Fuel xxx (2015) xxx–xxx

Contents lists available at ScienceDirect

Fuel

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

Effect of intake pre-heating and injection timing on combustion and emission characteristics of a methanol fumigated diesel engine at part load

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HIGHLIGHTS

- BTE at light load is improved by 7.3% by raising intake temperature.
- Combustion process is highly affected by intake temperature and injection timing.
- DMDF combustion becomes single-stage combustion as injection timing retarded.
- Soot-NO_x trade-off is completely broken at low intake temperature and high MSP.

ARTICLE INFO

Article history:
Received 27 January 2015
Received in revised form 7 July 2015
Accepted 9 July 2015
Available online xxxx

Keywords:
Dual fuel
Methanol fumigation
Combustion characteristics
Emissions
Light loads

ABSTRACT

Diesel–methanol dual fuel (DMDF) engines at light loads suffer from low thermal efficiency and high unburned percentages of fuel. Pilot fuel injection timing and intake temperature are two important parameters which affect the combustion process in DMDF engines. In present experimental work, the combined effects of intake temperature and injection timing on the performance of a DMDF engine have been studied. The experiments were conducted on a methanol-fumigated diesel engine at 25% of full load and the results concerning performance, combustion characteristics and emissions were analyzed. Results show that the low efficiency at light loads can be improved significantly by raising the intake temperature and advancing the injection timing of direct-injected diesel. Increasing the intake temperature also significantly decreases the heat release rate of premixed combustion and increases the combustion rate of methanol burned by flame propagation. Flame propagation of the methanol–air mixture disappears gradually and DMDF combustion transforms into single stage combustion as the injection timing is retarded. When injection timing is retarded after 4.6° crank angle, misfire occurs at higher methanol substitute percent (MSP) and lower intake temperature, while the auto-ignition of methanol occurs at lower MSP and higher intake temperature. Under DMDF operation, soot and nitrogen oxides trade-off dilemma is completely broken at lower intake temperature and higher MSP.

1. Introduction

Compared with spark-ignition engine, compression-ignition (CI) engine has attracted more attentions due to its better fuel economy with high compression ratio and no throttling loss. However, the conventional CI engine sustains with high nitrogen oxides (NO_x) and particulate matter (PM) emissions. Hence, the heavy-duty CI diesel engine has been a hot topic over the last two decades. Moreover, the sources of fossil fuel are dwindling, which results in raising price of petroleum oil, posing challenges to the availability of fossil fuel. Under these circumstances, the substitute for conventional fuels is significant to address energy security issues. Among the alternative fuels, methanol has received considerable attention as suitable diesel replacement. In particular, methanol is readily available from the conversion of biomass, coal and natural gas [1]. Moreover, the storage, transportation, distribution, and application of methanol are similar to those of traditional

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Abbreviations: DMDF, diesel methanol dual fuel; CI, compression-ignition; PM, particulate matter; DMCC, diesel methanol compound combustion; NO_x, nitrogen oxides; BTE, brake thermal efficiency; EGR, exhaust gas recirculation; LPG, liquefied petroleum gas; CNG, compressed natural gas; ECU, electronic control unit; CA, crank angle; AHRR, apparent heat release rate; ATDC, after top dead center; MSP, methanol substitution percent; BTDC, before top dead center; SOC, start of combustion; FSN, filter smoke number.

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http://dx.doi.org/10.1016/j.fuel.2015.07.032
0016-2361/© 2015 Published by Elsevier Ltd.

fossil oil such as gasoline and diesel as a liquid [2–5]. Therefore, the substitution of diesel with methanol is of great significances in countries such as China which has rich coal reserve, especially the huge amount of coke-oven gas resources [6].

However, the foremost drawback for the utilization of methanol in diesel engines is probably the low cetane number of methanol, which, depending on the measurement method, typically ranges from only 2 to 12 [7]. The very high latent heat of vaporization also weakens its auto-ignition property [8–10]. In this regard, the most favored method to introduce methanol into diesel engines is fumigation, which requires just a minor modification to the original engines as methanol injectors are fixed at the intake manifold [11–13]. However, methanol fumigation is unfavorable for cold start and low load operation. Based on the method of fumigation, Yao et al. [14,15] developed a diesel/methanol compound combustion (DMCC) system. Under DMCC mode, the engine operates on pure diesel at cold start and low speed conditions to ensure cold starting capability and to avoid aldehyde production. At medium to high loads, the engine operates on diesel methanol dual fuel (DMDF) mode, during which methanol is fumigated into intake manifold and the homogeneous air–methanol mixture is ignited by the diesel directly injected. The advantages of DMCC system include the following: (1) there is no cold start difficulty when the engine operates at dual fuel mode, (2) in case of lacking methanol supply, this engine could still run as the diesel cycle by switching from dual fuel mode to neat diesel mode [16] and (3) distinguished from natural gas-fumigated fuel engine, there is no simultaneous reduction of air supply [17], thus the compression pressure and the mean effective pressure of the engine would not be decreased but even boosted with methanol fumigation.

Many previous investigations have been performed with a DMCC system. Recently, using a 4-cylinder direct-injection diesel engine with fumigated methanol, Cheng et al. [18] showed that the concentration of nitrogen oxides (NO_x) is significantly reduced except under full load conditions. There is also a reduction in the smoke opacity and the particulate matter mass concentration. With the same engine setup and operating conditions, Zhang et al. [19] found that under low engine loads, the brake thermal efficiency (BTE) decreases with the increase of fumigation methanol; but under high loads, it is slightly boosted with the increase of fumigation methanol. On a direct injection, turbocharged diesel engine with an electronically controlled unit injection pump, Geng et al. [20] observed that the mass and number concentrations of particulate matter significantly decrease at low and medium loads, while they increase when the tested engine is operated at high loads. Li et al [21] developed a multi-dimensional model to investigate the combustion and emission characteristics of a fumigated methanol and diesel reactivity controlled compression ignition engine. They found that methanol addition is an effective way to achieve the efficient and clean combustion and all the emissions are reduced with moderate methanol addition.

However, the operation of dual fuel engines at lower loads still suffers from lower thermal efficiency and higher unburned percentages of fuel [22–29]. Results from our previous study showed that the worsened DMDF combustion progress resulted in the reduction of BTE from 25% to 22% at light loads, while it was boosted at medium and high load [30]. However, the trend to knock is considerable at high load when engine operates at dual fuel mode. Therefore, numerous researches have also been carried out to improve BTE at light load when diesel engines operate with dual fuel mode. Abd Alla et al. found that the low efficiency and poor emissions at light loads can be improved significantly by advancing the injection timing of the pilot fuel [22]. Huang et al. conducted the experiments in a CI engine fueled with diesel/methanol blend and found that the rapid burn duration and the total combustion duration increased with the advancing of the fuel delivery advance angle, which is more effective at low engine load [31,32]. Paykani et al. found that the use of exhaust gas recirculation (EGR) at high levels seems to be unable to improve the engine performance at part loads [23]. Experiments conducted by Poonia et al. showed that the intake temperature does not seem to have a significant effect on the heat release at these conditions [33]. However, the above researches were all about LPG-diesel (liquefied petroleum gas (LPG)) dual fuel or CNG-diesel (compressed natural gas (CNG)) dual fuel combustion, and there is hardly any researchers conducted the experiment concerning DMDF combustion. In this paper, tests were conducted to investigate the effect of intake pre-heating and injection timing of pilot diesel on the performance, combustion characteristics and emissions on a direct-injected diesel engine fueled with fumigated methanol.

2. Experimental apparatus and method

2.1. Test engine and fuels

The original engine was an in-line four-cylinder, direct injection, turbocharged diesel engine with an electronically controlled unit injection pump. Technical specifications of the engine are listed in Table 1. Fig. 1 shows the schematic of the engine layout. The engine was modified to run on DMDF mode with introducing methanol by 3 electronically controlled methanol injectors fixed at the intake manifold. The methanol was injected at a pressure of 0.4 MPa and the mass of methanol injected was controlled by an electronic control unit (ECU) developed by ourselves. Intake temperature was varied in the range of 35–115 °C by the coordination of an intercooler and an electric heater, with a precision of 2 °C. Injection timing and quantity of diesel were controlled by the ECU of the original diesel engine. The engine was coupled to an electronically controlled hydraulic dynamometer. Engine speed and torque could be controlled by the EMC2020 engine test system, which allowed changing engine speed and load as required.

The pressure trace in cylinder was measured with a Kistler 6125CU20 piezoelectric pressure transducer in series with an AVL 612 IndiSmart combustion analyzer, which had a signal amplifier for piezo inputs. A shaft encoder with 720 pulses per revolution was used to send engine speed, which supplied a resolution of 0.5° crank angle (CA). For each engine operating point, 100 consecutive cycles of cylinder pressure data were recorded. The collected cycles were ensemble averaged to yield a representative cylinder pressure trace, which was used to calculate the apparent heat release rate (AHRR) by the AVL 612 IndiSmart combustion analyzer. Diesel injection timing and injection quality were controlled by the ECU of the original engine. The methanol injection system was wholly independent of the diesel ECU. Diesel and methanol fuel consumption was independently measured gravimetrically using two coriolis meters with a precision of 0.1 g. Gaseous emissions in the exhaust pipe were sampled by a Horiba MEXA 7100DEGR analyzer. Engine coolant temperature and inlet air

Table 1
Parameters of the engine.

Parameters	Value
Number of cylinders	Four in-line
Displacement	4.214 L
Bore × stoke	108 × 115 mm
Compression ratio	17:1
Maximum power	103 kW@1600 r/min
Inlet valve opening	−130.3°CA ATDC
Exhaust valve opening	112.2°CA ATDC
Injection pressure	28 MPa

Please cite this article in press as: Wang Q et al. Effect of intake pre-heating and injection timing on combustion and emission characteristics of a methanol fumigated diesel engine at part load. Fuel (2015), http://dx.doi.org/10.1016/j.fuel.2015.07.032