

Development of an On-Board PM Sensor for the OBD System Based on an Electrochemical Polarization

Yoshinobu Yoshihara, Takaya Suzuki, Keita Tominaga
Ritsumeikan University

Keiichiro Aoki, Hiroki Nishijima
Toyota Motor Corporation

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ABSTRACT

An on-board particulate matter (PM) sensor, consisting of a gas-permeable electrochemical cell with a porous yttria-stabilized zirconia solid oxide electrolyte, was developed to assist the on-board diagnostics (OBD) system of a vehicle. Exhaust is pumped from the anode side to the cathode side and PM deposited on the anode is instantly oxidized by the catalytic effects of the metal component of the electrode at temperatures higher than 350 °C. The PM oxidation reaction occurs at the three-phase boundary between the anode, electrolyte and gas phase, and causes a slight change in the bulk average oxygen concentration, which produces electrochemical polarization by the difference in oxygen partial pressures between the anode and cathode. The developed PM sensor has a detection limit of 2 mg/m³, at which level will enable PM detection in the OBD system according to the EURO VI regulation.

INTRODUCTION

There is a desire to reduce particulate matter (PM) emitted from diesel engines or a direct injection spark ignition (SI) engines into urban air. Emission regulations for PM are continually becoming stricter with increasing requirements for monitoring the status of the exhaust system (OBD, on board diagnostics) in diesel powered vehicles. Many PM sensors have been developed that employ soot collection and burn off with measurement of carbon dioxide^(1,2), ion mobility⁽³⁾, electrical resistance of the soot layer deposited between electrodes⁽⁴⁾, and also sensors that employ optical methods⁽⁵⁾. However, to provide the OBD of PM for a diesel engine exhaust requires the development of new sensors that are more compact and have greater sensitivity. Schule et al. developed a soot sensor on a porous solid electrolyte cell⁽⁶⁾; non-Nernstian voltage

was generated when soot particles were deposited on the hot working electrode ($T > 500$ °C) by pumping soot-loaded exhaust gas through the porous solid electrolyte. On the contrary, we have demonstrated that Nernstian voltage is generated at temperatures lower than 500 °C by electrochemical polarization due to PM oxidation at the anode. Furthermore, we have elucidated the factors that influence the PM sensor output.

EXPERIMENTAL SETUP AND METHOD

The experimental apparatus developed for evaluation of the steady state performance of the PM sensor is schematically shown in Fig. 1. In the experiments, actual diesel exhaust was used to determine the sensitivity of the cell. To evaluate the influence of coexistent gases on the sensor output, the exhaust used had PM removed by filtering. Simulated exhaust that was prepared using a gas blender was also used to investigate the interference of CO, hydrocarbons (HC), NO and NO₂ on the PM sensor output. Figure 2 shows the experimental setup of the electrochemical cell (PM sensor). Electrically

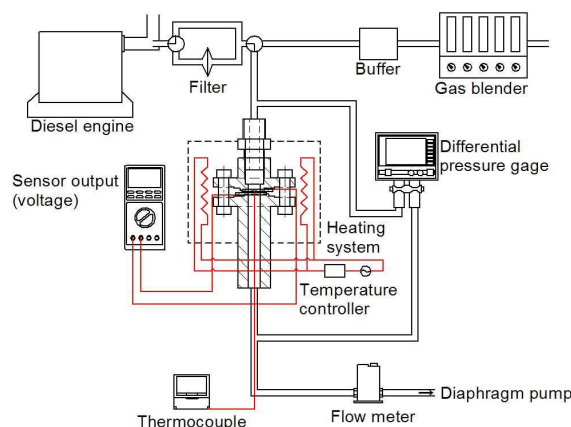


Figure 1: Schematic of the experimental apparatus.

insulated terminals hold the cell and graphite is used for the electric terminals, which also acts as a gas seal. The gas permeable structure of the electrochemical cell enables PM filtering on the anode by pumping PM-loaded exhaust gas through the anode side. If the temperature of the cell is sufficiently high, then PM deposited on the anode will be instantaneously oxidized by the catalytic effect of the metal component in the electrode. If this reaction takes place at the three-phase boundary between the anode, electrolyte and gas phase, the reaction will cause electrochemical polarization by the difference of oxygen partial pressure between the anode and cathode.

In the present study, yttria-stabilized zirconia (YSZ; $(\text{ZrO}_2)_{0.92}(\text{Y}_2\text{O}_5)_{0.08}$) was used as the electrolyte. A cermet formed with the electrolyte material and either Ag or Pt was used as the electrode to increase the three-phase boundary (electrolyte, electrode, and reactive gas), where the electrochemical reaction occurs. The cell structure is very similar to that of the solid oxide fuel cell (SOFC) system, except that the electrolyte used is permeable. The specifications for each cell used in the experiments are given in Table 1. The appearance of a typical cell is shown in Fig. 3. Figure 4 shows a cross sectional scanning electron microscopy (SEM) image of the porous electrolyte structure.

PROPERTIES OF THE CELL

The open circuit voltage (OCV) of an electrochemical cell is given by the Nernst equation as a function of oxygen partial pressures at both electrodes:

$$OCV = \frac{RT}{zF} \log \left(\frac{p_{O_2(\text{anode})}}{p_{O_2(\text{cathode})}} \right) \quad (1)$$

where R is the universal gas constant, T is the temperature, z is the number of electrons involved in the electrochemical reaction, and F is the Faraday constant. Figure 5 shows OCVs obtained from the 14 mm diameter airtight electrolyte cell with an Ag electrode at various temperatures and the voltage according to the Nernst equation. OCVs were obtained by supplying either air or the gas having lower O_2 concentration than air to the anode, while air was supplied to the cathode. The OCV output coincides well with the theoretical value at temperatures higher than 300 °C. At temperatures

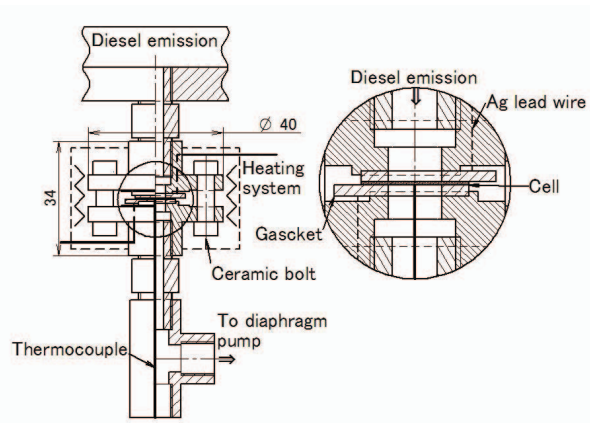


Figure 2: Setup of the electrochemical cell sensor.

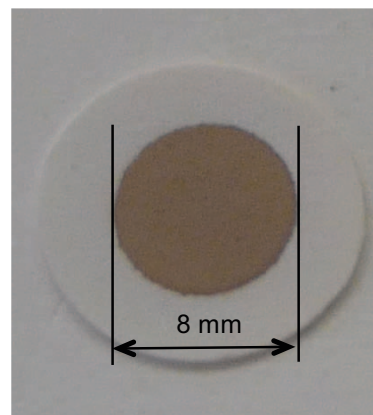


Figure 3: Photograph of the electrochemical cell.

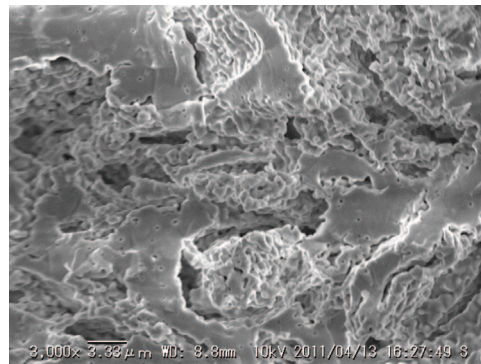


Figure 4: Cross-sectional SEM image of the electrolyte.

Table 1: Specifications of the electrochemical cells under test.

		Anode	Electrolyte	Cathode
ϕ 60Ag cell	Material	Ag(70%)–YSZ(30%)	YSZ	Ag(70%)–YSZ(30%)
	Thickness [μm]	20	380 (Voids:45%)	20
	Diameter [mm]	58	60	58
ϕ 14Ag cell	Material	Ag(70%)–YSZ(30%)	YSZ	Ag(70%)–YSZ(30%)
	Thickness [μm]	20	380 (Voids:45%)	20
	Diameter [mm]	8	14	8
ϕ 14Pt cell	Material	Pt(70%)–YSZ(30%)	YSZ	Pt(70%)–YSZ(30%)
	Thickness [μm]	20	380 (Voids:45%)	20
	Diameter [mm]	8	14	8