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Procedia Chemistry 1 (2009) 955–958

Procedia Chemistry

www.elsevier.com/locate/procedia

Proceedings of the Eurosensors XXIII conference

Laser Spectroscopic Oxygen Sensor for Real Time Combustion Optimization

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Abstract

A laser spectroscopic oxygen sensor aiming at combustion optimization is developed. The sensor allows for self-monitored operation and has a response time of 300 ms. The accuracy for the oxygen concentration is better than ±0.2 vol%. The laser optical sensor is inherently calibration-free and does not age compared to the conventional ZrO_2 probes. The spectroscopic oxygen sensor is based on a diffuse reflective geometry, which minimizes possible optical interference and also alignment problems caused by the thermal cycles of the furnace and an efficient evaluation algorithm that allows for long-term stable operation.

Keywords: laser spectroscopy; oxygen; wavelength modulation spectroscopy; combustion optimization; vertical-cavity surface-emitting-laser

1. Introduction

Optimization of the burning process for combustion application is very important for energy savings and reduction of pollutant emissions. Conventionally, zirconia (ZrO_2) based probes are used for oxygen monitoring in large heater appliances [1]. However, these sensors suffer from several drawbacks. First, they need protection from poisoning with heavy metals like Mn or Pb, which results in aging effects that make regular maintenance or replacement necessary. Due to the high operation temperature also a grid for flame protection is needed, which increases the sensor delay. Sensors based on tunable diode laser spectroscopy (TDLS) do not suffer from these limitations, due to the spectroscopic measurement. However, their wide applicability was limited in the past by the price of the optical components of the system, especially the laser diode itself as most expensive part. Due to the recent very successful commercialization of Vertical-Cavity Surface-Emitting lasers, which have significant advantages in manufacturing over conventional edge emitters like on wafer testability and high packing density on wafer, the realization of cost effective TDLAS based gas sensors with their excellent properties becomes more

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doi:10.1016/j.proche.2009.07.238

realistic. The requirements for the TDLAS based gas sensor are robustness because of harsh conditions in gas/oil furnaces and a low sensing delay to allow for a control loop for combustion optimization.

2. Sensor Design

The presented sensor is based on a GaAs-based VCSEL [2] and probes an absorption line in the Oxygen A-band around 763 nm [3]. The schematic optical setup and image of the assembled sensor including the electronics for data adaption and control is shown in Fig. 1 and Fig. 2, respectively. The sensor employs a reflective geometry with a concave stainless steel block as a diffuse reflector with a resulting optical path length of 20 cm. This sensor is mounted in the exhaust gas pipe of the gas/oil burner. Gas temperature measurement is done by a precision temperature sensor, whereas the operating temperature is up to 80 C° for condensing gas furnaces and up to 160 C° for oil furnaces.

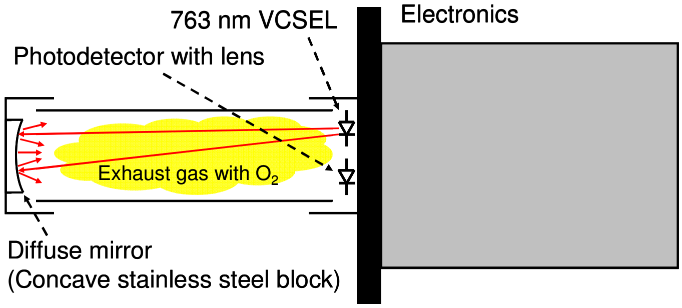

Fig. 1: Schematic of the sensor. The “tube” contains the absorption cell, i.e. the optical path where the absorption takes place. A diffuse reflector on the front reflects back the light, whereas laser and detector are mounted side by side and connected to the electronics, which implements sensor control and data adaption. The optical path length is 2×10 cm.

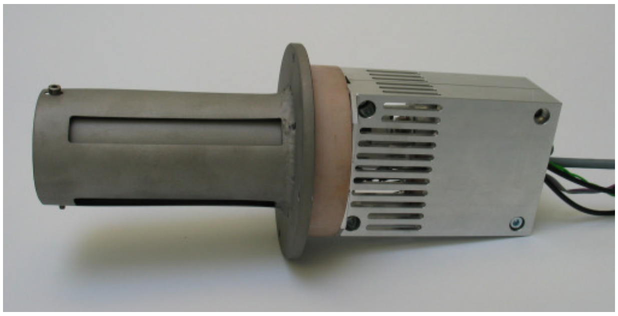

Fig. 2: Photograph of the assembled oxygen sensor.

Wavelength modulation spectroscopy with second harmonic detection [4] is employed in this sensor. For the long term stability of the sensor, curve fitting instead of one point (maximum) evaluation of the second harmonic spectrum is applied. The on-line curve fitting is done on the µC-based electronics with a signal model described in Ref [5] each 300 ms. The curve-fit algorithm using start values obtained from the characteristic values of the second harmonic spectrum only needs 2-3 iterations to find the best fit. It provides better stability than maximum point evaluation, because the curve fit compensates spectral baseline variations. The maximum to minimum ratio of the second harmonic spectrum of the O_2 absorption line is a central characteristic value for the algorithm, whereas the absolute wavelength scale and gas pressure are not needed for the determination of the oxygen gas concentration. The curve fitting algorithm works down to low concentrations of Oxygen below 1 vol%.

3. Measurement Results

Measurements in the exhaust gas of a furnace, which was periodically switched on and off, showed no visible impact of the temperature cycles on the sensor performance (Fig. 3). This clearly demonstrates the advantage of the simple geometry with the diffuse spherical reflector over a conventional spherical mirror. It is very difficult to guarantee correct alignment of a spherical mirror during sensor lifetime with thousands of thermal cycles. The sensor response time is 300 ms whereas the speed of the gas measurement is only limited by the time of gas exchange (Fig. 4). The fast response time together with the self-monitoring capabilities of TDLS sensors possibly also allow for new applications like flame monitoring, provided that the gas exchange time is not a limiting factor.

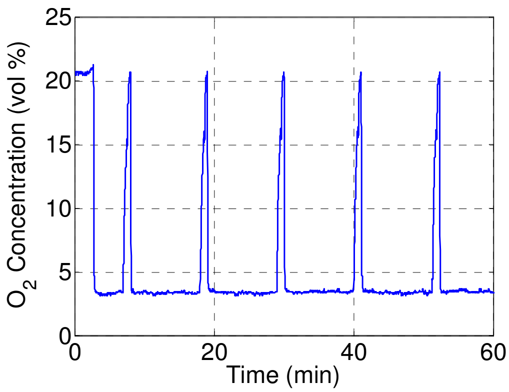

Fig. 3: Measurement during one hour in the exhaust gas of a gas furnace. Every 10 minutes the furnace was switched off for one minute, to test the sensors ability to withstand the typical thermal cycles that frequently occur under realistic conditions.

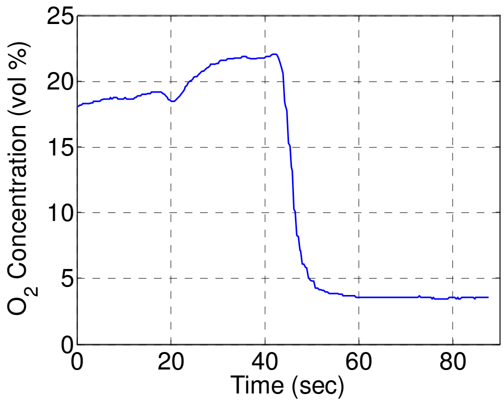

Fig. 4: Measurement demonstrating the fast response time of the sensor during start-up of the furnace. The decay is because of slow gas exchange and not due to an inherent sensor response time. The sensor output value is the instantaneous and spatially averaged O_2 concentration in the absorption cell. The "O_2 dip" (at 20 s) is caused by the gas exchange between burning chamber and exhaust gas pipe by on-switching of the burner and can be clearly observed using TDLS sensor thanks to the fast response time - a notable advantage over the conventional oxygen sensor.

Condensation happens when the hot gas arrived at colder optic surfaces, e.g. the laser window, photodetector window as well as the reflector and reduces transmitted light. However with this diffuse reflector configuration it turned out that an additional diffusion by water droplets has less impact as for the case of a focusing optic with a spherical mirror. During operation, the transmission decreased approximately by a factor of 5 when condensation was visible. During a long-term test over more than one year in an operated gas furnace the sensor showed no significant drift. The absolute transmission decreased by about 25% in the first few weeks and then remained stable, which shows that no contamination exists in gas furnaces and condensation has no influence on the measurement. The situation is different in oil furnaces where strong contaminations exist. In Fig. 5 the diffuse reflector is shown before and after a one month operation of the sensor in an oil furnace. During that time the transmission reduced to 10 % due to contamination on the reflector as well as the detector and laser window. This shows that additional means against contamination have to be applied to make the sensor suitable for maintenance-free operation over years in oil furnaces.

Fig. 5: Image of the diffuse reflector before (left) and after (right) deployment of the sensor in an oil furnace for one month.

4. Conclusion

A low-cost, robust laser-optical oxygen sensor is developed for the combustion optimization in gas/oil furnaces. The sensor allows for self monitored operation and has a response time of 300 ms. The sensing accuracy for the oxygen concentration is less than ±0.2 vol%. Because of the optical design with a diffuse mirror, the sensor shows no problems with condensation in gas furnace and optical misalignments due to thermal cycles. Using an efficient curve-fitting algorithm, long term stable operation of the sensor with fast time response is realized.

The sensor is approved to be suitable for combustion optimization in gas furnace and successfully operated over more than one year in the exhaust of such a furnace. In oil furnaces the transmission of the light decreases rapidly due to contamination of the optical surfaces. A reduction of the transmission by a factor of 10 in one month was observed. Further means against contamination or regular cleaning of the optical surfaces are necessary to employ the sensor in oil furnaces.

Acknowledgements

The authors gratefully acknowledge the financial support by the Federal Ministry of Education and Research of Germany (Project 'NOSE', No. 13N877).

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