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The effect of compression ratio on exhaust emissions from a PCCI diesel engine

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Abstract

A description of the development of a single-cylinder test facility is presented, being based on a production 4-cylinder DI Diesel engine and designed to allow study of the emissions characteristics over a very wide range of operating conditions. The objective was to establish how engine out NO_x emissions can be reduced to the estimated levels required by the next emissions target 'Euro 6' and thus be able to apply the findings to the original 4-cylinder engine and minimise the requirement for currently immature NO_x after-treatment. It has been proposed that further reduction in compression ratio beyond current levels would be beneficial to engine out emissions and specific power, and could be facilitated by developments in cold-start technology. The results of a study using this single-cylinder facility to evaluate the effect of reducing compression ratio from 18.4 to 16.0 are presented. It was found that, although there was a small CO and HC penalty, either reducing the compression ratio or retarding the injection timing greatly reduced NO_x and soot emissions when both premixed and diffusion–combustion phases were present. This effect was less significant when the combustion was solely premixed.

Keywords: Diesel emissions; Diesel combustion strategies; Compression ratio

1. Introduction

One of the most critical challenges ahead for the Diesel passenger-car engine is to meet future emissions regulations whilst improving performance and fuel economy with a minimal cost penalty. The current and emerging after-treatment technologies give encouraging results, but their cost and complexity threaten the competitiveness of the Diesel engine package. Conversely, over the past decade, research in Diesel homogeneous charge combustion has highlighted an alternative approach for significant engine out reductions of nitrogen oxides (NO_x) and Particulate Matter (PM) emissions [1–9]. Importantly, it demonstrates the capability of simultaneously reducing NO_x and PM emissions, thus potentially offering an extended use of Diesel engines without, or with greatly reduced, after-treatment requirements. There are two possible approaches to achieve this ultra-low emissions combustion, where both aim to obtain a lean and highly mixed charge prior to combustion.

The first is Homogeneous charge compression ignition (HCCI), relying on early injections to achieve a chemically and physically homogeneous mixture before auto-ignition. Homogeneous charge combustion is closer to the ideal constant-volume Otto cycle, as observed in Ref. [6]. There is no diffusion flame but a global near-instantaneous combustion, offering the same ultra-low NO_x and soot emissions characteristics as HCCI for the gasoline application. The locally lean nature of the mixture results in negligible soot emissions and ultra-low NO_x emissions due to the low flame temperatures. Typically, two distinct stages are present in the combustion with HCCI operation, the first stage is associated with the initial rupture of the long carbon chains, often referred to as cool combustion or low temperature oxidation [10]. This initiates the active radicals, which trigger the main combustion, also referred to as the high-temperature oxidation. For high Air-fuel ratios (AFRs),

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the cool combustion results in an increase in in-cylinder temperature until the main combustion is triggered (the second distinct peak of the heat release). Exhaust gas recirculation (EGR) is used to reduce the oxygen concentration and to control the rate of combustion by acting as a heat sink, especially for the higher loads where closer-to-stoichiometric mixtures are present.

The second approach to ultra-low emissions is Premixed charge compression ignition (PCCI), which relies on late injections and high EGR rates to delay the auto-ignition. Compared to HCCI, PCCI offers lower NO_x and soot reductions, but it does not exhibit the higher HC, CO, noise emissions, and the very tight requirements for homogeneity and leanness. PCCI is a single-stage combustion process closer to the premixed phase of conventional Diesel combustion, than the low and high temperature oxidations seen with HCCI [11]. PCCI is an approach generally more adapted to Diesel-fuelled applications as it does not rely on early injection timings when the piston is low in the cylinder and is therefore less prone to wall wetting with the inevitable high increases in HC and CO emissions. Furthermore, the combustion is not fully decoupled from the injection as in HCCI operation due to the late injections, allowing for greater control over the start of combustion.

The programme of work described here presents an exploration of the fundamentals of PCCI Diesel combustion to achieve low engine-out emissions, in particular the impact of reduced compression ratio on NO_x and soot emissions.

2. Experimental approach

2.1. Apparatus

In order to allow as wide an exploration as possible, a single-cylinder Diesel research engine was used with a configuration based on that of a current production 2.0 litre, four cylinder automotive engine. Two engine builds were available: Build #1 was a single-cylinder version of the four cylinder engine, and was used to define a baseline derived from existing multi-cylinder engine test data; Build #2 was the configuration to be used through the advanced combustion investigations. Details are shown in Table 1. The test cell was developed to offer independent control of inlet-air pressure and temperature, exhaust backpressure, EGR temperature, and injection pressure, opening the envelope beyond any hardware limiting characteristics such as those of an engine mounted high-pressure fuel pump or turbocharger.

A flush-mounted in-cylinder pressure transducer was selected for its ability to provide accurate high-speed transient pressure data, suitable for heat release calculations, which were considered as the key characteristics for the analysis of the combustion. Both oil and coolant engine-in temperatures were set at 90 °C with flows maintained constant. The exhaust and EGR systems were particularly complex since they had the difficult task of replicating the 4-cylinder engine systems by providing the same functionalities and gas handling dynamic characteristics while being fed by a single-cylinder. Beyond its primary role, the exhaust system was designed to provide a stable exhaust gas supply for EGR. In an effort to reduce the effect of pulsating gas flows, an exhaust chamber was inserted upstream from the EGR supply point. Although the overall size of the EGR circuit has been increased on the single-cylinder engine (over the production engine), the addition of two heat exchangers, a bypass, two temperature control valves and a rate valve have the advantage of providing a level of functionality rare in engine test facilities. The emissions analysis system comprised of an AVL 415 Variable Sampling Smoke Meter and a HORIBA MEXA 7100DEGR exhaust gas analyser. In addition an AVL 733 Dynamic Fuel Meter was used. The fuel used throughout the investigations was Diesel BP FORD reference fuel

Table 1
Summary of specifications for Build #1 and Build #2 engines.

		Build #1	Build #2
Engine	Swept volume	500 cc	
	Bore × stroke	86 mm × 86 mm	
	Inlet valves arrangement	One tangential and one helical valve	
	Speed range	750–4500 rev/min	
	Maximum in-cylinder pressure	1000 rev/min: 11 MPa 1250 rev/min: 13 MPa 1500 rev/min and higher: 15 MPa	
	Maximum exhaust temperature	760 °C	
	Compression ratio	18.4:1	16.0:1
	Piston bowl volume	22.0 cc	26.3 cc
	Level of swirl range	1.5–4.5 Rs	1.0–3.5 Rs
Injection equipment	Fuel type	Ultra-low Sulphur Diesel (reference fuel)	
	High-pressure pump	Delphi DFP 1.2	
	Fuel pressure range	30–160 MPa	
	Injector	Delphi NPO DFI 1.3	
	Injector nozzle	7-hole, 135 μm hole diameter, 680 cc/min, 154°, 0.76 coefficient of discharge	