How to test exhaust gas sensors? Influence of gas testing systems and experimental artifacts in exhaust gas sensors characterization.

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Abstract

A study on the influence of the gas testing systems in the behavior of solid-state electrochemical exhaust gas sensors is presented. Several YSZ-based exhaust gas sensors have been tested in different versions of gas testing chambers, with different architectures, volumes, exhaust gas flow dynamics, temperature regulation, etc. Sensors have been tested in synthetic gas testing chambers and in real combustion systems. Results show that parameters such as the response time or even the equilibrium open circuit voltage may be strongly dependent on the characteristics of the testing system. Moreover, a lack of gas flow homogeneity or a wrong temperature distribution in the testing chamber may dramatically influence the behavior of exhaust gas sensors. Optimum designs of experimental systems are presented in terms of the sensing characteristics to be tested.

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1. Introduction

The objectives of this work are: (i) to present different versions of reliable gas testing systems, (ii) to compare the behaviour of gas sensors in different own-designed experimental systems, and (iii) to optimize the sensing response by avoiding flow and/or temperature dependencies. We have focused on exhaust gas sensors based in a solid ceramic electrolyte with catalytically active electrodes, due to our experimental availability and to the importance of obtaining fast, repeatable and reproducible results in some of the applications of these sensors, such as combustion control in automotive engines. These sensors are commercially applied to characterize exhaust gas mixtures generated in combustion engines or burners, and are usually known as lambda sensors.
2. Experimental

Several versions of lambda sensors (with a resistive or electrochemical principle, thimble type or planar type, selective or not, etc.) exist. We chose to use electrochemical planar ceramic lambda sensors. They had the following planar structure:

\[(\text{measured gas}) / \text{porous layer} / \text{electrode} / \text{electrolyte} / \text{electrode} / (\text{reference gas})\]  

(1)

A schematic cross-sectional view of this structure can be found elsewhere [1-2]. We prepared our own sensors following a monolithic ceramic process. Details on the process can be found at [3]. Sensors were made of a 4.5%mol Y₂O₃-doped ZrO₂ (YSZ) with cermet Pt-YSZ electrodes and an embedded heating resistance. The diffusive layer over one of the electrodes was made of porous YSZ. Their real aspect can be seen in Fig.1. As indicated in (1), each electrode is exposed to a different atmosphere. The usual behaviour of these sensors was a binary 1V / 0V response in front of rich and lean exhaust gas mixtures (Fig.2). A rich mixture is defined [4] as an air/fuel ratio with an excess of fuel with respect to the stoichiometric ratio, thus causing reducing emissions after combustion (i.e. including CO, hydrocarbons, etc.). A lean mixture is defined as an air/fuel ratio with an excess of air with respect to the stoichiometric ratio. Exhaust gas mixtures are characterized by their combustion parameter \(\lambda\). \(\lambda = 1\) for a stoichiometric mixture, \(\lambda < 1\) for a rich mixture and \(\lambda > 1\) for a lean mixture.

![Fig.1. Real aspect of our own-designed conventional planar lambda sensor. A metallic track connects the measuring electrode (covered by a diffusive layer) to its corresponding contact. The white material is the ion conducting electrolyte. Reference electrode is not visible in the image as it is embedded, but its electric contact can be seen in the outer surface of the sensor.](image1)

2.1 Synthetic gas testing chambers

We used two different gas testing systems based in synthetic gas mixtures. This allowed us to compare the behaviour of the sensors in both chambers and establish if both systems were absolutely equivalent for measuring sensors or not. The main difference between both gas testing systems was that one of them (“System A”) implemented up to six different gas reservoirs, thus leading to the possibility of measuring multi-component gas mixtures by varying the concentrations of up to six components, whereas the other gas station (“System B”) had only two gas supplies: air and a prepared gas mixture. In the exhaust gas context, the prepared mixture was equivalent to a combustion parameter of \(\lambda = 0.94\). When the air flow controller was closed, the prepared mixture was the only gas to flow through the testing chamber. Exhaust gas mixtures with a combustion parameter \(\lambda\) higher than 0.94 could be generated by opening the air flow controller while the other flow controller was kept constant. Furthermore, the allocation of sensors in System A was symmetric with respect to the gas flow, whereas sensors were allocated one after the other in System B, thus causing possible flow vectorization.
problems and different response times in the case of System B. Table 1 summarizes the main characteristics of each gas testing system. Figure 3 depicts a schematic view of both gas stations, together with a detailed view of both testing chambers.

Table 1. Comparison between synthetic gas testing chambers A and B.

<table>
<thead>
<tr>
<th></th>
<th>System A</th>
<th>System B</th>
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<tbody>
<tr>
<td>Gas reservoirs</td>
<td>6 bottles: ( \text{N}_2, \text{CO}_2, \text{O}_2, \text{NO}, \text{C}_3\text{H}_8, \text{CO} )</td>
<td>1 compressed air connection + 1 bottle (Prepared mixture of ( \text{C}_3\text{H}_8, \text{CO}, \text{CO}_2 ) and ( \text{N}_2 ), equivalent to a combustion parameter of ( \lambda=0.94 ))</td>
</tr>
<tr>
<td>Carrier gas</td>
<td>Nitrogen</td>
<td>Air / Nitrogen</td>
</tr>
<tr>
<td>Testing chamber volume</td>
<td>Poliedric, ( \sim 500 \text{ cm}^3 )</td>
<td>( \sim 140 \text{ cm}^3 ) (22cm x 2.5cm x 2.5cm)</td>
</tr>
<tr>
<td>Allocation of sensors with respect of gas flow</td>
<td>Symmetric</td>
<td>Asymmetric (gas flow collided with sensors at different times)</td>
</tr>
<tr>
<td>Temperature control</td>
<td>External power able to heat the entire testing chamber, maximum temperature: 850ºC</td>
<td>No (Sensors could only be heated if they had an embedded heating resistance)</td>
</tr>
<tr>
<td>Combustion parameter ( \lambda ) range</td>
<td>( -0.7 &lt; \lambda &lt; \infty )</td>
<td>0.94 ( &lt; \lambda &lt; 1.70 )</td>
</tr>
<tr>
<td>Gas emission</td>
<td>To the external atmosphere (with fan)</td>
<td>To the room</td>
</tr>
</tbody>
</table>

It can be seen (Fig.4) that the systems were not completely equivalent, as both responses were very similar, but not identical. The signal was a bit noisier in System A and slightly higher in rich mixtures in System B. Both differences could be attributed to the fact that System A was a multi-component gas chamber with six different mass flow controllers: fluctuations in six MFCs (System A) could lead to higher noises than with two MFCs (System B). The transition time between 10 and 90% of the stationary response was in the order of tenths of seconds in all cases. In the transition between the \( \lambda=1.05 \) and \( \lambda=0.95 \) measurements, the mean response time was 400 ms for System A and 320 ms for System B. Probably, this response time difference could be also explained by the high number of MFCs.

2.2 Real combustion chambers

The objective was to get a cheap and safe experimental gas burner and to test sensors with it. We expected designed a system with the following requirements: (i) emission of exhaust gases when burning an air/fuel mixture; (ii) possibility of selecting a lean or a rich exhaust gas by modifying the air/fuel ratio in the burner; (iii) allocation of lambda sensors in the exhaust pipe; (iv) the exhaust gas flow colliding with the sensors should be high enough to heat the sensors and make them work without any other external heating power (no embedded heating resistance needed in the sensors); (v) when
placing several sensors in the exhaust pipe, they should be in similar conditions of incident gas flow, gas composition and temperature. Temperature should be between 550ºC and 650ºC in all sensors; (vi) the energy consumption should be significantly lower than the consumption of an ordinary automotive combustion engine (i.e. 20 kW). Fig.5 shows the initial and the improved design of the chamber. Three main subsystems can be described: the mixing subsystem, the combustion chamber and the exhaust pipe. Two gases (air from a compressed air system and butane as fuel) were mixed and sent to the burner’s electrodes. The flow of each gas was controlled by two manual valve regulators. A mixer membrane avoided a possible vectorization of the components and a subsequent abnormal combustion. The burner consisted in a combustion chamber with two high voltage electrodes. When desired, they were discharged at 8 kV and, if the air/fuel mixture was present, a flame was generated, thus turning into a real combustion. Depending on how the manual gas regulators were opened, the mixture could be lean or rich. The improved version worked burning very lean mixtures (with high excess of air) in the major part of the time, whereas it would generate rich mixtures for some short-duration stages. The schematic representation of this second prototype can be seen in Fig.5 as well. The main difference with respect to the previous system is that it did include a ventilation system in the upper part of the exhaust pipe. Ventilation pulled air from the combustion region and forced the exhaust gas to be always in lean conditions due to that excess of air. Compared to prototype A, a higher flow of exhaust gas colliding with the sensors should heat them quicker. When the ventilation was stopped, there would be no forced excess of air and subsequently the exhaust gas could turn to a rich mixture. Rich conditions should not last for long lapses of time, as the low gas flow could lead to a decrease in the sensors temperatures.

Fig.5. Initial proposal (Left) and improved version (Right) of a real combustion gas testing system. The definitive version was able to emit rich and lean mixtures with a low energy consumption.

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References