Determination of the soot mass by conductometric soot sensors

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Abstract

Soot sensors are required for on-board diagnostics (OBD) of automotive diesel particulate filters (DPF) to detect filter failures. If installed upstream of a DPF, the “engine-out” soot emissions can be determined by conductometric soot sensors. For that purpose, conductometric soot sensors were characterized in a diesel engine under varying operation conditions. Sensor data and soot analytics (SMPS) agree well. However, the orientation of the sensor electrodes with respect to the exhaust flow direction significantly affects the sensor signal.

1. Motivation

Stringent emission legislations require the use of diesel particulate filters (DPF) in the exhaust gas aftertreatment of lean-burn diesel vehicles [1]. For on-board diagnostics (OBD) purposes, a soot sensor is mounted downstream of the filter. Typically, these sensors are conductometric devices [2-6]. When a DPF failure occurs, i.e. when soot passes through the filter element, the electrically conductive soot particles get deposited on the sensor surface where they percolate between the sensor electrodes and lead to a measurable current between them. The present contribution investigates whether this principle could also give a measure of the soot mass when the sensor device is installed upstream of the DPF.

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2. Experimental

Simple soot sensors were built up on insulating alumina substrates. Interdigitated Pt-electrodes (IDE, line = space = 100 μm) were screen-printed on the top side, where the soot particles should be deposited. Heater structures for active regeneration were also screen-printed on the reverse side of the substrate. After wiring, the sensor elements were housed in a stainless steel tube and were mounted in the exhaust pipe of a 2.1l (2143 cm³) diesel engine downstream of an oxidation catalyst (Fig 1).

The sensor signal was achieved discontinuously. By applying 20 V (dc) on the IDE, a current $I$ appears (Fig. 2) after a characteristic “percolation time”, which is the threshold when first soot paths from one electrode to the other form due to electrophoretic deposition of electrically conducting soot particles. Since this is a typical accumulating (or integrating) type sensor, the time derivative may be an appropriate signal to determine the actual concentration [7]. Therefore, the slope of the current ($dI/dt$) was evaluated for each cycle and was considered as the sensor signal. After a distinct current value, a new cycle was started by heating the sensor to 600 °C to remove the previously deposited soot. The regeneration temperature was adjusted by a heater controller. During soot collection, the heater (four-wire connection) was used as a temperature sensor.

During soot collection, the current, $I$, increases constantly. Regeneration takes place by heating the sensor to 600 °C. Soot conductivity increases with temperature before soot is burned off. Evaluation of current derivative (slope $dI/dt$) is a measure for the amount of soot in the exhaust.
We conducted several measurements by varying typical engine parameters like boost pressure and/or injection pressure. For each operating point, a certain $\lambda$-value (lambda, air-fuel ratio) occurred. Speed and relative load were kept constant (1000 rpm / 25 % rel. load). Biodiesel-free fuel was used ("B0"). Soot generation was simultaneously analyzed by SMPS (scanning mobility particle sizer).

3. Results

While the injection pressure was constant, we found a good agreement between $\lambda$ and the boost pressure (see inset in Fig. 3). The dependency between soot (particle size and number distribution as an SMPS result) and boost pressure or $\lambda$ is given in Fig. 3. As expected, we found an increasing amount of soot with decreasing $\lambda$ values. The soot mass values can be calculated from the SMPS data assuming spherical particles with a density of 1.7 g/cm$^3$.

![Fig. 3. Result of SMPS measurements for different operation points @ 1000 rpm / 25 % relative load. Only the boost pressure ($p_{\text{boost}}$) was changed, the other parameters depend on engine characteristic map.](image)

Now, the sensor data (for each characteristic operation point, we measured the sensor signal, i.e. the slope of current, at least three times) are correlated with the operation conditions. Between two different measurement series (different days) we found a good and reproducible correlation, but of course one could observe a strong impact of the sensor orientation with respect to the exhaust flow direction. For that purpose, the sensors were orientated in a way that the IDE area either faced the gas flow (direct mode) or faced the tail pipe (indirect mode). As expected, the signals were higher when soot is directly deposited on the measuring electrodes (Fig.4).
Fig. 4. Correlation between evaluated sensor data (x-axis) and $\lambda$, depending on the sensor orientation. Direct deposition leads to higher signals. As known from Fig. 3, particle number and $\lambda$ depend on each other.

4. Conclusion

The present investigations should proof whether an OBD soot sensor is applicable for soot mass measurements upstream of a DPF. As a conclusion, we found a very good correlation between sensor data and soot generation under different operation conditions. For an application, it is crucial to focus on the development of an appropriate sensor housing including a protection cap, ensuring constant flow conditions on the sensors surface.

Further measurements will be conducted with different fuels (varying Biodiesel content). Another topic of future research will investigate, whether these results and contactless method for in-situ soot loading detection [8, 9] coincide. In addition further investigations of the influence of different engine operating conditions on the soot sensor signal will be done due to different soot characteristics [10, 11].

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