Energy Conversion and Management 110 (2016) 457–468

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Effects of pilot injection parameters on low temperature combustion diesel engines equipped with solenoid injectors featuring conventional and rate-shaped main injection

S. d'Ambrosio, A. Ferrari *

Energy Department – Politecnico di Torino, C.so duca degli Abruzzi, 24, 10129 Torino, Italy

ARTICLE INFO

Article history:
Received 27 August 2015
Accepted 10 December 2015
Available online 2 January 2016

Keywords:
Pilot injection
Dwell time sweeps
Swirl sweeps
Injection fusion

ABSTRACT

The potential of pilot injection has been assessed on a low-temperature combustion diesel engine for automotive applications, which was characterized by a reduced compression-ratio, high *EGR* rates and postponed main injection timings. Dwell time sweeps have been carried out for pilot injections with distinct energizing times under different representative steady-state working conditions of the medium load and speed area of the New European Driving Cycle. The results of in-cylinder analyses of the pressure, heat-release rate, temperature and emissions are presented.

Combustion noise has been shown to decrease significantly when the pilot injected mass increases, while it is scarcely affected by the dwell time between the pilot and main injections. The *HC*, *CO* and fuel consumption trends, with respect to both the pilot injection dwell time and mass, are in line with those of conventional combustion systems, and in particular decreasing trends occur as the pilot injection energizing time is increased. Furthermore, a reduced sensitivity of NO_x emissions to both dwell time and pilot injected mass has been found, compared to conventional combustion systems. Finally, it has been observed that soot emissions diminish as the energizing time is shortened, and their dependence on dwell time is influenced to a great extent by the presence of local zones with reduced air-to-fuel ratios within the cylinder. A combined analysis of the results of swirl sweeps and dwell time sweeps is here proposed as a methodology for the detection of any possible interference between pilot combustion burned gases and the main injected fuel.

The effect of pilot injection on engine performance and emissions has also been assessed in the presence of rate-shaped main injections. These main injection profiles have been implemented with solenoid injectors by designing the injection fusion between a pre injection shot, which is added after the pilot injection, and the main injection. This innovative strategy shows benefits, with respect to combustion noise, although it still results in a reduced impact on NO_x emissions. Furthermore, the brake specific fuel consumption and soot levels generally become worse than in the case of the simple pilot–main injection schedules. The injection fusion strategy has a significant impact on the soot versus dwell time dependence, which is influenced by the interference between the main injection and pilot combustion.

1. Introduction

Both the pilot injected quantity (q_{pil}) and the dwell time (*DT*) between the pilot and main injections have been shown to exert a significant influence on the trade-off between engine-out emissions, combustion noise (*CN*) and fuel consumption in conventional diesel combustion systems at low to medium load and speed engine working conditions [1–4].

Since a reduction in the premixed combustion portion of the main injection makes the highest flame temperatures of the burned gases diminish, NO_x emissions generally reduce in pilot–main schedules, compared to single-injection strategies [5]. However, the pilot injection burns under premixed combustion conditions, and this constitutes an additional source of NO_x emissions. When large pilot injected quantities are applied, the increase in the NO_x amount, due to pilot combustion, can prevail over the decrease in the main combustion NO_x emissions, due to the shortened ignition delay and less intense premixed main combustion [6], and, as a consequence, NO_x emissions can augment overall for the strategy that implements the pilot shot.

* Corresponding author.
E-mail address: alessandro.ferrari@polito.it (A. Ferrari).

http://dx.doi.org/10.1016/j.enconman.2015.12.014
0196-8904/

Nomenclature

ATDC	after top dead center
bmep	brake mean effective pressure
bsfc	brake specific fuel consumption
CA	crank angle (°)
CN	combustion noise
DT	dwell time between the pilot and main injection shot
DT_{pil}	dwell time between the pilot and pre injection shots
DT_{pre}	dwell time between the pre and main injection shots
ECU	electronic control unit
EGR	exhaust gas recirculation
EOI_{main}	electrical end of the main injection
HC	unburned hydrocarbons
HRR	heat release rate
$\dot{m}_a$	fresh-air mass flow-rate
$\dot{m}_{EGR}$	exhaust gas mass flow-rate
MFB50	angle at which 50% of the combustion mixture has burned
n	engine speed
NEDC	New European Driving Cycle
NO_x	nitrogen oxides
PCCI	Premixed Charge Compression Ignition
p_{cyl}	in-cylinder pressure
pm	pilot and main injection strategy
pmM	pilot and pre-main injection strategy (with injection fusion)
p_{rail}	nominal rail pressure level
q_{Pil}	volume of fuel injected in the pilot injection
SOI_{main}	electrical start of the main injection
SOI_{pil}	electrical start of the pilot injection
Sw	swirl actuator position
T_b	burned gas temperature
TDC	top dead center
X_{EGR}	mass fraction of exhaust gas recirculation
ε	engine compression ratio
ϕ	equivalence ratio
θ	crankshaft angle in the simulations

Furthermore, the earlier the pilot injection timing, which corresponds to a fixed pilot injected mass, the lower the heat release rate (*HRR*) peak of the pilot injection, and thus the more moderate the pilot combustion. This seems to suggest that an earlier pilot injection timing in conventional combustion systems limits the generation of the NO_x caused by pilot combustion [7], but aggravates the NO_x emissions produced in the main combustion.

Smoke emissions in pilot–main injections generally tend to increase at medium load and speed conditions, compared to single injections. In fact, the pilot injection leads to an increase in the in-cylinder temperature and a decrease in the oxygen concentration in the gases before the main injection has occurred, and both of these effects generally make the smoke emissions, produced during the main combustion, grow [7–9]. In general, the quantity of the pilot injection should be below a certain threshold (a general value of 4 mg can be prescribed) in order to contain the smoke amount [10]. Soot emissions generally increase as the *DT* between the pilot and main injection is reduced [11]; this occurs for the same reasons that lead to the increase in the soot emissions that is detected when a pilot shot is added to the main injection. However, when the *DT* is very short, the main shot fuel is injected slightly before the burning of the pilot injection, and as a result, a lower rise in the temperature of the in-cylinder charge occurs and the ignition delay of the main injection tends to increase [12]. Furthermore, a small pilot injection, closely-coupled to the main injection ($DT \leqslant 500\ \mu s$), can cause an increase in the velocity of the injector needle during the nozzle opening phase of the main injection, and this contributes to spray atomization enhancement [13]. Both these events can significantly improve the premixing phase of the main injected fuel with air and thus enable a reduction in the smoke emissions. On the other hand, the possible interference between the pilot combustion event and the main injection, which is more likely to occur for short *DT* values, can mask the benefits of both the increased ignition delay and the higher velocity of the needle at the beginning of the main injection, and this major interference can lead to an augment in the soot emissions.

The brake specific fuel consumption (*bsfc*) in the medium load and speed area of the New European Driving Cycle (*NEDC*) improves when a pilot injection is added to the main injection, and the improvement generally increases as the dwell time is reduced, because the pilot and main combustions are linked smoothly, and this has the potential of enhancing the combustion efficiency [14].

Finally, pilot injections are also effective in decreasing combustion noise: reductions of up to 5–8 dB are generally obtained in the *CN* value over the whole engine working area, even though the most obvious benefits are obtained at low loads and at idle [15–17]. Combustion noise normally decreases if the pilot injected mass augments, whereas the dependence of the *CN* on the pilot–main dwell time is more complex, because this trend is affected by the entity of the pilot injected mass, even though a decrease is generally observed as the dwell time is reduced [17].

The effects of pilot, post and multiple injection strategies on engine performance and emissions have been studied extensively at low to medium load and speed conditions in conventional diesel combustion modes with *EGR* fractions of up to 10–20% [18–21] and complete parametric analyses have been performed on several injection variables of the injection strategy [22]. In particular, the influence of the variations in the pilot injected quantity and the pilot–main dwell time has been investigated in detail for standard diesel combustion systems [23,24].

The implementation of sophisticated injection strategies to control the PCCI combustion mode is a more recent challenge [25,26]. Multiple injections are generally used in PCCI diesel engines to create a better air–fuel mixing charge with lowest possible wall-wetting [27], but there are few analyses in the literature about the effect of multiple injections on combustion noise and emissions in the presence of high EGR rates [25]. Multiple injections are usually focused on the extension of the high-load limits of the PCCI mode working area or on the emissions and noise of the PCCI engine [28]. The influence of an increase in the number of injection shots tends to be studied in general terms, and comprehensive analyses on the effects of some key-injection parameters, such as dwell times and fuel quantities injected in each shot, on engine performance are rare and very recent. Furthermore, investigations on multiple injections often refer to PCCI engines fueled with gasoline [29] or alternative fuels, such as propane [30] or DME [31]. Therefore, great attention is being paid to the effects of pilot injection on engine performance in low-temperature combustion systems characterized by heavy *EGR* rates and fueled with diesel oil [8,14,32–34].

In the current research investigation, dwell time sweeps have been studied within the 400–1600 μs range and at different values of the pilot injected mass in pilot–main injection schedules, when high EGR rates are applied to a PCCI engine fueled with diesel oil. Furthermore, an analysis of pilot injections with variable phasing and quantity in the PCCI engine has also been performed for