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Experimental investigation of the effects of simultaneous hydrogen and nitrogen addition on the emissions and combustion of a diesel engine☆

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ABSTRACT

Overcoming diesel engine emissions trade-off effects, especially NO_x and Bosch smoke number (BSN), requires investigation of novel systems which can potentially serve the automobile industry towards further emissions reduction. Enrichment of the intake charge with $H_2 + N_2$ containing gas mixture, obtained from diesel fuel reforming system, can lead to new generation low polluting diesel engines.

This paper investigates the effect of simultaneous $H_2 + N_2$ intake charge enrichment on the emissions and combustion of a compression ignition engine. Bottled $H_2 + N_2$ was simultaneously admitted into the intake pipe of the engine in 4% steps starting from 4% (2% H_2 + 2% N_2) up to 16% (v/v).

The results showed that under specific operating conditions $H_2 + N_2$ enrichment can offer simultaneous NO_x, BSN and CO emissions reduction. Apart from regulated emissions, nitrogen exhaust components were measured. Marginal N_2O and zero NH_3 emissions were obtained. NO/NO_2 ratio increases when speed or load increases. Under low speed low load operation the oxidation of NO is enhanced by the addition of $H_2 + N_2$ mixture. Finally, admission of $H_2 + N_2$ has a detrimental effect on fuel consumption.

1. Introduction

Reduction of diesel exhaust emissions can be accomplished either with in-cylinder emissions formation suppression [1] or with aftertreatment technologies [2]. The existence of inverse relationship between emissions, especially NO_x and PM, makes the in-cylinder emissions control a very challenging task. Hence, novel solutions are required in order to further reduce the levels of pollutants leaving the cylinder.

Some parameters affecting emissions formation which can be adjusted relatively easy through the ECU are injection timing, injection pressure and EGR volume fraction. Buyukkaya and Cerit [3] performed experiments on a low heat rejection diesel engine and found that retardation of injection timing lowers NO_x emissions at the expense of PM. A negative

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relationship between NO_x and PM emissions is observed when intake charge is diluted with EGR or injection pressure is varied [4]. Reduction of intake charge's oxygen concentration lowers NO_x at the expense of PM [5].

Various techniques that simultaneously suppress the formation of both NO_x and PM emissions have been investigated but only few of them have been put into massive production. Mkilaha et al. [6] modified a four cylinder indirect injection diesel engine to supply compressed air into the pre-chamber during combustion. At no load conditions they demonstrated simultaneous NO_x and PM reductions. They concluded that NO_x reduction is attributed to flame quenching while improved mixing resulting from air injection lowers PM. It has been reported by many researchers that dual fuelling is a feasible solution to the reduction of emissions which could also lead to sustainable transportation. Dual fuelling can affect various combustion parameters such as flame propagation, ignition delay, adiabatic flame temperature, flammability limits, reduction of intake's charge oxygen concentration and combustion duration which in turn influence engine's emissions and performance. Papagiannakis and Hountalas [7] investigated the effect of diesel-natural gas dual fuelling on performance and emissions of a DI diesel engine. They showed that in most of the operating points tested admission of natural gas resulted in simultaneous NO and PM emissions reduction. They also reported that fuel consumption, CO and HC emissions deteriorated under dual-fuel compared to baseline operation. Simultaneous NO_x and PM emissions reduction can also be realised when feeding the engine with combined hydrogen and EGR [8]. Bika et al. [9] reported that part substitution of diesel fuel with syngas introduced into the intake manifold of a compression ignition engine considerably increases CO emissions. Moreover, they detected unburned hydrogen into the exhaust gas and they also showed that due to poor gaseous fuel utilisation thermal efficiency decreased compared to baseline operation. Saleh [10] experimentally proved that admission of propane into the inlet manifold of a diesel engine increases fuel conversion efficiency when the mass fraction of the gaseous fuel supplied is up to 40%. He also compared the fuel conversion efficiency obtained when the engine was fuelled on neat propane and propane–butane blends and demonstrated that when the butane composition in the gas mixture is increased fuel conversion efficiency drops. Nevertheless, increasing butane fraction has a beneficial effect on NO_x emissions.

Roy et al. [11] combined in-cylinder and aftertreatment emissions reduction techniques in a single cylinder, naturally aspirated DI diesel engine. NO_x formation was suppressed using EGR whereas the increased PM emissions, associated with EGR, were treated by a cyclonic separator fitted into the exhaust pipe. The particles were subject to centrifugal forces enabling this way the separation of soot from the exhaust gas. Nakatani et al. [12] reported over 80% reductions in both NO_x and PM emissions by developing an aftertreatment system called DPNR (Diesel Particulate – NO_x Reduction System). In addition to the aftertreatment technology installed, the engine required periodical alternation from lean to rich combustion.

Johnson presented a review on NO_x control and PM reduction technologies [13]. Diesel particulate filter is the technology currently used to remove PM from the exhaust gas, whereas NO_x emissions are treated with the aim of a selective catalytic reduction system. The integration of both in the exhaust pipe allows simultaneous NO_x and PM aftertreatment. Yoshinobu et al. [14] proposed a simultaneous electrochemical reduction system to reduce NO_x and PM pollutants from diesel engines. They claimed NO_x and PM reductions over 90%.

The implementation of new PM emission regulations, i.e. introduction of the particulate number, reveals the importance to lower soot emissions. Valavanidis et al. [15] reviewed the results of the latest epidemiological and toxicological studies. They summarized that small PM are more harmful to human, compared to those having greater size. In addition, further NO_x emissions reduction will be beneficial to both human and environment since NO_x contribute, among others, to ozone depletion, acid rain and respiratory problems.

The objective of this paper is to present the effect of simultaneous hydrogen and nitrogen addition on the emissions and combustion of an HSDI diesel engine. Bottled gases, simulating diesel fuel reforming product gas were introduced into the engine through the intake port. Carbon monoxide at relatively high concentration is typically present in diesel reforming product gases, nevertheless, through the water gas shift reaction using a good low-temperature catalyst CO concentration can be reduced to ppm levels. The effect of combined syngas and nitrogen addition, aiming to build on the knowledge obtained on previous [16] and current study, is currently investigated by the authors and the results will be reported in a separate paper. In the current research effort, along with the regulated emissions, measurements of nitrogen exhaust components such as NO, NO_2, NH_3 and N_2O are provided.

2. Experimental setup

Fig. 1 shows the experimental setup which has been extensively described in previously published work [16]. At this point only a brief description of the experimental setup and experimental procedure is provided.

The experiments were carried out in a Ford Puma HSDI diesel engine. Its main specifications are: 4 cylinders, 2.0 L, 16 valves, turbo charged (not employed during the tests), water cooled, fuelled by ULSD, bore 86 mm, stroke 86 mm, compression ratio 18.2:1.

Speed and load variations were achieved through a Schenk eddy current dynamometer connected to engine's output shaft. In-cylinder pressure as a function of crank angle was recorded through the interaction of a LabView software, a Kistler 6125A pressure transducer, a Kistler 5001 charge amplifier and a shaft encoder. Throughout the experiments fuel consumption was measured by a Coriolis flow meter and a glass burette. The latter was actually employed for fuel flow verification purposes. Injection timing was controlled by a software that gave direct access to the ECU and allowed the user to program it.

Introduction of bottled gases into the engine through the intake port suggests that an equivalent volume of intake air was replaced by the gas mixture. The ambient air volume flow was measured by a positive displacement air flow meter while the volume of $H_2 + N_2$ entering the engine was measured by glass tube flowmeters. The gases were stored in separate