Fuel 260 (2020) 116414

Contents lists available at ScienceDirect

Fuel

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

Full Length Article

Impact of natural gas injection strategies on combustion and emissions of a dual fuel natural gas engine ignited with diesel at low loads

Jinwen You, Zhongchang Liu, Zhongshu Wang*, Dan Wang, Yun Xu

State Key Laboratory of Automotive Simulation and Control, Jilin University, Changchun 130025, China

ARTICLE INFO

Keywords:
Dual fuel engine
Natural gas
Injection timing
Injection direction
Injection position

ABSTRACT

Previous studies have shown that diesel ignited natural gas dual fuel engine is multi-point ignition, so a more uniform mixture of natural gas and air is conducive to engine combustion and emissions. To improve engine combustion and emission by improving mixture uniformity, the effects of natural gas injection timing, direction and position on combustion and emissions were studied experimentally on a 6-cylinder turbocharged intercooled diesel/natural gas dual fuel heavy-duty engine at low loads. The natural gas injection timing changes from 220 °CA BTDC (before top dead center) to 420 °CA BTDC. Natural gas injection nozzle lengthened by 2 cm (changing position) and downward injection (changing direction) were studied. The experiments kept the total fuel quantity and diesel injection strategy unchanged. The results show that advanced natural gas injection timing can improve mixture uniformity and engine combustion and emission, but too early injection timing will involve a part of natural gas scavenging and a little part of natural gas is concentrated at the bottom of the combustion chamber, making engine combustion and emission performance worse. The optimum injection timing of this engine is about 300 °CA BTDC. Pmax (maximum of cylinder pressure) has good linear relationship with PHRR2 (the second heat release rate peak) under the change of injection timing. Natural gas injection nozzle lengthened by 2 cm (B strategy) makes the combustion and emissions worse. Natural gas downward injection (C strategy) can improve the combustion and emissions. When λ is 1.9 and compared with original injection strategy (A strategy), the Pmax of C strategy rises 5.3%, and CO and THC decrease 12.9% and 19.9% respectively. In addition, the effect of natural gas injection timing on mixture uniformity was carried out by simulation and there came similar conclusions with previous studies.

1. Introduction

With the increasing energy crisis and environmental problems, more and more researchers are looking for high-efficiency and low-emission alternative fuels to replace traditional fuels [1–3], such as natural gas [1,2] and LPG [3]. Natural gas has attracted more and more attention because of its advantages as alternative fuels. Natural gas has the advantages of high H/C ratio, high octane number, abundant resources and low price [1,2,4]. In recent years, CI natural gas engine has attracted many research institutes because of its superiority in high compression ratio [5–7].

Diesel-ignited natural gas engines are mostly modified from diesel engines. Compared with diesel engines, dual-fuel engines can reduce NOx and soot emissions [5,11]. However, compared with diesel engine, dual fuel engine has the problems of low load thermal efficiency and high THC emission [5,11]. Some studies have shown that thermal efficiency and emissions can be improved by optimizing diesel injection timing [8,9,15,16]. RG Papagiannakis et al. studied the impact of diesel fuel injection timing on the performance and emissions of a natural gas-diesel engine at various load [8,10]. The results showed that a restricted increase in the diesel fuel injection timing could be a promising solution for engine efficiency improvement and CO emission mitigation. At the same time, some studies also show that the current problems of low thermal efficiency and high emissions can be improved by multiple injection of diesel oil [12–15]. Min Xu et al. [12,15,17] and Amin Yousefia et al. [13] have studied the impact of diesel split injection on emissions and thermal efficiency of natural gas/diesel dual-fuel engine. The results showed that closely pre-injection operations leaded to the advance of SOC which intensified combustion of in-cylinder mixture, thereby resulting in higher cylinder pressure and HRR (heat release rate), as well higher NOx emissions and lower HC and CO emissions. Other studies have shown that the natural gas energy substitution rate has a great influence on the emission and combustion of dual fuel engines. [18,19,22]. Amin Yousefi et al. [21] and Jun Shu et al. [20] had

* Corresponding author.
E-mail address: wangzhongshu@jlu.edu.cn (Z. Wang).

https://doi.org/10.1016/j.fuel.2019.116414
Received 31 July 2019; Received in revised form 7 October 2019; Accepted 10 October 2019

Nomenclature

ATDC	after top dead center
ABDC	after bottom dead center
BBDC	before bottom dead center
BTDC	before top dead center
CA	crank angle
CO	carbon monoxide
CO_2	carbon dioxide
CI	compression ignition
dQ	heat release rate
DR	dilution ratio
EGR	exhaust gas recirculation
NOx	nitrogen oxides
NG	natural gas
CNG	compressed natural gas
P	cylinder pressure
Pmax	maximum of cylinder pressure
ppm	parts per million
PHRR1	the first heat release rate peak
PHRR2	the second heat release rate peak
SI	spark ignition
THC	total hydrocarbon
T_{inj}	natural gas injection timing
TIVO	intake valve opening timing
TIVC	intake valve closing timing
TEVC	exhaust valve closing timing
TDI	diesel injection timing
λ	the air excess ratio

studied the impact of natural gas energy fraction on the performance and emissions of natural gas engine ignited with diesel. The results showed that a drastic reduction of NOx emissions was observed and combustion tended to deteriorate in comparison with that of only diesel combustion. And intake throttling can improve combustion and emissions of dual fuel engines. [23–25]. Jinbao Zheng et al. [23] had studied the effect of equivalence ratio on combustion and emissions with a low compression ratio of 14.2 in a dual fuel 6-cylinder engine. The results showed peak heat release rate and exhaust gas temperature increased, and decrease of combustion duration is obtained due to the high equivalence ratio in dual-fuel ignition mode. Rakesh Kumar Maury and Prashant Mishra [26] had studied the performance of EGR of a dual fuel (natural gas port injection and diesel pilot injection) engine. The results showed EGR has negligible effect on thermal efficiency in dual fuel operating range. Amir-Hasan Kakaee et al. [27] have studied the influence of fuel composition of natural gas on combustion and emissions characteristics of natural gas/diesel engine. The results showed the gas with higher Wobbe number (WN) displayed higher peak pressure, temperature and NOx emissions, and lower unburned hydrocarbon (UHC) and carbon monoxide (CO) emissions. Zuohua Huang et al. [44–46] studied on binary fuel ignition with n-heptane (diesel surrogate). The results shown that the ignition of n-heptane was mainly controlled by equivalence ratio, n-heptane blending ratios in the mixture. These results will be helpful for the study of auto-ignition characteristics and combustion process of natural gas/diesel dual fuel engine.

Of course, the influence of natural gas injection strategies on natural gas engine is also very important to engine performance. Some researchers had studied the influence of natural gas injection timing in direct-injection SI natural gas engine [28–30,33]. Tao Wang et al. [29] carried out that the in-cylinder velocity magnitude increases and a relatively richer mixture is distributed around the ignition position as fuel is injected later, which contributes to better combustion. While, some others had studied the effect of natural gas injection timing on the combustion performance and emissions in a dual-fuel engine fueled with diesel and natural gas [31,32]. Bo Yang et al. carried out that properly retarding natural gas injection timing could reduce the flame development duration and CA50 under low and part engine loads. Antonio P. Carlucci et al. [34] studied the effects of methane supply method on combustion and emissions in diesel -methane dual fuel engine. In the experiment, Antonio P Carlucci [35] coupled three natural gas injection positions with two intake ports to produce seven intake conditions. The results showed that methane supply method was a very effective strategy to reduce unburned hydrocarbons and nitric oxides concentrations, especially when implemented with variable intake geometry systems. Previous studies have shown that diesel spray produced multiple ignition points throughout the chamber, resulting in multiple flame fronts and a comparatively faster burn rate [5]. So the mixing uniformity of natural gas and air has a great influence on combustion and emissions.

Enzhe Song et al. [43] studied the effects of nozzle structure on the gas mixture uniformity in an MPI gas engine. The results shown that changing nozzle structure can affect uniformity of the intake gas mixture in a natural gas engine. What's more, IY Ohm et al. [42] studies the effects of injection timing on the lean misfire in an MPI spark ignition engine. The results show that changing natural gas injection timing can achieve axial stratification. While, very little research has been done on natural gas injection strategies for natural gas/diesel dual fuel engine with natural gas intake port injection. So it is necessary to study the effect of natural gas injection strategies on combustion and emission by mixture uniformity. In addition, in order to prove that the combustion is affected by adjusting the mixture uniformity with various natural gas injection timing and explain the reason of the experiment clearly, a simulation study of dual fuel engine was carried out. The following experiments were conducted on a 6-cylinder turbocharged intercooler diesel/natural gas dual fuel heavy-duty engine at 1335r/min and 25% load conditions. During the experiments, the total fuel quantity, the natural gas percentage energy substitution rate (PES) (90%), diesel injection strategies were unchanged with no EGR.

2. Experimental work

2.1. Experimental setup

The engine selected for this study was an 8.6L, four valves (two intake valves and two exhaust valves), 6-cylinder, turbocharged, intercooler diesel/natural gas dual fuel engine. The technical specifications of the engine are given in Table 1.

Fig. 1 shows a schematic of the engine experimental setup. Based on the electronic control system (ECU) of the original diesel engine, a set of

Table 1
Detailed technical specifications of the test engine.

Engine parameters	Specifications
Bore × Stroke	112 × 145 mm
Number of cylinders	6
Displacement	8.6 L
Rated power/speed	260 kW/2100 rpm
Rated torque/speed	1500 Nm/1400 rpm
Compression ratio	17.2:1
combustion chamber	ω
Number of injector nozzle holes	8
Intake valve opening timing	40 °CA BTDC
Intake valve closing timing	50 °CA ABDC
Exhaust valve opening timing	90 °CA BBDC
Exhaust valve closing timing	50 °CA ATDC