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Urea-SCR Temperature Investigation for NOx Control of Diesel Engine

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Abstract. SCR (selective catalytic reduction) system is continuously being analyzed by many researchers worldwide on various concerns due to the stringent nitrogen oxides (NOx) emissions legislation for heavy-duty diesel engines. Urea-SCR includes AdBlue as urea source, which subsequently decomposes to NH_3 (ammonia) being the reducing agent. Reaction temperature is a key factor for the performance of urea-SCR system, as urea decomposition rate is sensitive to a specific temperature range. This particular study was directed to investigate the temperature of the SCR system in diesel engine with the objective to confirm that whether the appropriate temperature is attained for occurrence of urea based catalytic reduction or otherwise and how the system performs on the prescribed temperature range. Diesel engine fitted with urea-SCR exhaust system has been operated on European standard cycle for emission testing to monitor the temperature and corresponding nitrogen oxides (NOx) values on specified points. Moreover, mathematical expressions for approximation of reaction temperature are also proposed which are derived by applying energy conservation principal and gas laws. Results of the investigation have shown that during the whole testing cycle system temperature has remained in the range where urea-SCR can take place with best optimum rate and the system performance on account of NOx reduction was exemplary as excellent NOx conversion rate is achieved. It has also been confirmed that selective catalytic reduction (SCR) is the best suitable technology for automotive engine-out NOx control.

1 Introduction

Selective catalytic reduction (SCR) of NOx by nitrogen compounds, such as ammonia or urea (commonly referred to as simply SCR) was originally developed for industrial and stationary application. However, the application of SCR for automobile diesel engines has also been the a proven catalyst technique for reducing NOx emissions to levels required by the latest emission standards. Urea-SCR has been selected by a number of manufacturers as the technology of choice for meeting the Euro V (2008) and other NOx limits [1]. Urea SCR utilizes added urea (AdBlue) in combination with a specifically-formulated catalyst to accomplish NOx reduction. AdBlue is an aqueous urea solution made with 32.5% urea. It serves as the ammonia precursor for reduction of exhaust emission NOx in the chemical reaction taken place on the catalyst surface. The process of urea decomposition to ammonia NH3 is highly sensitive to the reaction temperature as decomposition of urea does not reaches to completion in the gas phase at temperatures below 300 ºC. In fact, merely 20% or less of the urea decomposes to HNCO and NH3 in the gas phase at 330 ºC, and only about 50% decomposes at 400 ºC [2,3]. HNCO has been shown to be very stable in the gas phase, requiring an oxide surface to catalyze its decomposition to NH3 [4]. Therefore, only about 25% of the desired NH3 is available at the catalyst inlet at 400 ºC. Thus, best optimum temperature range for urea-SCR would be from 250-450 ºC when most of urea has been decomposed to NH_3. In this paper, the temperature and other related parameters of Urea-SCR are studied with following objectives:

- ✓ Whether or not the system temperature is sufficient for maximum urea decomposition.
- ✓ Mathematical approximation of SCR reaction temperature under various circumstances
- ✓ System performance on account of exhaust emission NOx conversion rate.

2 Experimental setup

2.1 Engine and catalysts

The layout of the test equipment and installation of thermocouples are shown in Fig. 1. The diesel engine used in this study is a four cylinders, turbocharged and diesel engine equipped with a commercial V_2O_5-WO_3/TiO_2 SCR catalyst. The V_2O_5 catalyst can achieve the best NOx conversion efficiency in the temperature range of 260-450ºC. Moreover, it has been reported that the application of the V_2O_5 catalyst not only improves NOx emissions reduction but also avoids sulphur-related catalyst poisoning effects [5]. Table-1 shows the detailed diesel engine specifications.

Table 1. Engine specifications

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Number of cylinders	4
Bore [mm]	93
Stoke [mm]	102
Displacement [L]	2.771
Compression ratio	18.2:1
Rated power [kW@ rpm]	85@3600
Maximum torque [N m@ rpm]	270@1900
Fuel type and system	Diesel, Common rail

The diesel engine was run on a dynamometer produced by the SIEMENS Company. The selective reducing agent adapted was urea because of its safety and low toxicity characteristics [6]. In automotive applications, Urea (AdBlue)-based SCR is a promising method for the control of NOx emissions [7]. PT100 type temperature sensor were used for calculating the temperature downstream of the catalyst. The porosity of the catalytic substrate is 200 cell/inch^2, and the volume is 10 L. NOx emissions, including NO and NO_2, were measured using a NOx sensor seated before and after the catalyst.

2.2 Procedure and findings

The SCR catalyst temperature was examined using the temperatures upstream and downstream of the catalyst, measured with two thermocouples seated before and after SCR catalyst. In the SCR system, the urea solution is pumped from the urea tank to the nozzle and then injected into the exhaust gas pipe before the SCR catalyst.

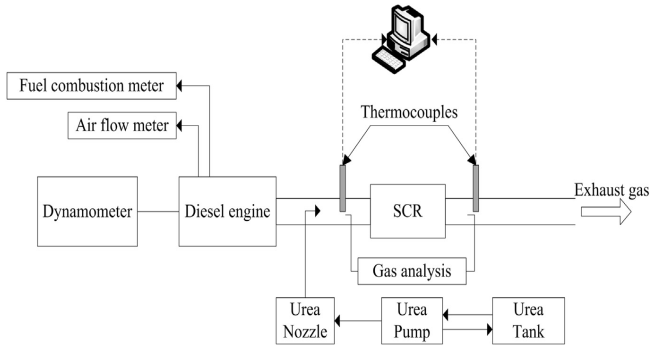

Figure 1. Layout of test equipment

In this experiment, the European standard cycle (ESC) was adopted to investigate the engine performance, including the exhaust gas temperature and NOx emissions, values of the parameters were measured under a set of 13 different engine operating points. The specific engine operating points are shown in Table-2. In SCR System, NOx reduction rate is mainly associated to the ample availability of the reducing agent. In our case the reducing agent i.e. NH_3 is obtained from the urea decomposition which as discussed above can take place at specific temperatures.

2.3 Reaction temperature

Keeping in view the axial heat losses along monolithic channels, 'mean temperature' has been considered as the 'reaction temperature' which is the average value of temperature at the upstream and downstream. The temperature lines of experiment as shown in Fig.2 indicate that the reaction temperature has remained on the specified range i.e. 250-450ºC.

Table 2. Engine operating points at ESC cycle

Operating point	Speed [rpm]	Load [Torque %age]	T_{US} [ºC]	T_{DS} [ºC]	Mean Temperature [ºC]	NOx_{US} [ppm]	NOx_{DS} [ppm]	Rate of NOx Conversion [%]
1	800	05	157	123	140	368	367	0.27
2	2040	100	470	420	445	585	95	83.76
3	2560	50	351	200	275.5	190	28	85.26
4	2560	75	434	298	366	298	43	85.57
5	2040	50	331	245	288	198	7.3	96.31
6	2040	75	417	365	391	451	15	96.67
7	2560	25	268	362	315	109	17	84.40
8	2560	100	426	380	403	420	22	94.76
9	2560	25	365	280	322.5	196	10	94.90
10	2950	100	586	468	527	227	26	88.55
11	2950	25	345	234	289.5	163	16	90.18
12	2950	75	448	349	398.5	185	13.5	92.70
13	2950	50	306	395	350.5	179	9	94.97

(*The subscriptions* $_{US}$ & $_{DS}$ *means parameter values at upstream and downstream.*)

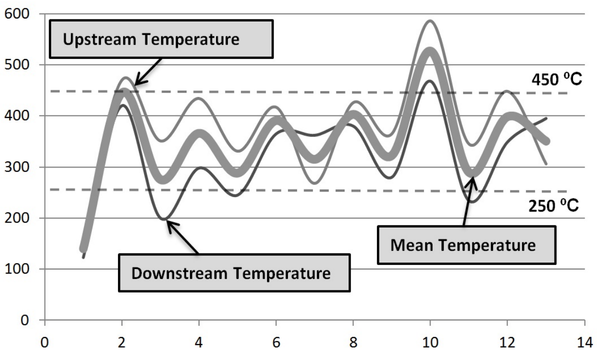

Figure 2. Temperature lines

3 Mathematical approximation of SCR reaction temperature

The engine exhaust gas enters into the SCR reactor (catalyst coated monolithic channels), flowing through the urea spray, undergoes through the reaction in catalyst coated channels and then discharged into the atmosphere; it exhibits a complicate physical and chemical phenomena of heat transfer and chemical reactions. Practically SCR reaction temperature is the temperature of the species undergoing through the reaction at the catalyst surface in the monolithic channels. Reaction temperature may be mathematically approximated using the energy conservation equation. By balancing the heat and energy transfer between the reacting species (gaseous phase) and the substrate, energy conservation equation of the system can be written as shown in Eq. (1):

$$k_h A_r (T_s - T_r) = m_r c_{pr}\, \partial T_r/\partial t + \dot{m}_r c_{pr}\, \partial T_r/\partial x \quad (1)$$

where k_h is the heat transfer coefficient (W/m^2 K), A_r is the gas-solid interface area (m^2), T_s and T_r are respectively the substrate and reactants temperatures (K), m_r is the mass of the reactants i.e. exhaust gases (kg), c_{pr} is the specific heat capacity of the reactants (J /kgK), $\dot{m}_r$ is the mas flow rate of reactants(kg/s), t is tine (s) and x is the longitudinal coordinate of the reactor (m). However, when conducting the engine test, the exhaust gas mass flow cannot be measured directly. Therefore, according to mass conservation principal the rate of air intake and fuel consumption is considered as the mass flow rate of the reactants as shown in Eq. (2):

$$\dot{m}_r = \dot{m}_{air} + \dot{m}_{fuel} \quad (2)$$

Thus reaction temperature would be a function of engine fuel consumption, speed and torque. On other hand it will also be a function of substrate material properties and reactor dimensions.

3.1 Calculation of SCR reaction temperature on various conditions

The temperature lines drawn in Fig.2 considers the mean temperature i.e. $(T_{US} + T_{DS})/2$ as reaction temperature. On other hands following expression can be applied to approximate the reaction temperature even if only T_{US} or T_{DS} is available or in case both the values are not available:

$$T_{r\,(approx.)} = \begin{cases} T_{US} - \Delta t & ;\ \Delta t = [k_h\,(T_{US} - T_{env}) / l\,\rho c_{pr}] & \text{only } T_{US} \text{ is available} \\ T_{DS} + \Delta t & ;\ \Delta t = [k_h\,(T_{DS} - T_{env}) / l\,\rho c_{pr}] & \text{only } T_{DS} \text{ is available} \\ pV/m_r R & & \text{both } T_{US}\ \&\ T_{DS} \text{ are not available} \end{cases} \quad (4)$$

Where $T_{r\ (approx.)}$ is the approximate reaction temperature, T_{env} is the environment temperature (k). l is the distance form thermocouple to the point of temperature investigation (m), ϱ is density of reacting species (kg/m^3), p is exhaust gas pressure (N/m^2). V is volume of exhaust duct till SCR inlet and R is gas constant.

4 SCR system performance

NOx conversion rate has been calculated by the method explained in Eq. (5):

$$\text{NOx Conversion Rate} = 100\,[(NOx_{US} - NOx_{DS})/NOx_{US}] \quad (5)$$

As per the results mentioned in Table-2 the NOx conversion rate has remained above 80% throughout the experiment depicting an excellent system efficiency with a maximum value of 96.76%. It is proved that reaction temperature is a critical parameter which directly effects system performance.

5 Conclusions

In this study, the experiment is done to investigate temperature characteristics of the SCR system operated under European Standard Cycle (ESC). It is concluded that system temperature has remained on the suitable range (250-450ºC) for optimum decomposition of urea to ammonia NH3, hence sufficient amount of reducing agent was available for optimum NOx reduction. The same has also been proven by achieving more than 96% NOx conversion rate. The system performance confirmed that SCR is the most promising technology to comply with the latest NOx emission standards.

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