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Automotive Exhaust Gas Sensing – Current Trends

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Abstract

Robust chemical sensors are required to efficiently control automotive combustion engines. For both gasoline and diesel applications, various types of the ceramic lambda probe for oxygen monitoring are well established. In the event of tighter limits of emission legislation and on-board diagnostics, interest in monitoring additional exhaust gas species grows continuously. This development leads to new generations of exhaust gas sensors, in particular for Diesel applications.

Key words: Lambda sensor, Diesel, exhaust gas, catalyst

Introduction

Due to more stringent environmental legislation, exhaust gas after treatment is crucial for both gasoline and diesel systems. Robust gas sensors play an important role in monitoring, control, and diagnostics of the involved after treatment components. Despite current developments in the field of electric vehicles (EV), conventional combustion engines (as stand-alone or hybrids) will play a major role for several years.

The present contribution reviews current exhaust gas systems of gasoline and diesel powered vehicles. Particular focus is laid on the applied exhaust gas sensors.

Gasoline systems

For best performance of gasoline-powered cars with three-way catalyst, the engine is operated close to stoichiometric combustion conditions (defined as λ=1-point). If combustion is conducted in oxygen excess (lean combustion, $\lambda > 1$), harmful nitrogen oxides (NO_x) are created. On the other hand, oxygen deficient combustion (rich, $\lambda < 1$) leads to higher fuel consumption and excess of partially burned hydrocarbons or CO in the exhaust gas. To achieve an appropriate closed-loop control, a robust sensor element for fast and reliable lambda detection is required.

As first ceramic exhaust gas sensor, the lambda (λ) sensor was introduced in 1976. The sensor principle replicates a simple Nernstian cell suitable to detect the sharp change in oxygen concentration around the λ=1-point with high precision and almost independent from temperature. As electrolyte material, oxygen-ion conducting yttria-stabilized zirconia is used [1].

While sufficiently accurate around this stoichiometric point, sensitivity of the sensor element decreases considerably when the engine is operated un-stoichiometrically. Accordingly, this sensor type is defined as “switching type” lambda sensor, distinguishing between the two states $\lambda < 1$ and $\lambda > 1$.

The λ measurement range was extended to both rich and lean combustion conditions with the introduction of the wideband lambda sensor in 1998. These advanced sensor elements in planar ceramic technology are based on an amperometric operation principle of a so-called pumping cell combined with a Nernstian cell [1,2].

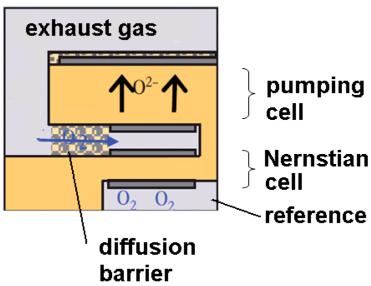

Fig. 1. Schematical set-up of the functional part of a wide-band lambda probe.

One electrode of the pumping cell is located in a small chamber separated from the exhaust gas by a porous diffusion barrier as shown schematically in Fig. 1. The oxygen content of the chamber is fixed and controlled to λ=1 by the adjacent Nernstian cell. If lean exhaust gas enters the chamber, a voltage is applied to the pumping electrode pair. The resulting oxygen current empties the chamber from excess oxygen (cf. right-hand side of Fig. 2) until the desired Nernstian voltage level is reached. In rich exhaust, direction of the pumped current is inverted, and oxygen is pumped into the chamber to yield again λ=1-equilibrium condition (cf. Fig. 2, left-hand side). While the sensor characteristics shown in Fig. 2 is nearly linear in the lean regime, the rich part is governed by exhaust gas composition.

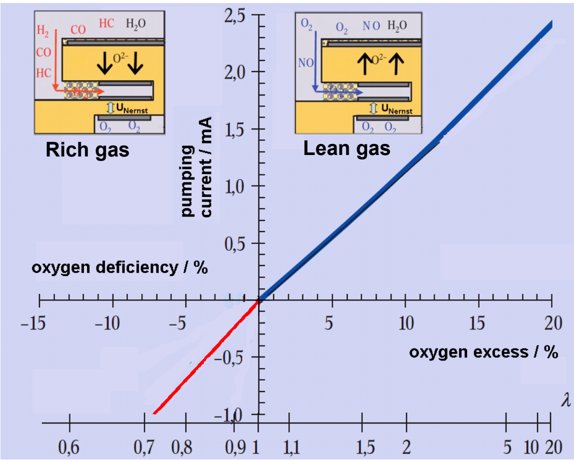

Fig. 2. Working principle of a wide-band lambda sensor in rich (left-hand side) and lean (right-hand side) exhaust gas.

Most modern gasoline systems with three-way catalyst are controlled by a combination of wide-band and switching type lambda sensors. Typically, a wide-band sensor located upstream catalyst is combined with a PID controller to adjust the ratio of injected fuel and intake air. In addition, a second switching-type sensor downstream catalyst is used to monitor and correct the first control loop [1,3].

Although well established in the market, development of lambda sensors continues in order to meet with more advanced requirements. Further tightening of emission legislation requires higher accuracy and fast sensor readiness after engine start. Appropriate measures [2] include

- a so-called pumped reference: this internal reference replaces the initial air reference channel. Thus, a more compact design of the ceramic element is enabled.
- very fast sensor signal availability after engine start
- a thermal shock protection layer required for operation of the heated ceramic sensor element in the presence of water droplets.

Diesel systems

The combination of energy efficient diesel engines with reliable exhaust gas treatment enables CO_2 and emission efficient mobility.

Similar to gasoline systems described above, wide-band lambda sensors are standard in diesel cars to ensure stable engine operation in optimized combustion conditions [2]. Beyond this, the introduction of gas sensors into diesel systems is still progressing.

In contrast to gasoline cars, diesel systems present a variety of filter and catalyst systems (eg., diesel particulate filter (DPF), oxidation catalyst, selective catalytic reduction (SCR) catalyst). According to novel legislation standards, these are to be diagnosed individually. Thus, modern Clean-Diesel systems employ a variety of exhaust gas sensors, which allow not only the measurement of gas compositions but also support the on-board diagnostics (OBD) of the employed catalysts.

For this purpose, a chemical measurement principle is not always required. To monitor the DPF, differential-pressure sensors based on piezo-resistive elements are used [4]. The DPF consists of a porous ceramic wall structure trapping soot particles. The accumulating soot leads to an increased pressure drop. As soon as a critical value is detected by the pressure sensors, regeneration procedures cleaning the DPF are started. Novel OBD principles employ ceramic particulate matter sensors with interdigitated electrode structures.

To monitor those components responsible for NO_x abatement, a chemical NO_x sensor is used [2,4]. As the conventional lambda probe, the corresponding sensor element is still based on planar ceramic technology. However, its complexity in terms of sensor design, sensor operation, and materials used is higher (cf. Fig. 3).

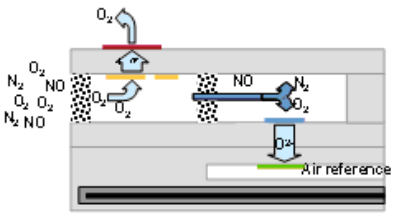

Fig. 3. Simplified scheme of an amperometric NOx-sensor

Sensor function of the ceramic NO_x sensor is based on two chambers separated by porous diffusion barriers. At a first stage, lean diesel exhaust gas enters chamber 1. The electrode located in this chamber is designed to pump out any oxygen present while leaving NO molecules intact. The high selectivity towards molecular oxygen is ensured by choosing an appropriate selective electrode material.

The remaining gaseous species then enter a second chamber. The electrode located there is prepared from a material with supreme NO_x cracking performance. NO_x is split into its components nitrogen and oxygen. While inert N_2 molecules remain in the gas, oxygen ions are pumped out. Since virtually no molecular oxygen enters the second chamber, the magnitude of the pumping current is proportional to the NO_x concentration.

Major challenges of this sensor principle include the preparation of highly selective pumping electrodes as well as the signal processing of very small NO_x pumping currents in the nano-amps range.

Conclusion and Outlook

Passenger cars and commercial vehicles with internal combustion engines are subject to the constant trend to improve fuel and CO_2 efficiency. At the same time, exhaust gas legislation tightens requirements for on-board diagnostics and monitoring of exhaust gas catalysts. Present sensor systems are designed and apt to meet with current requirements. In the face of future trends and challenges, development of sensor and catalyst systems is ongoing to ensure appropriate performance.

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