Energy 96 (2016) 155–165

Contents lists available at ScienceDirect

Energy

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

Partially premixed combustion based on different injection strategies in a light-duty diesel engine

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A R T I C L E I N F O

Article history:
Received 11 June 2015
Received in revised form
3 November 2015
Accepted 15 December 2015
Available online 11 January 2016

Keywords:
Partially premixed combustion
Diesel engine
Injection strategy
Emission
Efficiency

A B S T R A C T

The performance of partially premixed combustion (PPC) relies heavily on the proper mixing between the fuel and the in–cylinder gas. In this paper, two injection strategies, including single and multiple injection, were investigated to achieve PPC in a four-cylinder light-duty diesel engine, and were evaluated in terms of heat release rate, combustion phase, emissions and thermal efficiencies. The combustion process is dominated by premixed combustion and the diffusion combustion process is quite short at the early single injection mode. It shows the characteristics of both premixed combustion and low temperature combustion. However, the ratio of diffusion combustion increases at high load. NO_x and smoke emissions reduce at the same time with late injection mode. For the multiple injection strategy, the cylinder pressure and peak pressure rise rate is lower. As the pilot-main interval increases, the mixture is more homogeneous due to sufficient premixing time. However, diffusion combustion plays the dominant role in the double pilot injection mode. The BSFC (brake specific fuel consumption) and brake thermal efficiency are considerably improved with pilot injection mode at low load condition, compared with late injection mode. The NO_x decreases dramatically in double pilot injection PPC, while the smoke and CO increase, compared with single early injection mode.

1. Introduction

The regulations of pollutant emissions for diesel engines become stricter and stricter in the past two decades. These regulations are the main driving force for developing modern engine technologies. Conventional diesel engines suffer from high soot emission due to the over-rich regions in the core area of the jet and high NO_x emission due to the high flame temperature in the stoichiometric fuel-air mixture at the periphery of the jet [1]. In order to reduce both soot and NO_x emissions, soot-prone fuel-rich and NO_x-prone stoichiometric mixtures should be avoided simultaneously. An effective approach is to employ low-temperature premixed combustion. Compared with conventional diesel combustion, low-temperature premixed combustion shows lower soot emission by increasing ignition delay and avoiding local rich-mixture regions. Furthermore, the oxygen is diluted and thus NO_x can be reduced dramatically by implementing the exhaust gas recirculation (EGR) technology [2]. A variety of low temperature combustion strategies are proposed, such as homogeneous charge compression ignition (HCCI) combustion [3–6], partially premixed combustion (PPC) [7,8], stratified charge compression ignition (SCCI) combustion [9], and modulated kinetics (MK) combustion [10] and so on.

PPC can be considered as an intermediate process between the fully mixed HCCI and conventional spray and diffusion controlled compression ignition combustion. With very early injection timing and high EGR ratio, very thin and homogeneous mixture gas could be formed under high compression ratios in the cylinder, which leads to low NO_x and soot emissions and good fuel efficiency [11,12]. Compared to HCCI, the charge distributions for PPC are more heterogeneous at ignition, and include not only fuel-lean but also fuel-rich mixtures.

Abbreviations: ATDC, after top dead center; BMEP, break mean effective pressure; BSFC, break specific fuel consumption; BTDC, before top dead center; CA, crank angle; CA10, crank angle at 10% mass fraction burned; CO, carbonic oxide; EGR, exhaust gas recirculation; EPI, early pilot injection; HC, hydrocarbon compounds; HCCI, homogeneous charge compression ignition; HFID, heated flame ionization detector; IMEP, indicated mean effective pressure; MK, modulated kinetics; NDIR, non-dispersive infra-red; NO_x, nitrogen oxide; PM, particulate matter; PPC, partially premixed combustion; PPR, pressure rising rate; SCCI, stratified charge compression ignition; SOI, start of ignition; TDC, top dead center; UHC, unburned hydrocarbon compounds.

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http://dx.doi.org/10.1016/j.energy.2015.12.052
0360-5442/

As the development of the combustion strategies described above, the differences between them are becoming smaller and smaller. Currently, fuel injection system plays an even more important role in the performance and emissions of diesel engines than before. The electronic controlled high pressure common rail fuel injection system makes it possible to conduct a flexible and precise fuel injection, which can strongly influence spray characteristics and combustion evolution process [13].

PPC can be achieved by employing single or multiple injection strategies. Single injection strategy can be further divided into two subcategories according to the fuel-injection and combustion timing. The first subcategory is the early single injection strategy in which the fuel is injected in the middle to late compression stroke. In this condition, the fuel-air mixture is quite lean. The other one is the late single injection strategy in which the fuel is injected very close to the TDC or in the early expansion stroke. The ignition dwell (the period between end of injection and start of combustion) is usually positive due to a longer ignition delay, providing time for some degree of premixing for all of the injected fuel [14,15]. Compared with conventional diesel injection timing, the gas is cooler because of less compression (for early-injection) or expansion (for late-injection) in both subcategories. Kook et al. [16] investigated the effects of charge dilution on low-temperature diesel combustion and emissions in a small-bore single-cylinder diesel engine over a wide range of injection timing. Although the ignition delay increased with high dilution and early injection, the heat release analysis indicated that a large portion of the combustion and emissions formation processes were still dominated by the mixing-controlled phase rather than the premixed phase. Hardy et al. [17] investigated the cylinder charge preparation with optimized start-of-combustion timing. It was found that the mixing time increased and particulate matter (PM) emissions substantially decreased with the increase of EGR rate, though the equivalence ratio increased correspondingly. Cheng et al. [18] investigated a heavy-duty automotive diesel engine with single injection strategy in PPC combustion mode. The results showed that both early injection and late injection had a long mixing period, which helped to form a more homogeneous mixture, and no diffusion combustion was found in the heat release rate curves. Premixed combustion and low-temperature combustion are the key methods for reducing the PM and NO_x emissions simultaneously. To minimize fuel consumption and NO_x and PM emissions, Klingbeil et al. [19] performed optimizations on a heavy-duty diesel engine equipped with a conventional electronic unit injector. It was found that low emission operating points existed for the low speed low load condition when the injection was either very early or very late with high EGR ratio. For the high speed low load condition, it was found that low emissions were achieved when operating with early injection timing and high EGR ratio.

In multi-injection strategy, two main methods are employed which are pilot-main injection and main-post injection. Ehleskog et al. [20], Yun et al. [21] and Mueller et al. [22] achieved low temperature premixed combustion by employing pilot injection. Results showed that the early-injected fuel burned in an HCCI-like mode, which was characterized by the first stage heat release followed by premixed high temperature combustion. But with early pilot injection (EPI) and large amount of pilot fuel mass, low combustion efficiency was observed in the early-injection-only condition. One potential cause was over-penetration of the spray which led to liquid fuel impingement on cylinder walls. Benajes et al. [23] adopted the pilot injection with large amount of fuel and EPI mode to achieve partially premixed combustion. A narrow angle nozzle configuration was investigated with two different adapted piston bowl geometries in order to eliminate the impingement and adhesion of liquid fuel to the cylinder wall. Okude et al. [7,24] investigated the effects of the pilot injection fuel quantity and pilot injection timing on the combustion mode and exhaust emissions. The results shows that the method to reduce exhaust emissions of pilot injection mode is to reduce the emissions produced by the pilot combustion itself.

The homogeneity is more difficult to achieve as the engine load increases because the fueling rate increases. Consequently employing early injection timing and large amount of pilot injection fuel are effective methods. By doing so, the amount of pilot injection fuel is divided into several small pilot injections. The mixture is more homogenous and the wall-wetting is reduced.

In early pilot injection mode, a large amount of fuel is burned in the premixed combustion process. As a result, a higher ratio of premixed/mixing controlled combustion occurs. However, the fuel impinging on the cylinder wall leads to high brake specific fuel consumption (BSFC) and unburned hydrocarbon compounds (UHC) emission. The most important drawback is the extreme fuel dilution in the lubricant oil. This discards the injection strategy for commercial engines despite the promising results in terms of NO_x and soot emission reduction. To implement a large quantity pilot injection at early time while preventing cylinder wall wetting, some strategies are necessary to reduce the penetration of fuel spray. One of the practical strategies is injecting the pilot fuel in multiple injections. On the other hand, in real engines, too early pilot injection timing and too much pilot injection mass cannot be achieved considering the limitation of engine knock and BSFC. A strategy with an appropriate pilot injection timing and pilot injection mass is more practical. The investigation of PPC still focus on the control of the correlation between injection timing and combustion timing, and on the reduction of emissions at the cost of the least sacrifice of thermal efficiency. However, there are only a few investigations on the multi-injection strategies based on single early or late injection mode combining with small amount of pilot injection fuel so far. Moreover, the explanations of the combustion and emission performance and basic principles of this strategy are not clear.

In the present research, PPC was achieved by adopting single and multiple injection strategies in a four-cylinder light-duty diesel engine. The fundamental characteristics of PPC mode on different injection strategies and its main influence factors were carefully analyzed. The effects of the correlation between injection timing and start of combustion timing on the characteristics of the emission and fuel economy were investigated.

2. Experimental apparatus and method

Experiments were conducted on a 4-cylinder, light duty, direct-injection diesel engine equipped with common rail injection system and variable geometry turbocharger. Table 1 shows the engine specifications and Fig. 1 shows the schematic of experimental setup. Fuel injection system was a Bosch high pressure common rail system, where the injection pressure, injection timing and injection pulse width could be adjusted. The cylinder pressure was measured

Table 1
Specifications of engine.

Bore*stroke/(mm)	110*125
Compression ratio	17.5
Displacement/(L)	4.752
Max torque/(N·m)	650
Power/Speed/(kW)/(r/min)	147/2400
Fuel injection type	Common rail injection system
Injection pressure/(MPa)	80–160
Nozzle number	8
Spray angle/(°)	150