

Ammonia Sensor for Closed-Loop SCR Control

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ABSTRACT

Selective Catalytic Reduction (SCR) is the dominant solution for meeting future NO_x reduction regulations for heavy-duty diesel powertrains. SCR systems benefit from closed-loop control if an appropriate exhaust gas sensor were available. An ammonia sensor has recently been developed for use as a feedback element in closed-loop control of urea dosing in a diesel SCR aftertreatment system. Closed-loop control of SCR dosing enables the SCR system to be robust against disturbances and to meet conformity of production (COP) and in-use compliance norms.

The ammonia sensor is based on a non-equilibrium electrochemical principle and outputs emf signals. The sensor performs well when tested in a diesel engine exhaust environment and has minimum cross interference with CO, HC, NO, NO₂, SO₂, H₂O and O₂.

Previous work, done in a simulation environment, demonstrated that an ammonia sensor provides the optimal feedback for urea dosing control algorithms in closed-loop SCR systems. A model-based SCR control strategy deploying an ammonia feedback sensor demonstrated high NO_x conversion, low NH₃ slip and good robustness against disturbances. In this paper, FTP, ETC and ESC test data will be presented confirming these results. NO_x conversions as high as 91% are measured in combination with 30% urea injection error and a 25 ppm NH₃ slip constraint. Test results using the Delphi ammonia sensor for control are compared with test results utilizing a commercially available NO_x sensor for control.

INTRODUCTION

NH₃ sensor technology is available for vehicle applications [1]. The sensor is based on a non-equilibrium electrochemical principle. It senses NH₃ and outputs an emf signal that is linearly proportional to the logarithms of NH₃ concentration in the engine exhaust. Testing on a diesel engine has proven that the Delphi ammonia sensors performs well in the intended

environment and has reasonable durability [2]. It is of particular interest to determine the benefits such a sensor technology may bring to SCR aftertreatment systems in meeting future NO_x reduction and system OBD requirements.

To meet diesel engine emission requirements for year 2010 and beyond, maximum SCR NO_x conversion is required. In addition, care must be given to prevent undesirable levels of NH₃ slip. To accomplish these stringent requirements, closed-loop control of SCR urea dosing seems an attractive option. Closed-loop control makes the SCR system robust against urea dosage inaccuracy, catalyst ageing and NO_x engine-out variations; enabling the SCR system to meet conformity of productions and in-use compliance norms [3]-[9].

Recently an interesting study had been carried out [5]. In the study, three different SCR control strategies including open-loop map based control, NO_x sensor based control, and adaptive surface coverage/NH₃ slip control were compared in a simulation environment. The study showed that open-loop, map based, control was capable of achieving high NO_x conversion with acceptable NH₃ slip but failed to compensate for a 30% increase of engine-out NO_x emissions. A better result was obtained for NO_x sensor based control. It utilized a urea perturbation method for NH₃ cross-sensitivity compensation of the NO_x sensor and to adapt for changes in engine out NO_x emissions. However, the cross-sensitivity of the NO_x sensor limited the applicability of this control to stationary conditions. The best results were achieved by adaptive surface coverage/NH₃ slip control. Surface coverage/NH₃ slip control requires an NH₃ sensor output. It demonstrated the highest NO_x conversion efficiency with the best control of NH₃ slip.

The same study also discussed limits and challenges of closed-loop control for future development work. The limits include slow SCR catalyst dynamics and high SCR NH₃ storage. The challenges are achieving maximum NO_x conversion with a minimum level of NH₃ slip, enhanced low-temperature performance, and cost.

converters, and satisfying in-use compliance requirements.

In the present study, an NH_3 sensor was used for SCR control in an engine test cell. Our purpose was to verify previous simulation results and to examine potential benefits of such sensors to a SCR de- NO_x system. Tests were carried out utilizing over and under dosage of urea in FTP, ETC and ESC cycles. Complementary simulation runs were carried out for comparison.

AMMONIA SENSORS

Among many different NH_3 sensing principles, the non-equilibrium electrochemical principle is the one most suitable for vehicle diesel exhaust applications. It meets all the requirements of the applications: potential of economic cost, mass manufacturability, durability, and hostile high temperature exhaust environment.

The sensor device has a simple structure. Figure 1 shows a schematic cross-cut view of the device. It has an NH_3 sensing electrode and a reference electrode with yttria doped zirconia as the solid electrolyte. Both electrodes are exposed to the same exhaust gas. No air reference channel or oxygen pumping is required. An integral heater is fabricated into the device to maintain the sensor temperature (the heater circuit is not shown in Figure 1).

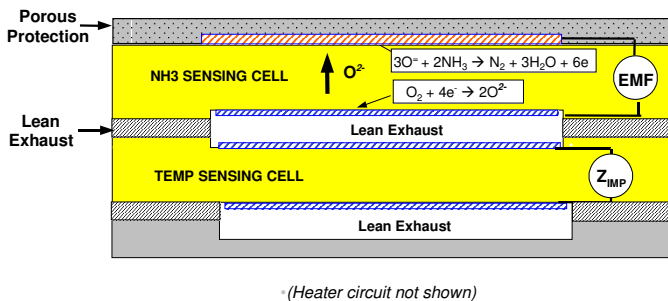
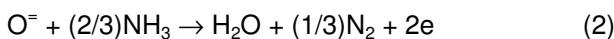


Figure 1. Cross-cut view of NH_3 sensor structure

FUNCTIONALITY – At the NH_3 sensing electrode, there are two competing electrochemical half reactions,



Where O^- is the oxide ion. At the reference electrode, only reaction (1) exists. There is no ammonia involved in the electrode reaction here due to the catalytic-oxidation activity of the reference electrode. The potential difference between the two electrodes produces an emf output,

$$\text{Emf} \approx (kT/3e)\ln(C_{\text{NH}_3}) - (kT/4e)\ln(C_{\text{O}_2}) - (kT/2e)\ln(C_{\text{H}_2\text{O}}) \quad (3)$$

Where k is the Boltzmann constant, T is the absolute temperature, and e is the electron charge unit.

Eq. (3) clearly shows that the emf is linearly proportional to the logarithm of the partial pressure of NH_3 . This semi-log linear relationship has been verified on a gas bench. NH_3 gas concentration was varied from 5 ppm to 1600 ppm while holding O_2 and H_2O constant. The total gas flow rate was fixed at 40 l/min. The result shows that the linear relationship holds true for the entire test range as shown in Figure 2.

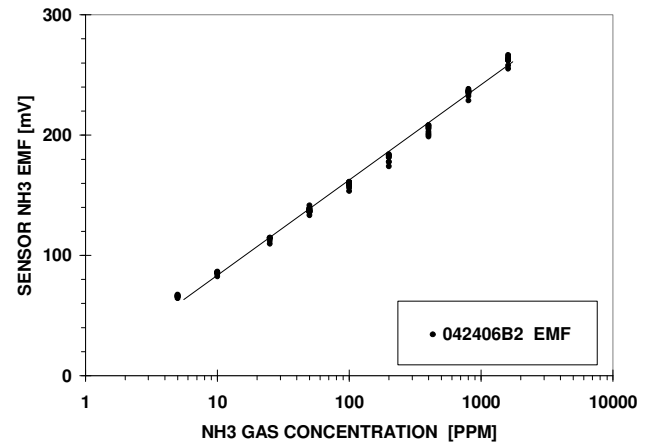


Figure 2. Semi-log plot of emf data vs. NH_3 concentration

Pressure Dependence – Tested on engine and gas bench, no noticeable total-pressure dependent effect was observed. This may be due to the fact that both NH_3 sensing and reference electrodes are exposed to the same engine exhaust atmosphere with the total pressure terms of both electrodes cancelling each other.

Gas Flow Rate Dependence – Engine test bench was used to study the gas flow rate dependency. Four sensors were tested at two pipe locations with different pipe diameter. In this way, sensors were tested with exhaust liner speed ranged from 2.46 m/s to 43.04 m/s. No significant flow-rate dependence was observed in this range.

CROSS INTERFERENCE – Engine exhaust contains CO , CO_2 , O_2 , H_2O , HC , N_2O , NO and NO_2 . Their interference effects on ammonia sensing have been studied both on lab gas bench and on the engine bench.

H_2O & O_2 – In engine exhaust, water and oxygen concentrations are a function of incoming-air humidity, air fuel (A/F) ratio and the fuel C/H ratio. Their effect on ammonia sensing emf is determined by Eq. (3). Assuming C/H to be equal to 1.8, H_2O and O_2 concentrations can be calculated as function of air humidity and A/F. Substituting these values in Eq. (3), the effect of water and oxygen on emf shifting can be determined. Figure 3 shows the relative emf shift from a reference point (A/F=20 and zero air humidity) plotted as function of A/F at various air humidity levels. The 7 air humidity levels range from 0 g/kg to 60 g/kg which cover air humidity realized across the global climate.

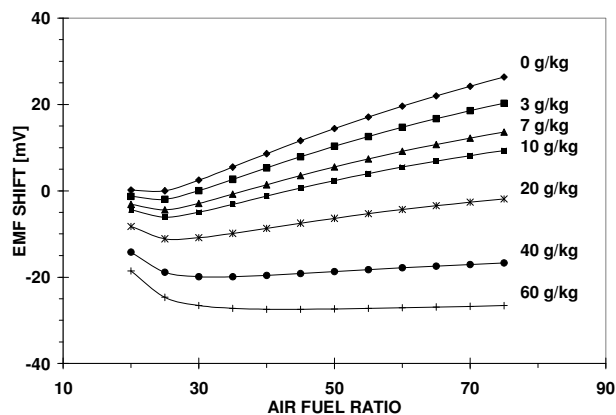


Figure 3. Water-oxygen emf difference as function of air humidity and A/F

Increasing air humidity has two effects on the ammonia sensing emf. It lowers emf and changes the shape of A/F-dependence. In the range of A/F ratio between 20 and 50 the maximum emf variation observed is 15 mV at 0 g/kg, 5 mV at 20 g/kg and 9 mV at 60 g/kg. For comparison, a 15 mV difference would yield ± 2.5 ppm NH_3 at 10 ppm NH_3 and a 9 mV difference in emf would correspond to ± 1.5 ppm NH_3 at 10 ppm NH_3 point.

The limited effect of A/F on NH_3 sensing emf is due to the fact that H_2O and O_2 concentrations change in opposite direction as function of A/F in diesel combustion. An increase of oxygen concentration will be accompanied with a decrease of water and vice versa. This self compensation effect leads to the possibility of sensor compensation through air humidity only or even calibration based on climate zone where the resultant inaccuracy is tolerated by the control system. To have highest accuracy of the NH_3 sensor, reliable inputs of air humidity and exhaust A/F ratio will be needed for $\text{H}_2\text{O}-\text{O}_2$ correction.

NO_2 – As a strong oxidizing agent, NO_2 interferes strongly with the NH_3 sensing signal. Data showing this effect has been published previously [2]. To compensate for this effect in situ NO_2 concentration information is required. To achieve this, an NO_2 electrochemical cell is built into the existing NH_3 sensor device. The NO_2 sensing cell is also based on the non-equilibrium electrochemical principle and shares a common reference electrode with the NH_3 sensing cell. The effectiveness of the NO_2 compensation, by such a dual-cell device, is illustrated in Figure 4. In this figure, the NH_3 sensing output of a dual-cell device tested at four different NO_x conditions: 200 ppm NO , 100/100 ppm of NO/NO_2 , 200 ppm of NO_2 , and 0 ppm of NO_x on a gas bench, are plotted against the dosing NH_3 levels, which are 0, 5, 10, 25, 50, and 100 ppm NH_3 . The figure demonstrates that good compensation of the NO_2 effect has been achieved.

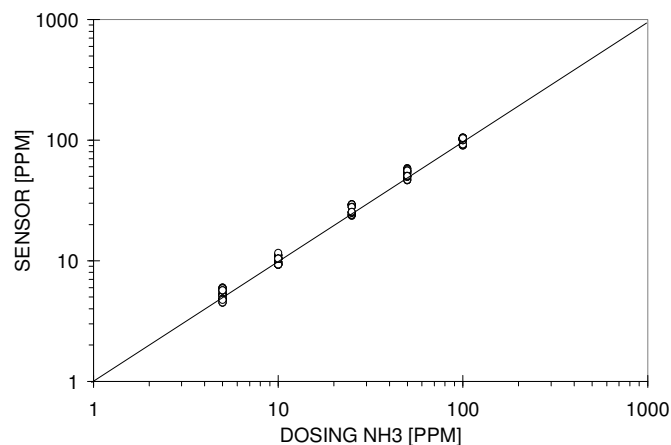


Figure 4. Log-log plots of sensor NH_3 data vs. dosing NH_3 values

NO , CO , HC , N_2O and SO_2 – The cross interference effects of these gases have been studied on a gas bench and some of the data have been published [2]. Up to 1000 ppm of NO , CO , and HC or mixing of them had been tested at the presence of NH_3 . No significant emf shifting was observed. Without the presence of NH_3 , NO , CO and HC do generate emf signals which are less than 5 ppm NH_3 if treated as NH_3 sensing emf. The composition of HC tested is a mixture of C_3H_6 and C_3H_8 with a ratio of 1:3.

N_2O was inert to the NH_3 sensor. Up to 400 ppm of N_2O had been introduced to the gas bench and no significant emf signal shift was detected with or without NH_3 .

SO_2 has strong cross interference effect on NH_3 sensing. On gas bench, the presence of 25, 45, and 90 ppm of SO_2 would increase original NH_3 reading by 40% to 70%. However, this poison effect can be reversed once the supply of SO_2 to the gas bench was stopped. Future diesel fuel will be low-sulfur content. This poison effect becomes less important.

Cold Start Interference – An abnormal cross interference phenomenon linked to long chain hydro-carbons (unburned diesel fuel for example) has been observed in some cold-start situations. The interference has been observed to be significant and can persist until the engine DOC reaches operational temperature. Likewise, the phenomenon can be produced by applying a thin film of diesel fuel directly to the outer surface of the sensor's metal lower shield before testing the sensor. The phenomenon is not seen in all applications and potential solutions are still under investigation.

POISON AND THERMAL AGING STUDY – Usually, exhaust gas sensors are susceptible to poisoning from silicon, engine oil deposit, and soot. High temperature exposure can cause an aging effect for exhaust gas sensors. Their effects on NH_3 sensors has been studied.

Silicon – This poison phenomenon was studied by adding siloxane to the fuel and exposing NH_3 sensors to the exhaust. NH_3 sensors, with bared electrodes, can be poisoned within 12 hours of exposure and results in a slow down of the sensor's response time. The poison effect is reversible if the poisoned sensors are exposed to silicon-free exhaust for an extended period. A protective coating layer proves to be an effective protection for the NH_3 sensors from this poison phenomenon.

Engine Oil Deposit – Concentrated amount of chemicals, calculated based on sensor life-time exposure to engine oil deposits, were added to the fuel to accelerate exposure. NH_3 sensors with bare electrodes were tested behind the DOC, Diesel Particulate Filter (DPF), and SCR. The observed poison effect was a slow down of sensor response time and a reduction in emf signal output. The symptoms are less severe when compared with silicon-poison. The poisoned sensors can be recovered by exposing the poisoned sensors to clean exhaust for an extended period. A protective coating layer will be an effective means to protect the NH_3 sensor from this effect.

Soot – Soot has lesser effect in poisoning NH_3 sensors. Bare sensors (without coating) tested behind DOC, DPF and SCR for 1100 h showed no observable deterioration

SENSOR DESIGN –

Sensing Element & Package – The sensing element has a planar structure and is built by a multi-layer thick film technology. The ceramic sensor body is made from co-fired zirconia and alumina ceramic layers with species gas sensing electrodes, a reference electrode, two temperature sensing electrode and a heater circuit. The integrated heater provides fast time to activity. An air reference is not required as both the gas sensing electrode and the reference electrode are exposed to exhaust gas. Alumina layers provide electrical isolation between the heater and sensor circuits. A porous protection coating layer provides poison resistance. The element is relatively small in size and packages in an existing planar oxygen sensor assembly, currently in production. A lower shield is provided to protect the sensing element. The lower shielding can be modified according to application requirements.

Mechanization – An NH_3 sensor system has been developed for vehicle applications. This system includes the NH_3 sensor and stand-alone electronics. The electronics interface with the sensor to provide signal processing and control of the heater circuit. The electronics also provide a CAN serial data link for communication with a vehicle.

PERFORMANCE TARGET –

Measurement Range – 0-100 ppm NH_3 . Tolerance is ± 5 ppm at 10 ppm NH_3 . Acceptable gas contents without

interference are NO , HC , CO and N_2O . Acceptable gas contents with cross-sensitivity are O_2 and H_2O

Temperature Range – Functional temperature range for ammonia sensing is 200 °C to 450 °C. Non functional safe temperature range is -40 °C to 750 °C.

Durability Targets – 5,000 hours or 250,000 km.

NO_x exhaust gas content – is 0 to 500 ppm (sensor performance within spec).

H_2O Exhaust Gas Content – 1% to 8% by mass (sensor performance within spec assuming intake air humidity compensation)

Response time – $T_{60} < 3$ second and $T_{90} < 5$ second.

Interface Electronics – Ambient temperature for NH_3 sensor interface electronics is -40 °C to 105 °C. Sensor system is compatible with either a 12V or 24V vehicle electrical system. Sensor system communicates to vehicle over a CAN bus.

Mounting/Installation – Sensor mounts directly to exhaust pipe via an M18x1.5 threaded boss. The sensor must be mounted 10° above horizontal to prevent pooling of water in shield.

TEST RESULTS – Sensors were tested at an engine test cell. Typically the sensors were installed into the exhaust system behind DOC, DPF, and SCR. An LDS NH_3 analyzer was positioned behind the sensors to measure NH_3 slip; its data is used to compare with the sensor output. One of the steady state test results is shown in Fig 5. The exhaust gas temperature is 400 °C.

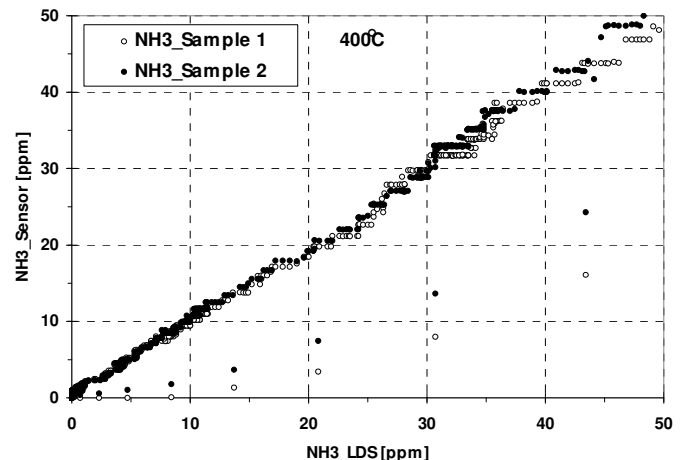


Figure 5. Plots of steady state of sensor data vs. LDS NH_3 data

Sensors were also tested during an ESC test cycle. Two sensors were positioned after the SCR catalyst in order to measure NH_3 slip behind the SCR. The results were plotted against the Siemens' LDS ammonia analyzer as shown in Figure 6. The solid lines represent