

Multi-criteria/Multi-sensor early Fire Detection in the Engine Compartment of Road Vehicles: Gas Sensors Performance at Elevated Ambient Temperature

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Abstract

A low cost laboratory setup ("fire simulator"), useful for evaluating the applicability of gas sensors for early fire detection in bus engine compartments, was previously presented [1]. The setup has since been improved and extended, and the gas sensors have been further evaluated in the lab and in the engine compartment of a van. Although the measurements are not yet conclusive, overall the field tests suggest that the gas sensor array is suitable for the early detection of fire in the engine compartment of utility vehicles. The established test procedures and results are presented in this paper.

Keywords: Gas sensor array, automotive, ambient temperature

Sensor selection

Three of the original gas sensors, Figaro TGS4161 for CO₂, Figaro TGS2600 for CO and VOCs, and AS-MLC for CO/NO₂, were tested. Both of the metal oxide based sensors, TGS2600 and AS-MLC, are still being operated. It was found that the initially used NO₂ sensor Figaro TGS2106 is not suited for operation at elevated ambient temperatures due to its plastic enclosure. Therefore, GGS5430T, marketed as a diesel exhaust NO₂ gas sensor by the manufacturer, was selected as a replacement. New electronics for amplification and conversion were developed and used; a multi-channel PWM controller is used to adapt the gas sensors' heating power to the ambient temperature.

Improvements to the fire simulator

Using the laboratory setup, vehicle parts are safely combusted in a muffle furnace. The resulting gas is then pumped from the chimney through a heated capillary to the sensors in the laboratory [1]. Originally, a single thermocouple was placed on the surface of the sample. The sample

temperature (and consequently its flash point) could not, however, be measured reliably, as the sample often melts and loses contact with the thermocouple. In order to add redundancy and increase the reliability, four longer thermocouples with a diameter of only 0.5 mm are now used. They reach the sample cup. Two of the tips are on the sample and two are positioned right above the cup, where they would be in the hottest zone in case of flashover. MCP9600 replaced AD8495 as a thermocouple measurement converter, because it has a digital interface and is more precise, especially at lower temperatures. The resulting compatibility issues are covered in another paper [2].

A significant addition to the fire simulator is a second sensor chamber. One of the chambers is heated in order to evaluate the sensors' behavior to combustion gases at elevated ambient temperatures. The second (downstream) chamber serves as a reference and is, therefore, not heated. When connected in series, reaction byproducts of the first chamber might influence the second chamber. It is expected, however, that the byproducts are low in comparison to the overall volume stream. This configuration ensured identical volume streams through both chambers. With more chambers, a more complicated parallel configuration is recommended [3] and was used in a later version of the setup. Fully integrated "digital" gas sensors (Bosch BME680 and ams CCS811 for CO/VOC, Sensirion SCD30 for CO₂) were added to the unheated chamber. Although they are specified for lower operating temperatures than occur in the vehicle engine compartment, in this measurement setup they serve as a reference.

For the same reason, the latter were also installed in the shack with the furnace, in order to get more information about the fresh air that is taken into the furnace chamber. In order to install the additional sensors, the second chamber is significantly larger. As a result the sensor signals were overall flattened and deferred in comparison to those of the sensors in the smaller heated chamber. This is expected as a result of the relatively low gas flow (ca. 100 ml/min) through the capillary from the furnace. The final additions to the setup were particulate matter (PM) sensors (Sensirion SPS30) for particles sizes between 0.3 µm and 10 µm. This should be helpful in identifying smoke production. Again, two were installed: one for fresh air near the furnace, another one for the exhaust air in the chimney.

Measurements with the gas mixing station

The effect of ambient temperature was experimentally examined in three steps. In the first step, the sensors were installed in a heated chamber, which had been thoroughly cleaned before. The sensors were exposed to defined gas concentrations from an automated gas mixing station. A series of pure sample gas concentrations was used to determine the sensors' response. Initially the chamber was not heated, i.e. the ambient temperature was room temperature (RT).

The measurement was then repeated with the chamber heated to 60°C, 80°C, and 100°C. As an effect of ambient temperatures above 60°C on each sensor's baseline was clearly visible, the measurement at room temperature was repeated daily for two weeks (Fig. 1). TGS4161, an electrochemical cell, significantly suffered from the high ambient temperatures. Unlike the other SMOX type sensors, TGS4161 did not completely recover. TGS2600 showed a weaker response towards its target gas CO at higher temperature, which is a result of the significantly reduced baseline. The response quickly recovered when the ambient temperature was lowered again. Its cross sensitivity towards NO₂ is generally low. Like TGS2600, AS-MLC, specified as a CO sensor, had a lower baseline resistance at higher ambient temperatures. It, however, recovered more slowly and only returned to the original values after approximately a week of operation at RT.

Interestingly, its cross sensitivity towards high concentrations of NO₂, already reported in the preceding paper [1], was negligibly affected. GGS5430T also showed a lower baseline resistance at higher ambient temperatures and seemed to lose its cross sensitivity towards CO. It, however, preserved its sensitivity towards NO₂ in relation to the new baseline. It recovered slowly, but completely. As the SMOX sensors' sensitive elements are heated to operating temperatures above 250°C, and as AS-MLC is technically approved by the manufacturer for ambient temperatures up to 120°C [4], it is improbable that the sensitive elements are actually harmed by the high ambient temperatures. We, thus, assume that their baseline is reduced by the presence of volatile organic compounds (VOC), towards which the sensors are known to respond similarly as to CO. The source of VOC contamination could not be determined, though; due to the sensors' high sensitivity, a small residue in the experimental setup may already be sufficient to cause the described effect. The sensors' enclosure, e.g. glue, might be another source.

Combustion experiments with the fire simulator

In the second step, two arrays of identical sensors in a heated and an unheated chamber were compared in the aforementioned fire simulator. Corrugated hose made of Polyamide or Polypropylene was chosen as a sample material, as it is commonly used and shows a reproducible combustion behavior. The furnace temperature was varied between 570°C and 630°C, and different sample amounts between 1 g and 10 g were tested. The temperature of the fresh air pulled into the furnace chamber by the fan was also varied. Through changes in these factors, it was possible to perform experiments during which the sample decomposed either with or without flashover. The latter case (smoldering) allowed a prolonged observation of the immediate pre-fire stage. The PM sensor in the chimney is a valuable addition, as it reports the highest concentrations of 16 to 200 mg/m³ while the sample is

smoldering, and reproducibly slightly lowered ones shortly before flashover and during combustion. Normal ambient levels are around $5 \mu\text{g}/\text{m}^3$, with spikes of up to $4 \text{ mg}/\text{m}^3$ when soot or dust is released by e.g. operating the furnace door. The average particle size increases reproducibly from 0.5 to $1.5 \mu\text{m}$ during thermal decomposition of a sample.

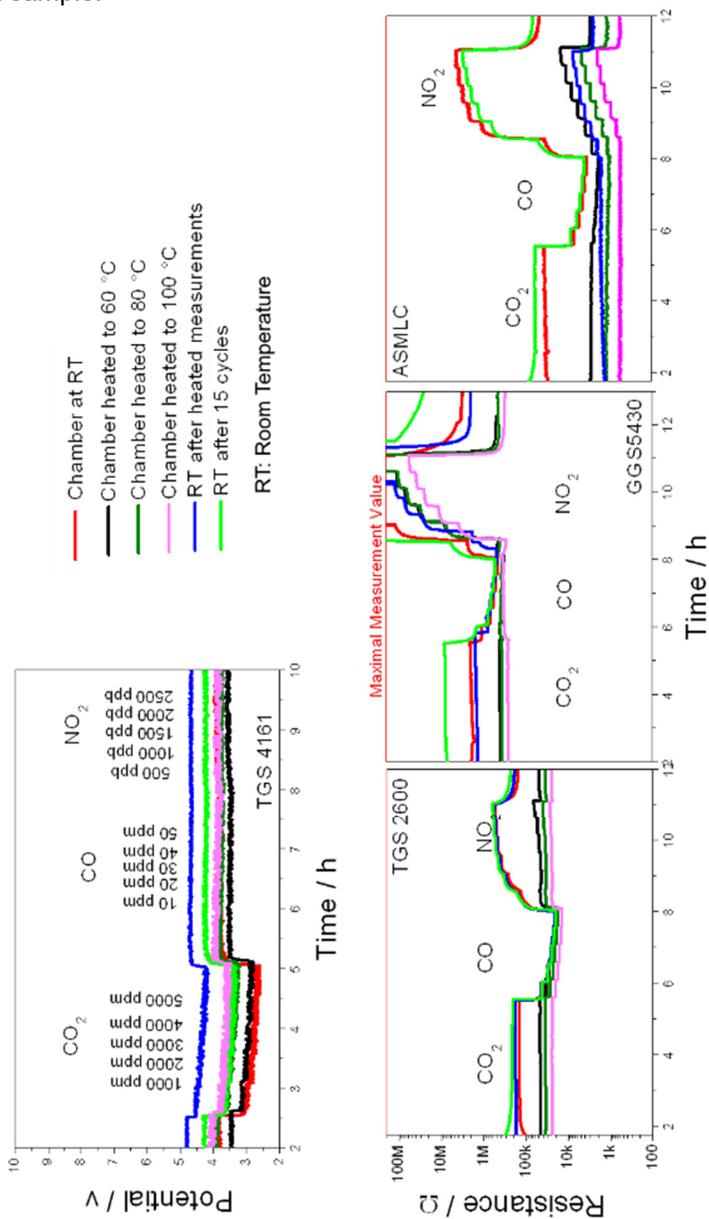


Fig. 1. Daily measurements with gas mixing station at different sensor chamber temperatures.

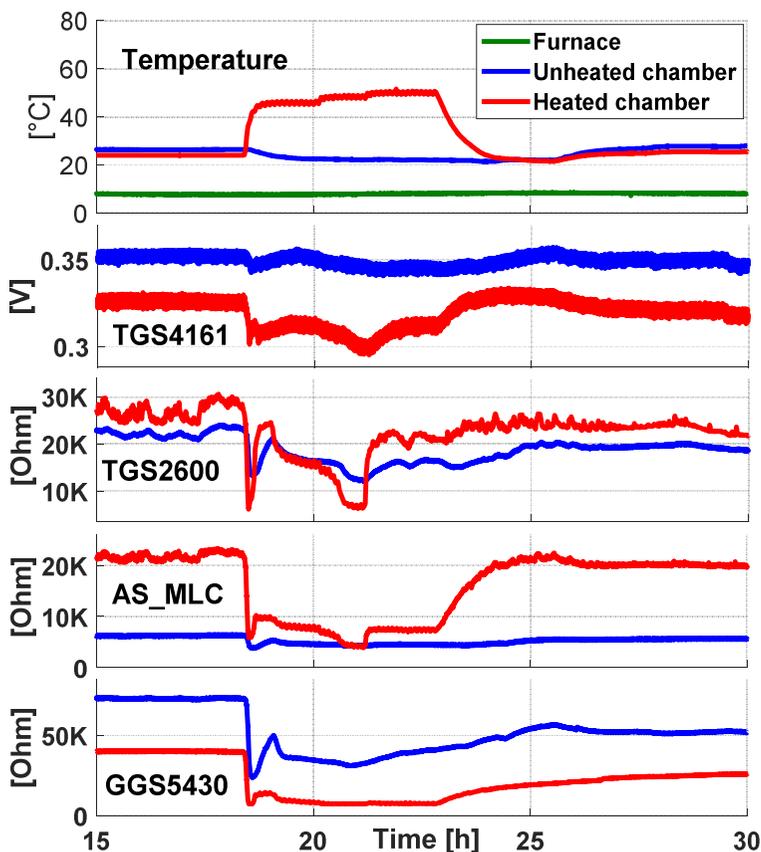


Fig. 2. Evaporation of residue when heating up the chamber to 50 °C.

As previously mentioned, the sensors' response in the larger unheated chamber was generally delayed and flatter than in the smaller heated chamber and is therefore not discussed in greater detail. Fig. 3 shows measured values from the sensors in the heated chamber during combustion experiments at different chamber temperatures. The results can be compared to those attained using the gas mixing station.

The CO₂ sensor TGS4161 lowered its baseline from about 350 mV at room temperature to 260 to 230 mV in a hot environment. In contrast to the experiments with the gas mixing station, the effect was quickly reversible. Its sensitivity was not significantly reduced. The baseline stabilized at a level of about 300 mV at room temperature after the first few heating cycles. As expected, it only responded in experiments with an ignition of the sample, i.e. a complete combustion with the emission of CO₂. That was confirmed by a rise of humidity in the sensor chamber in such cases, as water is another product of complete combustion of organic samples.

Table 1 shows two parameters helpful in assessing the sensors' behavior at different temperatures. The baseline shift R_{pre}/R_0 relates a sensor's "morning" baseline resistance R_0 (at RT about 30 minutes after switching it on) to its baseline resistance R_{pre} (shortly before a combustion experiment, and heated). Only the first experiment after switching the sensor on was considered for the table, as residue from a previous experiment could influence the sensors, too. The value should be as close to 1 as possible (and is at RT). The sensitivity R_{CO}/R_{pre} shows the peak response of a sensor to a combustion event in relation to its baseline before inserting the sample. It should be clearly lower than 1 in any case of combustion. In this case, 1 means that an event cannot be detected which is more probable for smoldering fires.

The baseline of the CO/VOC sensor TGS2600 was reduced at an ambient temperature of 80°C, whereas its absolute response to combustion gases remained almost unchanged, as it often showed a plateau, which was caused by saturation of the amplifier. Its overall behavior was comparable to the previous results, including the fast recovery. It showed no cross sensitivity to NO₂, which was produced during flashover of polyamide samples in many cases. The CO/NO₂ sensor AS-MLC showed a different behavior. Its strong cross sensitivity towards NO₂ became obvious in several experiments. It initially indicates CO emitted during smoldering by decreasing its resistance to typically half its baseline value (Table 1); then it indicates NO₂ after flashover by increasing its resistance to approximately twice its baseline value (Fig. 3 right). Recovery to the baseline value usually took about ten minutes in such cases – much longer than for TGS2600.

In case of smoldering samples, AS-MLC's decrease of resistance indicating CO was comparable to the flashover case, but lasted much longer, often half an hour, and could even affect the next combustion experiment. It showed a similar sensitivity as TGS2600 towards VOC residue evaporating from the capillary or the sensor chamber when heating up in the morning (Fig. 2). GGS5430T was most seriously affected by ambient heat. Its response towards all gases disappeared after a few temperature cycles. It continually responded to an elevated ambient temperature by decreasing its baseline. In contrast to the measurements with the gas mixing station, it was more likely to show a decrease of its resistance during exposure to a high concentration of CO than – as would be expected – show an increase of the resistance in the case of a flashover where a high concentration of NO₂ (indicated by AS-MLC increasing its resistance) is present. The latter case was no longer observable once the sensor had aged. AS-MLC's baseline resistance, however, recovered faster from heat in the fire simulator than in the gas mixing station. This finding further supports the assumption that a residue present during the gas mixing experiment contributed to the observed effects.

In the fire simulator, the baseline returned to a steady value almost linearly with the ambient temperature returning to the original room temperature value overnight.

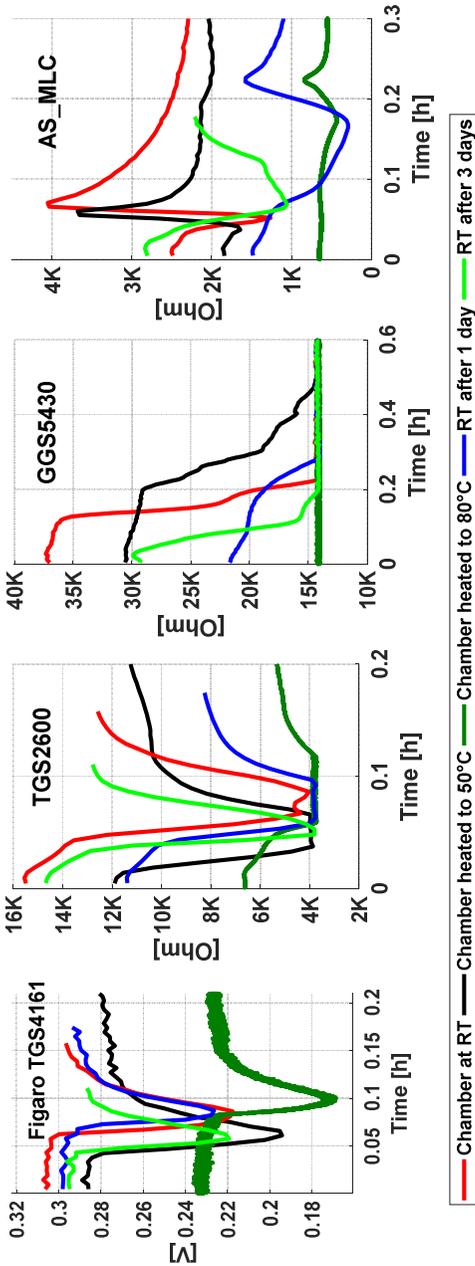


Fig. 3. Sensors' responses at different ambient temperatures during combustion experiments.

An important observation could be made when heating the sensor chamber after a series of combustion experiments during which it had not been heated (Fig. 2). In the sensor chamber, when not being heated, a combustion residue can accumulate. The residue evaporates when heating the sensor chamber later and lowers the SMOX sensors' resistance, causing a signal indistinguishable from that of CO, which is known not to be present at that time. TGS2600's baseline began to recover in the shown experiment before the chamber heating was turned off, indicating that the residue had been significantly reduced. The sensors in the unheated chamber also showed a comparable behavior to the residue as the heated sensors at an ambient temperature of 50°C. This finding indicates that the large effect of the ambient temperature on the sensor behavior is largely related to the evaporation of an impurity in the system. A similar, but weaker effect could also be observed when the capillary is heated. The reversibility of the effect could only be observed for a chamber temperature of 50°C. At 80°C, the effect on the sensors' baseline seems permanent (as long as the ambient temperature remains elevated). This could be explained by the evaporation of different compounds at a higher temperature, or that at this level the higher ambient temperature itself plays a role.

Table 1. Sensors' peak responses in combustion experiments.
 R_0 : resistance before heating the sensor chamber;
 R_{pre} : resistance before sample insertion;
 R_{CO} : lowest resistance during combustion.

Chamber temperature		TGS2600			AS-MLC		
		20°C	50°C	80°C	20°C	50°C	80°C
Baseline shift R_{pre}/R_0	Min	1	0,50	0,12	1	0,27	0,06
	Avg		0,66	0,22		0,37	0,09
	Max		0,78	0,40		0,50	0,12
Sensitivity R_{CO}/R_{pre}	Min	0,13	0,22	0,50	0,05	0,43	0,25
	Avg	0,35	0,43	0,79	0,28	0,57	0,76
	Max	0,71	0,83	0,99	0,85	0,86	1,16

Conclusion and outlook

The next step of the project was road tests. The sensors were installed in the engine compartment of a van. The measurement allowed the background in traffic to be determined and is covered in detail in another paper [5]. The combined use of a gas mixing station and the fire simulator, previously reported [1], was successfully used to investigate the influence of ambient temperature on the gas sensors. TGS2600 and AS-MLC show promise for early fire detection. Using combination of their signals, the transition from a smoldering to a flaming fire (flashover) can be detected. The influence of ambient heat and impurity on their baseline

(and, as a consequence, their effective sensitivity towards gases related to combustion) requires further investigation. An exact determination of the combustion residue and actual emission from an ongoing combustion of any kind is desirable especially at higher ambient temperatures. Of the examined sensors, two (TGS4161, AS-MLC), are no longer available. For AS-MLC, a replacement is needed. GGS5430T was examined as a replacement. Overall, its performance was suboptimal. It lost sensitivity towards its main target gas, NO₂, during the combustion experiments. As this is assumed to be important to estimate the influence of diesel exhaust gases on the other sensors in the vehicle, the sensor is ill-suited for integration in the fire detector. The monitoring of particulate matter (smoke) showed reproducible results and a promising signal-noise-ratio in the experiments with the fire simulator; it is unclear, though, how such a solution might perform on the road, as the used sensor is not heat resistant. Known background values are promising [6]. The unheated second chamber for the reference sensors in the fire simulator was too large. For future measurements, the reference chamber will be optimized to better match the heated one. More laboratory and road tests involving a vehicle will be performed.

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