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Dynamic properties of contact thermometers for high temperatures

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ABSTRACT

Temperature sensors used in exhaust systems of combustion engines have to measure enormous temperature differences within the shortest periods of time. This serves to protect the engine parts with respect to their temperature stability and to govern the energy efficient operation of the engine. Numerical calculations with the Finite Elements Method are used to estimate static-thermal measurement errors and dynamic characteristics primarily concerning medium specificity and construction of the temperature sensors. New test equipment requires comparing various thermometers under real conditions (high temperature steps and velocity). Prediction models are used to correct the dynamic behavior and to predict the fluid temperature faster accurately.

1. Introduction

When using temperature sensors – especially contact thermometers – in technical processes, they have to be adjusted to the corresponding demands for the respective processes in industrial use. This concerns not only the demands for precise temperature measurement but also the prerequisites for use; according to various planned applications, the sensor has to sustain extreme temperatures from −70 °C to 2500 °C, acids or extreme mechanical pressure. The sensor has to maintain free, stable, and operating for years at a time. At the same time the demand remains to keep developing more exact temperature measurement and even faster sensors. This sets even more extreme demands on the construction of the sensors, the selection of the materials used, and also on the evaluation electronics and data processing strategies.

Thermocouples used in exhaust systems of combustion engines are exposed to high temperature gradients and temperature steps ($\Delta T > 900$ K) and high flow speeds ($v > 100$ m/s). When designing these thermocouples, a compromise is needed between the resulting high demands on the mechanical–thermal stability and the fast response time required by the automobile industry. Thermocouples have to be able to determine the temperature in the engine within a few seconds. This exact temperature measurement is needed to protect engine parts and is also important to optimally control the engine and fuel economy.

This study will show how numerical calculations with the Finite Elements Method can be used to design the sensors in their construction and material selection in such a way that the above-mentioned demands are met. For description the boundary conditions of numerical calculation and to compare various temperature sensors it is also necessary to have standardized test equipment's with standardized conditions. We developed such a testing facility and integrated it in the new German guideline VDI/VDE 3522 "Zeitverhalten von Berührungsthermometern".

With the help of a special prediction model the dynamic errors as a function of the operating conditions can be corrected on-line.

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2. Numerical calculations

The sensors have to measure the temperature exactly up to a maximal gas temperature of $T_M \approx 1000\,°C$ [13]. The precision of the measured temperature is influenced by errors of sensor characteristic, errors in the evaluation electronics, by environmental conditions and thermal measuring errors.

The thermal measuring error $\Delta T_{th}(t)$ is the temperature difference between the mean sensor temperature $T_S(t)$ and the original gas temperature $T_M(t)$. This is subdivided into [1]:

Dynamic-thermal measuring error:

$$\Delta T_{th}(t) = T_S(t) - T_M(t) \tag{1}$$

Static-thermal measuring error:

$$\Delta T_{th} = T_S - T_M \quad \text{for } t \to \infty \tag{2}$$

The static-thermal measuring error only occurs if heat transmission to a wall or surroundings happens, whose temperature differs from the medium temperature ($T_A \neq T_M$).

Typical parameters characterizing the dynamic performance of the sensors are time constants and time percent values. The static-thermal measuring error and the time constants are determined by the effective thermal resistivity and by the heat transmission resistance as well as the heat capacity of the temperature sensor.

In order to optimize the static and dynamic behavior of temperature sensors, numerical calculations with the Finite Element Program ANSYS Workbench were conducted. The calculations are based on the solution of the Fourier Law of Heat Conduction [1,2] without internal heat sources:

$$c \cdot \rho \cdot \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(\lambda \cdot \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(\lambda \cdot \frac{\partial T}{\partial y}\right)\frac{\partial}{\partial z}\left(\lambda \cdot \frac{\partial T}{\partial z}\right) \tag{3}$$

The values of density ρ, specific heat capacity c and the thermal conductivity λ depend on the temperature; for example: c of MgO-ceramic increase in the temperature range (20 °C...000 °C) from 1060 J/kg K to 1320 J/kg K, λ decrease from 36 W/m K to 7 W/m K [1]. This case was marked by extreme temperature gradients of 20 °C...1000 °C, which is the reason why temperature dependence of material data had to be taken into consideration for the numerical calculations.

The initial model for numerical calculations can be seen in Fig. 1. It shows the installation of the sensor into a turbo charger that has partially also been modeled in order to determine the parameter dependence of the sensor position and the Finite-Element-Mesh. The mesh includes more than 1.5 Mio. elements.

To solve the differential equation of Fourier (3), the specific boundary conditions have to be known, along with constructive and material parameters. According to the specific problem situation, this could be fixed temperature distributions, impressed heat flux or heat transmission from convection or radiation [2,3]. The description of the boundary conditions is often problematic. There is no generally useful information in literature concerning the description of the boundary conditions in an engine compartment [4,5] or in exhaust tracts. Numerical flow field calculations have been conducted, but their results have not yet been proven to be experimentally verified in a turbocharger. In order to obtain initial experimental data, measurements of an engine test station were conducted using a specially prepared thermocouple element (Fig. 2).

Fig. 3 gives examples of the measured temperatures after engine start, change of speed ($t = 25$ s) and after switch-off of the engine at $t = 50$ s. As can be seen, at the time of $t = 50$ s there is a temperature difference of approx. 100 K in the engine compartment between the two mineral insulated thermocouples at the bottom and the middle, and of ≈580 K towards the thermocouple at the screwing, both of which have to be borne in mind when setting the boundary conditions.

Fig. 4 demonstrates the calculated temperature fields with a constant heat-transfer coefficient of $\alpha = 1000$ W/m^2 K, heat transfer by radiation and a constant medium temperature of $T_M = 980\,°C$. As for the surroundings, slightly moving air (heat-transfer coefficient of = 30 W/m^2 K) with an ambient temperature of $T_A = 25\,°C$ was assumed.

3. New test equipment

A good way to determine experimentally the dynamic properties of temperature sensor is application of a temperature step in a test medium with constant velocity and a known temperature field. Such test conditions are described in [11] for temperature steps in a range up to 20 K. In this range we have constant material properties. For testing the thermometers under real conditions (medium parameter: gas, temperature step up to 1000 K/s and high velocity until 100 m/s) we developed a new test equipment [12]. Realized parameters are close to the conditions in turbo chargers and to other test settings (Table 1).

Fig. 5 shows the principal construction of the test equipment. Temperatures above 1000 °C require Inconel 601 as material of the pipeline and good thermal insulation. The temperature step is realized by a special construction with two temperature probes mounted in a moving rack (Fig. 6).

Fig. 7 shows the result of first measurements, the velocity and temperature of the medium was $v = 20$ m/s and $T_M = 800\,°C$. At the end of the step response we can see temperature variation in a range less than 1 K.

Time percent values are determined usually by the step function response of a temperature sensor in our test equipment, which represents the temperature sequence of a sensor as a reaction to a sudden large change in the medium temperature. The characteristic time percent values t_{50}, t_{63} and t_{90} indicate when 50%, 63%, or 90% of the stationary final value is achieved [6].

This new test equipment is a part of the new guideline VDI/VDE 3522, which will be published in this year. With this equipment it is possible to determine the temperature dependency of time constants during heating and cooling