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Investigation of two-stage split-injection strategies for a Dieseline fuelled PPCI engine

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HIGHLIGHTS

- Single and two-stage injection strategies were studied in a Dieseline fuelled PPCI engine.
- Quantitative effects of injection parameters on emissions were found by Taguchi-DOE.
- Premixing process was improved by using optimised two-stage split-injection.
- Two-stage split-injection was proven effective for reducing NO_x and PM simultaneously.

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ABSTRACT

Two-stage split-injection strategies for partially premixed compression ignition (PPCI) combustion mode were investigated in a light duty 2.2 L four cylinder compression ignition engine fuelled with G50-Dieseline (50% ULG95 gasoline in EN590 diesel by volume). The investigation of two-stage split-injection has been focused on injection quantity-ratios and timings and it aims to achieve improved charge premixing and consequently reduce the oxides of nitrogen (NO_x) and particulate matter (PM) emissions simultaneously. Other parameters affecting combustion process (e.g. compression ratio) were fixed to identify the individual effects of parameters under study on the combustion and emission characteristics by the Taguchi-DOE (design of experiment) analysis. The investigation was conducted for two load groups of 1.37 and 2.97 bar BMEP selected from the new European driving cycle (NEDC) at an engine speed of 1800 RPM. Optimum operating values of injection parameters for generating the minimum and maximum combustion and emission characteristics were identified. Furthermore, very early first injection-timings were investigated for 2.97 bar BMEP with the combustion phase of 50% accumulative heat release (AHR-50) fixed. Compared with the single-injection strategy, $BSNO_x$ was reduced by approximately 39% to 59% through applying the two-stage split-injection. Accumulation particulate concentration as well as smoke number were reduced by approximately 90%. It is believed that with very early first-injection timings, fuel wall-impingement and over mixing may have resulted in lower combustion efficiency and thus BMEP drop. Consequently, the premixing process can reach a limit where the effect of required higher injected fuel quantity dominates combustion and emission characteristics. The two-stage split-injection developed in this study appears to be effective in improving the premixing process for PPCI combustion.

1. Introduction

Due to its impact on the environment, the emission from the transport sector is a point of great concern for many international societies. The diesel compression-ignition (CI) engine is favoured over the gasoline spark-ignition (SI) engine for its high efficiency which helps to reduce the CO_2 emission. On the other hand, significant emissions of nitrogen oxides (NO_x) and particulate matter (PM) are the drawbacks of the diesel CI engine. While high cost and weight of the exhaust after-treatment systems limit their application for NO_x and PM reduction, unconventional modes of combustion with low temperature combustion (LTC) strategies have been investigated for providing a more cost-effective solution to reduce the mentioned emissions [1,2]. Homogeneous charge compression ignition (HCCI) and partially premixed compression

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Nomenclature

Acc. C	accumulation mode concentration
Acc. CMD	accumulation mode count mean diameter
AFR	air–fuel ratio
AHR-50	combustion phase (CAD at which 50% of the accumulative heat release is achieved)
ANOVA	analysis of variance
° aTDC	CAD after top dead centre
BMEP	brake mean effective pressure
BS	brake-specific
BTE	brake-thermal efficiency
° bTDC	CAD before top dead centre
CAD	crank angle degree
CI	compression-ignition
CN	cetane number
DI	direct injection
Dieseline	blend of diesel and gasoline
DOE	design of experiment
ECU	engine control unit
EGR	exhaust gas recirculation
EOI	end of injection
FSN	filter smoke number
G50	blend of 50% (by volume) gasoline in diesel
HRR	heat release rate
IP	injection pressure
LTC	low temperature combustion
MRPR	maximum rate of pressure rise
NEDC	new european driving cycle
PCCI	premixed charge compression ignition
PPCI	partially premixed compression ignition
RPM	revolution per minute
SI	spark-ignition
S/N ratio	signal-to-noise ratio
SOC	start of combustion
VGT	variable-geometry turbocharger
UNIBUS	uniform bulky combustion system
λ	lambda (relative air–fuel ratio)

ignition (PPCI) are two modes of LTC. Control of ignition timing for HCCI engines in full load range is challenging due to the nature of auto-ignition of charge [3–6]. In PPCI engines, injection-timing of the fuel can be used to control ignition timing. However, the intention is to separate injection and ignition events for achieving premixed combustion in PPCI engines. Due to increased local lean fuel-air mixtures and consequently lower combustion temperature, premixed combustion can reduce NO_x and smoke simultaneously [6].

PPCI combustion can be accomplished by utilising a large amount of exhaust gas recirculation (EGR) and early injection of fuels having low cetane number (CN) and high volatility [3]. Reduced reactivity (lower CN) of a fuel in CI engines can prolong ignition delay [7]. Kalghatgi et al. [8] investigated gasoline fuelled PPCI engines and concluded that low CN is important for better premixing quality. Due to low auto-ignition quality (low CN), gasoline fuelled PPCI engines may face some limitations at low load. Zhang et al. [9] studied the effect of using blends of diesel and gasoline (Dieseline) in CI engines and compared them with the conventional diesel. Dieseline PPCI can reduce NO_x, smoke and particulate emissions effectively at low and medium loads [9,10]. Fuel injection strategy plays an important role for controlling mixture stratification [11]. Advanced injection-timing has been proven to be effective for providing more local lean mixtures as a result of higher ignition delay [1]. Two-stage split-injection strategy with advanced injection-timings such as uniform bulky combustion system (UNIBUS) [4] benefits from the long time intervals available for the injected fuel to be well-mixed with air. A proper split-injection strategy can be utilised to control the combustion phase and consequently the premixing process for gasoline-like fuelled CI engines [12].

Thus, it is necessary to find the effect of each injection parameter on the combustion and emission characteristics. It is also required to find the optimum parameters for achieving satisfactory combustion and emissions characteristics. Taguchi fractional factorial design of experiment (DOE) has been shown as an efficient and cost-effective method for the purpose of parametric analysis and optimisation [13].

The main objective of this investigation was to identify the effects of quantity-ratio and timing in two-stage split-injection on the combustion and emission characteristics of a light duty G50-Dieseline fuelled PPCI engine. The optimum injection parameters for achieving simultaneous minimum NO_x and smoke for 1.37 and 2.97 bar BMEP at the engine speed of 1800 RPM were identified by using Taguchi-DOE method. Combustion and emission characteristics achieved by the optimum two-stage split-injection parameters were compared to the single-injection strategy at each load. Furthermore, the effect of very early first injection-timings was investigated for the load condition of 2.97 bar BMEP under fixed combustion phase condition. It is expected that the findings of this work provide an insight into the application of two-stage split-injection strategy for PPCI engines.

2. Experimental system and methodology

2.1. Experimental system setup

Experiments were conducted on a 2.2 L, Ford Duratorq Puma compression ignition (CI) engine. It is a 4-cylinder in-line engine equipped with a common rail direct injection (DI) system and a variable-geometry turbocharger (VGT). The engine control unit (ECU) allows full control over EGR and injection parameters. The specifications of the engine are listed in Table 1.

Fig. 1 shows a schematic of the engine testing system. The EGR cooler utilises water (fixed at 20 °C) instead of engine coolant. In-cylinder pressure was measured by a Kistler quartz pressure transducer. The data was acquired by a National Instrument PCI6251 card at every single crank angle degree (CAD) and averaged over 50 consecutive engine cycles for each sample. Fuel consumption was measured by an AVL 733s dynamic fuel meter equipped with an AVL 752-60 fuel cooler and averaged over 2 min for each sample (3 samples per experiment).

Gaseous emissions including NO_x, CO, THC and O_2, as well as EGR ratio and relative air–fuel ratio or Lambda (λ), were measured by a Horiba MEXA-7100-EGR exhaust gas analyser and averaged

Table 1
Engine specifications.

Bore (mm)	86
Stroke (mm)	94.6
Capacity (cc)	2198
Compression Ratio	16.6:1
Max. power (kW)	96 (±5%) @ 3500 rpm
Max. torque (Nm)	310 (±5%) @ 1600–2500 rpm
Injection System	DI Common Rail
Injectors	6 Holes,153° (Included Angle)