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Fuels combustion effects on a passive mode silver/alumina HC-SCR catalyst activity in reducing NO_x

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ABSTRACT

The activity of a Ag/Al_2O_3 catalyst in reducing NO_x emissions in a passive mode hydrocarbon selective catalytic reduction (HC-SCR) was investigated using exhaust gas from the diesel engine operation on diesel, biodiesel (RME) and low temperature Fischer–Tropsch synthetic diesel (SD). The $HC_1:NO_x$ ratio in the engine exhaust from the combustion of these fuels followed the order: diesel > SD > biodiesel and this order was mirrored in the catalyst activity in reducing NO_x in presence of hydrogen (1000 ppm). Compared to diesel fuel, biodiesel combustion produces a higher amount of NO_x with reduced concentrations of HCs, while both HC and NO_x emissions were reduced in the engine exhaust from the combustion of SD fuel. Although, a higher NO_x reduction in the SCR process was seen in the case of diesel fuelling, due to higher $HC_1:NO_x$ ratio in the engine exhaust compared to biodiesel (RME) and SD, at low exhaust temperatures (190 °C) there was a gradual loss of the catalyst, NO_x reduction activity. The incorporation of EGR within the engine operation, increased significantly $HC_1:NO_x$ ratios in the exhaust, mainly by lowering the NO_x concentration. Under these conditions, which can assumed to represent typical $HC_1:NO_x$ ratios of a modern automotive diesel engine, higher NO_x conversion was seen with SD, followed by diesel and biodiesel. For all the cases examined here the SD fuelling provides the lowest tailpipe NO_x emissions. Hydrogen addition, i.e. at 500, 1000, 1500 and 3000 ppm in the passive mode Ag/Al_2O_3 SCR catalyst needs to be optimized for the different $HC_1:NO_x$ ratios and hydrocarbon species in the exhaust from the combustion of the three fuels.

1. Introduction

To date, several methods have been proposed as a way to reduce NO_x and PM emissions in diesel engines, and catalytic aftertreatment systems such as NO_x traps, Selective Catalyst Reduction (SCR) using urea, Diesel Oxidation Catalysts (DOCs) and Diesel Particulate Filters (DPF) have proved to be the most effective [e.g. 1]. The selective catalytic reduction of NO_x emissions in diesel engine exhaust gas with hydrocarbons (HC-SCR) has attracted considerable interest [e.g. 2]. Silver on alumina (Ag/Al_2O_3) catalysts are seen as the main candidates for this technology, and have been investigated in a laboratory and engine environment with model hydrocarbons and diesel fuel [e.g. 3–9]. However, there is only limited information on the activity of these catalysts under passive mode operation (no external hydrocarbon addition) and how the different species in a diesel engine exhaust (i.e. C-containing) from the combustion of the different fuels can influence their activity performance in reducing NO_x emissions.

The combustion of different diesel-type fuels (i.e. diesel, synthetic diesel (SD), biodiesel) produces exhaust with a range of $HC:NO_x$ ratios and hydrocarbon species that are mainly dependant on the physical and chemical properties of the fuels used for combustion. In Ag/Al_2O_3 HC-SCR, hydrocarbon concentration and composition are very influential in the effectiveness of the catalyst in removing NO_x emissions under lean conditions [4–6]. At low exhaust temperatures, increased carbon and nitrate species can deposit on the catalyst and reduce significantly the NO_x removal efficiency [5,10–12]. Recently, we have reported that in order to avoid catalyst deactivation at low temperatures a balance between accumulation rate and oxidation rate of these species on the catalyst surface is required. This can possibly be achieved by controlling the concentration of hydrocarbon emissions reaching the SCR catalyst, i.e. engine out and quantity of the hydrocarbons injected (active control) [5,7]. In addition, hydrogen in small concentrations (less than 1500 rpm) apart from improving the catalyst activity in reducing NO_x emission, can also keep the catalyst clean by enhancing NO to NO_2 oxidation over the catalyst that helps

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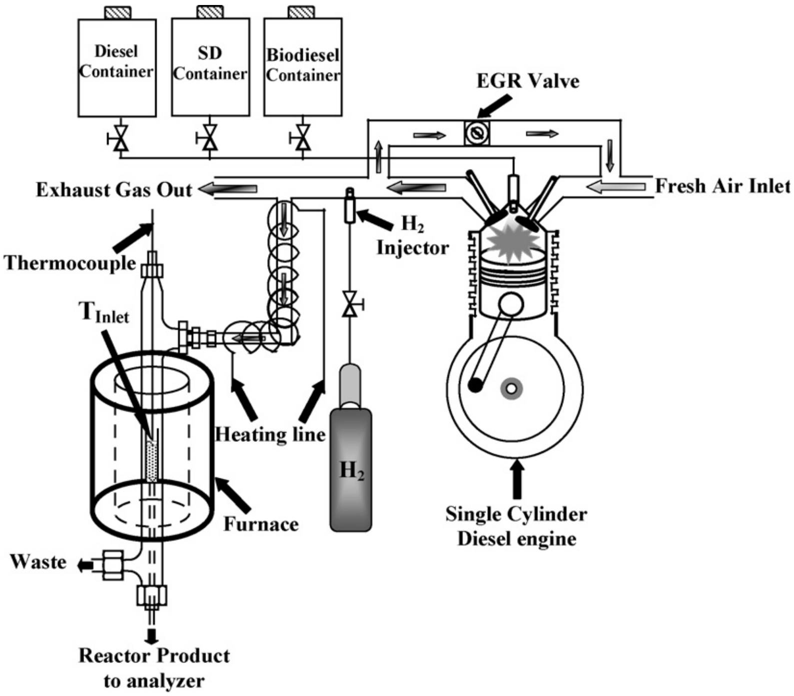

Fig. 1. Schematic diagram of diesel engine with SCR mini-reactor system.

in oxidizing the C-containing species (i.e. liquid fuel, soot) [5,6]. Hydrogen oxidation over the catalyst can also assist in maintaining the catalyst free of poisoning compounds through the increase of temperature and chemical interaction with the poisonous species [7,8].

In an earlier SCR study [13–20] using the same catalyst with simulated engine exhaust gas (e.g. CO, CO_2, NO_x, H_2O, O_2 in N_2), when diesel fuel was injected in the SCR system, the catalyst activity window was expanded to lower temperatures when compared to model hydrocarbons (e.g. octane, decane, dodecane). Catalyst deactivation was seen with both diesel fuels (synthetic and standard) but at low temperatures the maximum NO_x conversion was enhanced and the rate of catalyst deactivation was weaker when the longer chain free of aromatic hydrocarbons synthetic diesel fuels was used and compared to diesel.

In this work the Ag/Al_2O_3 HC-SCR catalyst activity in reducing NO_x emissions was examined under passive mode operation (no external fuel injection) with actual exhaust gas from the diesel engine operating on diesel, biodiesel (RME) and synthetic diesel (SD) fuels. The effect of unburned hydrocarbons from these fuels with different H_2 additions under real diesel engine conditions as well as the effect of introducing EGR within the engine operation in order to vary the HC_1:NO_x ratio and hydrocarbons concentration were studied.

2. Experimental

The experimental apparatus was set up as detailed in Fig. 1. The Lister Petter TR1 diesel engine was used for this study as a source of exhaust gas in the SCR converter. The engine is a single cylinder, direct injection and the test rig has been described in more details in previous work [7,8,21]. The main engine specifications are as follows: bore 98.4 mm, stroke 101.6 mm, conrod length 165.0 mm, displacement volume 773 cm^3, compression ratio 15.5, maximum power 8.6 kW at 2500 rpm and maximum torque 39.2 N m at 1800 rpm. This study was conducted at three engine loads of 2, 4 and 5 bar Indicated Mean Effective Pressure (IMEP) for engine fuelling on diesel (Ultra Low Sulphur Diesel), biodiesel (Rapeseed Methyl Ester) and synthetic diesel (SD). The fuels used were provided by Shell Global Solutions, UK and their properties are given in Table 1.

A part of the engine exhaust gas was cooled and recycled from the engine exhaust to the inlet (external EGR) and the volumetric flow rate of the EGR was calculated based on the reduction in the air volumetric flow rate. The effect of hydrogen concentration (500, 1000 and 3000 ppm) was investigated without the injection of any fuel into the HC-SCR mini-reactor system (passive mode).

The SCR mini reactor was located in a tubular furnace (Fig. 1). The H_2 was introduced and mixed with the engine exhaust gas before

Table 1
Fuels properties.

Fuel analysis	Method	Diesel (ULSD)	Synthetic diesel (SD)	Biodiesel (RME)
Cetane number	ASTM D613	53.9	80	54.7
Density at 15 °C ($kg\,m^{-3}$)	ASTM D4052	827.1	784.6	883.7
Viscosity at 40 °C (cSt)	ASTM D445	2.467	3.497	4.478
50% distillation (°C)	ASTM D86	264	295.2	335
90% distillation (°C)	ASTM D86	329	342.1	342
LCV ($MJ\,kg^{-1}$)		42.7	43.9	39
Sulphur ($mg\,kg^{-1}$)	ASTM D2622	46	0.05	5
AROMATICS (wt%)		24.4	<0.3	–
O_2 (wt%)		–	–	10.8

Table 2
Engine conditions and fuels tested (engine speed 1500 rpm), 0% EGR.

Fuel	IMEP (bar)	EGR (vol%)	T_{inlet} (°C)	O_2 (vol%)	HC (ppm)	NO_x (ppm)	HC:NO_x	BSN
Diesel	2	0	190	16.2	413	359	1.2	0.2
	4	0	250	14.6	418	622	0.7	0.7
	5	0	300	12.5	428	948	0.5	2
SD	2	0	190	16.9	182	208	0.9	0.1
	4	0	250	13.9	280	494	0.6	0.6
	5	0	300	12.2	385	697	0.6	1.8
Biodiesel	2	0	190	16.6	228	330	0.7	0.1
	4	0	250	13.6	319	732	0.5	0.5
	5	0	300	12.2	370	1025	0.4	1.2

a fraction (3 l/min) of the whole exhaust gas is directed through the powdered catalyst packed bed. The exhaust gas temperature at the inlet of the catalyst was controlled by means of a temperature controller and kept equal to the actual exhaust gas temperature measured 30 cm downstream the engine exhaust valve.

A generic silver catalyst (2 wt%) was prepared by impregnating γ-alumina (surface area ∼150 m^2/g) with aqueous $AgNO_3$, before drying and calcining (in air for 2 h at 500 °C). It was prepared as a powder, which was then granulated (for packed-bed testing). For each test 0.6 g (particle size $250 < d < 355$ μm) of catalyst were used with a gas mixture flow rate of 3 l/min.

Gas analysis included measurement of carbon dioxide, carbon monoxide (NDIR—Non-Dispersive Infrared), hydrocarbons (FID—Flame Ionization Detector), oxygen (electrochemical method) and $NO_x - NO$ (chemiluminescence) emissions. H_2 and N_2O concentrations (the last is not shown as it was significantly lower) were measured by gas chromatography. For all the conditions, upstream and downstream the catalyst measurements of NO_x ($NO + NO_2$), HC and N_2O were recorded. These measurements allowed us to distinguish between NO_x reduction and NO oxidation, and to determine the selectivity of NO_x reduction to N_2. Engine smoke was measured using a Bosch smoke meter and the readings are shown as Bosch Smoke Number (BSN).

3. Results and discussion

3.1. Effect of exhaust gas temperature and composition

The combustion of oxygenated biodiesel (RME) increases NO_x emissions in the engine exhaust, a trend that is mainly dependant on both fuel type and engine design. Similarly high cetane number paraffinic synthetic diesel (SD) reduces NO_x emissions, while both type of fuels reduce HC emissions in the exhaust compared to diesel and hence affect the aftertreatment systems performance (Table 2).

The NO_x conversion over the silver SCR catalyst in the absence of hydrogen was similar for all the exhaust gas compositions and temperatures (Fig. 2). The actual exhaust temperature was varied by increasing the engine load from 2 to 4 bar and 5 bar IMEP and the temperatures were replicated at the inlet of the SCR catalyst by the mean of tubular furnace.

Hydrogen addition, i.e. 1000 ppm, magnified the influence of HC:NO_x ratios and hydrocarbons quality from the combustion of the three fuels, on the passive mode catalyst activity (Figs. 2 and 3). The catalyst activity along the different engine conditions was in order of diesel > SD > biodiesel. The NO_x emission measurements were taken for 10 min (Fig. 3) after the inlet temperature was steady at each temperature point. In Fig. 2 only the final NO_x conversion recorded after 10 min is shown.

At low exhaust gas temperatures (∼190 °C, engine load 2 bar IMEP), with the presence of 1000 ppm H_2, the passive mode HC-SCR catalyst with diesel, shows significantly higher NO_x conversion (>90%, result is not directly shown) at the beginning of the tests, compared to RME and SD (<50%), but the catalyst activity was rapidly declining down to approximately 60% after 10 min (e.g. Figs. 2 and 3). For diesel fuelling a higher amount of C-containing species, resulted in these being progressively adsorbed onto the surface of the catalyst, promoting catalyst deactivation [5,12]. For the engine fuelling with SD or biodiesel the loss in the SCR activity at isothermal conditions, was less notable than diesel, revealing that for diesel fuelling higher H_2 additions are required (Fig. 3). According to Arve et al. [22] high molecule hydrocarbons (i.e. diesel fuel) are more effective in inhibit NO adsorption on the Ag/Al_2O_3 catalyst active sites, resulting in reduced catalyst activity. It can be speculated that apart from the amount of hydrocarbons that influences the catalyst deactivation, the molecules of the diesel fuelling combustion by products (i.e. HC; Particulate Matter, PM) are having molecule sizes higher than the ones produced for the SD and RME fuelling. Un-combusted fuel especially for diesel and RME fuelling, may condensed more rigorously on the surface of the catalyst.

At higher engine loads (e.g. 4 bar IMEP) and exhaust gas temperatures (i.e. 250 °C) the HC:NO_x ratios in the engine exhaust were reduced for all the fuels (Table 2). The HC:NO_x reduction was more significant for diesel, resulting in a considerable drop in NO_x conversion over the SCR catalyst. The higher competition between C-species oxidation and NO_x reduction reaction, as hydrocarbons/soot oxidation with oxygen or NO_2 [23] gradually becomes more dominant due to the increased temperature and NO_2 concentration. Even for diesel exhaust, loss in the catalyst NO_x reduction activity was seen (Fig. 3).

Hydrogen effectiveness in helping oxidize the carbonaceous impurities was more obvious in biodiesel fuel combustion followed by SD (Fig. 3). Despite the low NO_x conversion rates, at higher temperatures the amount of NO_x converting to N_2, was significantly improved for all the fuels. Reduced diffusion limitations in the

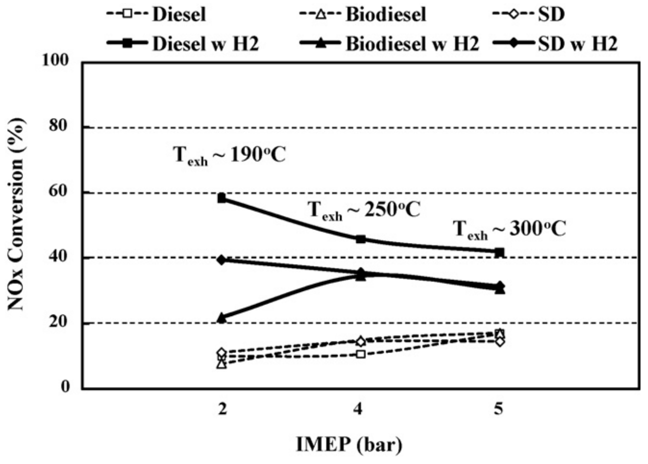

Fig. 2. NO_x conversion from the engine fuelling with diesel, biodiesel and SD at different engine loads at 1500 rpm speed. Hydrogen addition 0 and 1000 ppm.

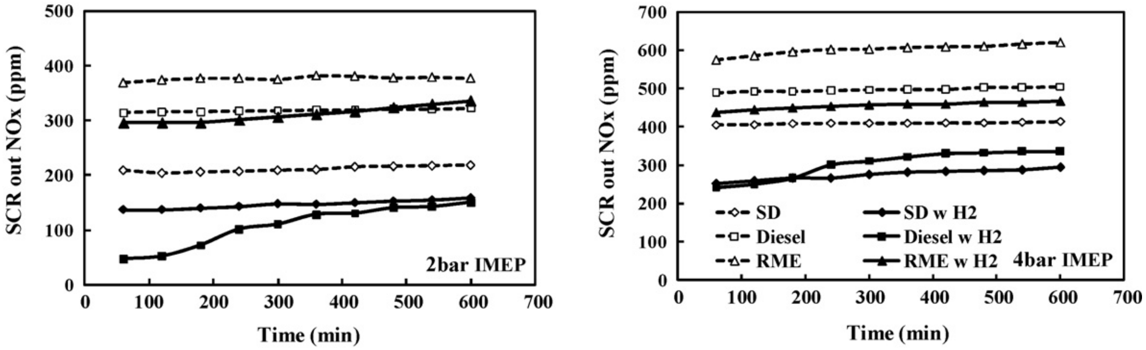

Fig. 3. NO_x emissions measured after the SCR. Engine speed of 1500 rpm, 0% EGR, 0 and 1000 ppm H_2 for engine load of 2 bar ($T = 190\,°C$) and 4 bar ($T = 250\,°C$) IMEP.

Table 3
Engine conditions and fuels tested (engine speed 1500 rpm), 20% EGR.

Fuel	IMEP (bar)	EGR (vol%)	T_{inlet} (°C)	O_2 (vol%)	HC (ppm)	NO_x (ppm)	HC:NO_x	BSN
Diesel	2	20	200	15.62	424	216	2.0	0.5
	4	20	260	13.3	444	386	1.2	1.3
	5	20	310	9.6	462	598	0.8	3.6
SD	2	20	200	15.99	191	127	1.5	0.4
	4	20	260	12.29	293	241	1.2	1.1
	5	20	310	9.87	396	490	0.8	3.0
Biodiesel	2	20	200	15.59	233	239	1.0	0.3
	4	20	260	11.8	327	418	0.8	0.7
	5	20	310	10.21	381	525	0.7	1.8

SCR (more available active sites due to clean catalyst surface) and increased probability of the reactants (HCs–NO_x-H_2) adsorption on the catalyst active sites, instead of passing through, are also made a contribution to hydrogen effectiveness.

3.2. The effect of EGR

The incorporation of exhaust gas recirculation (EGR) within the engine operation, increases the HC_1:NO_x ratio in the SCR system, primarily due to large NO_x emissions reduction (Table 3). The engine NO_x emissions reduction (ppm) was more significant for the biodiesel fuelling, a trend that we have previously explained [24]. In addition, there is also an increase in C-containing species such as HCs and smoke as illustrated in Table 3. At low temperatures (~190 °C), the SCR catalyst activity is higher for diesel (~40%) followed by SD (~35%) and biodiesel (~20%). As the exhaust temperature increased (i.e. on changing the regime from 2 bar IMEP to 4 and 5 bar), NO_x conversion in the SCR was significantly improved to approximately 50% for both, biodiesel and SD fuels.

Hydrogen addition (1000 ppm) with EGR enhanced NO_x conversion to approximately 75 and 90%, respectively, for biodiesel and SD, however at 190 °C exhaust temperature there is a gradual loss in the Ag/Al_2O_3 SCR catalyst activity (e.g. Fig. 5 for 2 bar IMEP). Un-optimized HC_1:H_2 ratios can accelerate C-containing species deposition onto the catalyst surface as we reported in our earlier work [25] and can be seen in Figs. 3 and 5. Although, Ag/Al_2O_3 catalyst design can further be modified, to enhance HC oxidation, some loss in SCR process of NO_x is expected.

At low exhaust temperatures, apart from the hydrocarbons, Particulate Matter (PM) and soot can also play an important role in catalyst activity and deactivation. In PM a large portion of the soluble organic fraction is adsorbed onto the soot layer leading to sticky particles which can cover the catalyst active sites without being able to be oxidized. As the temperature rises the catalyst can more effectively oxidize or even use in the SCR process the hydrocarbons adsorbed on the soot (part of the PM), strip off the soot/carbon that can blow out or possibly, but less likely, be oxidized on the catalyst [23]. The combustion of fuels such as RME and SD are reported to reduce PM concentration in the exhaust gas but also to produce PM free of soot or with lighter SOF (soluble organic fraction) adsorbed on the soot that are more likely to be oxidized [26]. Base metal catalysts such as Ag/Al_2O_3 catalyst used in this study are reported to be able to capture and also oxidize PM [27].

Modern diesel engines in order to control NO_x emissions, are operated with large EGR percentages (up to 50 vol%), so if the proposed or improved version of the SCR catalyst find an application in a diesel engine, hydrogen addition among other technologies (e.g. engine recalibration), can be proposed as a solution to prevent catalyst deactivation under passive operation and improve low temperature activity (Figs. 4 and 5).

For the synthetic diesel and biodiesel combustion with EGR, NO_x conversion over the SCR at temperature range of 250–300 °C was improved by approximately 30% as the quantity of HC_1:NO_x was

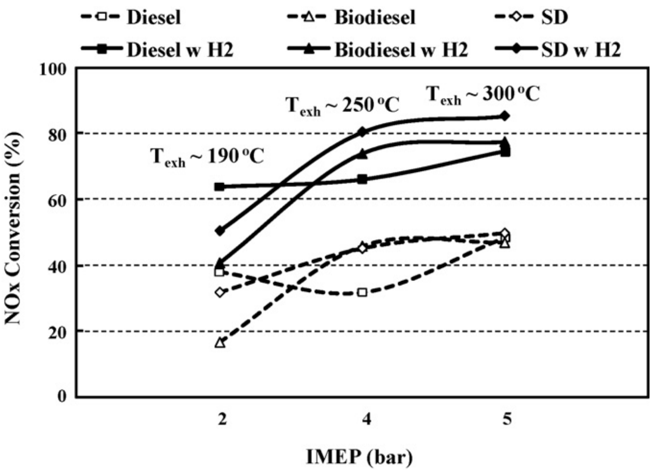

Fig. 4. HC-SCR activity in reducing NO_x from the engine operation with 20% EGR for diesel, biodiesel and SD engine fuelling. H_2 = 1000 ppm.

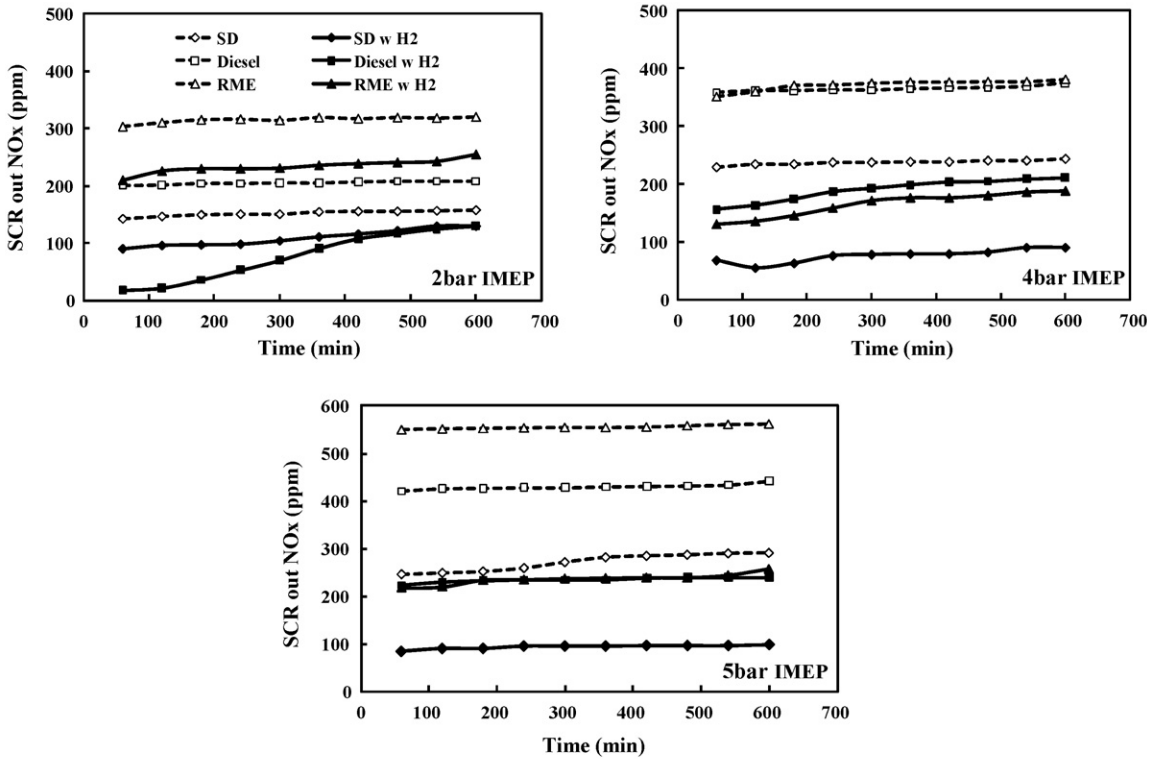

Fig. 5. NO_x emissions measured after the SCR. Engine speed of 1500 rpm, 20% EGR, 0 and 1000 ppm H_2 for engine load of 2 bar ($T = 190\,^\circ C$), 4 bar ($T = 250\,^\circ C$), IMEP and 5 bar ($T = 300\,^\circ C$).

near optimum for the 1000 ppm H_2 addition. The NO_x conversion trends (diesel > SD > biodiesel) seen over the SCR in the absence of H_2 at temperature of approximately 190 °C for the three fuels were similar when 1000 ppm H_2 was introduced, but about 20–25% higher. These SCR activity/deactivation trends seen with the combustion of the three fuels cannot be fully explained with the analysis carried out. However, it is believed that it is related to a combination of (a) the HC:NO_x ratios which was higher for diesel and (b) the range of hydrocarbons in the exhaust, that are expected to be more active from the simple component fuel (i.e. synthetic) compared to biodiesel and diesel [5,25]. The use of EGR significantly increases smoke and PM (soot and SOF) conditions that accelerate the loss in catalyst activity as can also be seen in Fig. 5. Engine fuelling with synthetic diesel such as gas-to-liquid (GTL) or biodiesel fuel is reported to be more tolerant to EGR percentages mainly due to cleaner combustion and reduced smoke/PM emissions, e.g. Table 3 and [24]. This can further enhance the Ag/Al_2O_3 SCR catalyst in removing NO_x emissions especially at high loads where the engine is less tolerant to EGR.

3.3. *Effect of hydrogen concentration*

Previous studies have shown that H_2 addition increases the performance of Ag/Al_2O_3 catalysts at low temperature operating conditions (<350 °C) [19,28–31]. Satsuma et al. reported that hydrogen addition enhanced the rate of the SCR-NO_x reaction by formation of small metallic charged Ag^+ clusters [15]. In this work the effect of hydrogen additions (i.e. approximately 500, 1000 and 3000 ppm) over a passive SCR system with engine exhaust gas from the combustion of the three fuels was investigated using exhaust and conditions from the low load engine operation (i.e. 2 bar IMEP). The NO_x conversion activity for diesel, SD and biodiesel fuelling was significantly promoted by increasing the H_2 amounts (Fig. 6). Hydrogen addition enhances the SCR catalyst performance and its effectiveness is dependant on the engine exhaust gas quality from the combustion of the three fuels.

In the combustion of diesel and synthetic diesel fuels, the exhaust gas contained enough unburnt hydrocarbon (HC_1), that can be utilized in the presence of increased hydrogen addition to improve the catalyst activity in reducing NO_x emissions. The maximum NO_x reduction peaked at approximately 70% in the presence of 3000 ppm hydrogen and occurred in both diesel and synthetic diesel fuels. However, the diesel fuel combustion exhibited higher rates of deactivation meaning that greater amounts of H_2 are required to maintain constant NO_x reduction. The silver catalyst exhibits strong selectivity for the removal of NO_x in the synthetic fuel exhaust gas due to HC_1:NO_x ratios and operating temperature being near optimum. In addition the reduced NO_x concentration from the combustion of SD fuel compared to diesel and biodiesel can reduce nitrate species formation and catalyst poisoning [11].

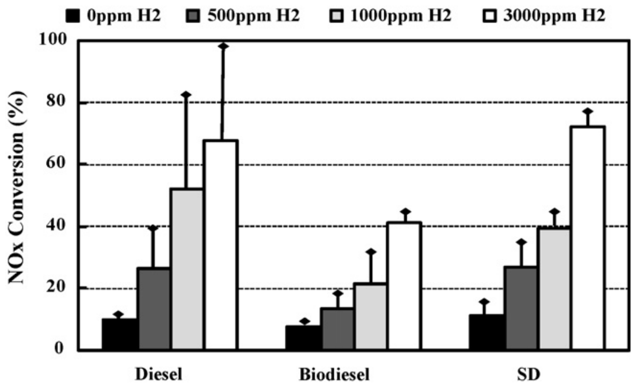

Fig. 6. The effect of H_2 additions. Engine speed of 1500 rpm, engine load of 2 bar IMEP ($T = 190\,^\circ C$).

In the biodiesel fuelling, increasing the amount of hydrogen led to the lowest observed activity, mainly due to lowest HC_1:NO_x ratios.

4. Conclusions

The use of Ag/Al_2O_3 catalysts in a passive mode HC-SCR system shows good NO_x reduction under the different HC_1:NO_x ratios, followed the order diesel > SD > RME when the respective fuels are used for combustion. Additionally, introduction of optimized H_2 concentrations to reduce catalyst deactivation is required under high HC_1:NO_x ratios at low temperatures in order to achieve maximum NO_x conversion efficiencies.

The combustion of biodiesel resulted in a lower rate of NO_x reduction over the Ag/Al_2O_3 catalyst, in the presence of hydrogen, compared to SD and diesel fuelled combustion due to the lower HC_1:NO_x ratios; high values of which are necessary for the NO_x reduction reaction. At the low operating temperature conditions (~190 °C), diesel fuel led to more noticeable deactivation of the catalyst, but in contrast, biodiesel and SD fuelled combustion did not possess this dramatic deactivation characteristic. At the higher temperatures, it can be pointed out that the presence of hydrogen alone does not effectively reduce the NO_x concentration, but hydrocarbon presence is also essential to achieve Ag/Al_2O_3 catalyst activity for NO_x, especially in terms of biodiesel fuelled combustions.

The use of EGR reduces the NO_x emissions and at the same time enhances the HC:NO_x ratios in the exhaust gas. EGR use with H_2 addition, in the case of biodiesel and SD fuels, dramatically improved the NO_x conversion over the Ag/Al_2O_3 catalyst due to the comparatively cleaner combustions which produce less, hydrocarbons, smoke and PM (soot + VOF) as opposed to that of diesel fuel. However, in the case of diesel combustion, higher concentrations of H_2 are required to improve the catalyst activity. As a result, optimized HC_1:H_2 ratios are very important for the improvement of the Ag/Al_2O_3 catalyst activity under different engine operating conditions.

From the work presented here and in accordance with the available literature it can be concluded that, engine fuel quality can influence significantly the performance of the aftertreatment systems in reducing emissions. Fuels such as synthetic diesel can also contribute in the improved engine-aftertreatment system efficiency and contribute in achieving future emissions regulations that include control of CO_2.

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References

[1] M. Iwamoto, H. Yashiro, S. Shundo, Y. Yu-u, N. Mizuno, N. Shokubai, Selective reduction of NO by lower hydrocarbons in the presence of O_2 and SO_2 over copper ion-exchanged zeolites, Shokubai (Catalyst) 32 (1990) 430–433.

[2] K. Arve, E.A. Popov, F. Klingstedt, K. Eränen, L.-E. Lindfors, J. Eloranta, D.Y. Murzin, HC-SCR of NO_x over Ag/alumina: a combination of heterogeneous and homogeneous radical reactions? Catal. Today 100 (2005) 229–236.

[3] K. Eränen, L.-E. Lindfors, A. Niemi, P. Elfving, L. Cider, Influence of hydrocarbons on the selective catalytic reduction of NO_x over Ag/Al_2O_3—laboratory and engine tests, SAE Paper 2000-01-2813, 2000.

[4] K. Arve, H. Backman, F. Klingstedt, K. Eränen, D.Y. Murzin, Hydrogen as a remedy for the detrimental effect of aromatic and cyclic compounds on the HC-SCR over Ag/alumina, Appl. Catal. B-Environ. 70 (2007) 65–72.

[5] V. Houel, P. Millington, R.R. Rajaram, A. Tsolakis, Promoting functions of H2 in diesel-SCR over silver catalyst, Appl. Catal. B-Environ. 77 (2007) 29–34.

[6] H. Dong, S. Shuai, R. Li, J. Wang, X. Shi, H. He, Study of NOx selective catalytic reduction by ethanol over Ag/Al_2O_3 catalyst on a HD diesel engine, Chem. Eng. J. 135 (2008) 195–201.

[7] K. Theinnoi, A. Tsolakis, S. Sitshebo, V. Houel, R.R. Rajaram, Hydrogen promotion of low-temperature passive hydrocarbon-SCR over a silver catalyst, Energy Fuels 22 (2008) 4109–4114.

[8] S. Sitshebo, A. Tsolakis, K. Theinnoi, J. Rodríguez-Fernández, P. Leung, Improving the low temperature NO_x reduction activity over a Ag–Al_2O_3 catalyst, Chem. Eng. J. 158 (2010) 402–410.

[9] B. Westerberg, C. Künkel, C.U.I. Odenbrand, Transient modelling of a HC-SCR catalyst for diesel exhaust aftertreatment, Chem. Eng. J. 29 (2003) 27–39.

[10] R. Burch, J.P. Breen, C.J. Hill, B. Krutzsch, B. Konrad, E. Jobson, L. Cider, K. Eränen, F. Klingstedt, L.-E. Lindfors, Exceptional activity for NO_x reduction at low temperatures using combinations of hydrogen and higher hydrocarbons on Ag/Al_2O_3 catalysts, Top. Catal. 30–31 (2004) 19–25.

[11] D. Creaser, H. Kannisto, J. Sjoblom, H.H. Ingelsten, Kinetic modeling of selective catalytic reduction of NO_x with octane over Ag–Al_2O_3, Appl. Catal. B-Environ. 90 (2009) 18–28.

[12] J.R. Hernández Carucci, A. Kurman, H. Karhu, K. Arve, K. Eränen, J. Wärnå, T. Salmi, D.Y. Murzin, Kinetics of the biofuels-assisted SCR of NOx over Ag/alumina-coated microchannels, Chem. Eng. J. 154 (2009) 34–44.

[13] K. Arve, K. Eränen, M. Snare, F. Klingstedt, D.Y. Murzin, Selective catalytic reduction of NOx over Ag/Al_2O_3 using various bio-diesel as reducing agents, Top. Catal. 42–43 (2007) 399–403.

[14] S. Satokawa, Enhancing the $NO/C_3H_8/O_2$ reaction by using H_2 over Ag/Al_2O_3 catalysts under lean-exhaust conditions, Chem. Lett. 3 (2000) 294–295.

[15] A. Satsuma, J. Shibata, A. Wada, Y. Shinozaki, T. Hattori, In-situ UV–visible spectroscopic study for dynamic analysis of silver catalyst, Stud. Surf. Sci. Catal. 145 (2003) 235–238.

[16] J. Shibata, K. Shimizu, S. Satokawa, A. Satsuma, T. Hattori, Promotion effect of hydrogen on surface steps in SCR of NO by propane over alumina-based silver catalyst as examined by transient FT-IR, Phys. Chem. Chem. Phys. 5 (2003) 2154–2160.

[17] M. Richter, U. Bentrup, R. Eckelt, M. Schneider, M.-M. Pohl, R. Fricke, The effect of hydrogen on the selective catalytic reduction of NO in excess oxygen over Ag/Al_2O_3, Appl. Catal. B-Environ. 51 (2004) 261–274.

[18] M. Richter, R. Fricke, R. Eckelt, Unusual activity enhancement of NO conversion over Ag/Al_2O_3 by using a mixed NH_3/H_2 reductant under lean conditions, Catal. Lett. 94 (2004) 115–118.

[19] J.P. Breen, R. Burch, A review of the effect of the addition of hydrogen in the selective catalytic reduction of NO_x with hydrocarbons on silver catalysts, Top. Catal. 39 (2006) 53–57.

[20] S. Satokawa, J. Shibata, K. Shimizu, A. Satsuma, T. Hattori, T. Kojima, Promotion effect of hydrogen on lean NO_x reduction by hydrocarbons over Ag/Al_2O_3 catalyst, Chem. Eng. Sci. 62 (2007) 5335–5337.

[21] K. Theinnoi, A. Tsolakis, V. Houel, R.R. Rajaram, Passive NO_x reduction activity of a silver catalyst under real diesel-engine exhaust conditions, SAE Paper No. 2007-01-1917, 2007.

[22] K. Arve, F. Klingstedt, K. Eranen, J. Warna, L.-E. Linfors, D.Y. Murzin, Kinetics of NOx reduction over Ag/alumina by higher hydrocarbon in excess of oxygen, Chem. Eng. J. 107 (2005) 215–220.

[23] K. Villani, R. Brosius, J.A. Martens, Catalytic carbon oxidation over Ag/Al_2O_3, J. Catal. 236 (2005) 172–175.

[24] A. Tsolakis, A. Megaritis, M.L. Wyszynski, K. Theinnoi, Engine performance and emissions of a diesel engine operating on diesel-RME (rapeseed methyl ester) blends with EGR (exhaust gas recirculation), Energy 32 (2007) 2072–2080.

[25] V. Houel, P. Millington, R.R. Rajaram, A. Tsolakis, Fuel effects on the activity of silver hydrocarbon-SCR catalysts, Appl. Catal. B-Environ. 73 (2007) 203–207.

[26] K. Theinnoi, P. Rounce, A. Tsolakis, M.L. Wyszynski, H.M. Xu, A.P.E. York, Activity of prototype catalysts on exhaust emissions from biodiesel fuelled engines, SAE Paper No. 2008-01-2514, 2008.

[27] A. Andreasen, H. Lynggaard, C. Stegelmann, P. Stoltze, Simplified kinetic models of methanol oxidation on silver, Appl. Catal. A-Gen. 289 (2005) 267–273.

[28] J.P. Breen, R. Burch, C. Hardacre, C.J. Hill, C. Rioche, A fast transient kinetic study of the effect of H_2 on the selective catalytic reduction of NO_x with octane using isotopically labeled ^{15}NO, J. Catal. 246 (2007) 1–9.

[29] J.P. Breen, R. Burch, C. Hardacre, C.J. Hill, Structural investigation of the promotional effect of hydrogen during the selective catalytic reduction of NO_x with hydrocarbons over Ag/Al_2O_3 catalysts, J. Phys. Chem. Lett. 109 (2005) 4805–4807.

[30] J. Shibata, K. Shimizu, Y. Takada, A. Shichi, H. Yoshida, S. Satokawa, A. Satsuma, T. Hattori, Structure of active Ag clusters in Ag zeolites for SCR of NO by propane in the presence of hydrogen, J. Catal. 227 (2004) 367–374.

[31] Y. Yu, H. He, Q. Feng, H. Gao, X. Yang, Mechanism of the selective catalytic reduction of NO_x by C_2H_5OH over Ag/Al_2O_3, Appl. Catal. B-Environ. 49 (2004) 159–171.