

Deposit Formation in Urea-SCR Systems

Vadim O. Strots, Shyam Santhanam, Brad J. Adelman,
Gregory A. Griffin and Edward M. Derybowski
Navistar Inc.

Copyright © 2009 SAE International

ABSTRACT

Formation of urea injection related deposits in a heavy-duty urea-SCR system was studied using an engine lab setup. The exhaust system was instrumented with thermocouples to track temperature changes caused by the liquid spray. Impact of operating parameters (exhaust and ambient temperature, urea solution injection rate) and system design modification (insulation, wiremesh insert) on the temperature profiles and deposit quantities was studied.

Deposits were found in all tests conducted under typical exhaust temperatures. Deposition rate increased with lower exhaust and ambient temperature, and with higher injection rate. Mixer insulation and wiremesh upstream of the mixer reduced the deposits.

INTRODUCTION

Selective catalytic reduction of nitrogen oxides by ammonia has been proposed as a solution for heavy-duty diesel engines to meet upcoming emission regulations. To deliver ammonia, a 32.5% aqueous urea solution (DEF in the US, AdBlue in Europe) is injected into the exhaust system. The liquid in the spray evaporates, and urea decomposes into ammonia and isocyanic acid. Both processes require heat energy that is provided by the exhaust gas. Integration of urea delivery into the SCR system poses a number of challenges recently summarized by Johnson [1]:

- Complexity of DEF storage and delivery systems
- Freezing of DEF at ambient temperature $< -12^{\circ}\text{C}$
- Generating sprays of sufficient quality
- Ensuring complete evaporation of DEF

- Mixing gaseous reductant species (NH_3 and HNCO) with the exhaust gas
- Controlling the DEF injection rate to maximize NO_x reduction while minimizing secondary emission (NH_3 , N_2O).

A variety of system configurations and devices have been proposed and extensively studied from the standpoint of achieving uniform reductant distribution in the gas flow [2-4].

In the process of developing a urea-SCR system, formation of deposits downstream of DEF injection was reported in the literature [4, 6-7] and observed in our vehicle tests [10]. The literature suggests that the chemical composition of these deposits is complex and changing continuously during system operation [4-6]. Schaber et. al. [5] and Fang and DaCosta [6] showed that, once exposed to temperatures typical for the diesel exhaust, dry urea decomposes into ammonia and isocyanic acid (HNCO). The decomposition is rather slow, allowing HNCO to react with urea to form biuret and cyanuric acid. The latter further reacts to form ammelide, ammeline, melamine, and more complex polymerization products that require very high temperatures to decompose (Figure 1). To date, no quantitative model of urea transformation can be found in the literature.

From an application standpoint, the data suggest that the exhaust system should be $\geq 200^{\circ}\text{C}$ to prevent deposits. Way et. al. [4] analyzed formation and decomposition of urea deposits in heavy-duty SCR systems and showed packaging solutions that may mitigate the deposit problem through the reduction of wall wetting and elimination of recirculation patterns near the injection point and installation of spray redirection

devices. Oesterle et. al. [2] stated that the low exhaust temperature observed in long exhaust pipes can promote deposit formation. However, neither provide quantitative insight into the deposit formation process.

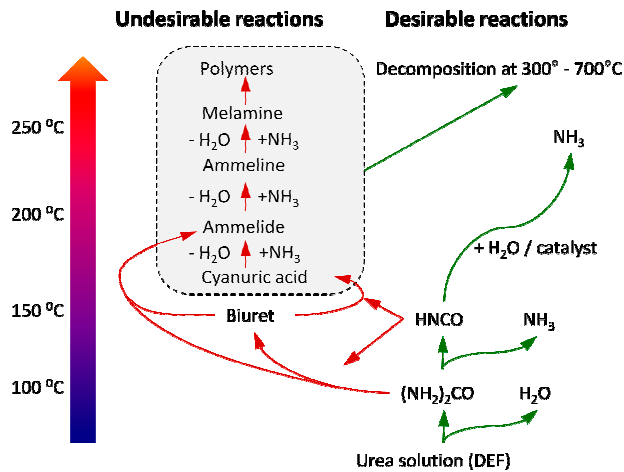


Figure 1. Reactions and byproducts involved in urea thermolysis [5-6].

The objective of this study was to evaluate experimentally the dynamics of deposit formation using a temperature controlled prototype heavy-duty urea-SCR system in an engine dyno. Of particular interest were quantities and locations of the deposits formed and the effect of operating conditions and system design modifications on the deposition rate.

EXPERIMENTAL

EXHAUST SYSTEM

An inline, six-cylinder, 7.6 L, 300 hp MY 2007 Navistar engine has been used in the study.

The urea-SCR exhaust system layout followed common architecture proposed for heavy-duty applications and included a diesel oxidation catalyst (DOC) followed by catalyzed diesel particulate filter (DPF), urea injector, mixer and selective catalytic reduction (SCR) catalyst.

Previous studies, such as [2], recommended installing the urea injector at a pipe bend to improve mixing. Apparently, such a design has another benefit of reduced wall wetting due to limited impingement of the spray on the exhaust pipe walls.

The system was instrumented with 19 thermocouples to monitor the temperature patterns caused by heat losses to the environment as well by DEF injection. The thermocouples were installed at the flow centerline, the periphery (roughly halfway from center to wall) and at the external wall surface (Figure 2). The system had single wall exhaust pipe thus allowing the external wall temperatures to be used as a measure of the cooling impact from the spray. The thermocouple TC-9

measured temperature in the area adjacent the urea injector nozzle. The exhaust temperature, T_{exh} , was monitored by TC-1 (installed at the centerline of the DPF outlet).

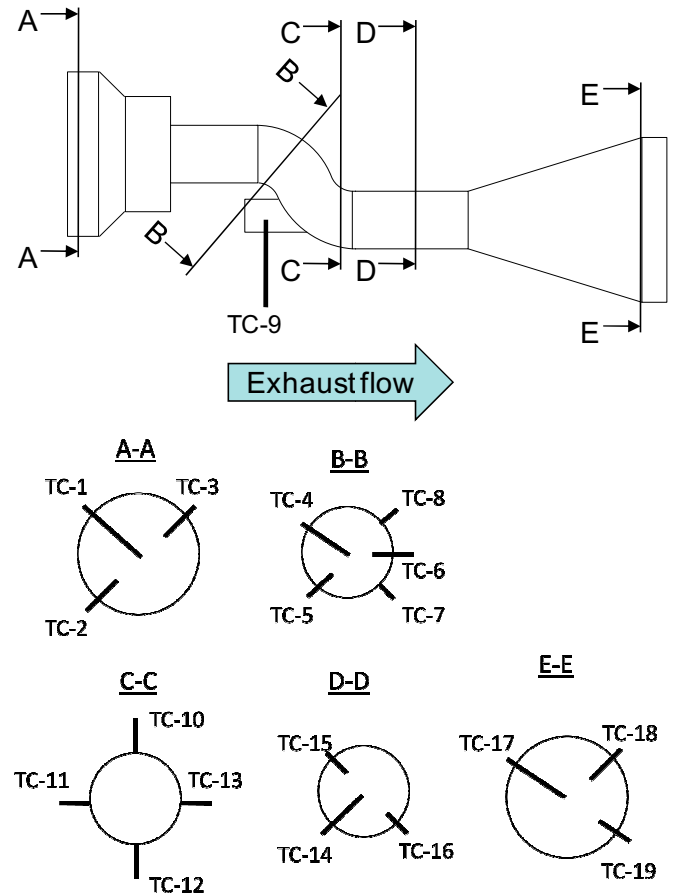


Figure 2. Exhaust system and thermocouple layout.

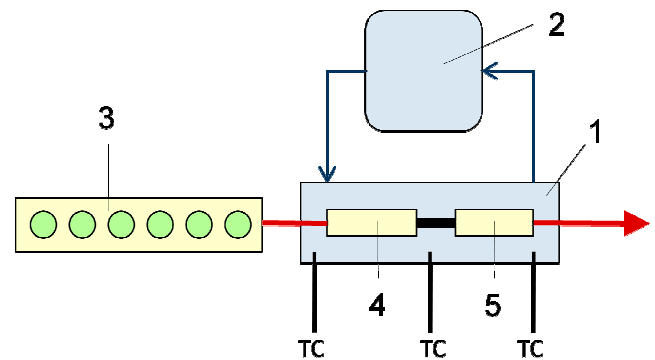


Figure 3. Principal diagram of the engine dyno test setup. 1: cooled box, 2: air chiller, 3: engine on a dynamometer, 4: DOC-DPF can, 5: SCR catalyst can

In order to study the effect of ambient temperature, the exhaust system was enclosed in an insulated box whose interior was cooled by chilled air. Three thermocouples were installed within the box to monitor ambient temperature, T_{amb} : near the DOC/DPF can, near the DEF injector and near the SCR can.

TEST PROCEDURE

The test matrix included variations of exhaust and ambient temperatures as well as the DEF injection rate (Table 1.)

Incomplete decomposition of urea and formation of deposits are expected to be the most severe at low exhaust temperature and flow, typically produced by an engine operating at low speed and light load. Therefore, 1200 rpm / 200 N·m operating point was chosen for the test program. At these conditions, the DPF outlet temperature was ~ 220°C. The use of in-cylinder post-injection of fuel allowed the exhaust temperatures to be increased and resulted in a concurrent increase in exhaust flow rate from ~ 230 to ~ 270 kg/hr. In two test runs, the engine speed and load were increased to demonstrate the impact of the exhaust flow rate on the deposit formation.

The range of ambient temperatures was limited by freezing of DEF in unheated supply hardware (-13°C) and by room temperature.

Table 1. Test parameters

DPF out temperature	°C	220, 350
Exhaust gas flow rate	kg/hr	230 – 270, 740
Ambient temperature	°C	-12, -3, 10, 20
DEF injection rate	g/s	0.06, 0.15, 0.3, 0.6

At the start of the test, the air chiller was run until the cold box temperature stabilized. The engine was started and then ran at the desired speed/load setpoint. After the system temperature stabilized (typically, 20 – 30 min), DEF injection was initiated and continued until 720g of DEF was injected into the exhaust.

Recorded data included engine operating parameters, temperatures in the exhaust system and the cold box, exhaust gas flow rate and DEF injection rate. Figure 4 shows a representative thermal trace of the recorded thermocouples.

Steady-state temperatures were calculated from second-by-second data by averaging over the DEF injection period except first 10 min of rapid change.

After the urea injection stopped, the engine was shut, and the exhaust system was allowed to cool. The box and the system were opened for pictures of the deposits to be taken as well as for the deposits to be collected. The total weight of combined deposits was measured. In a number of tests, the deposits from different parts of the system were weighed separately.

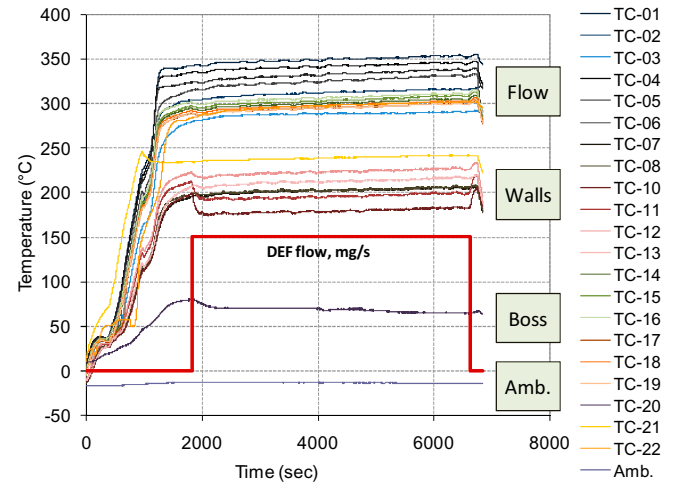


Figure 4. System temperature traces. $T_{\text{exh}} = 350^{\circ}\text{C}$, $T_{\text{amb}} = -13^{\circ}\text{C}$, $F_{\text{DEF}} = 0.15 \text{ g/s}$.

From the measured weight, deposit yield was determined as the percentage of the mass of the deposit to the mass of injected urea (dry basis):

$$\eta_D = \frac{W}{0.325 \cdot t_{\text{DEF}} \cdot F_{\text{DEF}}} \times 100\%$$

The deposit yield is related to the efficiency of urea conversion into gaseous reductants, η_u , as:

$$\eta_D = 1 - \eta_u$$

RESULTS

STEADY STATE TEMPERATURES

Figure 5 illustrates how heat losses to the environment as well as urea solution evaporation cause the exhaust gas temperature to decrease through the length of the system). The temperature drop was the most significant after the urea injection point (cross-section D-D).

The temperature of the exhaust was not uniform at the exit of the DPF (Figure 6); the temperature near the system walls was 25 – 65 °C lower than at the centerline. These differences depended on the location and test conditions.

In the exhaust pipe (cross-section B-B), the temperature differences in the flow decreased to < 20°C (Figure 6). Wall temperatures (TC-7 and TC-8) are much lower, with difference from the centerline temperature (TC-4) approaching 90°C. In addition, wall temperatures decreased more at lower ambient temperature (Figure 8), while the gas flow temperatures were not affected.

Only wall temperatures were recorded for the cross-section C-C immediately downstream of DEF injector. This prevented urea deposits from being collected.