Applied Thermal Engineering 109 (2016) 619–629

Contents lists available at ScienceDirect

Applied Thermal Engineering

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

Research Paper

Effect of fuel injection timings on performance and emissions of stratified combustion CNGDI engine

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HIGHLIGHTS

- Compressed natural-gas direct injection engine with stratified combustion is tested.
- The highest power, torque, mean effective pressure and lowest brake specific fuel consumption is at EOI 120 BTDC.
- Lambda is shown a lean mixture at all combustion conditions that decreased fuels' consumption.
- Carbon dioxide (CO_2) emission was high at 120 BTDC on the high engine speeds.
- The lowest (NO) and (HC) were founded at 120 BTDC.

ARTICLE INFO

Article history:
Received 15 March 2016
Revised 20 August 2016
Accepted 21 August 2016
Available online 23 August 2016

Keywords:
Injection timing
Performance
Emissions
Stratified combustion
CNGDI

ABSTRACT

This study investigates the effect of various injection timings on the performance and emissions of stratified combustion compressed natural-gas direct injection. The engine of 1.6 l, spark ignition, four cylinders fuelled with compressed natural gas was tested. The engine test bed using Kronos software and the exhaust emission were recorded using portable exhaust gas analyser Kane-May. All tests were occurred under wide throttle open with various injection timings (EOI 120, EOI 180, EOI 300, EOI 360) BTDC. Results show high power, torque and brake mean effective pressure (BMEP) at 120 BTDC. The lowest brake specific fuel consumption (BSFC) is at 120 BTDC. Lambda is shown higher than one, which is mean lean mixture air-fuel. Carbon monoxide (CO) emission is low at 360 BTDC at low speeds but at high speed, it was low at 120 BTDC. Carbon dioxide (CO_2) emission was high at 120 BTDC on the high engine speeds. The lowest (NO) and (HC) were founded at 120 BTDC. However, the combustion pressure and the PV were recorded for all injection timings under various engine speeds.

1. Introduction

The aim of the stratified combustion engine is to combine the benefits of the petrol SI (spark ignition) for controlled and complete combustion of the charge and diesel engine's CI (compression ignition) for lean burning and higher compression ratios/efficiencies in a single unit [1]. Charge stratification means providing different F/A mixtures at various places in the combustion chamber – a relatively rich mixture near the spark plug and a leaner mixture into the rest of the combustion chamber [2]. The enhanced fuel economy is mainly due to lean, stratified combustion, and reducing the pumping loss at fractional load conditions [3]. Furthermore, to an improved fuel economy the important choice as alternative fuel compressed natural gas for many reasons; high-octane number, fast flame speed, engines can operate with high compression ratio, low emission and low price compared with traditional fuel (petrol and diesel) [4]. The CNG air fuel ratio is 17.23 so the percentage of fuel is not as much of compared to other fuels (gasoline 14.37, diesel 14.4) [5].

The lean combustion limit for CNG direct injection is influenced on the timings of injection and ignition. Injection timing is a very important parameter for realizing better combustion in CNGDI. For stratified combustion engine, natural gas is injected at the late of compression stroke with suitable injection timing to assist the engine to have stable operation at a very lean overall mixture [6,7].

With the single-cylinder natural-gas direct injection experiment and compression ratio 8, experiment tested various injection timings. Results showed fuel injection timing had a large influence on the engine performance, combustion and emissions and these influences became largely in the case of late injection cases. Additionally, the volumetric efficiency is reduced with the

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http://dx.doi.org/10.1016/j.applthermaleng.2016.08.127
1359-4311/

advancement of fuel injection timing. Short combustion duration and short heat release duration decrease the level of HC and CO emissions [8]. Furthermore, another experiment using a single-cylinder direct injection spark ignition gasoline fuel with stratified operation was tested. Results are shown for the advanced injection timing; non-luminous blue flame was detected. On the other hand, as the injection timing was delayed, a portion of luminous flame was increased [9]. In additional, experiment results using a single-cylinder gasoline engine direct injection with lean stratified combustion are shown the lean combustion area with a late injection technique, reduced smoke emissions were not achieved when the injection pressure was increased to 20 MPa. Although spray penetration decreased at a higher back-pressure, fuel impingement still caused smoke emissions [10].

A test using a diesel engine single cylinder with different fuel injection pressures and injection timings at constant engine speed of 2500 RPM. Results show that, advanced start of injection increased brake mean effective pressure and brake thermal efficiency, while brake specific fuel consumption and exhaust gas temperature were reduced. Carbon dioxide (CO_2) and hydrocarbon (HC) emissions were also reduced [11]. Another study focused on the influence of injection timing on performance and emissions of diesel engine and other alternative fuels. Advancing injection timing reduced carbon monoxide (CO) and hydrocarbon (HC) emissions. Furthermore, it increased brake thermal efficiency and decrease brake specific fuel consumption [12]. In an experimental using a different load with four cylinders dual-fuel engine, the results indicated that under low and part engine loads, the flame development duration and crank angle where 50% total heat released can be reduced by properly retarding natural-gas injection timing, while the coefficient of variation indicated mean effective pressure increased with retarded natural-gas injection timing [13].

The empirical using four-cylinder natural-gas direct injection stratified combustion is tested. The objective of this investigation is to optimize the effects of injection timing on engine's performance and the emissions.

2. Materials and methods

A 1600 cm^3, 7.6 cm bore, 8.8 cm stroke, 4-cylinder spark ignition engine direct injection filled with compressed natural gas were installed to control CNG operation. The engine specifications are given in Table 1. CNG was used as fuel. The substantial advantage that CNG has in antiknock quality is related to the higher auto ignition temperature and higher octane number compared to that of gasoline as shown in Table 2. Furthermore, CNG has a high air fuel ratio $(A/F)_s$ and heating value with 17.23 and 47.377 (MJ/kg) respectively. The composition of CNG used in Malaysia is as shown in Table 3.

Table 1
Engine specifications.

Parameter	Value	Unit
Number of cylinders	4	–
Type	Inline	–
Capacity	1596	cm^3
Bore	76	mm
Stroke	88	mm
Connecting rod length	131	mm
Crank radius	44	mm
Compression ratio	14	–
Intake valve opening	12	BTDC
Intake valve closing	48	ABDC
Exhaust valve opening	45	BBDC
Exhaust valve closing	10	ATDC
Maximum intake valve lift	8.1	mm
Maximum exhaust valve lift	7.5	mm

Table 2
Combustion related properties of gasoline & CNG.

Properties	Gasoline	CNG
Motor octane number	80–90	120
Molar mass (g/Mol)	110	16.04
Carbon weight fraction (mass%)	87	75
$(A/F)_s$	14.7	17.23
Stoichiometric mixture density (kg/m^3)	1.38	1.24
Lower heating value (MJ/kg)	43.6	47.377
Lower heating value of stoic. mixture (MJ/kg)	2.83	2.72
Flammability limits (vol% in air)	1.3–7.1	5–15
Spontaneous ignition temperature (°C)	480–550	645

Table 3
Typical composition (vol.%) of CNG. *Source:* PETRONAS Research & Scientific Services

Component	Symbol	Volumetric%
Methane	CH_4	94.42
Ethane	C_2H_6	2.29
Propane	C_3H_8	0.03
Butane	C_4H_{10}	0.25
Carbon dioxide	CO_2	0.57
Nitrogen	N_2	0.44
Others	(H_2O+)	2.0

An engine control system and portable exhaust gas analyser were used for controlling engine operations and recording engine performance and emission's data. The KRONOS 4 software is the software of the test bench as shown in Fig. 1. Using water cooling, which consists of cooling tower, differential pressure switch, pipe strainer, filter and actuators (control moving water between dynamometer and engine). Fuel system had the pressure regulator to keep fuel pressure around 20 (Bar) which enter the combustion chamber. Installing the pressure sensor type (6125B-KISTLER) in cylinder one is to record pressure cylinder with fast test. Construction air mass flow sensor before the throttle valve is to record air mass flow. Using the dynamometer typed FR250 with maximum load 800 (N m) and calibration the torque by control levers and weights. Results were recorded in steady-state condition so ambient pressure, ambient temperature and humidity were noted to estimate air inlet density. Portable exhaust gas analyser Kane-May which is an International Organization of Legal Metrology (OIML) class one certificate was calibrated for each test to get correct results. ECU setting is modified using Motec software by change the end of injection (EOI) 120 BTDC, 180 BTDC, 300 BTDC, 360 BTDC.

The engine was running under full load wide-open throttle. The stratified piston crown is used. The piston crown, the fuel injector and the spark plug are shown in Fig. 2.

3. Results and discussion

3.1. Brake Power

Fig. 3 shows the results of brake power versus engine speed with various injection timings. The ignition timing is fixed for all. From results, the maximum power occurs at EOI 120 BTDC with 54.25 (kW). At all speeds, the power was more at 120 BTDC. It was more than (180, 300, 360) with (1%, 20%, 10.8%) respectively. The reasons of high power are according to high pressure and high-heat release. Additionally, the late of injection timing with high pressure and suitable combustion duration increase the engine performance and will get good propagation flame. Compare to another study by Zeng et al. too late of injection timing will produce insufficient time for the mix fuel-air with long combustion duration and high HC emission. However, the optimum fuel