SOLID STATE ELECTROCHEMICAL SENSOR FOR MONITORING LEAN DIRECT INJECTION ENGINES

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ABSTRACT
This work presents a novel scheme for the use of an oxygen sensor operating in dynamic engine conditions. Our modeling and experimental work show that a solid state, single cell, amperometric oxygen sensor located inside the cylinder of a lean direct injection engine produces a signal that provides different information depending on the stroke. During the intake stroke, the sensor’s signal is proportional to the partial pressure of oxygen, facilitating exhaust gas recirculation. During the compression stroke of a diesel engine prior to fuel injection, the sensor’s output indicates the cylinder pressure, which is useful for control and diagnostic purposes. The signal during the power stroke confirms combustion. During the exhaust stroke, the sensor’s signal indicates the oxygen quantity after combustion.

Our model of engine and sensor operation simulates the changes in air properties including temperature, pressure, and oxygen concentration over the entire four strokes of the diesel cycle; these parameters affect the diffusivity of oxygen and the signal output. The model describes a sensor signal limited by diffusion or electrolytic conductivity depending on electrode design parameters (dimensions, porosity, tortuosity, etc). Knowledge of the sensor temperature and the engine crank angle are required in order to evaluate the signal.

Experimental results confirm the pressure dependence of the oxygen sensor’s output signal when using air as the analyte fluid.

INTRODUCTION
The higher efficiency of lean engines make them attractive compared to conventional gasoline engines. Recent advances in computer control and in exhaust cleanup address historical problems with diesel engines [1]. Further advances in efficiency are possible by sensors under development that facilitate improved engine operation.

Several excellent review articles provide details on the operation of solid state electrochemical gas sensors located in exhaust manifolds and tailpipes of automobiles [2, 3, 4, 5, 6, 7, 8]. Locating an amperometric sensor inside the cylinder of a lean direct injection engine enables advanced engine control and diagnostics. Although some have proposed optical detectors for sensing oxygen, the view ports get fouled, restricting their use to the laboratory [9, 10]. A single cell, amperometric sensor composed of partially stabilized zirconia responds to variations in temperature and pressure. Changes in temperature and pressure affect the diffusivity of oxygen to the cathode, the site of the electrochemical reduction of oxygen. When temperature is known or held constant, a single cell oxygen sensor designed for operation in the mass transport limited regime yields a signal that can be calibrated to indicate pressure during compression. Monitoring the pressure is useful for (1) determination of pilot fuel injection (2) diagnostic information about each cylinder such as seals, gaskets, valves, blow-by etc., (3) detection of misfire, and (4) calculation of PV-work.
We are investigating the adaptation of existing yttria-stabilized zirconia (YSZ) oxygen sensor technology to fabricate a single cell, amperometric pressure sensor for in situ gas analysis of lean direct injection engines. Amperometric oxygen sensor technology already exists, but not for use inside engine cylinders. Conventional oxygen sensors are neither engineered to withstand the high pressure (10MPa) of combustion, nor were they designed to provide response times fast enough to monitor events in cylinders (in single milliseconds).

YSZ has been used for years in oxygen sensors. It has the unique property of conducting oxygen ions (O²⁻) at high temperature but not electrons [11]. Yttrium substitutes some zirconium atoms in the ceramic electrolyte. The difference in their valences introduces defects into the ceramic lattice. Ions are transported from one vacancy to the next via a hopping mechanism. The ytria also prevents phase changes from one crystallographic state to the next. Although maximum ionic conductivity occurs at approximately 8% ytria, the high defect concentration weakens the material. Consequently, partially stabilized zirconia with 4% yttria is typically used due to superior mechanical properties [12].

Existing oxygen sensors reside in the exhaust pipe, where they see relatively constant temperature, pressure, and partial pressure of oxygen (PO₂). They usually require reference air. The challenge of designing in situ sensors is to make them generate a useful signal over a wide range of dynamically changing conditions (pressure, temperature, oxygen partial pressure, etc.), ensuring that they survive in a harsh environment, and in making them operate absent of reference air.

The mole fraction of oxygen remains constant during compression prior to fuel injection. When the sensor temperature is known, pressure monitoring is possible because the current response is inversely proportional to pressure for a diffusion-limited cell.

Figure 1 shows how a single cell, amperometric sensor functions. Oxygen diffuses through a diffusion barrier to the cathode, where it adsorbs and dissociates. At the cathode, the monatomic oxygen accepts electrons from the external circuit to form ions. They migrate across the YSZ electrolyte to the anode where they evolve back to gaseous oxygen. In doing so, they relinquish their electrons to the external circuit, which can be measured as current. One can extract information from the current signal.

In a diffusion-limited sensor, the amount of current is proportional to the arrival rate of oxygen at the cathode. The device performs as an oxygen sensor under isobaric conditions such as in the exhaust, where these sensors are conventionally located. Our work indicates that under conditions where the pressure changes, but not oxygen quantity (such as during the compression stroke of a diesel engine), the sensor’s signal can be calibrated for pressure if the sensor temperature is established.

This research and development effort is novel in these respects: We are the first to propose mounting a solid state sensor in engine cylinders. We have performed the first ever simulation of an oxygen sensor operating under dynamic engine conditions.

In the following, we discuss our simulation work and present preliminary experimental results that confirm the use of an oxygen sensor to detect pressure.

**NOMENCLATURE**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
<th>Unit</th>
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<tbody>
<tr>
<td>A</td>
<td>Surface area of electrode in diffusion equation</td>
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</tr>
<tr>
<td>A</td>
<td>Oxygen ion flux area in drift equation</td>
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<tr>
<td>Co₂</td>
<td>Concentration of oxygen</td>
<td></td>
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<tr>
<td>Do₂</td>
<td>Diffusivity of oxygen</td>
<td></td>
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<tr>
<td>E</td>
<td>applied potential</td>
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<tr>
<td>δ</td>
<td>Electric field</td>
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<td>EGR</td>
<td>Exhaust Gas Recirculation</td>
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<tr>
<td>F</td>
<td>Faraday’s constant</td>
<td></td>
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<tr>
<td>Iₐdiff</td>
<td>Diffusion current</td>
<td></td>
</tr>
<tr>
<td>Iₐdrift</td>
<td>Drift current</td>
<td></td>
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<tr>
<td>J</td>
<td>Electrolytic current density</td>
<td></td>
</tr>
<tr>
<td>L</td>
<td>Length of the electrolytic path</td>
<td></td>
</tr>
<tr>
<td>n</td>
<td>Electron exchange number</td>
<td></td>
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<tr>
<td>PO₂</td>
<td>Partial pressure of oxygen</td>
<td></td>
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<tr>
<td>P₅ₐ₉</td>
<td>Total Pressure</td>
<td></td>
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<tr>
<td>P₉gauge</td>
<td>Gauge Pressure</td>
<td></td>
</tr>
<tr>
<td>φo₂</td>
<td>Flux of oxygen</td>
<td></td>
</tr>
<tr>
<td>ϕ</td>
<td>Porosity correction function</td>
<td></td>
</tr>
<tr>
<td>σ</td>
<td>Conductivity</td>
<td></td>
</tr>
<tr>
<td>T</td>
<td>Temperature</td>
<td></td>
</tr>
<tr>
<td>τ</td>
<td>Tortuosity</td>
<td></td>
</tr>
<tr>
<td>Yo₂</td>
<td>Mole fraction of oxygen</td>
<td></td>
</tr>
<tr>
<td>YSZ</td>
<td>Yttria Stabilized Zirconia</td>
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In steady state operation, diffusion is usually the rate limiting step that determines current. In some cases, however, ion conduction limits output (e.g. when the device has not warmed up, or when the electrodes have not been designed to be diffusion-limited). Conductivity is strongly dependent on temperature. Our model examines both the diffusion-limited and conduction-limited current over the cycle. For diffusion, we used Fick’s First Law to deduce oxygen flux (corrected for porosity $\varphi$ and tortuosity $\tau$) as shown below.

$$\Phi_{O_2} = -D_{O_2} \frac{\varphi}{\tau} \frac{dC_{O_2}}{dx}$$

Equation 1

Subsequently we calculated the mass transport limited diffusion current according to:

$$I_{avg} = -nF\Phi_{O_2} = nFA\frac{\varphi}{\tau} \frac{C_{O_2}}{L}$$

Equation 2

where $n$ is the number of electrons exchanged (in this case, 4); $F$ is Faraday’s constant; and $A$ is the surface area of the electrodes.

We also examined ionic drift current, which gave us the conduction limited current. We used the following equation for current density:

$$J = \sigma \Phi = \sigma (E/L)$$

Equation 3

where $\sigma$ is conductivity; $E$ is the electric field; $E$ is applied potential; and $L$ is the length of the electrolytic path. We obtained values for conductivity from the literature, and from them calculated a temperature dependent expression for conductivity. The ionic drift current was then calculated as follows:

$$I_{drift} = \varphi \sigma A (E/L)$$

Equation 4

where $\varphi$ is a function that adjusts the conductivity values for porosity according to work by DeJonghe.

The sensor output is taken to be the lesser of the diffusion and drift currents.

Note that this simulation does not take into account the temporal aspect of sensor operation. A response time in single milliseconds is desirable in order to be competitive with commercially available sensors.

**Experimental Methods**

We created single cell amperometric sensors from commercially available potentiometric ones by applying a bias. We purchased potentiometric oxygen sensors, including both a thimble type (Bosch 13276) and a planar type (Bosch 13761). We mounted the sensors in a pressure vessel. We used a feedback control loop on the built-in heaters to hold the temperature at a constant value (800°C for the thimble, and 400° for the planar sensor). We performed voltage sweeps at various gauge pressure levels. We did not exceed 1000mV when applying the bias to obviate electrolysis of the ceramic electrolyte. We measured the current response using a Keithley current-voltage source and measurement device.

We also performed a transient analysis in order to examine the dynamic response of the sensor. We charged and discharged a pressure vessel with air, and monitored the sensor signal. We held the bias voltage at 1000mV and the heater temperature at 400°C.

**Results and Discussion**

**A. Computer Model**

We first used our model to simulate the diesel cycle, as shown in the $P$-$V$ diagram in Figure 3. In our model, we held the sensor temperature constant at 900°C; when the sensor temperature was allowed to follow gas temperature, then the concomitant effects of changing pressure, temperature, and partial pressure of oxygen rendered the signal output inconclusive.
Figure 4 examines pressure in the cases of combustion and misfire. During the compression stroke, the sensor current signal diminishes on account of the increase in pressure which decreases the diffusivity of oxygen (\(D \sim 1/P_{\text{tot}}\)).

Note that a result similar to a misfire could also be due to a failure of the head gasket, rings, or an improperly seated valve. A misfire is a single event, whereas these hardware defects persist over multiple cycles.

The dynamic environment of an engine has fluctuations in mole fraction of oxygen, volume, and total cylinder pressure. Figure 5 shows simulation results of these parameters over the entire cycle.

Knowledge of some parameters (\(Y_{O_2}, P, T\)) allows calculation of others during the different strokes of the diesel engine. During the intake stroke, for example, pressure is known due to the manifold absolute pressure sensor; piston volume is known due to the crank position sensor; and temperature of the sensor can be deduced by the resistivity of the heater. The built-in heater is a thermistor, showing temperature dependent resistivity. Thus the only unknown parameter is the mole fraction of oxygen, which is proportional to the sensor output.

During the compression stroke prior to combustion, the pressure is unknown, but the other parameters have been established. The output signal can be calibrated to determine total cylinder pressure, knowing that the signal is inversely dependent on pressure (\(D \sim P_{\text{tot}}^{-3/2}\)).

The signal during the power stroke is affected by changing temperature, pressure, and oxygen mole fraction; the sensor signal can be used to detect misfire.

During the exhaust stroke, the signal output is proportional to the partial pressure of oxygen, which assists with EGR control.

Figure 6 shows a simulation of the oxygen sensor output. During the intake stroke, the output is proportional to the partial pressure of oxygen. This is useful to control EGR. During the compression stroke prior to combustion, the signal decreases on account of the lower diffusivity of oxygen. Thus it acts as a pressure sensor. During the power stroke, the sensor detects misfire. Combustion causes a further reduction in diffusivity because of the attendant increase in pressure, as seen in Figure 6 by the decay in the diffusion limited current from top dead center to 45°. Thereafter combustion is assumed to be complete; the signal increases despite decreasing oxygen content due to the effect of decreased pressure on diffusivity caused by expansion. Thus a low signal that persists past top dead center confirms combustion. A large increase in the signal indicates a misfire or equipment failure (head gasket, rings, or improperly seated valve), lower than during the intake stroke despite higher temperature due to the decreased oxygen content. During the exhaust stroke, the signal is lower than during the intake stroke despite higher temperature due to the decreased oxygen content.

The model yielded the following results:
- Sensor temperature must be high (900°C) when using a porous electrolyte in order to obtain acceptable conductivity.
• Ion transport path must be micron scale for fast response.
• The magnitude of the signal is in milliamps, which may be too small to be useful inside an engine. One could make the electrodes larger to increase the surface area for electrochemical reactions, but the area of electrodes cannot be too large or diffusion will not be the rate-limiting step, rendering calibration difficult if not impossible.
• Temperature must be known or deduced to process the signal.

In brief, during different strokes the sensor yields different information that can be deduced by calibrating the galvanometric signal. The sensor must be designed to be diffusion-limited with an appropriate diffusion barrier; otherwise the signal will not be repeatable and cannot be accurately calibrated.

B. Laboratory Results

Our experiments with the thimble sensor yielded currents that were two orders of magnitude less than the planar sensor, probably due to larger electrode surface area, so we limit our discussion to the planar sensor.

Figure 7 shows the results of voltage sweeps of the planar sensor. The current response signal decreases as pressure increases. This is the expected result of pressure’s effect on diffusivity. The sensor returned a range of currents for any given gauge pressure. The currents were a fraction of a milliampere. Where curves overlap, we posit that the sensor’s built-in heater locally increased diffusivity due to heating of the pressure vessel’s walls. In summary, we produced a calibration graph that allows one to determine gauge pressure for any particular bias potential as long as temperature is known or deduced via a thermistor.

In order to examine the dynamic response of the sensor, we charged and discharged a pressure vessel with air, and monitored the sensor signal. Note that our modeling effort did not address this scenario. The output current (Figure 8) shows an inverse relationship to pressure. The response lagged the pressure somewhat. The sensor that we used was not designed to function as an amperometric sensor. A sensor with an electrolyte path on the order of single microns will have a much faster response time.

CONCLUSION

We have presented a model of a single cell oxygen sensor that is limited by either diffusion or by ionic transport, depending on the physical conditions. In the laboratory we have demonstrated the use of conventional oxygen sensors to detect pressure. Existing commercial sensors are not sufficiently fast for real time measurements required for engine control. A microscale, single cell, analog oxygen sensor in the cylinder of a lean direct injection engine can be calibrated to establish oxygen quantity during the intake and exhaust strokes; to determine pressure during the compression stroke prior to combustion; and to detect misfire during the combustion stroke.

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REFERENCES