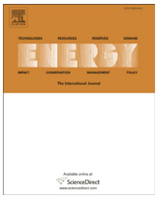
Energy 66 (2014) 509–522

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy



Pollutants emission and particle behavior in a pre-turbo aftertreatment light-duty diesel engine

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ARTICLE INFO

Article history:
Received 27 May 2013
Received in revised form
17 January 2014
Accepted 1 February 2014
Available online 21 February 2014

Keywords:
Diesel engines
Pre-turbo aftertreatment
Pollutants emission
Particle emission
DPF efficiency

ABSTRACT

Diesel particulate filters are a standard technology used in diesel engines in order to comply with actual and forthcoming regulations, regarding soot emissions and particulate matter in exhaust gases. In recent years, pre-turbo aftertreatment response has been investigated as opposed to the traditional aftertreatment location downstream from the turbine but just regarding engine performance. Previous studies do not deal in detail with gaseous and particle emission analysis in a pre-turbo aftertreatment configuration. This paper focuses on these topics. The gaseous and particle emissions have been assessed in a 4-cylinder, light-duty diesel EURO 4 engine typically used in European passenger car vehicles. Different steady-state operating points have been considered in order to extend the study over a wide range of operating conditions. Additionally, the New European Driving Cycle has been performed with the aim of reaching a comprehensive understanding of the aftertreatment dynamic response in terms of pollutant emissions. An increase in the amount of NO_2 converted from NO and a reduction in emitted CO have been found at low load steady-state operating conditions with pre-turbo aftertreatment placement. In driving cycle conditions, a shift from nucleation to accumulation mode particles have been found, being the filtration efficiency scarcely affected.

1. Introduction

In the automotive sector, diesel engines are a major source of PM (particulate matter) and nitrogen oxides (NO_x). It is well known that these pollutants are precursors for other chemical compounds, producing significant damage to the environment [1] and human health [2]. In recent years, different strategies have been developed to reduce pollutant emissions: EGR (exhaust gas recirculation) [3], common-rail injection [4], improvements in the fuel-air mixture process, optimized engine control [5], exhaust manifolds with improved heat transfer losses [6], etc. Owing to the application of the results obtained in these studies, and the progress carried out in the combustion process [7], a reduction has been achieved in the soot mass emitted by diesel engines. In addition, with the introduction of DPF (diesel particulate filters) in the aftertreatment systems of the exhaust gas, soot mass emission has reduced by about 99% [8]. However, a decrease in mass emission is not always accompanied by a reduction in particle emission. In this sense, the reduction in mass due to soot mass trapped at the DPF may be accompanied by an increase in the number of particles emitted with a size below 100 nm. According to Setter et al. [9], a new conceptualization of particle size distribution shows an increase in particle numbers below 100 nm for the new generation of engines. These small particles can pass more easily through the DPF [10], so that an increase in total particle number at the DPF outlet has been observed. Furthermore, due to the detrimental effect on human airways that this type of particles can have [11], emission regulations are becoming increasingly stringent on this issue [12].

Nowadays, most DPFs are made of ceramic substrates with a honeycomb wall-flow structure. These systems are characterized by high filtration efficiency and low penalty in fuel consumption due to the active regeneration strategies that are carried out when the soot load inside the DPF reaches certain level [13]. In this regard, studies are mainly conducted to increase the maximum amount of ash that the DPF can tolerate [14], to better understanding on the pressure drop dynamics across this element [15], to analyze heat transfer phenomena [16], to the development of advanced catalytic materials [17], to the analysis of the soot filtration efficiency [18], or to study the relative position of the aftertreatment system with respect to the turbine [19].

Recently, some studies have attempted to find the optimal position of the aftertreatment system by varying the DOC (diesel

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http://dx.doi.org/10.1016/j.energy.2014.02.004

oxidation catalyst) and DPF placement. Windsor and Baumgard [20] propose that these be located at the cylinder outlet before the turbocharger. In turbocharged engines, the aftertreatment system is traditionally placed downstream from the turbine, with the DOC upstream of the DPF. This configuration uses the NO_2 produced in the DOC for further oxidation of particulate matter in the DPF. Placing the aftertreatment system upstream from the turbine offer certain advantages such as clean high pressure EGR. In this sense, the pre-turbo aftertreatment approach ensures that the exhaust gas first passes through the DPF, and it is then recirculated into the intake manifold before passing through the turbocharger. It provides a soot-free exhaust gas to the high pressure EGR system thus the durability of the elements of this system is increased [21]. Other advantages of the pre-turbo aftertreatment configuration are the high temperatures reached at the DPF inlet, which can serve to promote passive regenerations and reduce time up to DOC light-off [22]; and the pressure drop reduction along the aftertreatment system due to the higher gas density [23]. On one hand, this effect leads to fuel savings because it mitigates the increase of exhaust back-pressure especially when soot accumulation within the DPF increases [24]. On the other hand, an additional reduction in fuel consumption is obtained due to the reduction of active regenerations required to clean the DPF [25].

Table 2
Aftertreatment characteristics.

DOC		DPF	
Length	0.105 [m]	Length	0.165 [m]
Diameter	0.145 [m]	Diameter	0.135 [m]
Volume	1.73 [L]	Volume	2.36 [L]
Cell density	400 [cpsi]	Cell density	200 [cpsi]
Cell size	0.94 [mm]	Cell size	1.47 [mm]
Wall thickness	0.33 [mm]	Wall thickness	0.32 [mm]
Number of channels	10,240 [−]	Number of channels	4470 [−]
Catalytic surface	4.04 [m^2]	Filtration surface	2.17 [m^2]
		Permeability	3.175×10^{-13} [mm]

Table 3
Fuel properties.

Cetane number	51.6 [−]
Viscosity at 40 °C	2.46 [mm^2/s]
Density at 15 °C	0.843 [kg/l]
Lower heating value	42.055 [MJ/kg]
Sulfur content	6.6 [ppm]
Water content	96 [ppm]

2. Experimental setup

The measurements were carried out in the exhaust aftertreatment system of a 2.0 L, 4-cylinders, HSDI (high-speed direct injection) turbocharged diesel engine for passenger car application which complies with EURO 4 standards. Further detailed specifications of the engine characteristics and the aftertreatment system used are given in Table 1 and Table 2. The engine was installed in a fully equipped test cell with all the auxiliary devices required for appropriate engine operation and control. The test cell was designed using the criteria detailed by Martyr and Plint [26]. Regarding engine fuel, USLD (ultralow sulfur diesel) has been used in all the test being its properties shown in Table 3.

The test bench was equipped with a 250 kW asynchronous dynamometer SHENCK®Dynas Li250, which allows instant engine speed and torque control. In order to perform modifications to the engine operating parameters, the ETAS®INCA software was used to modify the engine calibration in an ECU (engine control unit). K type thermocouples and KISTLER®4045A5 piezoresistive sensors with the original cooler adapter, whose main characteristics are shown in Table 4, were suitably located in the intake and exhaust zones of the engine. Fuel consumption was determined by two systems. The first consists of a fuel gravimetric system with an AVL®733S Dynamic Fuel Meter. The measurement device consists of a measuring vessel filled with the fuel and suspended on a balance system. Fuel consumption values are obtained by calculating the vessel's weight loss over time. Since the response time of this system might possibly be too long for measurement under transient operation, the fuel consumption signal provided by the ECU was calibrated in steady-state operating conditions. After calibration, the ECU was used as a second fuel consumption measurement system [27]. The Sensyflow®P Sensycon hot-plate anemometer system was used to measure the flow rate of the intake air mass. The measurement range of the anemometer is 0–720 kg/h.

Table 1
Engine's main characteristics.

Type	4-cycle
Displacement	1997 [cm^3]
Diameter	85 [mm]
Stroke	88 [mm]
Number of cylinders	4 [−]
Valves by cylinder	4 [−]
Compression ratio	18:1 [−]
Maximum power	100 [kW] at 4000 rpm
Maximum torque	320 [N.m] at 1750 rpm
Spray cone angle	140 [°]
Nozzle holes	6 x 146 [μm]

Different equipment has been used in this study for measuring particle and pollutant emissions. For particle measurement, a TSI-®EEPS (Engine Exhaust Particle Sizer) Spectrometer has been employed in order to obtain fast response particle measurements during dynamic cycles [28]. EEPS is capable to measure particle size distribution at a sample-rate of up to 1 Hz and providing a measurement range between 5.6 and 560 nm. A valve system was installed in order to provide measurements upstream and downstream of the DPF in steady-state conditions and allow filtration efficiency calculation.

A similar valve system concept was installed to assess the DOC conversion during the steady-state operating points. In this case, a HORIBA®Mexa 6000 F-TIR analyzer was used to provide a figure of unregulated pollutant emissions. Finally, an HORIBA®Mexa 7100 DEGR was installed at the end of the exhaust line downstream of the aftertreatment to measure tailpipe emission of regulated pollutants. Fig. 1 shows the experimental setup for this study.

2.1. *Operating mode*

Extensive experimental work has been carried out in order to assess the effect of aftertreatment system placement in the exhaust line in terms of gaseous pollutants and particle emissions. The study was conducted comparing the pre-turbo aftertreatment configuration versus the post-turbo aftertreatment configuration

Table 4
Technical data of piezoresistive pressure sensors.

Range	0–5 [bar(abs)]
Overload	12.5 [bar(abs)]
Sensitivity	25 [mV/bar/mA]
Linearity	≤0.1 [%FSO]
Temperature range	0–140 [°C]