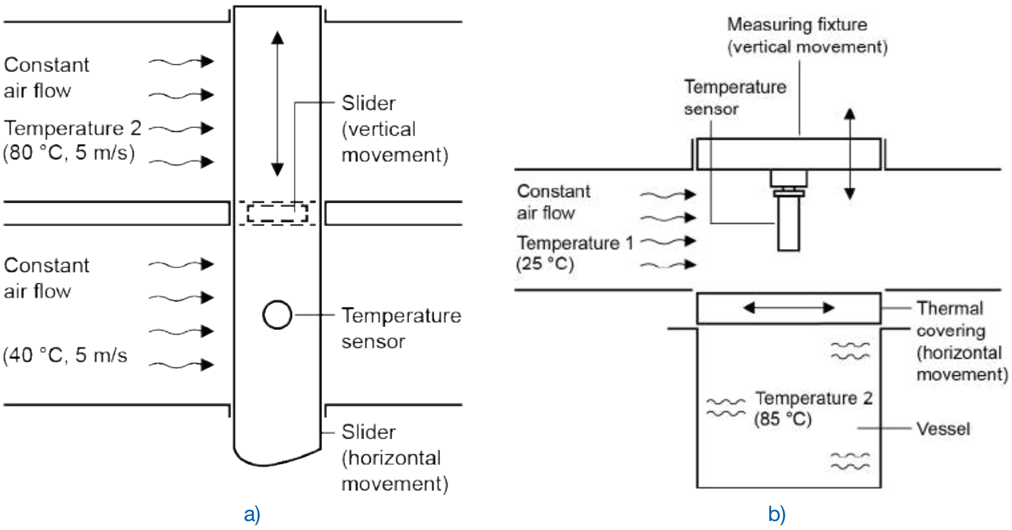


Figure 8: Principles of measuring the response time

3 Response Time Measurement and Application-Specific Simulation

It is important to understand as much as possible about the environment and other application requirements before selecting the right temperature sensor. Part of that is evaluating the response time of the temperature sensor.

3.1 Response time definition

The response time of a temperature sensor is defined by its thermal time constant. The time constant is a function of the sensor's design, including size, material and mounting. Knowing the time constant allows a measurement system to understand when the measurement is stable.

The standard EN 60539 covers the process of measuring the time constant and it involves two methods, using air or water as the medium. In each case, the medium is maintained at two temperatures and the sensor is first exposed to one and then to the other. For the method using air, the temperatures used are 40 °C and 80 °C. For water, the temperatures are 25 °C and 85 °C

The time it takes for the sensor to respond between 63 % and 90 % of the test temperature defines the time constant. The curve of the time constant is generally exponential.

3.2 Simulation methodology for optimal sensor design

Understanding the response time under ideal conditions, using air or water at controlled temperatures is useful, but it does not reflect what happens in a real application. In practice, it is clear that the construction of the sensor contributes to an optimal response time. This includes the way it is packaged, the thermal properties of the components used, such as potting compound, and the orientation of the sensor.

Taking into account the combination of materials and thermal masses, all mechanical and electrical contacts and thermal conductive paths provide a more accurate assessment of response time in an application. For example, the metal leads of the sensor will dissipate or absorb heat depending on the ambient conditions, which will impact response time. The thickness of the metal casing will also be relevant, as is the solder used. Taking all of these aspects into account produces a property for thermal diffusivity, which will also include the Thermal Contact Conductance (TCC).

Through simulation at this level, it is possible to select the materials, orientation and configuration that provide the best response behavior. This includes how the sensor makes contact with the surface of the object being monitored.

3.3 Solid to solid surface contact

3.3.1 Modeling thermal contact and FE analysis of aluminum housing variation for battery surface temperature sensor

TDK's own studies show that thermal diffusivity characterizes the response time of an NTC sensor. In the case where physical contact is used between the sensor and a surface being monitored, it is also shown that the contact area, the condition of the surface (rough or smooth) and the force with which contact is made all contribute to TCC, as shown in Figure 9.

In this diagram, three sensors are compared, each with different profiles and surface areas. The TCC varied based on fill radius, sensor area and pressure applied, as shown below.

Case 1: sensor area = 2.52 mm², fill radius of 0.6 mm.

3 N:	1722 W/m²K
5 N:	2883 W/m²K
10 N:	5339 W/m²K

Case 2: sensor area = 1.54 mm², fill radius of 0.8 mm.

3 N:	2732 W/m²K
5 N:	4416 W/m²K
10 N:	8473 W/m²K

Case 3: sensor area = 0.78 mm², fill radius of 1.0 mm.

3 N:	5143 W/m²K
5 N:	8313 W/m²K
10 N:	15849 W/m²K

By modeling these parameters, it is possible to develop a more responsive sensor using simulation and Finite Element (FE) analysis. Figure 10 generally shows that a greater applied contact force to smoother surfaces enables the sensor to reach the actual temperature faster.

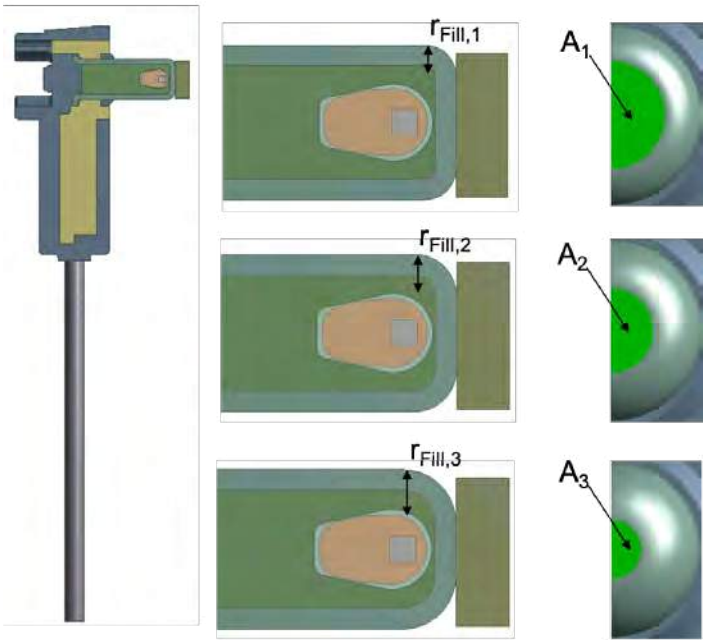


Figure 9: Battery surface temperature sensor with different settings

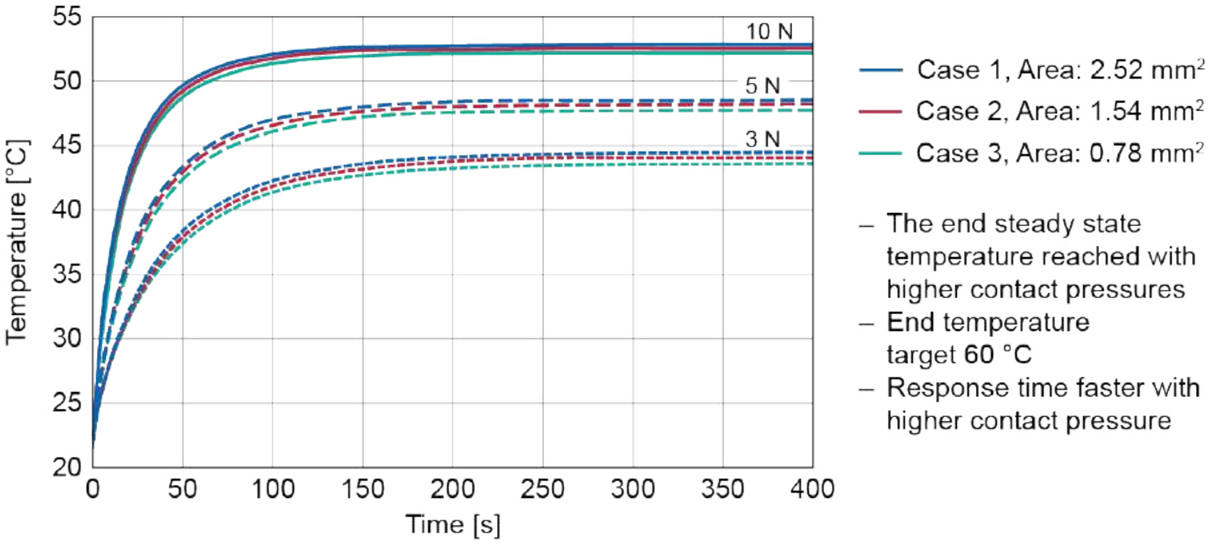


Figure 10: Results of response time depending on pressure force and sensor area

In this graph, the blue lines represent the sensor with a surface area of 2.52 mm², the red lines for the sensors with a surface area of 1.54 mm² and the green lines for the sensors with a surface area of 0.78 mm².

The objective here was to reach a steady-state temperature target of 60 °C. As can be seen, increasing the contact pressure enables the sensor to measure a temperature closer to the target temperature. Also, in general, applying more pressure gives a faster response time. In addition, the sensors with the largest surface area give marginally faster response.

3.3.2 Design optimization for clip-on temperature sensors for refrigerant cooling cycle

As described earlier, one of the key applications in EVs is monitoring the temperature of the coolant fluid used to maintain the battery cells at an optimal temperature. This typically involves using a clip-on NTC sensor, shown in Figure 11, attached to the inlet and outlet pipes carrying the coolant.

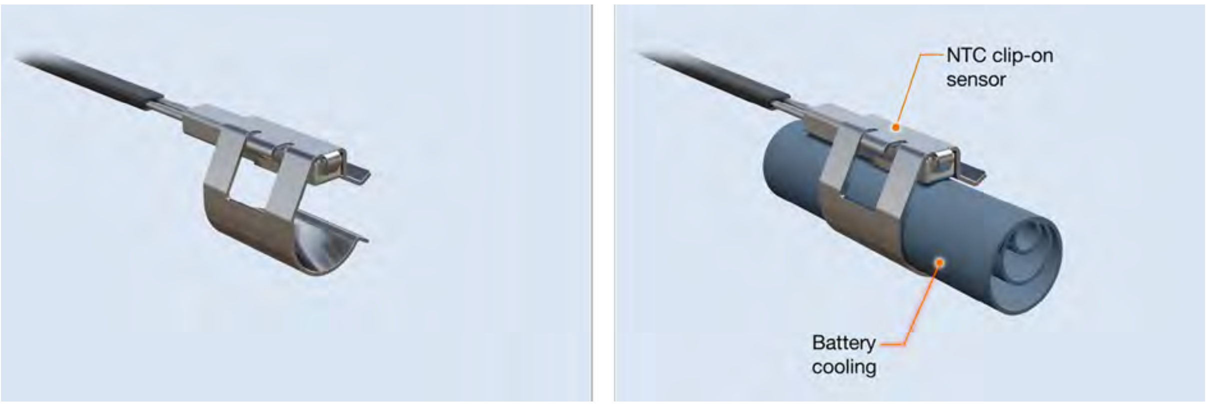


Figure 11: Clip-on pipe temperature sensor – metal type

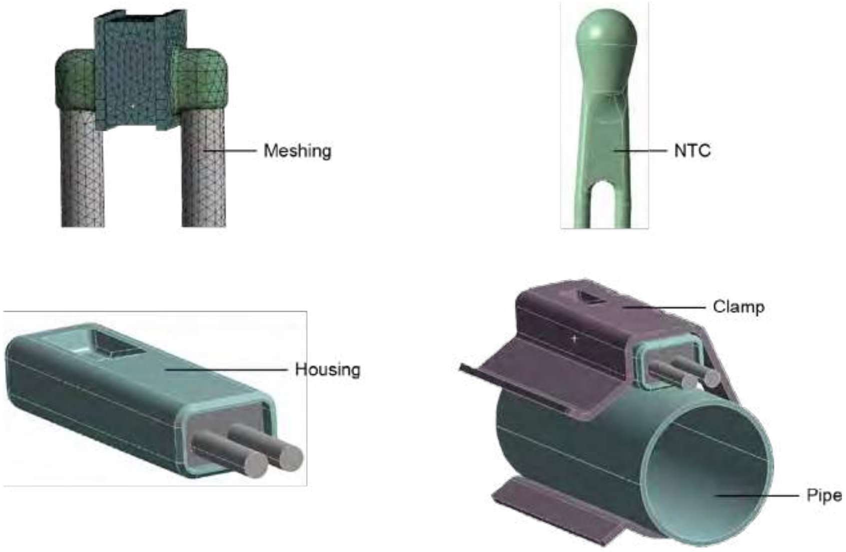


Figure 12: Computer-aided model of the clip-on sensor for temperature simulation

The pipes are generally round, while the NTC sensor house is generally flat-sided. This presents a situation where the contact surface area is extremely limited. Modeling and simulation help in this scenario, by allowing various different types of materials and configurations to be modeled before manufacturing.

The overview below in Figure 13 shows nine variations of the sensing sub-system, comprising nine different materials as they would be used. Each material represents another layer in the sub-system.

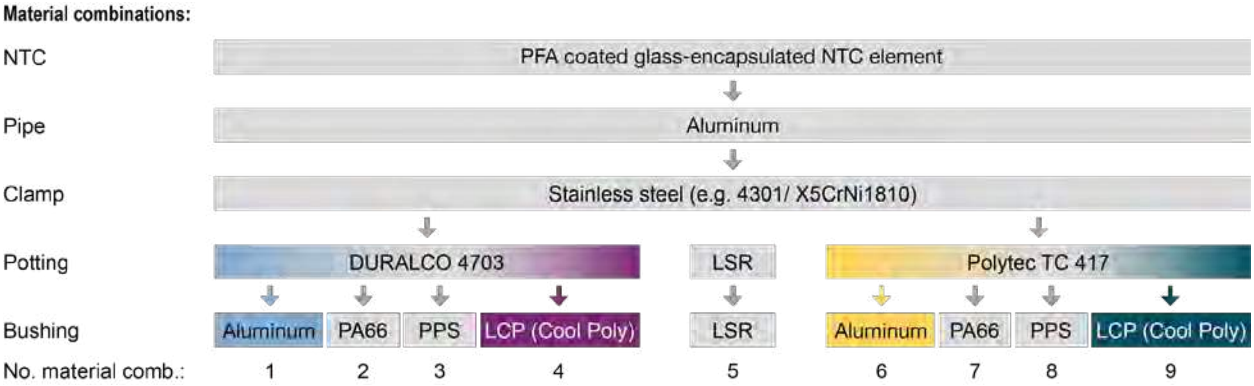


Figure 13: Material combinations for simulation

Simulating these nine configurations produces the response time curves as shown in Figure 14. The plots illustrate how the choice of potting compounds and sensor housing will affect the response time of the NTC sensor, based on the surface area available. Each line represents a different configuration using a varying number and type of intermediate materials.

MC	Materials (Potting + Housing)	t63 [s]
1 ①	Duralco + Aluminum	1.75
6 ②	Polytec + Aluminum	2.65
4 ③	Duralco + Cool Poly	6.5
9 ④	Polytec + Cool Poly	10.1

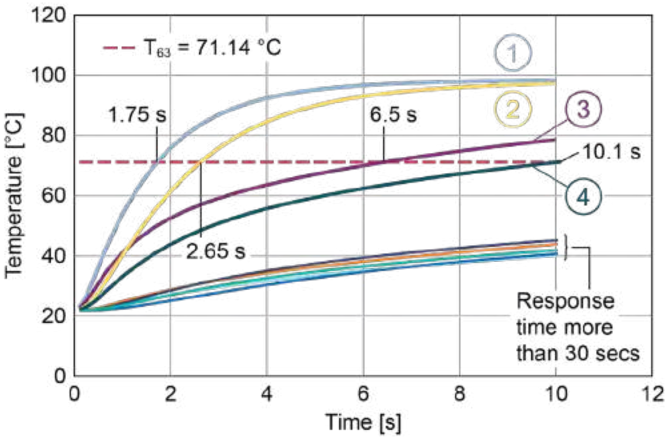


Figure 14: Response time results with different material combination

The table included in Figure 14 gives the detailed results for the four best performing configurations. The time taken for the sensor to reach 63 % of the final temperature (in this case, 71.14 °C) shows that the configuration for sensor 1 offers the fastest response time.

3.4 Solid to fluid contact: pT sensor simulation

With sensors immersing in a fluid or gas flow the response behavior additionally depends on the fluid dynamic of the surrounding media. Convection plays a great role in defining the amount of heat transfer. Due to the number of variables involved, empirical measurement data are typically supplemented to with simulation. Modeling the sensor and its surrounding gives valuable insights into how the system will react in different application conditions: As a full computational fluid dynamics (CFD) requires special tools and long computation time usually, a finite element analysis of the liquid / solid boundary layer is used.

3.4.1 Building an FEA Model as approach to fluid dynamics

The heat transfer into and from the fluid takes place within the so-called "Prandtl boundary layer" of the thickness (δ) and can be described in a simplified model by an effective heat transfer coefficient called the thermal film coefficient α. (Figure 15).

The convective heat transfer can be described by the following relationship:

$$\bar{Q} = \alpha \cdot A \cdot \Delta T$$

With $\bar{Q}$: Heat Flow

α : Thermal Film Coefficient

A : Heat transfer area

ΔT : Temperature difference between solid and fluid

For simple geometries the thermal film coefficient can be estimated by the Nusselt number that relates the convective and conductive heat transfer at a boundary in a fluid:

$$Nu = \frac{\alpha \cdot L}{\lambda}$$

L : charateristic length

λ : thermal conductivity of the fluid

The Nusselt number as well as the Prandtl and Reynolds number are dimensionless characteristics that describe fluid dynamic and heat transfer behavior. Solid – Fluid boundaries with similar characteristic numbers have similar flow or heat transfer behavior.

With known fluid velocity, characteristic length and material properties of the fluid, analytical and empirical Nusselt numbers can be found in the literature for a high variety of geometries.

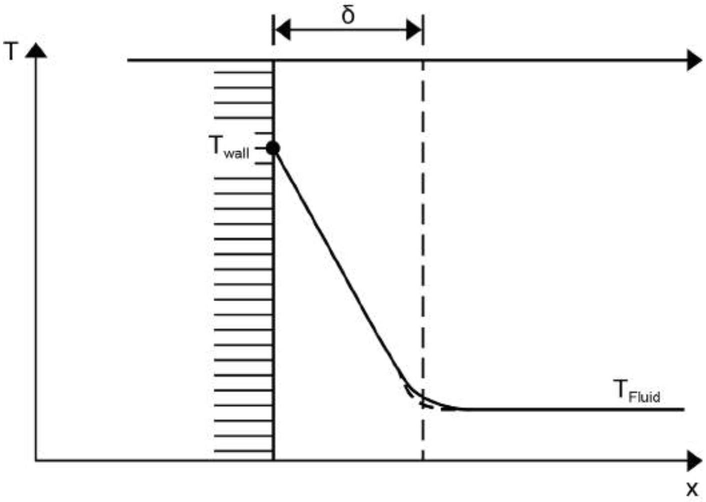


Figure 15: Heat transfer to and from the fluid through the Prandtl layer [Prandtl]

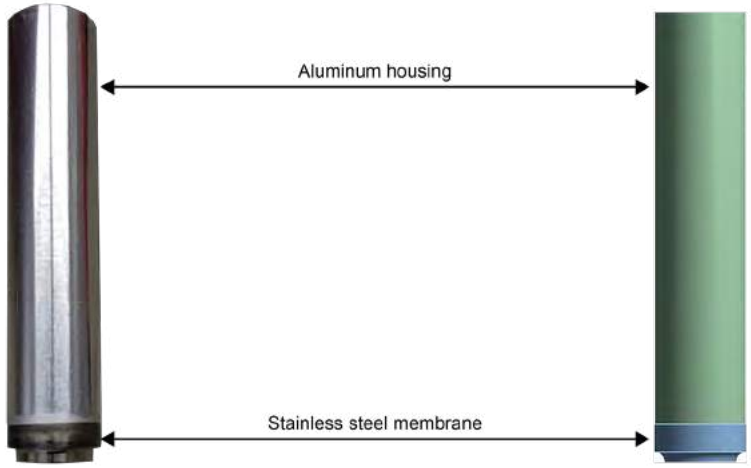


Figure 16: Sensor probe and 3D model being used for the determination of the film transfer coefficient of the pT sensor membrane

3.4.2 Verifying and improving the FEA Model with reference data

To assess the film transfer coefficient of the sensitive diaphragm of the pT sensor (Figure 16) a test probe was used. The probe was alternately submerged in baths of Galden at a temperature of 25 °C and 80 °C flowing at a velocity of 0.5 m/s while the thermal response time was recorded. The results were compared to the response time simulation based on Thermal film coefficients that were calculated from the Nuesselt numbers.

The comparison of actual sensor response data with simulated data shows a simulation error of approximately +/- 5 %. The film transfer coefficient model can be used for future response time simulations in use-cases with similar fluid dynamic.

4 Summary

The move to e-mobility comes with significant demands. Using electricity exclusively for both motive power and auxiliary features introduces entirely new electromechanical architectures and sub-systems into the automotive domain.

Manufacturers are eager to develop the most efficient solutions, to provide maximum range and convenience to the growing market. Consumer demand must be nurtured in order to address the main concerns of purchase cost, range and reliability.

Temperature and pressure sensing is now a major part of the solution. The operation of all critical sub-systems relies heavily on the thermal management of critical components, such as battery cells, cooling fluids, electric motors and high-power conversion circuits.

Response time of temperature sensors is shown to be a key parameter. This is particularly apparent where surface temperature is being monitored. With multiple and complex constructions, the response time of surface-mounted temperature sensors must be carefully managed. Selecting the right sensor for each position in the system must be treated with individual attention to the application.

While the internal construction of the sensor is fundamental to achieving good thermal diffusivity, the TCC is also important. All of these parameters contribute to the sensor’s response time. Optimizing sensor design and selection for response time can be addressed through modeling and simulation.

By understanding the application areas and the intricacy of sensor design, coupled with the application of modeling and simulation, TDK is actively developing temperature sensors that offer optimal response time with the size, weight and shape needed by BEV manufacturers.

One of the major design aspects found to affect thermal conductivity is the metal casing outer surface. This, coupled with contact pressure, contribute to the responsiveness achieved. Modeling the internal construction with the outer package condition can show how improvements in response time of up to 50 % can be achieved.

IMPORTANT NOTES

Learn more about the broad portfolio of TDK sensors for thermal management of BEVs here.

NOTICE TO READERS:

Release 2021-08