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Electrophoretic and thermophoretic effects on conductometric soot sensing: special challenges when using synthetic soot

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Abstract
Recently, particulate filters became an inevitable part not only in Diesel but even also in exhaust gas aftertreatment systems of gasoline driven engines. As the soot particles are significantly smaller in that case, for monitoring purposes or on-board-diagnostics improved soot sensors concerning sensitivity and response time are needed. Development of such devices could be supported by the use of soot generators in the lab. The present contribution tries to transfer findings in real Diesel exhaust to the behavior of conductometric soot sensors under test in synthetic soot atmosphere. The influence of applied voltage and sensor temperature on the electrophoretic and thermophoretic soot deposition was reproduced but could not be easily measured by the current signal because synthetic soot shows complex conductivity properties.

Key words: interdigital electrodes, conductance measurement, miniCAST soot generator, soot sensor

Introduction

According to recent emissions legislation for combustion engines, particulate number is also limited in addition to particulate mass. So, gasoline-driven engines that produce not less but smaller soot particles need to be equipped also with special particulate filters (gasoline particle filters, GPF) in their exhaust gas aftertreatment system. State-of-the-art sensing devices for filter load monitoring or on-board-diagnostics might not meet the application requirements concerning less sensitivity or too short response time because of the size and concentration of particles to be measured. Conductometric sensing devices comprise an interdigital electrode structure on its surface where a voltage is applied during soot collection. Electrophoretic enhanced soot deposition leads to an increasing current between the electrodes. As sensor signal, the slope of this current increase is a measure of the actual soot concentration [1]. It was recently shown that the applied voltage is directly responsible for electrophoretic soot collection, increasing the sensors temperature on the other hand causes thermophoresis, affecting the soot deposition negatively [2].

For the above-mentioned purpose, further development of conductometric soot sensors is needed, especially the sensitivity need to be improved. Utilizing soot generators in the lab might save costs and efforts in contrast to real exhaust testing. Furthermore, synthetic soot exhibits defined particle morphology in a tight size distribution so that the influence of development steps on the sensing mechanism can be seen in a more reproducible way compared to real engine exhaust tests.

The aim of the present contribution is to reproduce results achieved in real Diesel exhaust now with synthetic soot from a commercial soot generator (Jing, miniCAST). Similar dependencies from two parameters are expected: 1) the applied voltage (increasing voltage should lead to an increasing sensor response due to electrophoresis) and 2) the sensor temperature (increasing the sensor temperature – compared to the ambient gas flow temperature should lead to a lower response due to thermophoresis). Both parameters, the voltage and the sensor temperature are main regulating screws in sensor operation for sensitivity purposes besides electrode geometry or approaching flow characteristics.

Experimental

Measurements were conducted by operating the soot sensors in synthetic exhaust from a soot generator (miniCAST, Operation Point OP1, particles with 210 nm, constant soot concentration). Sensors, made by Pt screen-printing as already described in [1] (IDE electrodes on the front side, line = space = 100 µm, heating element on the reverse side, 4-wire structure for temperature control), directly face the gas flow with its front side (Fig. 1).

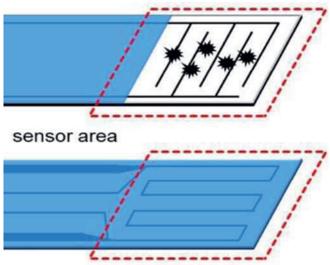

Fig. 1. Scheme of the sensor tip, which is exposed to exhaust.

For each soot collection phase with a defined applied voltage (from 5 up to 100 V), a subsequent regeneration phase (heating the device up to 600 °C) followed. The sensor response was evaluated as a conductance signal G. To evaluate the influence of several parameters, the slope of conductance $\mathrm{d}G/\mathrm{d}t$ serves as comparative sensor response.

Results

In a first measurements series, different voltages were applied (3 times for each collecting phase). As expected, the slope of the conductance increases linearly with the applied voltages (dependency: $\mathrm{d}G/\mathrm{d}t$ = 0.55 nS/s for $\mathrm{d}U$ = 100 V).

Secondly, the sensor was operated at 60 V constantly. Its temperature was set to a stepwise increased temperature value ($\mathrm{d}T$ compared to the ambient gas) after each regenerations step. Our former results showed decreasing slopes due to higher thermophoretic influence, resulting in less soot deposition [2]. Here, in synthetic soot, the conductance behavior is completely different (see Fig. 2). Up to $\mathrm{d}T$ = 90 K, the signal response increases, and – at higher temperature differences – decreases again. In further data evaluation it could be shown, that thermophoresis occurs as before. Regarding the integral value of the conductance curve over time during regeneration (this is a peak area related to the amount of soot deposited on the sensor before regeneration), one can clearly see that with increasing $\mathrm{d}T$ values, soot deposition decreases exponentially. The reason for the misleading conductance curves was found in the temperature dependent conductivity of the synthetic soot, which is exponentially increasing (thermally activated) between 50 and 450 °C.

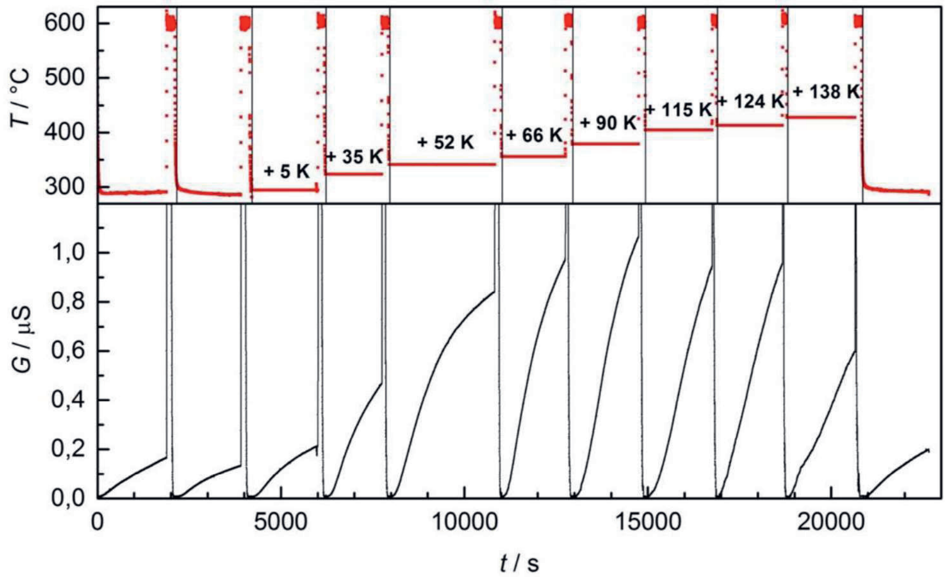

Fig.2.Sensor measurement over time for several loading and regeneration cycles in constant soot concentration (CAST OP 1) and constantly applied voltage (60 V) under variation of the sensors temperature. The gas flow directly faces the sensors front side.

Conclusions

Special properties of synthetic soot, such as its temperature dependent conductivity, have to be taken in account for sensor development purposes. Similar effects may be considered for gasoline soot as well.

References

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[2] G. Hagen et al., Proceedings of the 16th International Meeting on Chemical Sensors, IMCS 2016, 10th - 13th July 2016, Jeju, Korea.