Multi-criteria/multi-sensor early fire detection in the engine compartment of road vehicles: Evaluation process of gas sensors

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Abstract

The goal of the reported research is to develop a multi-sensor/multi-criteria early fire detector for the engine compartment of busses. A discrete gas sensor array has been devised and its suitability for early fire detection has been evaluated. The preliminary tests have been performed using specially developed fire simulator which provided the test atmosphere by burning vehicle components. The response of the gas sensors towards the fire exhaust have been compared with the data from a quadrupol mass spectrometer. The preliminary results are promising.

Keywords: Vehicle fire, gas sensors, mass spectrometer, test stand, multi-criteria/multi-sensor

Introduction

Fires on trucks and busses present a serious problem for the transportation industry. Studies from the USA [1], Germany [2], etc., report that each year there is a fire on 1% of busses and that most start in the engine compartment. Usually, different kinds of temperature sensors are utilized, but because these sensors depend on heat convection they are very slow. During the detection delay, the fire can grow in intensity, destroy key vehicle components and be more difficult to fight and put out. It also increases the passengers' risks, as the available time for vehicle evacuation is reduced. Early fire recognition procedures that complement the existing thermal methods are needed. To address this need, we are currently developing a multi-criteria/multi-sensor fire detection system based on gas, infrared, and environment sensors. It will use multivariate data analysis and machine learning approaches to enable the early detection of fire. The ability to detect fire before the ignition, during the smoldering phase, would reduce the damage and danger level. The investigations into an early detection method are progressing in several successive stages: During the *1st stage,* suitable commercially available gas sensors (GS) are selected and tested in a controlled environment. For laboratory tests either a gas mixing system or a fire simulator are used. The *2nd stage* is devoted to field experiments with the fire detection system under real operation conditions but without fire. The goal is to determine the gas concentrations in the engine compartment under safe, regular vehicle operation. Pertinent acquired data will be saved, compressed and sent through a telematics unit to a server for further processing. The *3rd stage* encompasses the machine learning phase. The information obtained during previous stages is used to teach a support vector machine (SVM), which, afterwards, will be able to make fire event predictions based on actual data input. Additionally, the SVM will ensure detection system immunity against changes in environmental factors and sensor aging. The *4th stage* consists of final tests, where a mock-up engine compartment and an old bus will be set on fire, and the full fire detection system will be verified. The 1st stage's experimental setup and results are reported here.

Experimental setup

The gas sensor array (SA, Fig. 1.) of the fire detection system initially contained 7 sensors with high sensitivity and fair selectivity for gases typically encountered in fire events [3]: Figaro TGS2600 and TGS2620 for reducing gases, TGS4161 for CO_2, TGS2106 for NO_2, AS-MLC for CO, HYT939 for humidity and temperature and FCX-MLV for oxygen. The sensors have been adequately interfaced to a readout prototype board and a Raspberry Pi 3 used as a controller (Fig. 3.C). Driver and readout software has been developed. A preliminary laboratory evaluation of different sensor arrays has been performed in a dedicated measuring chamber connected to a computer controlled gas mixing and measuring system (GMMS), as presented in [4]. The exposure protocol included gaseous mixtures relevant for the application. A Hiden mass spectrometer (MS) completed the experimental setup, providing reference mass spectra.

Fig. 1. Initial gas sensor array

Subsequently several sensor arrays have been tested using the laboratory fire simulator (Fig. 2.). It is a semi-automated, low-cost and space-efficient setup developed to heat and burn small samples of different parts (fuel, oil, insulation material, plastic housings, belts, air filters, and hoses) normally found in an engine compartment. Its central component is a laboratory muffle furnace in a metal shack outside the main building (Fig. 3.A). The furnace chamber (Fig. 3.B) has a volume of five liters and consists of a flame resistant ceramic material. It is equipped with thermocouples to measure the inner air temperature and the one on the surface of the samples. Additional environmental sensors (for temperature, humidity and pressure of the intake air) have been included on top of the furnace. A radial fan adjusts the air flow through the furnace chamber between 5 and 10 liters/second (i.e., between one and two atmospheric replacements in the chamber), which is the minimal required value to prevent exhaust from leaking. From the furnace gas exhaust a small amount of 60 ml/min is pumped towards the sensor array and to the mass spectrometer, with a latency of about one minute. The whole piping and spectrometer inlet capillary are insulated with mineral wool and heated above 100 °C to avoid condensation of water or volatile compounds, and to ensure the temperature range expected for the engine compartment. An easily cleanable particle filter prevents smoke particles from entering (and thereby clogging) the capillary of the mass spectrometer.

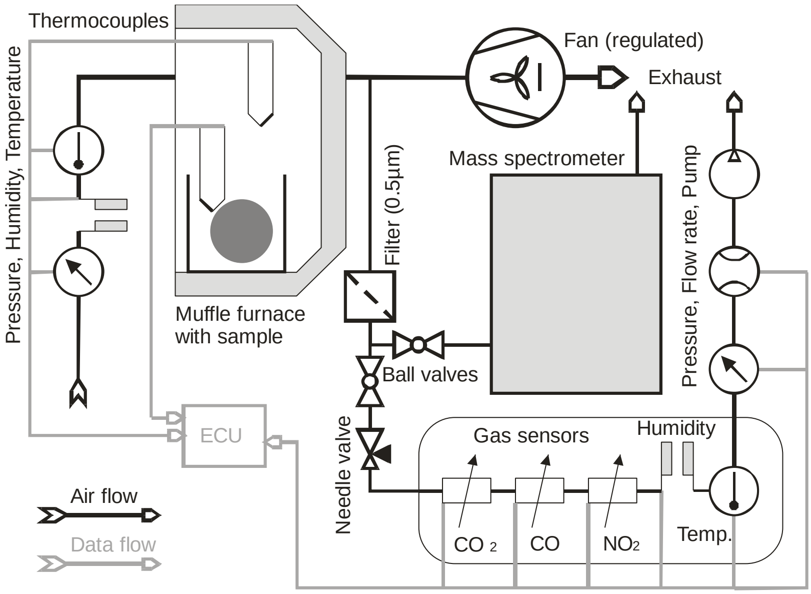

Fig. 2. Schematic of the laboratory fire simulator

A potentially flammable sample is inserted into the furnace in a ceramic cup (Fig. 4.), with a flexible thermocouple placed on the sample's surface; the moment of insertion is detected by a reed contact on the furnace door. The sample is heated from 200°C to 600°C, in order to identify the flashpoint. The gas signatures before, during and after ignition are acquired and stored.

Between experiments, the furnace can be cooled by increasing the air flow through the chamber with the radial fan. After a series of experiments, remaining soot can be removed from the furnace by heating to 1020 °C for about one hour using an integrated timer (pyrolysis cleaning).

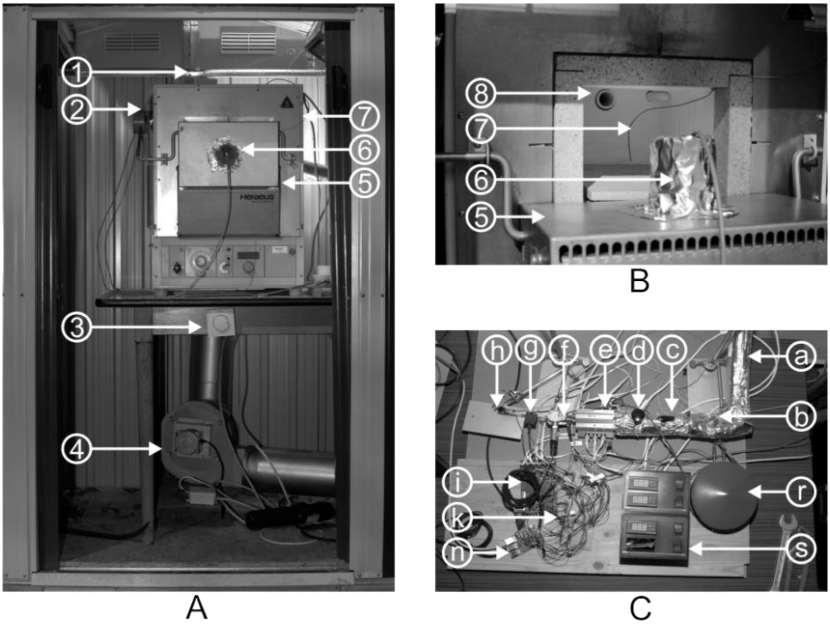

Fig. 3. Fire simulator. A) Furnace and fan. B) Furnace chamber. C) Sensors and electronics. 1) environment sensor, 2) reed contact, 3) radial fan controller, 4) radial fan, 5) front door, 6) thermocouple for chamber temperature, 7) thermocouple for sample temperature, 8) exhaust pipe, a) inlet pipe from furnace, b) particle filter, c) ball valve, d) needle valve, e) heated gas sensor chamber, f) pressure sensor, g) flow sensor, h) pump, i) measurement amplifiers, k) gas sensor heating controllers, n) main controller, r) power supply for gas sensor chamber heating, s) heating controllers for pipe and gas sensor chamber.

Results and discussions

The significant responses from the sensor array (see Fig. 5.) towards low gas concentration in GMMS serve as an initial proof of concept for the devised fire detection system. The functionality of the driving and readout electronics fulfilled the sensitivity and stability requirements under laboratory conditions.

A significant covariance of the TGS2600 and TGS2620 sensor signals and the suitability of AS-MLC for the detection of both CO and NO_2 traces were observed. This can lead to a simplification of the sensor array's structure, making it more cost-efficient.

Results from the fire simulator measurements provide information relevant for the future application. It was found that the materials used in the engine compartment are rather difficult to ignite, and most samples had to be heated over 480°C to start burning (Fig. 6. bottom). The respective samples are shown in Fig. 4.

Aged elastomers are atypical as they tend to keep glowing after removal from the furnace, so that they might even re-ignite after incomplete extinction.

Fig. 4. Two samples before (top) and after (bottom) combustion.
(Left) Hydraulic pipe from a truck, fiber enforced elastomer.
(Right) Corrugated hose from a passenger car's cable harness, polyamide-6.

The mass spectrometer was used to certify the presence of expected gases exhaust and identify unexpected components with a mass between 1 and 65 atomic mass units (amu) in the fire simulator exhaust. CO_2 and H_2O could be clearly detected (Fig. 6. top), while some species like CO could not be resolved because of equal mass with natural components of air (the molecular mass of CO is 28 amu as the one of molecular nitrogen). Low concentrations of NO_2 (mass 46 amu) were detected by the mass spectrometer but the results could not be quantified, because of the partial overlap of the NO_2 spectral line with the CO_2 one (44 amu). No other gases or volatile compounds were discernable on the mass spectra. Simultaneous measurements done with the sensor array indicated the presence of specific fire products in the gas phase, but with much higher sensitivity than by the mass spectrometer (Fig. 6. mid). It confirmed small amounts of NO_2, which the mass spectrometer failed to discriminate quantitatively from CO_2.

Combined analysis of fire dynamics and the sensor array's signals indicate that CO and NO_2 generally develop in smoldering fire, whereas CO_2 and humidity are strongly related to free burning fires. This is in agreement with the chemistry behind the oxidation of the organic sample compounds at different reaction stages and experimental conditions.

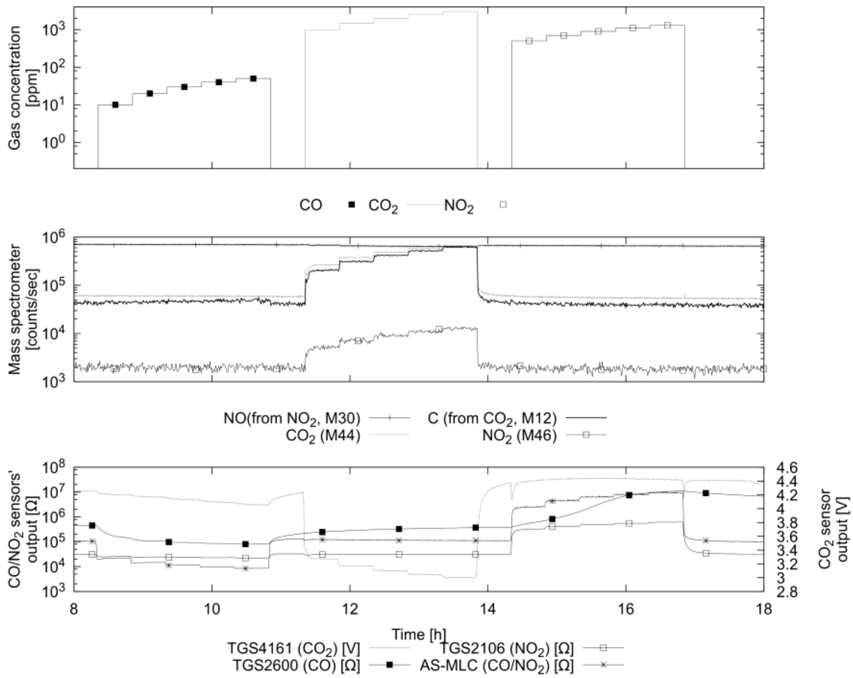

Fig. 5. An example of the measurements done under lab conditions using a gas mixing system and pure gases. Both the results of the mass spectrometer (mid) and the gas sensor array (bottom) are shown.

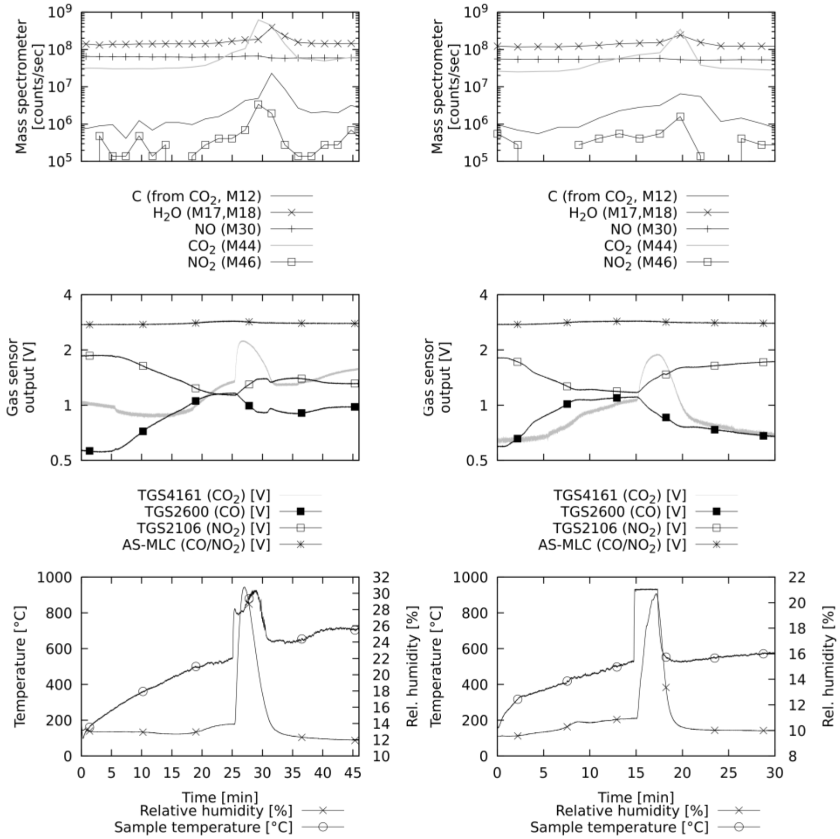

Fig. 6. Results of two combustion experiments with hydraulic pipe (left) and corrugated hose (right).

Conclusion and outlook

The fire detection systems based on gas sensor arrays with multiple parameter readout appears to be, at least at the present stage of the investigations, a promising tool for the early detection of vehicle fires. They are tested in different types of vehicles as part of the project's 2nd stage.

The fire simulator was proven to be a valuable tool to evaluate the suitability of gas sensors for fire detection and the ignition of combustible materials.

Acknowledgment

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References

[1] M. Ahrens, "VEHICLE FIRES INVOLVING BUSES AND SCHOOL BUSES," Quincy, MA, 2006.

[2] M. Egelhaaf and F. A. Berg, "MOTOR COACH FIRES – ANALYSIS AND SUGGESTIONS FOR SAFETY," DEKRA Automobil GmbH, 2005.

[3] R. Hammarström, J. Axelsson, M. Försth, P. Johansson and B. Sundström, "Bus Fire Safety," SP Technical Research Institute of Sweden, 2008.

[4] J. Kappler, A. Tomescu, N. Barsan and U. Weimar, "CO consumption of Pd doped SnO2 based sensors," *Thin Solid Films,* vol. 391, no. 2, pp. 186-191, 2001.