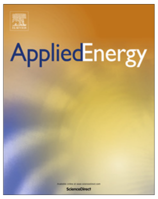
Applied Energy 119 (2014) 454–466

Contents lists available at ScienceDirect

Applied Energy

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



Effect of air–fuel mixing quality on characteristics of conventional and low temperature diesel combustion

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HIGHLIGHTS

- Effect of air–fuel mixing quality on conventional and low temperature diesel combustion was investigated.
- Higher injection pressure and intake pressure reduced exhaust emissions in both combustion regimes.
- The combustion phase in low temperature diesel combustion was more influenced by air–fuel mixing quality.
- Direct flame imaging was conducted to analyze the differences between each combustion regime.

ARTICLE INFO

Article history:
Received 24 July 2013
Received in revised form 28 October 2013
Accepted 18 December 2013
Available online 2 February 2014

Keywords:
Diesel engine
Low temperature diesel combustion (LTC)
Conventional combustion
Injection pressure
Intake pressure

ABSTRACT

A comparative study on the effects of air–fuel mixing quality on combustion characteristics was carried out in both conventional and low temperature diesel combustion (LTC) regimes. The injection pressure and intake pressure were considered as variables as they are important factors which influence the air–fuel mixing process. The intake O_2 concentration was varied to realize different combustion regimes. Improved air–fuel mixing with a higher injection pressure enhanced the combustion process in both conventional combustion and LTC regimes, resulting in higher peaks of in-cylinder pressure and heat release rate. The combustion phase in the LTC regime was more influenced by injection pressure due to longer premixing time than that of conventional combustion. A higher injection pressure reduced CO and HC emissions over a wide range of intake O_2 concentrations. The reduction of CO and HC emissions in the conventional combustion regime was due to higher combustion temperature, while that in the LTC regime was due to decreased under-mixed fuel by improved air–fuel mixing. Soot emissions at a higher injection pressure were reduced, particularly, in the conventional combustion regime where the soot formation rate is high. The increase of intake pressure was also advantageous in reducing CO, HC and soot emissions due to improved air–fuel mixing as well as enrichment of absolute amount of oxygen, which lead to enhanced combustion process. A direct flame image was taken to observe the flame structure of two different combustion regimes to correlate with the exhaust emission results and combustion characteristics. High flame luminosity was observed around the periphery of the spray jet in the conventional combustion regime, which was a direct indication of soot formation and high temperature combustion; while low luminosity was observed around the piston bowl in the swirl direction in the LTC regime, which indicated a longer air–fuel mixing period and low temperature combustion.

1. Introduction

As the fossil fuels resources have been predicted to be limited, diesel engines have been regarded as an attractive means for automotive vehicles due to their high thermal efficiency and thus high fuel economy. However, high levels of nitrogen oxide (NOx) and soot emissions are still a major concern for diesel engines due to stringent emissions legislations. The major reason for the high levels of NOx and soot in conventional diesel combustion is the non-uniform fuel distribution, which mainly results from direct fuel injection and thus a short time for mixture preparation. NOx emissions are formed in the near-stoichiometric regions due to high combustion temperature, while soot emissions occur in the fuel-rich regions in conventional diesel combustion [1,2]. In addition, the rate of burning, which is closely related to engine performance, is greatly influenced by the air–fuel mixing process. These features highlight the importance of the air–fuel mixing

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http://dx.doi.org/10.1016/j.apenergy.2013.12.045

Nomenclature

ATDC	after top dead centre
CA10	burn point of 10%
CA50	burn point of 50%
CA90	burn point of 90%
CAD	crank angle degree
CO	carbon monoxide
EC	eddy current
ECU	electronic control unit
EGR	exhaust gas recirculation
FNH	flame non-homogeneity
FSF	flame spatial fluctuation
FSN	filter smoke number
HC	hydrocarbon
HCCI	homogeneous charge compression ignition
HRR	heat release rate
IMEP	indicated mean effective pressure
ISFC	indicated specific fuel consumption
LTC	low temperature diesel combustion
NOx	nitrogen oxide
PCCI	premixed charge compression ignition
SINL	spatially integrated natural luminosity

process in conventional diesel combustion, where the mixing-controlled combustion phase is dominant.

The air–fuel mixing process is also an important issue in the advanced diesel combustion modes such as homogeneous charge compression ignition (HCCI), premixed charge compression ignition (PCCI), and low temperature diesel combustion (LTC). These combustion strategies have in common the simultaneous reduction of NOx and soot with low combustion temperature. However, their combustion processes are significantly different from each other [3–5]. HCCI uses a lean homogeneous mixture as a way to lower the combustion temperature. Such a mixture can be achieved by extending the ignition delay period with extremely advanced injection timing. Most of the fuel is premixed, such that the mixture at the occurrence of ignition is nearly homogeneous. Therefore, the premixed combustion phase is predominant in HCCI. In PCCI, low combustion temperature is typically achieved with less advanced injection timing (but more advanced than for conventional combustion) and a moderate exhaust gas recirculation (EGR) rate. These conditions result in extended ignition delay and hence offer sufficient mixing time for the low local equivalence ratio as well as low combustion temperature. This combustion mode also has a greater premixed combustion fraction compared to conventional combustion. In contrast, for the LTC, lowering the combustion temperature is achieved through a high level of charge dilution with a large amount of EGR. LTC is sometimes considered as a generic terminology which covers a wide range of advanced combustion modes, because HCCI and PCCI also experience the combustion process under relatively lower combustion temperature compared to conventional diesel combustion. However, the concept of LTC is occasionally separated apart from other advanced combustion modes under extreme cases with high EGR rate beyond 60%. It was named as highly-diluted LTC [3,6], or LTC for short [7]. The terminology LTC is used in the text for the simplicity. In such cases, the average equivalence ratio at ignition timing remains quite high because of the lack of oxygen (O_2), even though the ignition delay is prolonged by charge dilution [8,9]. Therefore, a greater amount of ambient gas must be used in the mixing process to achieve a lower equivalence ratio and lower exhaust emissions. This implies that a mixing-controlled combustion phase remains important under highly diluted conditions, unlike other advanced diesel combustion modes. From this point of view, the improvement of air–fuel mixing process in LTC is also considered as an important issue for better engine performance as in the conventional diesel combustion.

Several studies concerning the influence of air–fuel mixing quality have been conducted under both conventional diesel combustion and LTC, respectively [10–13]. Simulations combined with experimental results were also conducted to discover the control parameters to improve the air–fuel mixing quality. The injection timing and swirl ratio were assessed to determine the optimum values for the best mixing process, evaluated with engine efficiency and CO emissions [14]. Several numerical models were proposed to predict the soot formation process with respect to the ambient O_2 concentration under different ambient densities [15]. Besides, the effect of cetane number of the fuel and volatility, which is chemical and physical properties, respectively, was demonstrated to examine the feasibility in the LTC regime. The emissions and the fuel consumption were numerically evaluated in terms of the mixing procedure between the fuel and the air [16]. The general conclusions of these literatures were that soot emission and fuel consumption could be reduced by improving the mixing process, regardless of combustion regime. However, most studies have been confined to the investigation performed in each combustion regime. It is suspected that different circumstances from each combustion regime can lead to different effects with regard to air–fuel mixing quality. The objective of this study is then to investigate the effects of air–fuel mixing quality on the characteristics of conventional diesel combustion and LTC. The main focus was to investigate and compare the differences of such mixing effects on the combustion under different combustion regimes. In this study, injection pressure and intake pressure were taken as the variables which determine the air–fuel mixing quality, since they can directly affect the mixing process. Tests with different injection pressure and intake pressure conditions were carried out over a wide range of intake O_2 concentrations. Two intake O_2 concentrations, which represent each combustion regime, were selected for the intensive analysis: 21% for conventional diesel combustion and 11.25% for LTC. Combustion characteristics were analyzed based on heat release rate, combustion phase and exhaust emissions. In addition, direct flame images were used to characterize the combustion process according to the air–fuel mixing process in each combustion regime. A quantitative analysis of the combustion flame direct images was conducted to provide a comprehensive study of the phenomenon. The combustion flames of two different combustion regimes were directly compared with the quantified data of the images.

2. Experiments

2.1. Experimental setup

A four-stroke, five-cylinder, direct injection diesel engine was used for the investigation. A schematic diagram of the research engine system is shown in Fig. 1, and its specifications are summarized in Table 1. The engine was a typical automotive-size diesel engine with a bore of 86.2 mm and a stroke of 92.4 mm, yielding a displacement of 539 cc. Fuel injection parameters including