Fuel 218 (2018) 295–305

Contents lists available at ScienceDirect

Fuel

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

Full Length Article

To extend the operating range of high MSP with ultra-low emissions for DMDF unit pump engine

Bin Wang, Chunde Yao*, Chao Chen, Jun Feng, Han Lu, Luyu Feng

State Key Laboratory of Engines, Tianjin University, Tianjin 300072, China

ARTICLE INFO

Keywords:
Ultra-low emissions
Exhaust gas recirculation
Combustion characteristics
Diesel engine

ABSTRACT

Experiments were conducted to extend the operation range of Diesel/Methanol Compound Combustion (DMCC), as to further reduce the emissions of Diesel Methanol Dual Fuel (DMDF) engine at full load. The engine was operated under 100% of full engine load at three different speeds of 1660 r/min (speed A), 2090 r/min (speed B), and 2520 r/min (speed C), respectively, as well as 75% of full load at the speed of 1660 r/min. At full load, the results showed that the methanol substitution for diesel proportion (MSP) of DMDF engine could be greatly extended to 80% by using suitable combustion control strategy, which was restricted less than 15% in the previous study. Simultaneously, the knock tendency was reduced into an unobservable magnitude at such a high MSP. Furthermore, the nitrogen oxides (NOx) emission could be significantly reduced, and the lowest NOx emission was down to 1.25 g/kW.h at MSP73 under A75 test point. Meanwhile, the soot emission could be reduced to ultra-low level when the diesel fuel injection duration is shorter than the ignition delay of diesel combustion. The lowest soot emission is decreased to 0.004 g/kW·h at MSP72 under B100 test point, which is lower than the requirement of EURO VI limitation. The results demonstrated that methanol has the advantage of smokeless and flameless while burning, thus soot production could be reduced when the engine fueled with more methanol fuel. The testing results also showed that the total hydrocarbons (THC) and the carbon monoxide (CO) emissions are increased with increasing MSP.

1. Introduction

In recent years, in order to reduce nitrogen oxides (NOx) and Particulate Matter (PM) emissions of diesel engine, many kinds of advanced engine combustion strategies have been proposed, such as Homogeneous Charge Compression Ignition (HCCI), Premixed Charge Compression Ignition (PCCI), and Reactivity Controlled Compression Ignition (RCCI) [1–3]. Low Temperature Combustion (LTC) is the key to achieving ultra-low emissions of diesel engine. LTC is enabled by the control of charge density and dilution, coupling with the modulation of fuel injection parameters [4]. Due to its low emission and high thermal efficiency, HCCI has been extensively researched [5–8]. However, the ignition time of HCCI entirely relies on chemical reactions [9], and the cylinder pressure exceeds the designed limit at high load [10], which make it difficult to be practical utilization. One of the most promising combustion concepts is HCCI combustion strategy implemented in modern direct injection diesel engines through PCCI, where fuel and air are not fully homogenous. However, the ignition timing is determined by the main injection timing with PCCI [11]. The NOx and soot emissions are reduced to a certain extent with PCCI, but the main injection fuels are still faced with the same problems as traditional combustion mode [12–14]. Currently, RCCI becomes the most hotspot of recent researches. Quasi-homogeneous combustion can be achieved by RCCI, and the moment of ignition is still determined by the main injection timing [15,16]. However, the operation range of RCCI is relatively narrow [17,18], and it is not able to realize wide-range practical application.

Premixed high-octane fuel is a way to achieve low temperature combustion, and high octane fuels mainly include gasoline, ethanol, natural gas and methanol [19,20]. Compared with other fuels, methanol has higher oxygen content, flame propagation speed and latent heat of vaporization [21], so methanol is widely used by researchers.

Abbreviations: DMDF, diesel methanol dual fuel; MSP, methanol substitution percent; EGR, exhaust gas recirculation; NO_x, nitrogen oxides; THC, total hydrocarbons; CO, carbon monoxide; PM, particulate matter; HCCI, homogeneous charge compression ignition; PCCI, premixed charge compression ignition; RCCI, reactivity controlled compression ignition; LTC, low temperature combustion; NO, nitrogen oxide; DMCC, diesel methanol compound combustion; IRD, infrared detector; FID, flame lionization detector; CLD, chemiluminescence detector; BTE, brake thermal efficiency; BSFC, brake specific fuel consumption; ECU, electronic control unit; CA, crank angle; HRR, heat release rate; TDC, top dead center; ATDC, after top dead center; BTDC, before top dead center; PRR, pressure rise rate; SOC, start of combustion

* Corresponding author at: Tianjin University, No. 92 Weijin Road, Nankai District, Tianjin 300072, China.
E-mail address: arcdyao@tju.edu.cn (C. Yao).

https://doi.org/10.1016/j.fuel.2018.01.028
Received 26 August 2017; Received in revised form 19 December 2017; Accepted 8 January 2018

Methanol premixed combustion can be realized by blend and fumigation method. For blend method, the homogeneous mixture of methanol and fresh air is unable to be formed. At the same time, methanol is difficult to be mingled with diesel. Therefore, the scope of blend method application is limited [22–24]. For fumigation method, methanol is injected in the intake manifold, the homogeneous mixture of methanol and fresh air is formed in the intake and compression stroke [25]. Through reasonable combustion controlling method, fumigation method not only improves the combustion efficiency but also significantly reduces emissions [26,27]. Li et al. [28] experimentally investigated the optimization of an RCCI engine fueled with methanol and diesel. They found that the RCCI combustion with high methanol fraction and advanced start of injection exhibited higher fuel efficiency and lower emissions. Sangjun et al. [29] investigated the effect of methanol addition on the performance and NOx emission of a diesel engine using one-dimensional engine cycle simulation. They found that the cylinder pressure and temperature is reduced by the increase of methanol content; the BSFC was increased to 28.0% and the NOx emission was decreased to 47.5% on average when the methanol energy fraction was 15%.

Cheng et al. proposed a DMCC scheme [30], which belongs to the fumigation method. In the DMCC system, single diesel fuel mode is used for engine cold starting and for low load operation, and then switches to the DMDF mode at the rest of operating conditions [31,32]. Three problems in applying methanol to compression ignition engine are solved by DMCC: 1) methanol is hardly mingled with diesel, 2) the high temperature of auto-ignition, 3) bad vaporization [33,34]. Currently, DMCC scheme has been widely applied to the heavy-duty vehicles in China. However, previous study showed that the operation range of DMCC was restricted by four boundaries: partial burning, misfire, roar combustion and knock [35]. At high load, higher MSP is restricted as the knock tendency is more severe. Wang et al. found that as the engine load continued to rise, engine knock occurs. The maximum MSP continues to fall down to about 10% of the full load, which was limited by its peak cylinder pressure of 15 MPa [35]. Wei et al. [34] found that at the high engine load of 0.88 MPa, the MSP was limited to 40% and the maximum in-cylinder pressure reached to 14 MPa, which was close to the mechanical limit of the engine. Saxena found that [36] the premixing ratio limit of the fuels was varying with engine load based on ignition timings, and the maximum methanol premixing ratio was 30% at 100% engine load.

Boundaries existed in DMCC hinder the development of the application of methanol to compression ignition engines which can meet more stringent legislation on exhaust emissions. In this article, tests were conducted to look for a technical routine to increase the MSP, and extend the operation range at high load, at the same time to reduce the emissions of DMDF engine. The effects of MSP on the exhaust emissions and engine performance were experimentally investigated in a 4-cylinder turbocharged intercooled unit pump diesel engine with EGR.

2. Experimental apparatus and method

2.1. Test engine and fuels

Fig. 1 shows the schematic of the engine layout. The original engine is an in-line four-cylinder, direct injection, turbocharged diesel engine with an electronic controlled unit injection pump. Technical specifications of the engine are listed in Table 1. The engine was modified with a methanol rail, and four methanol injectors were added to the intake manifold. The methanol was injected at a pressure of 0.5 MPa to form homogeneous methanol/air mixture. The mass of methanol injected was controlled by an electronic control unit (ECU) developed by ourselves. Injection timing and quantity of diesel were controlled by the ECU of the original diesel engine, and the methanol injection system is wholly independent of the diesel ECU. The engine was coupled to an electronical controlled hydraulic dynamometer. Engine speed and torque could be controlled by the EMC2020 engine test system. The consumption of diesel and methanol fuels was independently measured gravimetrically using two Coriolis meters with a precision of 0.1 g. Intake air temperature was controlled by the coordination of an intercooler and an electric heater with a precision of 2 °C [35]. The temperature of diesel and methanol fuel was fixed at 25 °C, and it was controlled by the PID Temperature Controller. Engine coolant temperature and inlet air temperature were recorded by a resistance thermometer sensor, and exhaust temperature was recorded using K type thermocouples with an accuracy of 0.1 °C. The diesel used in the test was commercial 0# diesel fuel, of which sulfur content was less than 10 ppm, and the properties of diesel were provided by the manufacturer. The implementation standard of diesel fuel was China standard DB11/239-2012. The cetane number of the fuel was measured according to China standard GB/t 386-2010 (standard test method for cetane number of diesel fuel oil). The methanol was industrial grade with a purity of 99.99%. Table 2 shows the general properties of two fuels. The amount of EGR is regulated by adjusting the EGR valve opening and the backpressure, which is regulated by an exhaust backpressure valve downstream of the exhaust pipe. Shell and tube exchanger was used to reduce EGR temperature by fresh water. In this work, the EGR rate is defined as the ratio of CO_2 concentrations in the intake and exhaust gases.

The gaseous emissions were measured both in the intake and exhaust systems by a Horiba MEXA-7100 DEGR analyzer, including CO, HC and NOx emissions. THC was measured by a flame lionization detector (FID) analyzer. CO_2 and CO were measured with an infrared detector (IRD) analyzer. NOx and NO concentrations were measured with a chemiluminescence detector (CLD) analyzer. Soot emissions were measured by a smoke meter (415SE; AVL). The in-cylinder pressure trace 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). Table 3 shows the accuracy of the measurements. For each engine operating point, 500 consecutive cycles of cylinder pressure data were recorded. The collecting cycles were ensemble averaged to yield a representative cylinder pressure trace, which was used to calculate the apparent HRR (AHRR) and in-cylinder mean charge temperature by the AVL 612 IndiSmart combustion analyzer.

2.2. Engine operating method and test conditions

The engine was operated under 100% of full engine load at three different speeds 1660 r/min, 2090 r/min and 2520 r/min, as well as 75% of full load at the speed of 1660 r/min. The test conditions at different speeds, torque and MSP are given in Table 4. Injection timing was near to the compression TDC which could avoid the in-cylinder pressure beyond the design limit of the engine, and it could also keep the corresponding crank angle of the maximum in-cylinder pressure at 15–18 °CA ATDC. However, injection timing was needed to be advanced at 2520r/min. Because at higher engine speed, the reaction time of diesel fuel at low temperature was shorter than that of lower speed. In the test, the EGR valve was fully opened at 1660 r/min, if the gas pressure before the turbine was lower than the inlet pressure, the backpressure was needed to be increased. First, tests were conducted at pure diesel mode to obtain the performance, combustion and emission characteristics of the baseline engine. Then the injection mass of diesel was reduced, and the rest of input energy was supplied by methanol until the engine misfired. Next, injection timing and EGR rate were varied to investigate their effects on DMDF engine. Finally, the same procedure was repeated at other speed and loads. Before data logging, each test point was maintained about 3 min to ensure the engine parameters were stable, and experimental data was the weighted average of the data stream. Based on the engine load and the mass