Determination of the dynamic behaviour of high-speed temperature sensors

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Currently at manufacturers of thermocouples, development is being continued on thermometers especially suited for applications in the automobile and aircraft industries. These thermometers have to react very quickly to sometimes very large temperature jumps, which is where emphasis in design optimisation with respect to small time-percentage characteristics has been placed. These sensors are applied in areas with large temperature gradients and high flow velocities. In order to optimise the dynamic and static parameters (response times, thermal conduction errors), the Department of Process Measurement Technology in cooperation with Temperaturmesstechnik Geraberg GmbH and other manufactures is constructing a testing apparatus, in which the sensors characteristics can be determined as close as possible to standard conditions. In parallel, numerical calculation of the static and dynamic behaviour can be done for various possible designs, taking the assembly points into account with the help of the finite element method.
For these calculations the temperature dependence of the material properties (thermal conductance, thermal capacity, coefficient of thermal expansion) should be included in the model computations. The FEM simulations are therefore not only non-steady-state but also nonlinear. Consideration of the temperature dependence of the material characteristics is necessary because the previous knowledge gained experimentally shows that the time behaviour of the sensors is significantly different for various step heights and directions.

As an example we use a typical thermometer for application in the field of automotive engineering.
This concerns a sheath thermocouple which diameter reduced by special mechanical treatment in an engine wall, whose show for numerical calculations in half section. This thermometer immersed 25 mm into the medium; the housing wall is 10 mm thick. The diameter of the lower part is 3.5 mm, in the upper part 4.5 mm. The material of the gauge slide and the wall was Inconel; assumed as powders an alumina ceramic.

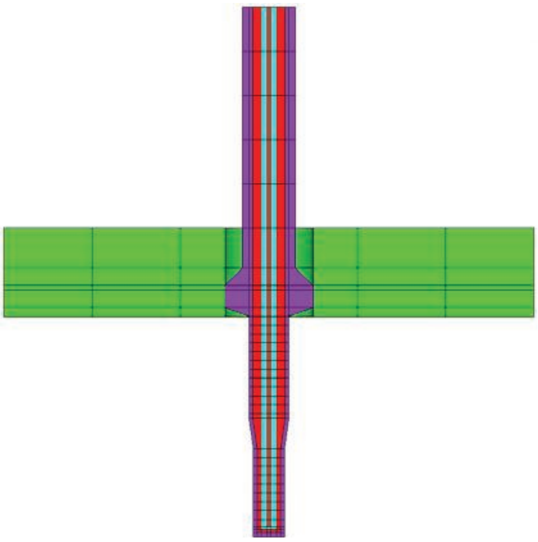

Fig. 1: Model for fitting in the sled well

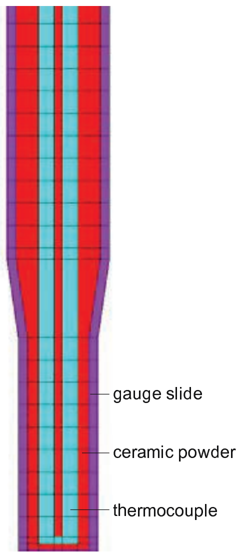

Fig. 2: Part in the medium

The typical application temperature range in the engine lies in a range of approx. 1,000 °C. The indication of a heat transition coefficient is however very with difficulty and highly dependent of the operating condition, the gas composition and the speed and/or pressure distribution. The distribution of velocity and temperature plays a special role as well as the droplet formation of the gas mixture at the engine wall [1], [2]. In [3] the heat transfer coefficient α in petrol engines was determined for different crank angle both

experimentally and numerically and found to be within the range from 200 to 1,000 W/m²K. Reference from literature for the computation of the heat transfer coefficient in the exhaust gas system or turbocharger is not yet known.
We can describe the time response of the assigned thermometers approximate as a RC-model 2nd order as suggest by [4]. Effective resistances are the heat transfer resistance R_α from the medium on the thermometer surface as well as two thermal conduction resistance R_1 und R_2 (figure 3). We have two effective capacities C_1 and C_2 respectively. The size of the thermal conduction resistance and -capacities depends on the appropriate material parameters (λ, c, ρ) as well as the constructional structure of the thermometers. The heat transfer resistance is given by the formula $R_\alpha = \frac{1}{\alpha \cdot A}$. One recognizes, the larger the heat transfer coefficient α is, the smaller becomes the resistance. Therefore the thermal conduction resistance dominate with large heat transition coefficients.

The transmission behaviour in the frequency range for a structure according to fig. 3 can be written as:

$$G(p) = \frac{T_S(p)}{T_M(p)} = \frac{T_2(p)}{T_M(p)} = \frac{1}{(1+p\cdot\tau_1)\cdot(1+p\cdot\tau_2)}$$

For the denominator of the transmission behaviour $(1+p\cdot\tau_1)\cdot(1+p\cdot\tau_2) = 1 + a_{12}\cdot p + a_{22}\cdot p$ the following connections between the coefficients and the thermal resistances and capacities of the model exist [4]:

$$a_{12} = R_1\cdot C_1 + (R_2 + R_\alpha)\cdot(C_1 + C_2) = \tau_1 + \tau_2 = \tau_\Sigma$$
$$a_{22} = R_1\cdot C_1\cdot(R_2 + R_\alpha)\cdot C_2 = \tau_1\cdot\tau_2$$

The dependence of the sum time constant τ_Σ on α is:

$$\begin{aligned}\tau_\Sigma(\alpha) &= R_1\cdot C_1 + (R_2 + R_\alpha)\cdot(C_1 + C_2)\\ &= R_1\cdot C_1 + R_2\cdot(C_1+C_2) + \frac{C_1 + C_2}{\alpha\cdot A}\\ &= \tau_\Sigma(\infty) + \frac{C_1+C_2}{\alpha\cdot A} = a_1 + \frac{b_1}{\alpha}\end{aligned}$$

This dependence shows fig. 4. In this fig. will show that within a range from α > 1,000 W/m²K the sum time constant τ_Σ approaches a constant value, which only depends of the internal thermal conduction resistance and - capacities.

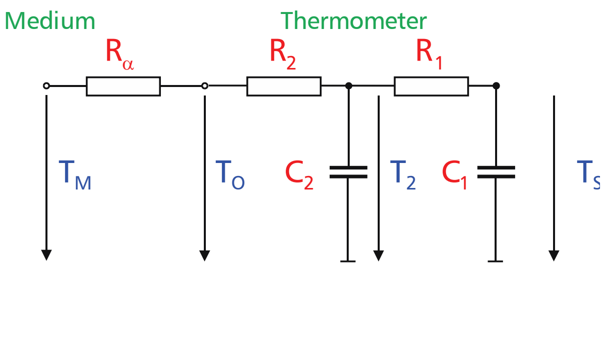

Fig. 3: Description of the thermometer as RC element 2nd order

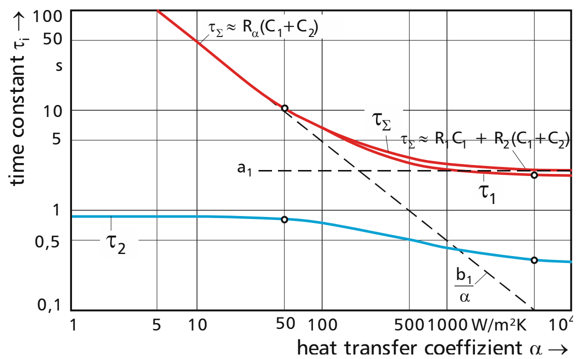

Fig. 4: Dependence of the time constants τ_1, τ_2 and τ_Σ on the heat transfer coefficient α

In the following all the computations with α = 1,000 W/m²K are descriptive in more detail.
In order to represent the dependence of the dynamic behaviour of the step height or step direction, a temperature step was simulated first with a uniform steady temperature of 100 °C to 1,000 °C and

afterwards in reverse direction. The heat transfer coefficient in the range of the installation place amounted to 1,000 W/m²K, in the outstanding part to 80 W/m²K. The radial heat portion was considered proportionally on the basis of the relation:

$$\alpha_S = \varepsilon \cdot \sigma_S \cdot \frac{T_U^4 - T_W^4}{T_U - T_W}$$

The computations were accomplished with the FEM program system ANSYS. For interpretation the computed stationary and intermittent temperature fields were evaluated, as they are represented exemplarily in fig. 5.

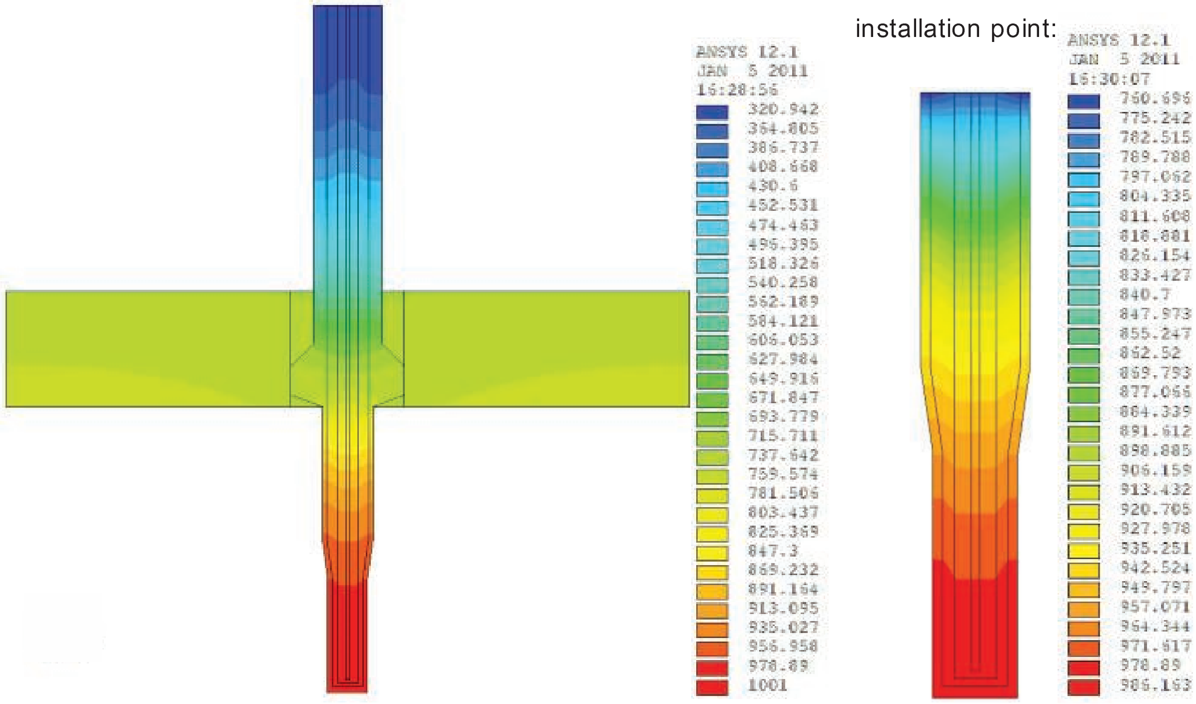

Fig. 5: Example of a computed temperature field of thermocouple according to fig. 2

Fig. 6 shows the step response for both computations in the range of the tip of the thermocouple. Like the computations described later, this example not yet compared with experimental values. Only by the experimental comparison of individual computation results for selected cases of application it is possible with numeric temperature field computations to examine the correctness of the constructional and material parameters as well as the input of the boundary conditions. That should be considered with in the following represented results in any case.

One recognizes that in the initial range of the skip function larger differences arise, which are caused by different materials data (heat conductivity, specific thermal capacity and density) with the initial temperatures 1,000 °C and/or 100 °C. The differences particularly affect thereby the determination of the time constants as well as the time per cent characteristic value t_{90}, as table 1 shows.

	$t_{50\%}$ in s	$t_{63\%}$ in s	$t_{90\%}$ in s	τ_1 in s	τ_2 in s
Cooling down (ab)	4,2	5,7	12,6	5,2	0,6
Heating up (auf)	4,1	5,4	11,4	4,6	0,9

Table 1: Dynamic characteristic values with heating up and cooling down

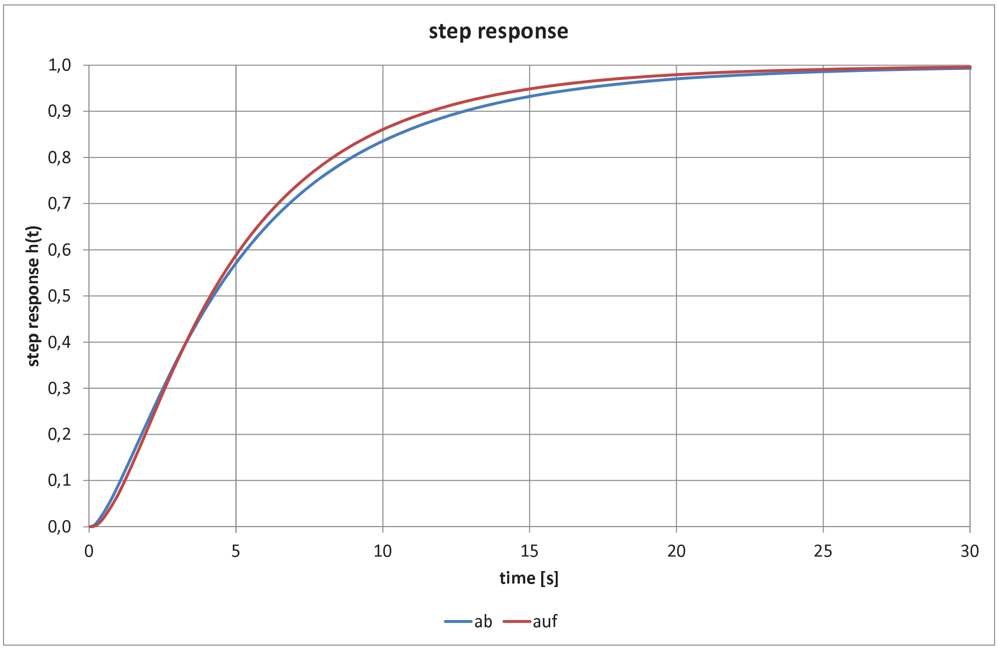

Fig. 6: Step response with the cooling („ab“) and/or heating (“auf”) the thermocouple from fig. 2

In this computation the temperature and load-sensitiveness of the heat transfer coefficient was not considered. Thus if the dynamic characteristic values are to be numerically computed by thermometers within the range of large temperature gradients and high flow rates, both the temperature and/or load-sensitiveness of the materials dates and boundary conditions and the direction of the change of temperature have to be considered.

In order to measure further static and dynamic characteristic values for the temperature sensors described above, additional computations were accomplished according to the installation error and to the dynamic behaviour. The installation error (also static-thermal measurement error) results from thermal conduction from the sensor to the environment and/or housing wall, if ambient temperature $T_U \neq$ medium temperature T_M. First the typical factors of influence were co-ordinated with the users, which will probably affect the installation error and the dynamic behaviour:

<u>Cause of static-thermal measurement error:</u>

1. Tolerance of the installation length/place
   - length tolerance of the thermometer ± 0,2 mm
   - tolerance of the installation point ± 0,5 mm
   - ΔEL = 1,4 mm
2. Change of the engine ambient temperature
   - cool air/warm air
   - summer/winter operation
   - $\Delta T_U \approx$ 100 K
3. Different wall thickness of the installation place
   - dependently on place of the installation point
   - dependently on the motor type
   - Δd = 3...10 mm
4. Change of the flow profile
   - load-dependent
   - temperature-dependent
5. Constructional one and material parameter of thermometer and installation place

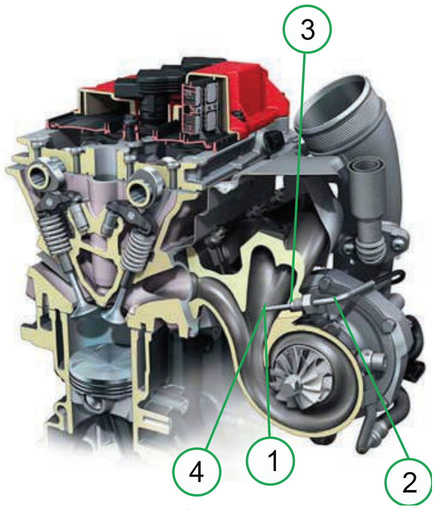

Fig. 7: Example of application

For the investigation of the dependence of the characteristic values of the flow profile it was accepted that the speed (and concomitantly the heat transfer coefficient) and the temperature drop to the housing wall. With high heat transfer coefficients only small differences could be recognized, they lay in the millisecond range with the determination of the dynamic characteristic values. The differences of the dynamic characteristic values for the computations with constant and/or to the housing dropping α in the computations with a heat transfer coefficient of 200 W/m²K were likewise relatively small (see table 2), what is to be led back on the temperature and speed waste only starting from an installation length of approx. 15 mm.

	$t_{50\%}$ in s	$t_{63\%}$ in s	$t_{90\%}$ in s	τ_1 in s	τ_V in s
α const.	15,2	22,4	62,1	29,2	4,6
α dropping	16,1	23,4	62,8	29,0	3,7

Table 2: Dynamic characteristic values when heating up with different profile (α = 200 … 100 W/m²K)

The different profiles affect more strongly installations errors (fig. 8).

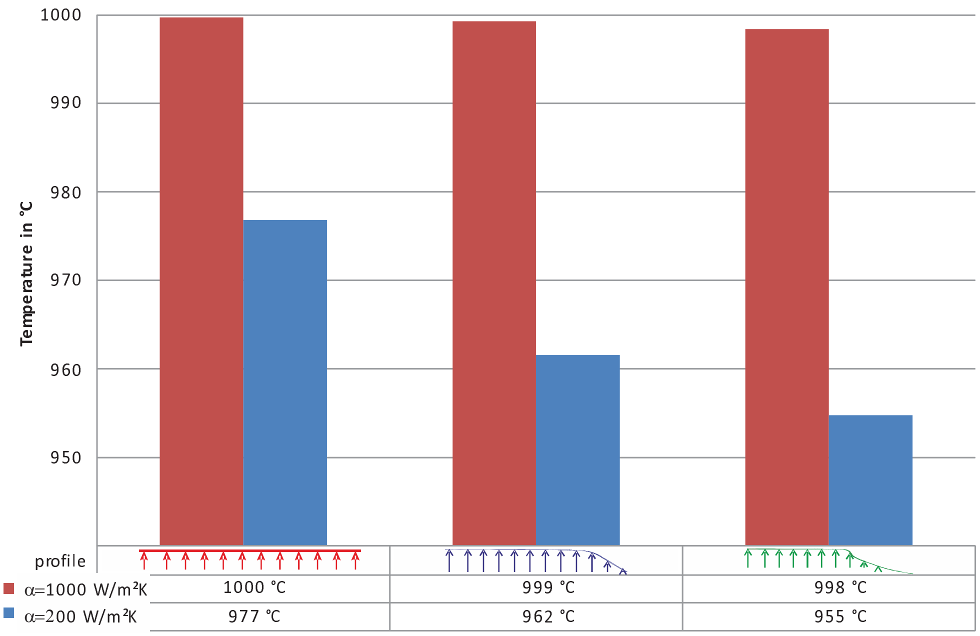

Fig. 8: Dependence of the installation error on the flow profile and the size of the heat transfer coefficient

With a heat transfer coefficient 1,000 W/m²K the maximum installation error is within the range of ΔT = 2 K. With α = 200 W/m²K it amounts to a constant distribution of velocity and temperature within the range of the medium in relation to the larger heat transfer coefficient 33 K. Between the individual profiles already arises then again a difference of ΔT = 22 K.

The variation of the thickness of the installation wall within the range of 3 to 10 mm as well as the ambient temperature of 50 to 150 °C has an influence in a similar way only with α = 200 W/m²K (fig. 9). The installation error is relatively small in the here available model with a housing wall from Inconel. The difference of the temperature of the thermoelement with the installation in a 3 and/or 10 mm thick installation wall amounts to only $\Delta T \approx 2$ K. Interesting is also that a change of the ambient temperature within a range of 100 K has only small effects ($\Delta T \approx 3$ K).

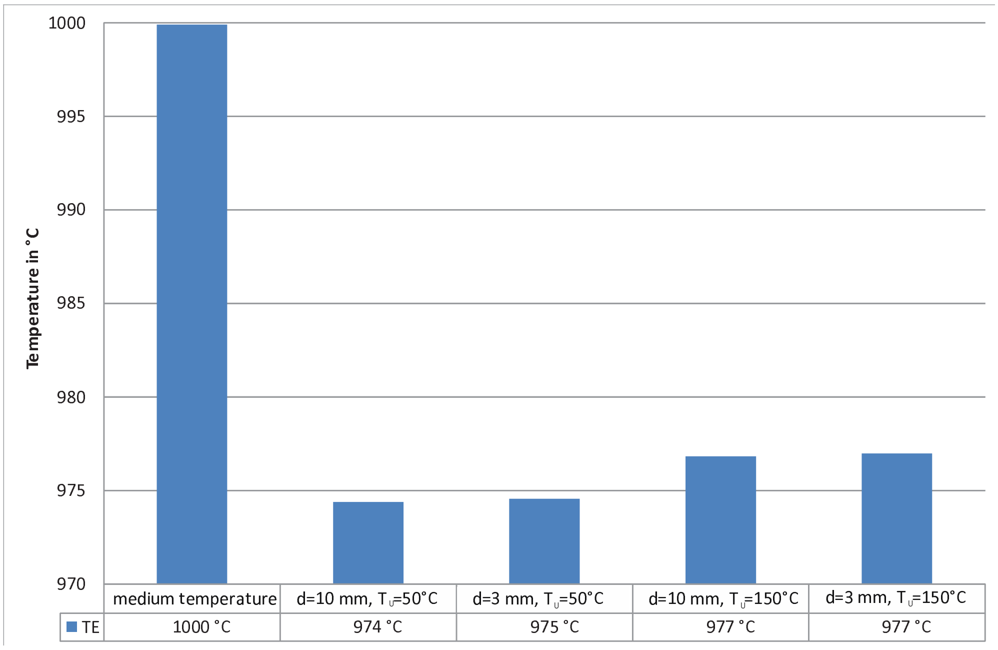

Fig. 9: Result as a function of wall thickness and T_U

To sum up it can be said that results of the accomplished numeric computations which were here represented exemplarily depend strongly on the knowledge of the temperature-dependent materials data as well as the specification of the boundary conditions. As already mentioned above in order to verify the results a comparison with experimental results under certain conditions is necessary.

For the comparative determination of the dynamic characteristic values of temperature sensors the VDI/VDE guideline 3522 „Zeitverhalten von Berührungsthermometern“ is still valid at present [5]. Here the experimental equipments and/or the procedures for the determination of the time characteristic values for temperature steps are fixed within the range of 20 to 40°C. In order to meet the requirements specified above to the determination of the dynamic characteristic values up to a range from 1,000 °C, new test set-ups and evaluation procedures have to be developed and be specified in a new guideline obligatorily. At present a VDI committee consisting of representatives of the thermometer manufacturers and -users as well as the science work on this topic.

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