Applied Energy xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Applied Energy

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

Numerical investigation of the effect of two-stage injection strategy on combustion and emission characteristics of a diesel engine☆

Hanzhengnan Yu[a,b], Xingyu Liang[a,*], Gequn Shu[a], Yuesen Wang[a], Xiuxiu Sun[a], Hongsheng Zhang[a]

[a] State Key Laboratory of Engines, Tianjin University, Tianjin, 300072, China
[b] China Automotive Technology and Research Center, Tianjin, 300300, China

HIGHLIGHTS

- Two-stage injection strategy has been divided into pilot and early strategies.
- The NOx-soot trade-off relationships can be broken using early injection strategy.
- The two-stage injection interval is recommended set between 30 and 40°CA.
- The first-stage injection proportion is recommended set between 30% and 60%.

ARTICLE INFO

Keywords:
Two-stage injection
Two-stage injection interval
First-stage fuel injection proportion
Combustion characteristic
Emission characteristic

ABSTRACT

This work assessed two types of two-stage injection strategies for the operation of a diesel engine: pilot and early injection. The effects of the two-stage injection interval and the first-stage fuel injection proportion on the combustion and emission characteristics when employing these two injection strategies were investigated by numerical modeling, dividing the in-cylinder zone into three different regions. Variations in the NOx, soot, HC and CO emissions in each region were determined at various values of two-stage injection interval and first-stage fuel injection proportion for both strategies. The results demonstrate that, considering both the engine combustion and emission characteristics, a two-stage injection strategy in conjunction with an injection interval of 30–40°CA and a first-stage fuel injection proportion of 30–60% is advisable.

1. Introduction

Homogeneous charge compression ignition (HCCI) combustion has been widely researched as a means of solving the trade-off problem between NOx and soot emissions from conventional diesel engines. This has proven to be a promising technique that allows the simultaneous reduction of both soot and NOx while maintaining high thermal efficiency [1–3]. One critical challenge related to HCCI combustion is obtaining the required homogeneous air-fuel mixture. Early injection strategies have been widely utilized for this purpose. However, early injection may cause the fuel spray to impinge on the cylinder wall owing to the low in-cylinder pressure and temperature. This can lead to low combustion efficiency, incomplete combustion, and oil dilution. Another challenge is the difficulty in controlling combustion phasing owing to the high cetane number of conventional diesel fuel.

To overcome these two problems, a two-stage injection strategy has been proposed. The first-stage injection takes place during the compression stroke to generate a homogenous in-cylinder fuel-air mixture. Because of the decrease in the injected fuel mass in the early injection period, the impinging fuel mass is also decreased. This portion of the fuel undergoes clean HCCI combustion. The second-stage injection is timed to occur near TDC so as to control the combustion phasing and to help burn out the incomplete combustion products from the first-stage injection. This portion of the fuel undergoes conventional combustion.

Abdullah et al. [4], Mobasheri et al. [5], Yin et al. [6], Lee et al. [7], Huang et al. [8] and Jeon et al. [9] all investigated the effects of first-stage injection timing on the performance and emissions of diesel engines. The first-stage injection timing was varied from 70°CA BTDC to 10°CA BTDC, and the results all showed that advanced first injection timing decreased soot emissions. However, the NOx emissions were found to be inconsistent, either increasing, decreasing or initially decreasing then increasing with advances in the first-stage injection

☆ The short version of the paper was presented at ICAE2016 on Oct 8-11, Beijing, China. This paper is a substantial extension of the short version of the conference paper.

* Corresponding author.
E-mail address: lxy@tju.edu.cn (X. Liang).

http://dx.doi.org/10.1016/j.apenergy.2017.09.014
Received 9 January 2017; Received in revised form 22 August 2017; Accepted 8 September 2017

Nomenclature

NOx	nitrogen oxide
HC	hydrocarbon compounds
CO	carbon monoxide
ISFC	indicate specific fuel consumption
TDC	top dead center
BTDC	before top dead center
ATDC	after top dead center
HRR_{max}	maximum of heat release rate
PRR_{max}	maximum of pressure rise rate
CA10	crank angle when the accumulated heat release reached 10% of the total heat release
CA50	crank angle when the accumulated heat release reached 50% of the total heat release
CA90	crank angle when the accumulated heat release reached 90% of the total heat release

Table 1
Sub-model group.

Turbulence model	k-zeta-f model
Atomization/breakup model	Dukowicz/WAVE model
Combustion model	SKLE model
NOx formation model	Extended Zeldovich Model
Soot formation model	Kennedy/Hiroyasu/Magnussen Model

timing. These variations can likely be attributed to differences in the first-stage fuel injection proportion.

With increases in the first-stage fuel injection proportion, more fuel will be mixed with air prior to the second-stage injection, resulting in a greater injection proportion of the fuel being combusted in the HCCI mode. This, in turn, will reduce the ignition delay and increase the heat release rate. Broatch et al. [10] and Zheng et al. [11] investigated the effect of the injection proportion on engine performance, and found that increasing the injection proportion decreased the NOx emissions but had little effect on soot output. In contrast, Lee et al. [12] and Huang et al. [8] reported that soot emissions were increased, primarily as a result of the reduced ignition delay time associated with the second combustion and variations in the degree of spray-wall impingement. Lee et al. [7] determined that NOx emissions increased as the injection proportion was increased above 50%, while the lowest NOx emissions were obtained below this value. Moreover, the soot emissions also increased rapidly as the injection proportion increased. Zheng et al. [11], Kumar et al. [13], Min et al. [14], Bae et al. [15] and Neely et al. [16] all reported that increasing the injection proportion elevated both HC and CO emissions owing to the increased extent of spray-wall impingement.

In the present study, the two-stage injection process was divided into pilot and early injection types, according to the first-stage fuel injection proportion [17]. A proportion below 50% was defined as the pilot injection strategy, while a proportion above this level was defined as the early injection strategy. The effects of both approaches on the combustion and emission characteristics of a diesel engine were subsequently investigated by numerical modeling methods. Herein, the effects of both the two-stage injection interval and the first-stage fuel injection proportion were discussed. In addition, the in-cylinder zone was divided into three different regions, defined as the combustion chamber, central and wall wetting regions. The variations in the NOx, soot, HC and CO emissions in each region when employing different two-stage injection intervals and first-stage fuel injection proportions in conjunction with both pilot and early injection strategies were also summarized herein.

2. Modeling methodology

2.1. Sub-models

The numerical model was constructed using the commercially-available three-dimensional computational fluid dynamics code AVL Fire. The sub-models, including turbulence, spray breakup and atomization, combustion, and emission models, are presented in Table 1. The SKLE reduced reaction mechanism developed by Su [18] for *n*-heptane (with 44 species and 72 reactions) was coupled with AVL Fire code to simulate diesel fuel combustion. Considering the reaction rate calculated by chemical mechanism was only related to the local mixture temperature and molarity, Kong [19] model was introduced to simulate the enhanced effects of turbulence on the combustion process. In this study, the total aldehyde (formaldehyde, acetaldehyde, propionaldehyde), alkene (ethylene, propylene, 1,3-butadiene) and alkane (*n*-heptane) outputs were considered to represent the engine HC emissions.

The spray-wall impingement model used in this study was first developed by Jia [20,21] with a special emphasis on the conditions associated with high injection pressures and intermediate-to-high ambient pressures.

2.2. Calculation meshes and initial conditions

The specifications of the diesel engine used for modeling are presented in Table 2 and the fuel injection parameters are provided in Table 3. The engine speed was fixed at 2000 rpm.

The calculation mesh employed in this study consisted of a 1/6 sector model of a single fuel spray based on assuming cyclic symmetry, and was composed of approximately 71,280 cells, as shown in Fig. 1. Calculations were carried out for a closed system, starting from closing of the intake valve at 132°BTDC to opening of the exhaust valve at 114°ATDC. The initial conditions including charging pressure (2.01 bar), charging temperature (340 K), piston head temperature (550 K), cylinder head temperature (550 K) and cylinder wall temperature (475 K).

Table 2
Engine specification (YN4100QBZL).

Parameters	Value
Type	4 cylinder inline, naturally aspirated
Bore × stroke	100 × 105 mm
Compression ratio	17.5:1
Swirl ratio	3.4
Type of combustion chamber	Ω type

Table 3
Injection system specification.

Parameters	Value
Mass of fuel injected/injector/nozzle	5 mg
Spray angle	160-degree
Spray cone angle	8-degree
Holes no./nozzle diam.	6/0.24 mm
Start of the injection timing	10°BTDC