Fractional Factorial Experimental Design Applied to the Development of an Impedancemetric NO$_x$ Sensor

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Abstract

Four single cell impedancemetric NO$_x$ sensors were fabricated in the context of a two level, half fractional factorial experimental design (2$^{3-1}$) to determine the effect of design features on sensitivity to NO or NO$_2$. Three design factors were varied: number of working electrode sensing wires, electrolyte thickness, and the distance between sensing wires. Sensing ability was measured by performing electrochemical impedance spectroscopy and calculating the phase angle difference at 10 Hz for 50 ppm NO or NO$_2$ in 10% oxygen. As determined by ANOVA, the most significant effect was electrolyte thickness for NO sensing. One sensor investigated in depth showed a linear relationship between phase angle difference and NO at low concentration, insensitivity to total flow rate, and the larger sensitivity to NO$_2$ species than O$_2$ by several orders of magnitude. A larger response for NO$_2$ compared to NO was found. At 10$^5$ Hz, phase angles were linearly related to temperature, independent of gas species.

Introduction

Diesel engines offer higher fuel efficiency than stoichiometric ones on account of their higher compression ratios, but the attendant emissions of both particulate matter and nitrogen oxides (NO$_x$) are deleterious to the health of people [1], buildings [2], and the natural environment [3]. To address particulate emissions, a particulate trap can be used that gets regenerated by periodic pulses of rich gases [4]. To mitigate NO$_x$ emissions, either a NO$_x$ trap or selective catalytic reduction (SCR) are possible. The NO$_x$ trap regeneration penalizes fuel economy whereas SCR requires a supply of ammonia or urea [5].

Typically the NO$_x$ from combustion processes consists overwhelmingly of NO in the concentration of several hundred parts per million (ppm) to several thousand ppm. NO$_2$ is also present in the range of tens of ppm [6]. Other forms of NO$_x$ exist but in much lower concentration than NO and NO$_2$.

A NO$_x$ sensor can be used to abate emissions by providing a signal to the engine control unit. Commercial NO$_x$ sensors for diesel exhaust analysis consist of two electrochemical cells in series: the first removes O$_2$ so that the second can determine NO$_x$ concentration, which is proportional to the pumping current as NO$_x$ species are expelled [7].

A simpler sensor design featuring one single electrochemical cell and no reference to ambient air is possible with a single electrochemical cell interrogated at a specific frequency usually below 100 Hz. An impedance measurement provides information about the gas concentration [8].

Impedancemetric NO$_x$ sensors show improved sensitivity and stability over commercially available amperometric sensors [9], which are inadequate to meet stringent Tier 2 Bin 5 emissions regulations [10]. In addition, impedancemetric NO$_x$ sensors have an advantage over the mixed potential variety: both NO and NO$_2$ cause a shift in signal in the same direction using impedance-based techniques, which is contrary to the mixed potential sensors whose output EMF is negative with NO and positive with NO$_2$ [11]. As a result, these responses interfere with one another and hinder accurate NO$_x$ detection.

To perform an impedance measurement on an electrochemical cell, an alternating current is applied at a specific frequency, and the resulting impedance reading is recorded [12]. By sweeping a range of frequencies and plotting the impedances on a Nyquist plot, the capacitive arcs that result reveal information about the sensor.

Figure 1 depicts a Nyquist plot of impedance sweeps at two concentrations of NO. A Nyquist plot shows the resistive and capacitive contributions of impedance, but it does not explicitly show frequencies. For both sweeps, two arcs resulted. The high frequency arc (approximately f>10$^4$ Hz) provides information on kinetically controlled phenomena. The low frequency arc (approximately f<10$^4$ Hz) is sensitive to mass transfer events; it varies in the presence of various gas species [13]. Figure 1 shows overlap in the high frequency arcs even when the gas concentrations differ.

Two measurements that are derived from the impedance measurement can be used to detect gas concentration: the modulus and the phase angle. The modulus (|Z|) is the length of the vector from the origin to an impedance measurement at a specific frequency (10 Hz). The phase angle (Θ) is the arctangent of the ratio

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of the capacitive contribution of the impedance to the resistive at a specific frequency.

Martin reported that the phase angle is more sensitive to NO$_x$ concentration than the modulus, and thus is the preferred metric to analyze gas concentration with impedancemetric sensors. He also stated that phase angle shift ($\Delta \Theta = \Theta_2 - \Theta_1$) due to NO$_x$ is linearly proportional to NO$_x$ concentration between 8-50 ppm [9,12].

Electrodes and operating temperatures can be tailored to make a sensor selective to desired species. The NO$_x$ sensors under investigation consist of a working electrode of porous platinum, an electrolyte of zirconia fully stabilized by yttria (YSZ), and a counter electrode of porous platinum. These elements are stacked vertically on a tile of dense alumina (Figure 2). Leads of porous platinum provide conduction paths to the edge of the tile, where they connect with gold wires to interrogate the cell (not shown).

Operation of the sensor proceeds as follows: gaseous species such as NO, NO$_2$, and O$_2$ diffuse through the porous electrolyte topcoat. This layer increases the interface between the electrode and electrolyte, enhancing the detection of NO$_x$ species. The simultaneous oxidation of NO and the reduction of O$_2$ occur at the triple phase boundary, which is defined as the confluence of the working electrode, electrolyte, and gaseous species [9], according to the following reactions:

$$\text{NO} + \text{O}^\cdot \rightarrow \text{NO}_2 + 2\text{e}^-$$

$$\text{O}_2 + 2\text{e}^- \rightarrow \text{O}^\cdot$$

On the YSZ electrolyte, the reduction of NO$_2$ results in decomposition, albeit incomplete for $T < 800^\circ$C [14]:

$$\text{NO}_2 \rightarrow \text{NO} + \frac{1}{2}\text{O}_2$$

These electrochemical reactions and the attendant transfer of electrons alter the conductivity between the leads, which is detected by an impedance measurement.

**Specific Objectives**

This investigation has the following goals:

- Determine the effect and significance of the three controlled factors (number of dense gold working electrode sensing wires, electrolyte thickness, and the spacing between sensing wires) on sensor impedance.

**Experimental Methods**

Design of experiments techniques were used to investigate various design aspects of single cell, impedancemetric NO$_x$ sensors. Four sensors were fabricated by varying three factors according to a half fractional factorial experiment of resolution three ($2^{3-1}$) as shown in Table 1. One sample of each particular design was fabricated; variation between samples was not investigated.

The experimental design matrix in Table 2 shows that the design is balanced with the same number of observations for all treatments. All factors occur and low and high levels the same number of times, which is also true for interactions. The columns are orthogonal. The alias structure has factor C confounded with the interaction of A and B. The defining relation is $I=ABC$. Since this relation has 3 letters, the resolution is III. Resolution addresses ability to separate main effects from low order interactions. For resolution III, the main effects are aliased with 2-order interactions. Both NO and NO$_2$ were investigated separately at 50 ppm. Two replicate impedance sweeps were recorded for each gas.

### Table 1. Factors and their values at two levels

<table>
<thead>
<tr>
<th>Factor</th>
<th>Description</th>
<th>Low level (-)</th>
<th>High level (+)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Number of sensing wires</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>B</td>
<td>Thickness of electrolyte (number of coats)</td>
<td>6</td>
<td>10</td>
</tr>
<tr>
<td>C</td>
<td>Distance between working electrode wires</td>
<td>1 mm</td>
<td>2 mm</td>
</tr>
</tbody>
</table>

**Figure 1.** Nyquist plot of sensor response to 100 ppm NO: low frequency arc shifts inward.

**Figure 2.** Schematic cross section of a single cell impedancemetric NO$_x$ sensor (not to scale).
The four sensors were constructed on dense alumina substrates by painting leads of platinum ink (Engelhard 6082) in parallel stripes 1 mm wide and 1 mm apart and allowed to dry. On top of the platinum stripe (counter electrode) and allowed to dry. On top of the electrolyte, gold wires measuring 10mm in length were placed and attached to the other platinum lead using gold/palladium conductive paste (Engelhard A3770), thereby forming the working electrode. The sensing wires were anchored to the alumina tile with alumina paste (Aremco Resbond 920). The sensing wires were also coated with three coats of electrolytic slurry. In order to provide a means to interrogate the sensors, gold wires were attached to the platinum leads using the gold/palladium paste. These wires were also anchored to the substrate using alumina cement. The sensors were loaded into a quartz tube and then fired at 1200°C for 2 hours, once again taking care to ramp the temperature gradually to burn out organic species. Electrolyte thickness was measured with an Alpha Step IQ profilometer.

The sensors were loaded into a quartz tube and evaluated at 650°C. Gases flowed at 500sccm and with 10% O₂ with the balance N₂ or NOₓ. All sensors were tested with 0 ppm, 25 ppm, 50 ppm, and 100 ppm NO by diluting 1000 ppm NO in N₂. The same set of experiments were performed for NO₂.

Electrochemical impedance spectroscopy (EIS) was used to evaluate the sensors. Frequency sweeps between 1 MHz and 1 Hz were performed at 25mV excitation amplitude and the impedance response was recorded using a Solartron Analytical SI 1260 impedance/gain-phase analyzer in combination with a Solartron Analytical SI 1287 electrochemical interface controlled by ZPlot data acquisition software (Scribner Associates, Inc.). Ten measurements per decade were recorded. Two sweeps were performed for each sensor and each NOₓ concentration. Phase angles were calculated at a specific frequency (10 Hz) and subtracted from the base case of 0 ppm NOₓ in order to obtain the phase angle difference. This difference in phase angle was the primary metric used to evaluate sensor performance.

The phase angles at 50 ppm were used as the primary performance metric in the statistical analysis. NO and NO₂ were considered separately. Plots of the main effects were made for both gases. Analysis of Variance (ANOVA) was performed to determine the significance of each main effect. The predicting equations were derived from the estimates. Sensor I was more extensively evaluated in order to corroborate previous findings on NOₓ sensors in the literature. To confirm the linear relationship between NO concentration and phase angle difference, additional impedance sweeps were performed at different concentrations of NO. Sensitivity to flow rate was investigated by performing EIS on a gas stream comprised of 10% O₂ with 100 ppm NO at different flow rates. The relative sensitivity to O₂, NO, and NO₂ were also investigated. Finally, the temperature dependence of the high frequency arc was analyzed.

**Results and Discussion**

In order to perform the statistical analysis, the data obtained by recording each sensor’s impedance response to both NO and NO₂ was analyzed by making Nyquist plots and by calculating phase angle differences at 10 Hz. For brevity, only the Nyquist plots of sensor I are shown in Figure 3 and Figure 4 for NO and NO₂, respectively. The Nyquist plots exhibit a small high frequency arc and a larger low frequency arc, which are consistent with previous findings [8, 9, 15]. Both NO and NO₂ evoke an inward shift of the low frequency arc. An examination of Figure 3 and Figure 4 reveals that NO₂ evokes a larger shift than NO when evaluated at 650°C. Another source reported nearly identical responses to NO and to NO₂ at 700°C regardless of their relative concentrations [11].

All sensors were exposed to NO and NO₂ at 0, 25, 50, and 100 ppm. Sensor I was evaluated at additional NO concentrations (30, 40, and 75 ppm) in order to confirm the linear relationship between phase angle difference and NO concentration below 50 ppm. Figure 5 demonstrates this linear relationship – a confirmation of Martin’s work in which he reported a linear relationship down to 8 ppm [9,12]. The experimental setup for this study limited NOₓ concentrations to 20 ppm. A linear regression of the experimental data had an R² value of 0.9882, indicating an excellent fit.

**Statistical Analysis**

Table 3 shows the design matrix with replicated responses in the form of the absolute value of phase angle differences for both NO and NO₂ evaluated at 50 ppm and 10 Hz.

From the responses, main effects for each factor were calculated by subtracting the average of the responses at the high (+1) level from that of the low (-1) level [16].

\[
X_{i} = \bar{y}_{+} - \bar{y}_{-}
\]

Main effects appear in Table 4 and Table 6 for NO and NO₂, respectively. Plots of main effect are presented in Figure 6 and Figure 7. The plots with the largest slopes indicate the largest effects. All of the main effects for NO

<table>
<thead>
<tr>
<th>Sensor</th>
<th>A</th>
<th>B</th>
<th>C</th>
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</thead>
<tbody>
<tr>
<td>I</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>II</td>
<td>+</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>III</td>
<td>-</td>
<td>+</td>
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</tr>
<tr>
<td>IV</td>
<td>-</td>
<td>-</td>
<td>+</td>
</tr>
</tbody>
</table>

Table 2. Experimental design matrix
Effects are significant for $F$ calculated $> F_{crit}$ for the 95% level from statistical tables of the $F$ distribution [18]. The appropriate number of degrees of freedom (DOF) and the tables were compared with critical $F$ values for the significance, the calculated $F$ values in the ANOVA of variance (ANOVA) were constructed for NO and NO sensing at the 95% level ($F_{crit}(1,4,0.95)=74.14$), thereby rejecting the null hypothesis. For NO sensing, the null hypothesis was confirmed at the 99% level ($F_{crit}(1,4,0.99)=21.2$). This effect’s calculated $F$ value is only half of the minimum $F$ value found for NO sensing, however, suggesting that the design criteria have a much larger impact on NO sensing. Since NO concentration typically exceeds NO sensing. This result is the most substantial finding of these experiments. The electrolyte thickness measured approximately 27$\mu$ and 63$\mu$ for the low and high levels, respectively.

A small benefit is also observed with fewer wires, factor A, but from practical experience, sensors with fewer wires tend to result in less reliable signals; they are noisier due to inhomogenieties in the conduction path. By nature fewer wires make a less robust sensor. Factor C, the distance between sensing wires, has a small effect on the output of NO sensing with larger distance being better.

For NO$_2$ sensing, the null hypothesis was confirmed for factors A (number of wires) and B (electrolyte thickness); their observed effects may result from random noise or experimental error at the 95% level. Only factor C, wire spacing, was significant at the 95% level and even at the 99% level ($F_{crit}(1,4,0.99)=21.2$). This effect’s calculated $F$ value is only half of the minimum $F$ value found for NO sensing, however, suggesting that the design criteria have a much larger impact on NO sensing. Since NO concentration typically exceeds NO$_2$ concentration by an order of magnitude, sensor design should favor NO sensing.

By far the most significant effect was electrolyte thickness for NO sensing. Its calculated $F$ value greatly exceeded all others for both NO and NO$_2$ sensing. This result is the most substantial finding of these experiments. This finding must be tempered, however, with the knowledge that ceramic electrochemical system performance is often beset by issues of reproducibility due to variation from one sensor to another and due to changes in microstructure over time. Therefore, more extensive tests are necessary to further support these findings.

The trends of the effects in the main effect plots (Figure 6 and Figure 7) were the same for all factors except for factor C, spacing between sensing wires. As mentioned above, sensor design should favor NO sensing due to its preponderance.

Predicting equations were calculated according to Devor [19]:

$y_{NO} = + 0.87 + (-0.31)*x_1 + (0.75)*x_2 + (-0.25)*x_3$

$y_{NO2} = + 3.64 + (-0.18)*x_1 + (0.11)*x_2 + (0.41)*x_3$

where $x_i$ is either +1 or -1 according to the factor level. Significance tests for lack of fit were not performed.

Variance was analyzed in order to determine the statistical significance of these effects. Tables of analysis of variance (ANOVA) were constructed for NO and NO$_2$ sensing (Table 5 and Table 7) [17]. To test for significance, the calculated $F$ values in the ANOVA tables were compared with critical $F$ values for the appropriate number of degrees of freedom (DOF) and the 95% level from statistical tables of the $F$ distribution [18]. Effects are significant for $F$ calculated $> F_{critical}$.

All of effects were found to be significant for NO sensing at the 95% level ($F_{crit}(1,4,0.95)=7.71$) and even at the 99.9% level ($F_{crit}(1,4,0.999)=74.14$), thereby rejecting the null hypothesis for each factor. Factor B, the electrolyte thickness (number of slurry coats), causes the largest effect. The electrolyte thickness measured approximately 27$\mu$ and 63$\mu$ for the low and high levels, respectively.

A small benefit is also observed with fewer wires, factor A, but from practical experience, sensors with fewer wires tend to result in less reliable signals; they are noisier due to inhomogenieties in the conduction path. By nature fewer wires make a less robust sensor. Factor C, the distance between sensing wires, has a small effect on the output of NO sensing with larger distance being better.

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where $x_i$ is either +1 or -1 according to the factor level. Significance tests for lack of fit were not performed.
Nitric Oxide (NO) Results

<table>
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<th></th>
<th>A</th>
<th>B</th>
<th>C</th>
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<td>-0.6</td>
<td>1.5</td>
<td>-0.5</td>
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<tr>
<td>Electrolyte thickness</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spacing between wires</td>
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Table 4. Main effects for NO

![Figure 6. Main effect plots for NO](image1)

<table>
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<tr>
<th>Sources of Variation</th>
<th>Sum of Squares</th>
<th>DOF</th>
<th>Mean Square</th>
<th>Calculated F Value</th>
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<tr>
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<td>1</td>
<td>6.109</td>
<td>1101</td>
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<tr>
<td>A</td>
<td>0.78</td>
<td>1</td>
<td>0.781</td>
<td>141</td>
</tr>
<tr>
<td>B</td>
<td>4.55</td>
<td>1</td>
<td>4.549</td>
<td>820</td>
</tr>
<tr>
<td>C</td>
<td>0.516</td>
<td>1</td>
<td>0.516</td>
<td>93</td>
</tr>
<tr>
<td>Pure Error</td>
<td>0.02</td>
<td>4</td>
<td>0.006</td>
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<tr>
<td>Total</td>
<td>11.98</td>
<td>8</td>
<td>-</td>
<td>-</td>
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</table>

Table 5. ANOVA table for NO

Nitrogen Dioxide (NO₂) Results

<table>
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<th></th>
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<th>C</th>
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<tbody>
<tr>
<td>Number of wires</td>
<td>-0.4</td>
<td>0.2</td>
<td>0.8</td>
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<tr>
<td>Electrolyte thickness</td>
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<tr>
<td>Spacing between wires</td>
<td></td>
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Table 6. Main effects for NO₂

![Figure 7. Main effect plots for NO₂](image2)

<table>
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<tr>
<th>Sources of Variation</th>
<th>Sum of Squares</th>
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<tbody>
<tr>
<td>Mean</td>
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<td>1</td>
<td>105.873</td>
<td>2886</td>
</tr>
<tr>
<td>A</td>
<td>0.26</td>
<td>1</td>
<td>0.257</td>
<td>7</td>
</tr>
<tr>
<td>B</td>
<td>0.10</td>
<td>1</td>
<td>0.105</td>
<td>3</td>
</tr>
<tr>
<td>C</td>
<td>1.371</td>
<td>1</td>
<td>1.371</td>
<td>37</td>
</tr>
<tr>
<td>Pure Error</td>
<td>0.15</td>
<td>4</td>
<td>0.037</td>
<td>-</td>
</tr>
<tr>
<td>Total</td>
<td>107.75</td>
<td>8</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 7. ANOVA table for NO₂
Although the authors strove to eliminate sources of variation in the fabrication and testing of the sensors, some variation was present. In particular, difficulty existed in controlling one fabrication parameter: electrolyte slurry consistency, which introduced variation between sensors.

In addition, sensor III was fabricated three times due to poor performance. The sensors initially made according to sensor III’s design specifications exhibited open circuit defects and would not reliably resolve the low frequency arc necessary to detect gaseous species. The electrolyte slurries were made anew each time. On the third version of sensor III, the electrolyte slurry topcoat appeared thicker than other sensors. The thickness of the topcoat thus served as a source of variation. During testing, sensor III showed itself to be the best sensor for NO, as indicated by the largest difference in phase angles for NO sensing in Table 3. Further experimentation is required in order to pinpoint the contribution of the topcoat. It is interesting to note that the factor with the most significant effect for NO sensing is the electrolyte thickness, which is also made from a slurry.

**Effect of Flow Rate on Impedance Signal**

Figure 8 shows that the signal a gaseous mixture of 10% O\textsubscript{2} with 100 ppm NO evokes the same impedance response regardless of flow rate. Whereas the high frequency arcs overlap regardless of gas mixture, in this case, the low frequency arcs overlap as well. Impedance measurements are independent of flow rate; they depend only on the composition of the mixture. Nakatou and Miura found similar results for an impedance-based sensor for a different analyte gas.[20]

**Effect of Variable O\textsubscript{2} on Impedance Signal**

Figure 9 depicts the effect that changing the oxygen concentration has on the response signal. Figure 10 shows the result of the same conditions but with 100 ppm NO added. The high frequency arcs in Figure 9Figure 10 are the same regardless of gas concentration, as expected. In both figures, the low frequency arcs shift inwards with increasing O\textsubscript{2} concentration. The addition of NO shifts the low frequency arcs even further inward, increasing the phase angle.

Figure 11 better illustrates the effect of 100 ppm NO on the phase angle at 10 Hz. This figure was derived from Figure 9Figure 10. It is interesting to note that the presence of NO decreases the phase angle at 10 Hz for all O\textsubscript{2} concentrations.

By subtracting the phase angles at 10 Hz in Figure 11, one obtains a set of subtrahends that is loosely approximated as linear in Figure 12. The difference in phase angle due to 100 ppm NO varies with O\textsubscript{2} concentration. The regression line has an R\textsuperscript{2} value of 0.68, indicating that the difference in phase angles versus O\textsubscript{2} concentration is only approximately described as a linear relationship.

**Relative Effect of O\textsubscript{2}, NO, and NO\textsubscript{2} on Impedance Signal**

In Figure 13, the overlapping low frequency arcs show a similar impedance response of differing amounts of O\textsubscript{2}, NO, and NO\textsubscript{2} at 650°C. Adding an additional 4% O\textsubscript{2} to a 10% O\textsubscript{2} gas mixture has approximately the same effect as adding 25 ppm NO\textsubscript{2} or 100 ppm NO. The oxides of nitrogen evoke a response that is several orders of magni-
The addition of 100 ppm NO decreases phase angles at 10 Hz at all O₂ concentrations.

Some sources report that an impedancemetric NOₓ sensor has nearly an identical response to NO as to NO₂ regardless of their relative concentrations at specific temperatures [11, 15, 21].

An equivalent impedance response is possible for different amounts of O₂, NO, and NO₂. Numerals indicate the log of the interrogation frequency.

Effect of Temperature on High Frequency Arc

High frequency arcs consisting of measurements from approximately 10⁴ to 10⁶ Hz in 10% O₂ are shown in Figure 14. (The low frequency arcs were omitted for clarity.) Identical measurements were taken under the same conditions but with the addition of 100 ppm NO which as expected, did not shift the high frequency arc (not shown). At each temperature, the phase angle at 10⁵ Hz was calculated and plotted in Figure 15, which shows that the phase angle at 10⁵ Hz is directly proportional to temperature.

Conclusions

A 2³⁻¹ half fractional factorial experimental design was performed by fabricating four NOₓ sensors in which three design elements were varied: number of working electrode sensing wires, electrolyte thickness, and the distance between sensing wires. Electrochemical impedance spectroscopy was performed and the phase angle difference was calculated at 10 Hz between NO or NO₂ and 10% oxygen. The difference in phase angles characterized the sensing ability of each sensor for which two replicates were recorded. Variation between sensors with identical design features was not examined. Within the design space investigated, changing sensor design parameters affected the ability to sense NO and NO₂ differently. Significant effects were found for sensing both gases as determined by ANOVA, but electrolyte thickness in NO sensing was statistically the largest main effect. Increasing it augmented the phase angle shift due to NO. This effect was considerably larger than other effects; it is the most dominant factor in sensor design. Due to variation in reproducibility of results from identical sensors, further work is necessary to confirm this finding.
Since NOx in diesel exhaust consists predominantly of NO, this work suggests that the thick electrolyte coatings that have been shown to enhance NO sensitivity should be applied to the design of future impedancemetric sensors. The linear relationship between low NO concentration (20-50 ppm) and phase angle has been confirmed. The invariability of the impedance response to flow rate has been demonstrated. It has been shown that the sensor is more sensitive to NO and to NO2 than to O2 by several orders of magnitude by examination of the difference in phase angle obtained at 10 Hz. Among the NOx species, NO2 evokes a larger response than an equivalent amount of NO.

At frequencies of 1 kHz and larger, the sensors did not exhibit a dependence of phase angle on gas concentration thereby precluding the use of the sensors under investigation to self compensate by simultaneously determining O2 and NOx concentrations.

Finally, phase angles at 105 Hz are linearly related to temperature, independent of gas species, thereby permitting temperature detection.

Acknowledgements

The authors gratefully acknowledge Dr. Robert Glass and Dr. Leta Y. Woo of Lawrence Livermore National Laboratory for assistance with sensor fabrication and evaluation.

References


[18] Ibid., pp. 795-797.

[19] Ibid., p. 651.
