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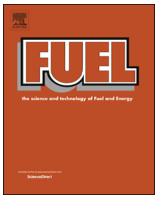

Full Length Article

Effect of diesel late-injection on combustion and emissions characteristics of diesel/methanol dual fuel engine

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ABSTRACT

The late-injection strategy (close after main-injection) of common-rail diesel engine is capable of enhancing combustion turbulence and reducing particulate matter (PM) emissions. In this work, experimental study was performed to investigate the effect of diesel late-injection on combustion and emissions characteristics of diesel/methanol dual fuel (DMDF) engine. The experiments were carried out at a constant engine speed of 1340 rpm and a medium load of 1.0 MPa brake mean effective pressure (BMEP) with various methanol substitution ratio (MSR) on a common rail DMDF engine. The results reveal that higher MSR caused simultaneous decrease of nitric oxides (NO_x) and accumulation mode PM emissions in spite of late-injection strategy. In particular, an augment of up to 12.8% in nucleation mode particle number (PN) was observed as MSR increased from 15% to 50%. A small late-injection of diesel (< 7.5 mg/cycle) had little impact on in-cylinder pressure and heat release rate (HRR). However, enhanced or retarded late-injection led to a decline in peak gas mean temperature (GMT) but an increase in later combustion temperature. With late-injection quantity (LIQ) increased from 1.5 mg/cycle to 7.5 mg/cycle, both NO_x and accumulation mode PM decreased. Meanwhile, nucleation mode PM was almost unchanged and even rebounded slightly with overmuch LIQ (7.5 mg/cycle) in DMDF mode. Retarded late-injection led to a continuous reduction of 12.9% at most in NO_x emissions in DMDF operation. As the interval between main-late injections (MLII) increased from 800 μs to 1200 μs, a trade-off relation appeared between nucleation mode and accumulation mode particles due to the mutual transformation of them. Furthermore, too delayed late-injection (MLII $>$ 1200 μs) induced a simultaneous increase of particles with different size.

1. Introduction

Reducing exhaust emissions of diesel engine, especially nitric oxides (NO_x) and particulate matter (PM) emissions, remains a major challenge to engine manufacturers and internal combustion engine researchers [1,2]. A variety of advanced technologies of interior purification and exhaust after-treatment were researched and developed forced by increasingly strict emission regulations around the world. These attempts and applications include ultra high pressure injection [3], low temperature combustion (LTC) [4], exhaust gas recirculation (EGR) [5], selective catalytic reduction (SCR) [6] and diesel particulate filter (DPF) [7] etc.

Taking the oil depletion and environmental pollution into account, many researchers have also worked to develop clean alternative fuels for petroleum, such as natural gas [8], biodiesel [9], alcohol ether fuels [10] and hydrogen [11], etc. Among these fuels, methanol is considered one of the competitive alternative fuels for petroleum due to its extensive production sources, convenient storage and low cost. Methanol can be synthesized from a variety of raw materials such as coal, oil, natural gas, renewable biomass, and even CO_2 [12]. In addition, methanol has a cooling effect due to its higher latent heat of vaporization during the combustion process, resulting in lower thermal NO_x during its combustion process. Furthermore, the adoption of methanol suppress the generation of precursor of soot, such as PAHs in burning process supported by high oxygen content (50%) and no C−C bond of methanol [13]. Therefore, previous studies [14,15] have shown that the utilization of methanol in diesel engines can simultaneously reduce the NO_x and PM emissions.

Abbreviations: NO_x, nitric oxides; PM, particulate matter; PN, particle number; DMDF, diesel/methanol dual fuel; DPOC, diesel oxidation catalyst coupled with particulate oxidation catalyst; HSDI, high speed direct injection; LIQ, late-injection quantity; MLII, the interval between main-late injections; LTC, low temperature combustion; EGR, exhaust gas recirculation; SCR, selective catalytic reduction; DPF, diesel particulate filter; PAHs, polycyclic aromatic hydrocarbons; H_2, hydrogen; HC, hydrocarbon; CH_4, methane; CO, carbon monoxide; TDC, top dead center; ATDC, after top dead center; BTDC, before top dead center; ECU, electronic control unit; ESC, European steady-state cycle; CA, crank angle; CHN, China; HRR, heat release rate; GMT, gas mean temperature; COV_{IMEP}, coefficient of variation of indicated mean effective pressure; H_2O_2, hydrogen peroxide; OH·, hydroxyl radicals; N_2, nitrogen; NO, nitric oxide; NO_2, nitrogen dioxide; N_2O, nitrous oxide; HSDI, high speed direct injection

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Nomenclature

BMEP	brake mean effective pressure
MPa	*MSR*, methanol substitution ratio, %
Dp	diameter of particles nm
$\dot{m}_{D'D}$	consumption rate of diesel in pure diesel mode, kg/h
$\dot{m}_{D'DMDF}$	consumption rate of diesel in DMDF mode, kg/h
Φ_M	methanol equivalence ratio
Φ_G	global equivalence ratio
λ_D^s	stoichiometric air/fuel ratio of diesel
λ_M^s	stoichiometric air/fuel ratio of methanol
$\dot{m}_D$	consumption rate of diesel, kg/h
$\dot{m}_M$	consumption rate of methanol in DMDF mode, kg/h
$\dot{m}_{air}$	mass flow rate of air consumption, kg/h

In previous studies, the application modes of methanol in compression ignition engine mainly include blending, fumigation, and direct dual injection etc [13,15]. Among these methods, methanol fumigation has become the main route of methanol application in compression ignition engines due to flexible operation and permit of high methanol substitution ratio (beyond 70%) [16]. Generally, in diesel/methanol dual fuel (DMDF) engines with methanol fumigation, premixed methanol/air mixture is formed during the intake and compression strokes, which will be ignited by direct injection of diesel in cylinder [17]. Previous investigation has proved the great potential of DMDF combustion in improving thermal efficiency and exhaust emissions [18]. Recent research by Wei et al. [19] shows that methanol fumigation combined with DPOC (diesel oxidation catalyst coupled with particulate oxidation catalyst) can help the Euro IV baseline engine equipped with EGR system meet Euro V emission regulation without the assist of urea.

However, with the increasingly serious environmental pollution, the exhaust emissions from motor vehicles, especially diesel vehicles, have become the focus of social attention. As emissions regulation tightened gradually, the reduction of NO_x and PM from diesel becomes more and more challenging [7]. The technical measures already adopted on DMDF engines are not sufficient to meet the demand of Euro VI and more stringent emissions regulations. Therefore, it is a necessary and urgent assignment to investigate new technical strategies to further reduce the exhaust emissions from DMDF engines. As we know, methanol is a low-reactivity fuel due to its low cetane number, whose ignition and combustion characteristics are highly depended on pilot diesel and in-cylinder atmosphere in DMDF mode [20].

Based on these above, the diesel injection strategy has a dominant influence on efficiency and pollutant emissions of dual fuel combustion. Multiple-injection of diesel by means of high pressure common rail system allows for flexible and precise injection control. Therefore, multiple-injection has become an important means to optimize combustion process of diesel [21], and was considered to be a necessary technical route to achieve ultra-low emissions for diesel engines in the future [22]. In particular, the late-injection, some researchers calls it “post-injection”, which injects a handful diesel close after main-injection into cylinder, has shown the effectiveness on reduction of exhaust emissions from diesel engines [23–28].

Hotta et al. [23] found the reduction of soot with late-injection strategy in a high speed direct injection (HSDI) diesel engine. They ascribed it to the improved turbulence and increased in-cylinder temperature due to the combustion of late-injection fuel. Hardy and Reitz et al. [27] proved that a late injection can lead to a slight decrease of PM attributed to enhanced in-cylinder charge mixing caused by the shock of late-injection fuel. Further systematic research by Desantes et al. [28] indicates that a small late-injection close coupled with main injection can effectively reduce PM emissions due to the accelerated late-combustion process. O’Connor et al. [25] found that the interaction of fluid, heat and chemical reactions between main and late-injection resulted in a decrease in hydrocarbon (HC) emissions. Liu et al. [26] showed that NO_x and soot emissions decreased simultaneously as late-injection delayed in HSDI diesel engines. These above studies have proved that late-injection has the effectiveness in reducing the NO_x and PM emissions from conventional diesel engines due to reduced main-injection quantity, enhanced in-cylinder turbulence and increased temperature in late combustion.

To the best of our knowledge, the potential of late-injection has rarely investigated in optimizing of DMDF combustion. Based on this, the objective of this study is to further reduce the original emissions of DMDF engine using diesel late-injection strategy. In this work, the effect of late-injection strategy on combustion and main emissions (include NO_x and PM) were experimentally investigated in detail on a DMDF engine. The experiments were conducted at a constant engine speed of 1340 rpm and a medium load of 1.0 MPa BMEP in various MSR operations (from 0 to 50%). The combustion characteristics, NO_x and PM emissions as well as equivalence ratio under different operating conditions were discussed and investigated. The knowledge gained in this paper contributes to developing optimal calibration strategy to achieve ultralow emissions targets on DMDF engines.

2. Experimental setup and procedure

2.1. Test setup and fuels

The tests were carried out in a 6-cylinder common rail, turbocharged, intercooled, heavy duty diesel engine, whose intake manifold was added with three electrically controlled methanol injectors to run in DMDF mode. The technical specifications of the engine are presented in Table 1, and the experimental setup is schematically showed in Fig. 1. The engine was equipped with a hydraulic dynamometer and a corresponding closed-loop control system to regulate the operating conditions accurately. The methanol and diesel fuel were supplied separately by two sets of independent fuel supply systems. The methanol injection pressure was maintained at 0.42 MPa, while the injection timing and pulse width were controlled by a specialized electronic control unit (ECU) according to engine speed, pedal position and coolant temperature. Moreover, the diesel fuel injection strategy can be regulated flexibly on INCA 7.0 platform with ES590 hardware manufactured by ETAS company.

In this study, the port injected fuel is methanol with purity of 99.9%, and the directly injected fuel is −10# commercial CHN V diesel with sulfur content less than 10 ppm. The physicochemical properties of the methanol and diesel used in this study are listed in Table 2.

Table 1
Specifications of the test engine.

Model	Specifications
Engine Type	In-line,6-Cylinder, 4-stroke
Bore/stroke (mm)	126/130
Engine displacement (L)	9.726
Compression ratio	17.0
Fuel Injection system	High pressure common rail
Combustion chamber	ω bowl in piston
Intake valve open	−36°CA ATDC
Intake valve close	246°CA ATDC
Exhaust valve open	−258°CA ATDC
Exhaust valve close	30°CA ATDC
Max.torque/speed (Nm/rpm)	1550/1200–1400
Rated power/speed (kW/rpm)	247/1900