

## **Development of a Rich Air/Fuel-Ratio Sensor Correction System**

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### **Abstract**

Automotive universal exhaust gas oxygen (UEGO) sensors are being used in emission control research to provide fast response information about air:fuel ratio (AFR). These sensors were initially developed for spark-ignition gasoline engines, but are commonly used now in diesel research. Spark-ignition (homogeneous charge) engines operate at the chemically correct (stoichiometric) AFR (14.5:1) most of the time, whereas diesels normally operate lean (AFR ranges from ~20:1 at full load to over 100:1 at idle). Because some near-term diesel exhaust emission controls (lean NO<sub>x</sub> traps) require periodic rich excursions (AFR<14.5:1), UEGOs are commonly used to monitor the AFR. Experiments at ORNL with UEGOs in the exhaust of diesels uncovered a problem with sensor accuracy in the rich regime. This seed money project focused on developing a simple system to overcome biasing of these sensors to provide more accurate AFR information for operating engines. A system consisting of critical flow orifices, pumps, and an oxidation catalyst was assembled and evaluated on the bench using a wide range of simulated rich exhaust gas mixtures. By controlling the mass flows of simulated exhaust and excess air and reacting the mixed gases over a heated oxidation catalyst, we were able to produce a lean mixture for the UEGO from which the initial rich AFR can be determined. The feasibility of this system was proven and follow-on funding from DOE has been secured to improve the system and improve the understanding of the sensor bias and possibly explore means to improving the sensors for diesel use. Also, UT-Battelle, LLC has elected to retain title to an invention using the method described herein.

### **Introduction**

In order to reduce nitrogen oxide (NO<sub>x</sub>) emissions produced by internal combustion engines, catalysts are often utilized to convert NO<sub>x</sub> to elemental nitrogen. Conventional catalysts, used on modern gasoline-fueled vehicles, require the exhaust chemistry to be maintained at the stoichiometric air:fuel ratio (AFR) corresponding to complete combustion. Theoretically, the combustion products formed during the stoichiometric combustion reaction would be elemental nitrogen, CO<sub>2</sub>, and H<sub>2</sub>O (neither oxygen nor unburned hydrocarbons would be present). As the exhaust chemistry for these stoichiometric engines drifts slightly lean or slightly rich of the target AFR, the oxygen sensor feedback signals the engine control computer to make small adjustments to the fuel flow to maintain the stoichiometric AFR, enabling the optimal reduction of NO<sub>x</sub> and simultaneous oxidation of carbon monoxide (CO) and hydrocarbons (HC) in the three-way exhaust catalyst. A similar catalyst technology is now being adapted to the control of emissions from diesel engines, although the new technology (NO<sub>x</sub> adsorber catalysis) also contains a sorbent that will store NO<sub>x</sub> during lean (excess oxygen) operation, since NO<sub>x</sub> cannot be readily reduced under oxidizing conditions. In contrast to stoichiometric gasoline engine operation, diesel engines normally run under lean conditions. To meet proposed emission regulations for diesel engines, several promising aftertreatment systems have been developed which demonstrate good NO<sub>x</sub> conversion efficiencies, however they need to be regenerated periodically under rich exhaust conditions.

Regeneration is effected by a momentary rich excursion obtained by direct injection of diesel fuel or other reductant into the exhaust in concert with intake air throttling, or by coupling throttling with manipulation of the fuel injection events. Normal lean operation for a diesel is within the range of about 20:1 AFR at high load to over 100:1 at light loads. For diesel fuel the stoichiometric AFR is 14.5:1. Conventional wide-range UEGO (universal exhaust gas oxygen) sensors are fairly accurate at measuring AFR under

lean conditions ( $AFR > 14.5$ ), but have been shown to be unreliable for rich operation ( $AFR < 14.5$ ) due to interference (or biasing) from the various reductant or fuel-derived species in the rich exhaust.

Optimal operation of NO<sub>x</sub> adsorbers (and other emission control technologies) requires precise measurement of the AFR. Unfortunately, because UEGO sensors are affected by rich exhaust species such as hydrogen, CO, and HC compounds, the sensor readout is biased and the resulting AFR is incorrect. This seed money project focused on developing a simple system to overcome biasing of these sensors to provide more accurate AFR information for operating engines. The objectives of this project were to 1) perform a feasibility study showing that novel arrangement of critical flow orifices and a catalyst can be used to accurately measure AFR during rich operation, and 2) understand how interfering species influence sensor performance. Successful demonstration is expected to lead to follow-on funding from DOE to improve the system and to enable sensor use in diesel engines.

### Technical Approach

A UEGO sensor consists of three basic components: (1) a cavity separated from the exhaust by a diffusion passage, (2) a Heated Exhaust Gas Oxygen (HEGO) sensor that detects the presence of oxygen, and (3) a pumping cell that can pump oxygen into or out of the cavity based on the polarity of current applied to the pump. The sensor determines the AFR by how much oxygen needs to be pumped into or out of the cavity, as determined by the magnitude of the current applied, to maintain a stoichiometric condition inside the cavity.

During lean (excess oxygen and little to no HC or CO present) operation of the wide range UEGO sensor, the AFR is determined by measuring the level of oxygen in the exhaust. Exhaust gas passes through the diffusion passage and into a cavity in contact with a solid-state electrolyte, typically zirconia. The oxygen molecules are pumped out of the cavity through the electrolyte by applying a current across the pump. The current required to pump all the oxygen out of the cavity is proportional to the excess oxygen in the exhaust, which in turn is proportional to the AFR during lean conditions.

During rich combustion, excess fuel species (HC, CO, and H<sub>2</sub>) are present in the exhaust. Under these conditions the AFR is proportional to the amount of oxygen required to complete the oxidation of the excess fuel species. To measure AFR under these conditions the sensor electrochemically pumps oxygen from the atmosphere to the cell. Ideally this oxygen reacts with the remaining fuel components to form H<sub>2</sub>O and CO<sub>2</sub>. The current required to pump in enough oxygen to fully react the excess fuel species is used to determine AFR ratio during rich operation. This approach, while theoretically accurate, is subject to errors associated with the different diffusion rates of the rich species (i.e., H<sub>2</sub> has a much higher diffusion rate, while the diffusion rates for CO and the various HC species are lower). This affect is empirically accounted for and corrected for SI engines, but not for diesel engine operation.

A bench apparatus was constructed to measure rich AFR using the same fundamental principles as the UEGO, but on a larger scale. The design takes advantage of the UEGO's fast response and accurate sensing in the lean regime, but avoids problems associated with diffusion of different species through the sensor. In practice the apparatus will take a fixed mass flow rate sample of raw exhaust, mix it with a fixed mass flow rate of clean air, react the remaining fuel components and oxygen to completion across an oxidation catalyst at high temperature, then flow this new lean sample over a UEGO. For the experiments described herein, simulated exhaust mixes with known CO, H<sub>2</sub>, and HC concentrations were used instead of raw engine exhaust. For well-defined, known concentrations of fuel species the theoretical rich AFR is known. The raw, indicated AFR for each mix was measured with one UEGO, while a second UEGO measured the resulting lean AFR of the mix after the oxidation catalyst. Given the relationship between the mass flow of rich exhaust and mass flow of air, the lean measurement was then used to calculate the corrected AFR.

## Results and Discussion

An apparatus as described above was successfully assembled and evaluated. A wide range of rich and lean gas mixes were blended and sampled by the apparatus, providing the raw indicated AFR and lean AFR. The lean AFR was used to calculate a corrected AFR. Results of these experiments are shown in Figure 1. Solid symbols denote the raw, indicated AFR of the blended gas, while the open symbols denote the corrected AFR. As expected at the onset, H<sub>2</sub> has a significant effect of biasing the sensor output rich (that is, indicated AFR is richer than the actual AFR), while CO or HC alone tend to bias the sensor lean. While the families of datasets are for various H<sub>2</sub> concentrations, the CO and HC were also varied in these experiments. In discussions with a sensor manufacturer we have found that they are aware of the problem and design the sensor for the H<sub>2</sub>/CO mix commonly found in spark ignition (SI) engines. HC levels in SI engines are typically very low and the species are of relatively low molecular weight. In the diesel application, the number and molecular weight of HC species are much higher, and total HC concentration can be much higher. Note in Figure 1 that certain gas mixtures yielded raw indicated AFRs that fall on or very close to the 1:1 line (solid symbols, uncorrected). Close inspection of these data reveals a CO:H<sub>2</sub> ratio of 2 or 3 with very low HC concentration, conditions typical of SI engines.

We are very pleased with the results of this seed money project. We have successfully constructed an apparatus for measuring actual AFR in our operating engine experiments, and we have obtained follow-on funding from our DOE sponsor to further refine the design and research the sensor biasing issue. Accurately determining AFR in our ongoing NO<sub>x</sub> adsorber research is critical to improving the value of the data and the understanding of the catalyst function with various fuel-derived species (reductants).

## Benefits

As noted above, we have secured follow-on funding from DOE to refine the design and further explore the sensor biasing issue. The benefits to our DOE sponsor are an improvement in the quality of data we will acquire from our ongoing NO<sub>x</sub> adsorber research programs. In researching the effectiveness of various regeneration strategies it is critical that the strategies being studied both provide the catalyst with similar stoichiometry. Using this apparatus, we can accurately measure AFR and determine the most effective species for regeneration.

## Figure Caption

Fig. 1. Indicated Air:Fuel ratio (AFR) vs. actual AFR. Raw indicated AFR (solid symbols) measured in simulated exhaust containing known concentrations of CO, H<sub>2</sub>, or HC. Corrected AFR (open symbols) calculated from AFR measured after addition of excess air and oxidation of fuel species. Note that for zero H<sub>2</sub> cases the raw sensor response is biased lean, while increasing H<sub>2</sub> biases the sensor rich. Each open symbol corresponds to a solid symbol data point that has been corrected.