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The effect of a stepped lip piston design on performance and emissions from a high-speed diesel engine

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HIGHLIGHTS

- A stepped lip and standard piston are compared in a high speed diesel engine.
- An excellent experimental-CFD match is observed and used to understand the results.
- Previously unobserved slower burn rates are noted for the stepped lip piston.
- The geometry of the stepped lip explains this variation.

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ABSTRACT

Understanding engine-out NO_x and soot emissions from light-duty diesel engines is vital for improving combustion system design and ultimately for reducing aftertreatment requirements. In this work two piston bowl shapes, a standard re-entrant bowl and a bowl with a stepped lip, are tested experimentally and numerically at two part-load operating points (1500 rpm/6.8 bar net IMEP and 1750 rpm/13.5 bar net IMEP), and four full-load operating points (1500, 2000, 3000, and 4000 rpm). The results show that the stepped lip design consistently increases the 50–90% MFB duration across all operating conditions due to the trapping of the flame in the region of the stepped lip. Use of the stepped bowl allowed injection timing to be advanced at full load, a condition constrained, in this work, by strict limits of cylinder pressure and exhaust temperature. However, despite these changes in combustion behavior engine out emissions were found to be largely insensitive to the bowl shape. No statistical difference in NO_x and soot emissions between the two bowl geometries was observed at part load. A minor penalty in NO_x emissions, statistically significant at ~67% CI, is reported for the stepped bowl design at some full load points.

1. Introduction

Light duty diesel engines are acknowledged to decrease CO_2 emissions and fuel consumption in comparison to similar gasoline engines, however at the cost of increased engine-out NO_x and soot emissions [1]. Today these emissions can be successfully controlled using aftertreatment. However, the costs of diesel exhaust aftertreatment are notably higher than for gasoline engines [2]. Reducing diesel emissions on an engine-out basis would reduce this aftertreatment burden.

Combustion chamber geometry is known to have a major influence on in-cylinder NO_x and soot formation in diesels; spray targeting—and the interaction of the spray and piston at the lip of the piston bowl—-will have a significant influence on local fuel/air ratios in both the squish region and the bowl [3–6] and will affect in-cylinder heat transfer [7,8]. The geometric detail of the combustion chamber and bowl will also have a similar influence [8–10].

Typically, diesel engines use omega shaped combustion bowls, promoting fuel-air mixing upon fuel injection. Several studies have shown that, for the same compression ratio, a stepped, or ramped, lip on the piston bowl can reduce soot and CO emissions, as well as improving fuel consumption relative to a conventional re-entrant bowl [7,11,12]. These studies, although referring to a stepped-lip piston, actually use geometry which is ramped; this allows part of the fuel spray to be directed up away from the bowl improving air utilisation [13] and EGR tolerance [14]. Recently the Mercedes-Benz OM654 engine was launched with a stepped bowl piston (in this case a definite orthogonal step, rather than a ramped shape), this has reported excellent air utilisation, low particulate emissions and higher efficiency

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Definitions and abbreviations

AMR	Adaptive Mesh Refinement
CA b(a)TDC	Crank Angle before (after) Top Dead Centre
CA10	Angle of 10% mass fraction burned
CA50	Angle of 50% mass fraction burned
CA90	Angle of 90% mass fraction burned
CAD	Crank Angle Degrees
CFD	Computational Fluid Dynamics
CI	Confidence Interval
EGR	Exhaust Gas Recirculation
FEA	Finite Element Analysis
IMEP	Indicated Mean Effective Pressure
ISFC	Indicated Specific Fuel Consumption
ISNOx	Indicated Specific Nitrogen Oxides
MFB	Mass Fraction Burned
nIMEP	Net Indicated Mean Effective Pressure
NO_x	Nitrogen oxides
NTP	Nozzle Tip Protrusion
Q	Heat energy released
TDC	Top Dead Centre
TKI	Tabulated Kinetic Injection

(due to a higher burn rate and in reduced heat loss across the cylinder) [15,16]. Stepped lip pistons which are ramped, in general, will reduce the heat transfer across the piston due to their lower surface area to volume ratio [7] – this change in surface area to volume ratio need not be there for a true orthogonal step.

The referenced literature suggest that the major effect of such a lip is to increase oxygen availability at the point where the spray is targeted, leading to better fuel/air mixing and more complete combustion. All of these studies report a decrease in combustion duration with a stepped lip due to this improved mixing in the lip region. This decrease in combustion duration, combined with reduced heat transfer will lead to the increases in efficiency and decreases in fuel consumption reported.

In this work we investigate the emissions and performance of a modern light-duty high-speed diesel engine when varying the piston bowl shape between a standard bowl and a stepped lip design back-to-back in order to be able to ascertain exactly the effect of the stepped lip shape (as distinct from ramped lip shapes) is having on the combustion and emissions relative to the standard bowl shape. Multi-dimensional modelling, validated against the experimental data, is used to explain and understand the experimental results.

2. Experimental method

2.1. Engine

A single cylinder diesel engine with a top-end matching the Jaguar Land Rover AJ200D "Ingenium" engine [17] and a production standard fuel injection system was used in this work. The bottom end of the engine is a Ricardo Hydra. The engine and test cell installation has been fully described in [18]. Key engine specifications of the single-cylinder engine are shown in Table 1.

2.2. Piston bowls

Two piston bowl shapes are tested: a conventional re-entrant bowl (as used in the Jaguar Land Rover AJ200D "Ingenium" engine), and a bowl fitted with a novel stepped lip geometry. The stepped lip bowl is designed to be as similar a design as possible to the conventional re-entrant bowl - the bowl volume and hence compression ratio is held constant between the two designs. The stepped lip bowl has a small step around the circumference of the bowl lip with a minor adjustment to the omega part of the bowl to retain the same volume. A relative comparison between the two shapes is shown in Fig. 1.

2.3. Instrumentation

The instrumentation used in this work and their associated uncertainties are detailed in [18], key components are outlined here and in Table 2 for convenience; a schematic of the test facility is shown in Fig. 2. The single cylinder engine is not fitted with a turbocharger, rather the inlet air conditions are supplied by an external boosting rig. Cooled, high pressure EGR (driven by pressure difference between the inlet and exhaust) is inserted approximately 1 m upstream of a small mixing plenum, ensuring that the EGR is well mixed with the inlet air. Exhaust emissions are measured by a Horiba MEXA-ONE emissions analyser, and an AVL415S smoke meter. In addition to the MEXA unit, an ETAS ES430 compatible lambda sensor was used as a cross-check. The engine is not fitted with a catalyst, nor a DPF, hence the emissions measured are raw engine out emissions, which are sampled approximately 1 m downstream from the exhaust back-pressure valve at approximately atmospheric pressure.

A Pi Innovo M670 OpenECU is used for engine control. This ECU, based on a Jaguar Land Rover built Simulink model, offers full control of the fuel injection equipment, as well as the EGR valve fitted to the engine. Low-speed data is logged at 1 Hz, whereas high speed data acquisition, captured with 0.1 CAD resolution using an AVL IndiSet, is used for four Kistler pressure transducers (cylinder pressure, exhaust pressure, and individual intake port pressures [20]) as well as a current clamp signal indicating fuel injector triggering.

3. Fuel

A standard (EN590) B0 test diesel was used [21]. The properties of this diesel fuel are shown in Table 3:

3.1. CFD – model

A commercial CFD code capable of modelling unsteady turbulent combusting flows with moving boundaries was used for all simulations [22]. The computational setup used in this investigation is based on work carried out in [23]; hence, only a brief overview of the models will be given.

The ECFM-3Z model coupled with tabulated kinetic ignition (TKI) was used for combustion modelling [24]. Turbulence closure was accounted for through the well-known RNG-k-epsilon model [25] with heat transfer to the walls being modelled with the Han & Reitz model [26]. The discrete droplet methodology was used to simulate the liquid phase with spray injection and breakup modelled by the Reitz-Diwakar [27] and KH-RT [28] models respectively. Additionally, dynamic droplet drag [29], NTC collisions [30] and the Frossling correlation [31] were used to model droplet drag, collisions and vaporisation.

The computational domain was limited to a 45 degree sector of the engine cylinder only simulating a single nozzle of the equispaced injector. The CFD code generates the grid at runtime using a Cartesian cut cell algorithm with the possibility of using adaptive mesh refinement

Table 1
Specifications of the single-cylinder diesel engine.

Bore × Stroke	83 × 92.4 mm
Displacement	500 cm^3
Valves per Cylinder	2 intake, 2 exhaust
Compression Ratio	15.4 : 1
Fuel Pressure	400–1800 bar
Injector	Production 'Ingenium' engine injector