Fuel 193 (2017) 308–314

Contents lists available at ScienceDirect

Fuel

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

Full Length Article

Investigation of late-cycle soot oxidation using laser extinction and in-cylinder gas sampling at varying inlet oxygen concentrations in diesel engines

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HIGHLIGHTS

- Optical and in-cylinder sampling data show a slower soot oxidation when inlet oxygen is reduced.
- Reduced intake O_2 lowers the maximum adiabatic flame temperature limiting OH production.
- The results point towards OH being the dominant oxidizer under diesel combustion.

ARTICLE INFO

Article history:
Received 13 September 2016
Received in revised form 27 October 2016
Accepted 7 December 2016
Available online 29 December 2016

Keywords:
Soot oxidation
PM
OH
EGR
Gas-sampling
Laser extinction

ABSTRACT

This study focuses on the relative importance of O_2 and OH as oxidizers of soot during the late cycle in diesel engines, where the soot oxidation is characterized in an optically accessible engine using laser extinction measurements. These are combined with in-cylinder gas sampling data from a single-cylinder engine fitted with a fast gas-sampling valve. Both measurements confirm that the in-cylinder soot oxidation slows down when the inlet concentration of O_2 is reduced. A 38% decrease in intake O_2 concentration reduces the soot oxidation rate by 83%, a non-linearity suggesting that O_2 in itself is not the main soot oxidizing species. Chemical kinetics simulations of OH concentrations in the oxidation zone and estimates of the OH-soot oxidation rates point towards OH being the dominant oxidizer.

1. Introduction

Diesel engines are favored by high efficiencies but are challenged by high emissions of nitrous oxides (NO_x) and particulate matter (PM), if not coupled with adequate exhaust aftertreatment technologies such as NO_x adsorbers and diesel particulate filters (DPF). Diluting the charge by Exhaust Gas Recirculation (EGR) is a widespread method for reducing the NO_x emissions by decreasing the combustion temperature. On the other hand, EGR generally increases PM emissions due to deteriorating in-cylinder soot oxidation rates [1,2]. Previous studies indicate that, under most conditions applicable to diesel engines, this oxidation has a dominating influence on the soot emission levels [2–5].

EGR reduces the intake oxygen concentration. This has a number of potential effects on the soot oxidation process. First, it will decrease the availability of oxygen during the late cycle, which could limit the oxidation rate. It also lowers the flame temperature, slowing the chemical kinetics of the oxidation process as well as decreasing the formation of hydroxyl radicals (OH) [6], which is believed to be the main oxidizing species [7–11]. A few experimental studies have studied the impact of EGR on the soot oxidation during diesel combustion in the cylinder. For example, Payri et al. measured the PM mass, size, and number density in the exhaust gases while varying intake O_2 between 9% and 13%. Though the study was concerning low temperature combustion (LTC) strategies, they could highlight the poor oxidation affecting

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http://dx.doi.org/10.1016/j.fuel.2016.12.013
0016-2361/

the emissions before the inhibited formation dominated the emission trends at lower O_2 inlet concentration [12]. Using the same methodology to characterize the oxidation process, Gallo et al. [2] used the decay of the optical thickness (*KL*) of the extinction signal whereas Lopez et al. [13] used the *KL* from two-color pyrometry measurements. Both studies reached the conclusion that a reduction of inlet O_2 leads to a slower soot oxidation rate. Also using two-color pyrometry, a study by Huestis et al. showed that decreasing the intake O_2 from 21% to 9% decreased the late cycle soot oxidation rates monotonically, and that the emissions followed the late cycle trends in in-cylinder soot mass [14]. While this last study pointed out the importance temperature on the oxidation process, none of these studies proposed an explanation for the mechanisms behind the reduction of oxidation rate observed at lower O_2 availabilities in the cylinder.

The purpose of this study is to cast light on the relative importance of O_2 and OH as soot oxidizers during the late cycle. It is based on data from optical measurements and in-cylinder gas sampling. The optical measurements are made using laser extinction in an optically accessible single-cylinder engine fitted with a Bowditch-type piston extender [15]. The gas sampling data are acquired from a single-cylinder engine without optical access, fitted with a fast gas sampling valve. The analysis is complemented with a simulation of OH availability in the flame using a zero-dimensional (0-D) reactor model.

2. Terminology

Different terms for soot are used in different communities. These include particulate matter (PM), soot, and black carbon (BC). PM is the generic term describing the particles contained in an aerosol. In the engine community, PM is defined as the constituents of the diluted exhaust gases that are adsorbed on a filter in a gravimetric test. In such a test, the exhausts are drawn through an efficient filter, which is weighed before and after the test. The difference in mass (due to both solid and liquid particles) is the PM mass. A soot particle is an agglomerate of roughly spherical primary particles consisting primarily of carbon. Soot is by far the dominating constituent of PM. Black carbon is roughly equivalent to soot, i.e. light-absorbing carbonaceous particles originating from combustion sources. As it is measured optically, its name derives from its optical properties. BC is a term more commonly encountered in environmental contexts like aerosol physics, atmospheric chemistry or geophysical fields. As engine-out PM mostly consists of combustion-generated soot particles, it is an accepted approximation in the automotive and combustion engineering fields to use the terms PM, soot and BC more or less interchangeably.

3. Experimental facilities

3.1. Engine setup

The engine used for the optical study is a heavy-duty direct-injection diesel engine based on a Scania D12, operated as a single-cylinder engine. A single-cylinder version of a Scania D13 is used for the in-cylinder gas sampling measurements. These engines are henceforth referred to as the optical and the all-metal engine. In order to produce as similar conditions as possible, both configurations employ the same cylinder head leading to identical swirl levels and the same injector for identical fuel flows. A Scania XPI common-rail fuel injection system capable of fuel pressures up to 2500 bar is used. The injector is a stock item with eight nozzle holes. The fuel used is Swedish MK1 diesel. Specifications of the engines, fuel system and fuel are given in Table 1.

Table 1
Engine and fuel specifications.

Engine base type	Scania D12 DI diesel	Scania D13 DI diesel
Bore	127 mm	130 mm
Stroke	154 mm	160 mm
Comp. ratio	15.6	16
Swirl	1.6	
Displacement	1.95 L	2.12 L
EGR	External	Internal
Injection system	XPI common rail	
Nozzle flow number	2174 cm^3/min	
Number of holes	8	
Firedeck angle	17°	
Hole diameter	0.175 mm	
Fuel type	MK1 diesel	
Cetane number	51	
Density	815 kg/m^3	
Lower heating value	42.9 MJ/kg	
Carbon-to-hydrogen ratio	0.53	

The two setups use different sources of EGR. On the optical engine, exhaust gases are produced using a diesel furnace operating at stoichiometric conditions. These are mixed with fresh air, heated and compressed to the desired inlet conditions in order to achieve a stable external source of "EGR". On the all-metal engine, exhaust gases are taken from the exhaust manifold and fed to the intake manifold, using flow and back pressure valves to control the flow. The intake O_2 concentration is used to measure the EGR rate. In the optical engine, it is measured during engine operation without injection by a lambda sensor located in the exhaust. For the all-metal engine, the concentration of inlet O_2 is calculated as:

$$O_{2,in} = \frac{CO_{2,in}}{CO_{2,ex}}(O_{2,ex} - O_{2,amb}). \tag{1}$$

where $O_{2,ex}$ is the exhaust O_2 concentration measured by a lambda sensor, $O_{2,amb}$ is the ambient O_2 concentration set at 20.95%. $CO_{2,in}$ and $CO_{2,ex}$ are the CO_2 concentrations of inlet and exhaust both measured using an infrared detector in an AVL AMA i60 emission system.

Another difference between the setups is the shape of the piston bowl. In the D12 engine, the bottom of the bowl is flat in order to facilitate the optical access, while the D13 engine has a slightly conical bowl bottom. As shown in Fig. 1, both configurations had open combustion chambers. These differences could cause variations in the in-cylinder flow that could affect the late-cycle mixing process. This may lead to different soot oxidation rates and, thus, different average soot emissions from the two engines. It should be noted, however, that the experiment consists in a variation in the intake oxygen concentration. This variation is the same in both engines and affects chemical aspects of the soot oxidation rather than the flow. For this reason, the trends in soot oxidation rates that result from the intake O_2 variation are expected to be the same in both engines.

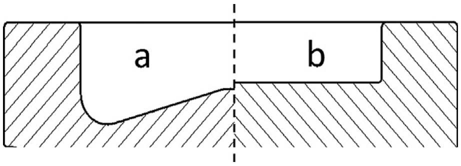

Fig. 1. Profile of the metal piston used in the D13 engine (a) and of the quartz piston used in the D12 engine (b).