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Experimental investigation into the effects of two-stage injection on fuel injection quantity, combustion and emissions in a high-speed optical common rail diesel engine

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HIGHLIGHTS

- ▶ The effects of two-stage injection on fuel injection quantity, diesel combustion and emissions using diesel fuel.
- ▶ Significant interactions were found between two closely spaced two-stage injections.
- ▶ Combustion analysis indicated the possibility of simultaneous reduction of NO_x and soot emissions.

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ABSTRACT

Diesel combustion and the formation of pollutants are directly influenced by the spatial and temporal distributions of the fuel within the combustion chamber of an internal combustion engine. The requirements for more efficient and responsive diesel engines have led to the introduction and implementation of multiple injection strategies. However, the effects of such injection modes on the hydraulic systems, such as the high pressure pipes and fuel injectors, must be thoroughly examined and compensated for. The objective of this study was to investigate the effects of fuel injection equipment characterisation and optimisation on diesel combustion and emissions with two-stage fuel injection. The fuel injection system was characterised and optimised through the measurement of the fuel injection rate and quantity, in particular, the interaction between the two injection events was quantified and compensated for. The effects of twin and variable split two-stage injection and dwell angle on diesel combustion and emissions were investigated in a high-speed direct injection single-cylinder optical diesel engine using heat release analysis and high-speed fuel spray and combustion visualisation technique. The results indicated that two-stage injection has the potential for simultaneous reduction of NO_x and soot emissions. Nevertheless, the studied two-stage strategies resulted in higher soot emission, mainly due to the interaction between two consecutive fuel injection events, whereby the fuel sprays during the second injection were injected into burning regions, generating fuel-rich combustion. In addition, the variable two-stage strategies produced high levels of uHC emission in comparison to single and twin split injection cases. This was mainly attributed to firstly greater fuel quantity injected during the second injection and secondly poor mixing and air utilisation during the second fuel injection event.

1. Introduction

A significant cost of industrialisation has been the environmental damages inflicted, to a large extent by the use of fossil fuels, within which the significant growth in the use and production of internal combustion engines have since been considered as one of the primary contributing factors. Due to ever increasing concern over the environmental impacts of the exhaust pollutants, emissions legislations have been progressively enforced since the 1960s. In recognition of the need to further reduce vehicle exhaust emissions and the greenhouse effect of CO_2, there has been a lot of interest in developing cleaner and more efficient energy saving vehicle powertrain. In response to social, legislative and environmental pressures, there is a large body of engine research work demonstrating the large energy saving and emissions reducing benefits of two-stage fuel injection. The introduction of common rail (CR) fuel injection system in the 1990s and further advancements thereafter allowed greater control and flexibility on fuel injection pressure, rate, quantity and timing over the entire operat-

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nomenclature

ΔP	change in pressure
ΔV	change in volume
γ	ratio of specific heats
k	bulk modulus
P	pressure
t	time
V	volume

Abbreviations

AFR	air–fuel ratio
ATDC	after top dead centre
BTDC	before top dead centre
CAD	crank angle degree
CMOS	complementary metal–oxide semiconductor
CR	common rail
DA	dwell angle
DI	direct injection
EGR	exhaust gas recirculation
ET	energising time
FIE	fuel injection equipment
FSN	filter smoke number
FVC	first visible combustion
HCCI	homogenous charge compression ignition
HRR	heat release rate
MHRR	maximum heat release rate
NA	naturally aspirated
NO_x	nitrogen oxides
PCCI	premixed charge compression ignition
SHR	single stage heat release
SOFI	start of first injection
SOSI	start of second injection
TDC	top dead centre
TSC	two-stage combustion
uHC	unburned hydrocarbon
VCO	valve covered orifice

ing range of diesel engines, facilitating successful application of such fuel injection strategies.

The initial investigations on using alternative injection strategies were primarily focused on the application of pilot and main injections or split injections with equal fuel demand per injection (50/50%) [1–3]. The results demonstrated that shorter ignition delay was achieved due to pilot injection, indicating less premixed combustion, lowering the peak heat release rate (HRR). Therefore, nitrogen oxides (NO_x) emission as well as combustion noise was considerably reduced in comparison to the conventional diesel combustion. In addition, the effect of post injection on further reduction of soot emission was examined by Han et al. [4] and Farrell et al. [5]. Their results showed that soot emission was reduced due to improved soot oxidation which was attributed to higher combustion temperature during mixing controlled combustion phase caused by the combustion of fuel injected during post injection. Furthermore, the potential for further reduction of exhaust emissions using exhaust gas recirculation (EGR) has been extensively investigated. Montgomery and Reitz [6] studied the effect of EGR in a heavy-duty diesel engine using 50/50%, 55/45% and 70/30% two-stage injection strategies with EGR levels varying between 10% and 25%. Their investigation revealed the potential for simultaneous reduction of NO_x and soot emissions using two-stage injection with EGR. The use of EGR decreased the NO_x emission by limiting the peak HRR due to premixed combustion, thus lowering the in-cylinder temperature. The soot emission was reduced due to improved mixing in conjunction with the effect of late fuel injection which resulted in higher in-cylinder temperatures during diffusion combustion, maximising soot oxidation.

In order to better understand the mixing process, Zhang et al. [7] carried out a series of investigations involving detailed analysis of fuel–air mixing process in a constant volume vessel through the application of laser absorption scattering. They investigated the mixing process using conventional single injection and compared their results to those obtained through two-stage injection strategies 75/25%, 50/50% and 25/75%. It was reported that the 75/25% strategy resulted in maximum soot reduction under the tested engine operating conditions. This was mainly attributed to improved mixing due to increased in-cylinder turbulence caused by the combustion of fuel injected during the second injection. Shayler et al. [8] compared the combustion and emissions characteristics of single and two-stage injections in a light-duty diesel engine. In this study all the two-stage injection strategies were accompanied by a pilot injection whereby relatively small quantity of fuel was injected in order to improve fuel evaporation. The results indicated that strategies with more fuel quantity during the first injection resulted in less soot emission with no increase in NO_x emission.

Koyanagi et al. [9] investigated the effects of engine design and operating parameters, in particular injector stability, spray symmetry, nozzle geometry, injection rate, pilot injection and swirl in a light-duty single-cylinder optical diesel engine with similar production-type combustion chamber geometry. The authors reported that the pilot-main strategy was characterised by a complete premixed combustion of the fuel injected during the pilot injection, 10% of the total injected fuel quantity in this case. Therefore, ignition delay time was reduced due to increased in-cylinder pressure and temperature and the presence of active radicals. Consequently higher soot emission was produced due to deteriorated mixing of the main injected fuel; however, such an effect could be controlled through the use of a suitable dwell angle (DA). Badami et al. [10] also studied the effect of pilot injection quantity and DA on diesel combustion and emissions in a light-duty diesel engine. In this study, the effects of pilot injection, less than 1–15% of the total injected fuel quantity, were investigated. It was reported that soot and NO_x emissions increased as the quantity of the pilot injection increased. The former was attributed to the increase in the in-cylinder pressure and temperature, due to the main combustion advance, while the latter was ascribed to the reduction of the premixed combustion. The same trend was observed as the DA was reduced. The authors also reported on the hydraulic effects of pilot injection on the combustion characteristics and the fluid-dynamic conditions at the start of the main injection.

Schmid et al. [11] studied the effect of nozzle hole geometry, rail pressure and pre-injection in a single-cylinder transparent light-duty diesel engine. The authors reported that the pre-injection (i.e. pilot) could lead to shorter ignition delay which in turn could result in the penetration of the main injection into burning regions. Kook and Bae [12] examined the effect of two-stage fuel injection in a single-cylinder direct injection (DI) premixed charge compression ignition (PCCI) engine. In this study the majority of the fuel was injected early during the first injection to form the premixed charge while a small quantity of fuel was injected close to top dead centre (TDC), serving as the ignition promoter. The re-

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